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STRAIN GAUGE BASED MICROSENSOR FOR SPATIAL STRESS ANALYSIS IN BUILDING STRUCTURES

Falk Tegtmeier and Manfred Peters

Mechanics and Acoustics Division
Physikalisch-Technische Bundesanstalt
D-38116 Braunschweig, Germany

Abstract: Strain gauges are suitable for stress analysis in buildings due to their high signal resolution. A long-term supervision requires an encapsulated adaptation because of the chemical sensibility of strain gauge applications. The sensor lifetime depends on the encapsulation seal protecting the strain gauge. Therefore, different concepts were examined and adapted to the specific requests in climatic simulation facilities. The mechanical adaptation of the sensor is decisive for its measuring uncertainty. Various concepts were investigated and a process of mechanical distortion of two conical bodies developed such that the useful measuring range covers the range of elastic deformation of construction steels.

Keywords: surveillance, stress analyses, strain gauge, multicomponent, encapsulation

1. INTRODUCTION

In Europe a sustained structural change in building policy is taking place. With the total value of the current construction volume in the Republic of Germany rated at almost 20 billion Euro, and for an assumed lifetime of 50 to 100 years, a substantial financial outlay will be required for the future restoration and maintenance of buildings. It is of great importance to the political economy that these costs be a minimum. To develop a building supervision system for early damage prognosis and minimize restoration costs, a collaborative research centre (SFB) of the German research corporation (DFG) has been established at the Technical University of Braunschweig. A sub-project is currently underway at the PTB. To determine the stress situation in buildings, and also to detect weak spots by the changes in transfer states, compact multicomponent force transducers are being developed for implementation in a structure.

2. SCOPE

The sensor transfers the measurand strain from the measuring drill to the strain gauge encapsulated within it. The uncertainty of the measurement depends critically upon the adaptation model which describes the mechanical coupling of the drill inner surface in the structure to the strain gauge inside the sensor. The sensor lifetime is determined by the strain gauge encapsulation. For the development of the adaptation model and the encapsulation, the mechanical and climatic environmental conditions had to be simulated in the laboratory.

Dummy structures, which can demonstrate typical damage scenarios, help to determine the appropriate measuring range and uncertainty for damage detection. For the calibration special calibration devices are employed, besides the future utilization of a multi-component force and torque reference machine.

Fast forward climatic ageing in water-baths and climate chambers allow the optimization and best choice of encapsulation to be made. At the same time the lifetime prognosis can be established for the sensor.

3. ADAPTATION MODEL

A suitable adaptation model was determined out of numerous variations which belong to four basic types: clamping, screwing, adhesion and moulding. For choice and optimization, different systems to describe all spatial stress components were used, as previously presented in /1/. In order to describe the necessary measuring characteristics of the adaptation model, typical damage to buildings had to be studied and a measuring method developed for the detection on dummy structures in the laboratory. These were constructed as girders with the weak points typical in bridge building, such as cutouts, windows or welding seams. Changes in structure and cracks can be detected early by the differential method described in /1/. In this way a set of tables is produced for typical adaptation sites for sensors used to monitor specific ageing processes. Individual numerical analysis can thus be avoided.

For early damage detection the sensor should cover a strain measuring range larger than 2 ‰ with an uncertainty better than 10^{-3} . To avoid introducing unnecessary weak points into the construction by the sensor drilling, the latter should be smaller than 20 mm.

These requirements of the adaptation model were satisfied by a clamped polygonal crossection design. Here the conical surfaces of an inner and outer component are clamped together under stress. The inner component widens the outer, which has multiple slits at the front and back in the drill axis, such that the sensor becomes fixed in the construction drill. The chosen conic angle ensures auto-inhibition.

Several development steps led to the improvement of various construction details as described in /2/. The measuring range could not however be extended beyond one third of the elastic strain range of steel, for reasons of principle. The decisive improvement was achieved by an angular transducer design (see crossection in **Fig. 1**).

