

Multicomponent Sensor for Stress Analysis in Buildings

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Abstract

An important element in the supervision of buildings is the necessary precise and continuous measurement of stress conditions. For this purpose, an encapsulated measuring sensor was developed which protects the sensitive strain-gauge technology within it and which can be easily inserted into measurement boreholes.

The mechanical adaptation is effected by optimising a process of deformation of two