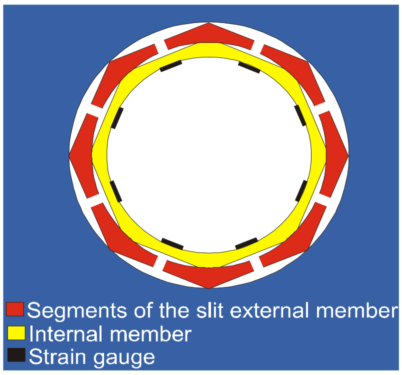

Fig. 1: Concept of the square-formed, clamped sensor

For surface contact at the drill circumference, the casting between sensor and building sets a relatively low limit for the hysteresis-free measuring range. The initial radial stress caused by the clamping results in tangential casting which may not be interrupted at any point on the drill inner surface, otherwise hysteresis will occur. The axial, line-shaped contacts of the angular sensor ameliorate the restrictions in the measuring range of the surface extension described above. The extension is integrated along the circumference between these contact points and transmitted to the inner component with its attached strip gauges. The radial clamping of the line contacts, leading to casting, and the tangential elasticity of the sensor were adjusted such that, within the elastic range for steel, an almost hysteresis-free, linear transmission characteristic was achieved.

To permit the best possible placing of the measuring grid and simple wiring in the small sensor body, a gauge strip layout was designed that incorporates several measuring grids with the chosen wiring, which, as regards their measuring surfaces, are suitably fitted to the sensor geometry. The strips can be fixed to a point on the inner circumference, rolled out and glued into place. The gauge shown in **Fig. 2** has three full Wheatstone-bridges.

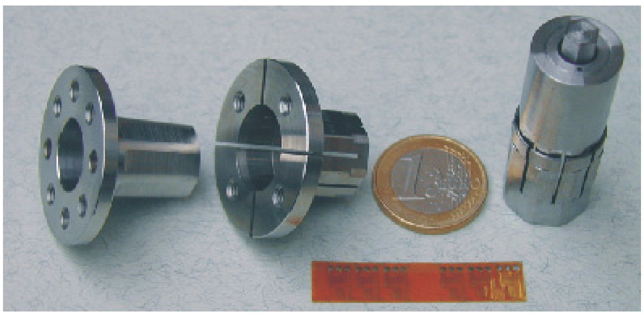

Fig. 2: Internal and externel parts, specified strain gauge, inside-screwed sensor for measuring in deep boreholes

From its measuring signals both the two axial components as well as the shear component may be derived. The gauge strip was taped and fixed using a special adhesive device exerting the best experimentally determined adhesive pressure. This method allowed a reproducible adhesive layer to be applied, better than by hand.

4. CALIBRATION DEVICES AND METHODS

For the calibration a device shown in **Fig. 3** was developed to reproduce plain states of stress. It can be rotated in its bearings about the central axis of the measuring drill. The incorporated sensor is rotated in the bearings with the rotation device in steps of preferably 5 degrees and subjected to load in the force reference machine. The calibration in differently oriented rotational positions of the principal stress relative to the sensor is performed without dismantling the sensor.

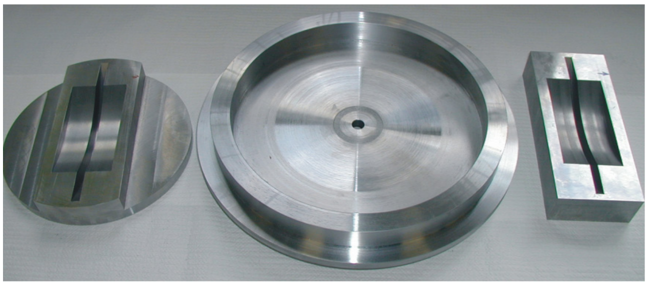

Fig. 3: Rotatable calibration body with bearing

The tangential states of stress at the measuring drill were derived according to [3] from the Airys stress function:

$$\sigma_t = \frac{\partial^2 V}{\partial r^2} = \frac{p}{2}\left[1 + \frac{a^2}{r^2} - \left(1 + 3\frac{a^4}{r^4}\right)\cos 2\varphi\right] \qquad (1)$$

where α and φ are the polar coordinates around the drill axis, r is the drill radius. The resultant function has a constant term and a cosine term revolving round the drill circumference at twice the inherent frequency. The measuring results as obtained by the described adaptation model are similar to the tangential stresses in the drill circumference.

Using the method of least squares, sinusoidal functions were fitted to the output signal. From the measurement signals with the appropriate principal stresses and their orientations a characteristic calibration formula may be derived, as for the example of a ¼ bridge of a sensor described by equation (2):

$$M = 0{,}92 \cdot (\varepsilon_{H1} + \varepsilon_{H2}) + 0{,}30 \cdot (\varepsilon_{H1} - \varepsilon_{H2}) \cdot \cos(2\varphi - 10°) \quad (2)$$

Here M is the measured value in mV/V, ε_{H1} is the principal stress, ε_{H2} is its second component, φ is the angle between the principal stress direction and the sensor. The large fault angle of 10° for the measuring signal compared with the theoretical position is typical. In the example of Equation 2, this is the consequence of a small displacement of the single strain gauge. If the measuring signal at an arbitrary point on the inner component shows a proper sine-shaped characteristic for rotation of the principal stress, the angular dependence for constant principal stress is not sine-shaped when observed over the inner circumference of the inner component. The angularly dependent change in the strain is smaller in the region between the contact areas than in the measuring area where the strain gauges are fixed. A small displacement of the strain gauge thus leads to an increase in the angular deviation of the measuring signal from the theoretical position. This does not have an appreciable effect on the accuracy of the strain value determined from the measuring signal and the calibration formula.

For a full Wheatstone-bridge setup of four relative to each other improperly placed measuring grids, the measuring signal can be greatly diminished when the displacements are contra-rotating. For this reason the multi-grid strain gauge was developed which, by exact positioning of the measuring grids relative to each other, avoids larger uncertainties through a smaller measuring signal.

A multicomponent force and torque reference machine, shown in **Fig. 4**, is currently being set up in PTB to calibrate the sensor for spatial stress components [4]. A rod-shaped load device with incorporated sensor is fitted for this purpose.

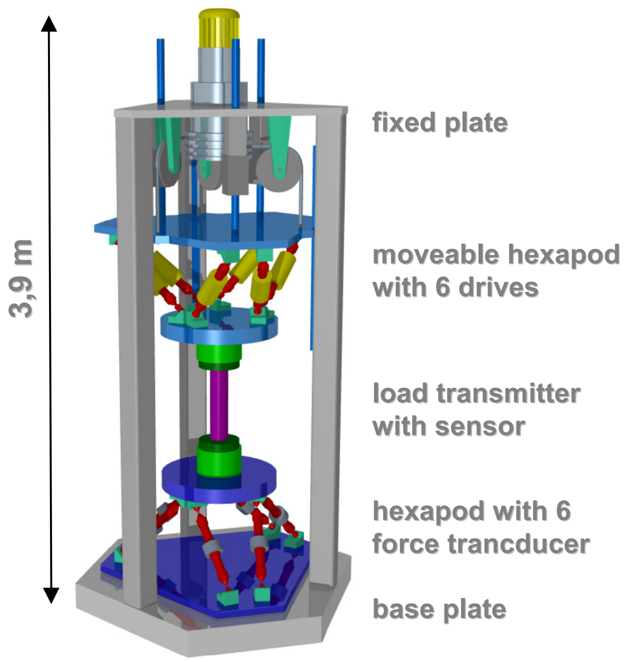

Fig.4: Multicomponent force and torque reference-machine

Studies in [5] showed that customary force transducers in part produce large deviations under dynamic stimulus. To investigate these effects for the building sensors they are dynamically calibrated by mounting them in a load rod on a shaker. In dynamic calibration [5] in the eigenfrequency range of buildings, the sensors show no appreciable deviations from the static sensitivity. The reason for the constant frequency curve in the eigenfrequency range of buildings, shown in **Fig. 5**, is the micro-mechanically strong, frictionless bond with the environment, as well as the very low mass relative to the stiffness, which would only begin to oscillate at higher frequencies. In further measurements the signal-to-noise ratio will be improved by using a new shaker with a larger dynamic force of 18 KN instead of the 1 KN hitherto, besides the multicomponent acceleration reference machine (to 10 KN) presented in [6]. The effects of higher frequency or impulse-type of incitation shall in future be observed using the force-pulse calibration device described in [7].

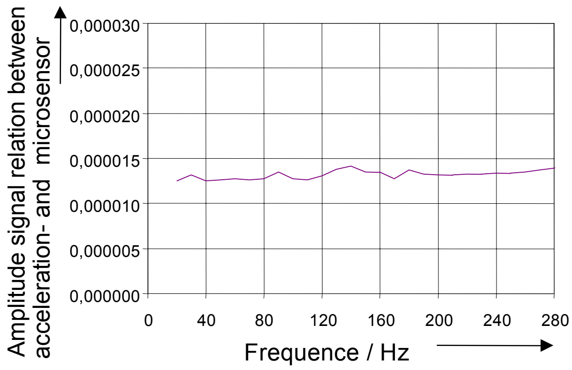

Fig. 5: Dynamic behaviour of the sensor

5 STRAIN GAUGE ENCAPSULATION

Permanent enclosure of the strain gauges for protection against external influences must be guaranteed to ensure a useful life adapted to the structure. For this purpose, the interior of the sensor is closed with a PTFE membrane ensuring pressure compensation between sensor interior and environment. The protection of the strain gauges against unwanted humidity is achieved by a plastic layer. However, many plastics allow considerable water diffusion (a 20 g sample of conventional silicon rubber, for example, absorbs up to 0,5 g of water). Different coating materials were therefore tested in a temperature-regulated water bath. The strain gauges provided with protective coatings were mounted on a special steel plate as for an example shown in **Fig. 6**. A great number of rubber types, acrylates, epoxy resins and wax layers were investigated. In some of the investigations an additional metal foil coating was used. The thickness of the sealing was choosen between 1 and 2 mm.

Fig. 6: Testing plate for the assesment of plastic-coatings

In addition to the water bath, the above test samples as well as sealed sensors incorporated in tension bars were tested in air-conditioned testing chambers. These investigations were based on DIN IEC 68 2-30. To allow for a realistic structural environment, the tests had to be carried out with increased maximum temperature and a temperature and humidity leading to the formation of condensate. 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.

. At present, test plates are exposed to outdoor climatic influences on the roof of a building to determine correlation with artificial ageing in the water bath. First results indicate a factor greater 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 has proved to be suitable. **Fig. 7** shows this sealing in compared with different rubber and lacquer sealings. The bridge-detuning should stay stable as long as possible.

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, however, are 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 strongly polar water and are infiltrated in the long term.

The detachment caused by the water can be easily recognised in **Fig. 8.** Those parts still in contact allow the underlying metal to show through, whereas the detached part reflects the light at the air gap and appears white.

Fig. 8: Detachment of an acrylat-sealing

For a permanent, chemically stable bond between the 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. **Fig. 9** demonstrates this by the increased lifetime of the measuring sensitivity in DIN IEC 68 2-30 cycles (with the maximum temperature increased to 55 °C).

During manufacture of the encapsulation it is important to strictly observe the chemical, water-tight bond between the encapsulation material and the metal. For example, the mounted sensor only has a 2 mm wide strip infront of the strain gauge on which the adhesive is in contact with the metal. Impurities inevitably introduced by the strain gauge adhesive are removed by granulation. The strain gauge is protected by a cover throughout.

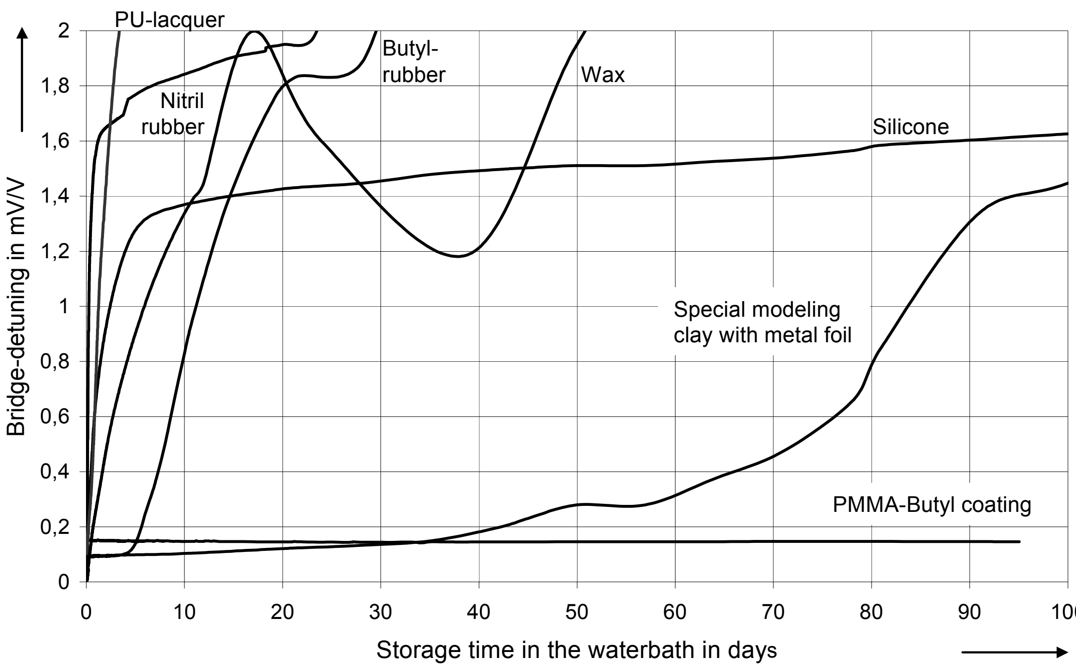

Fig. 7: Comparison between different sealing compounds

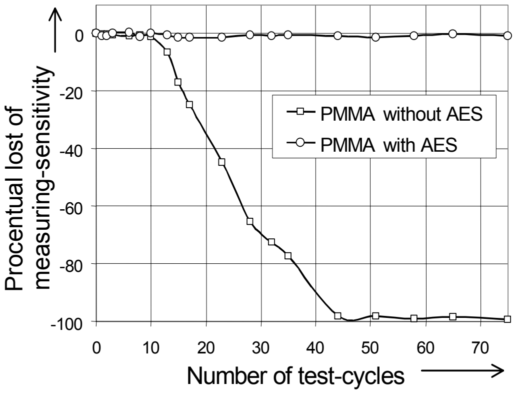

Fig 9: Gain of adhesion enhancing substances (AES)

However, there were still appreciable differences in the service life of different samples of identical production. The zero signal either stayed constant for 100 days, or changed after a setup-time of about 7 days. The reason for the fast ageing of some samples lies in the diffusion of moisture in the only 50 μm thick polyethylene insulation layer of the wiring. Since the same length of PMMA coating was always used on the insulated wire, the setup-time of the zero displacement remained constant. On some samples at welding points there was a sufficiently coat-free area where the PMMA inhibited the water transport. These samples had a significantly longer service life. In consequence the wires are now stripped to 5mm and tinned. Coating the tin with adhesion catalysts is, as for stainless steel, advantageous for the anticipated lifetime.

Experiments to use PMMA with adhesion catalysts as a glue for the strain gauges were unsuccessful because of the nonlinear elastic properties of PMMA. Creep characteristics were dominant and introduced 10 times the uncertainty compared with the adaptation model and were unsuitable for precision measurement.

6. CONCLUSION

The operational suitability of the sensor based on strain gauge technology was proved. Questions concerning the adaptation model, calibration and measuring methods could be answered. The future will show the usefulness of the sensor and particularly its encapsulation when tested in real buildings. The stress measurement will be extended to all six spatial components with the aid of new loading equipment.

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Authors: Dipl.-Ing. Falk L. Tegtmeier, Prof. Dr.-Ing. Manfred Peters, Division 1, Physikalisch Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany, phone +49 531 592 1107, +49 531 592 1010, fax +49 531 592 1105, E-mail: Falk.Tegtmeier@PTB.de , Manfred.Peters@PTB.de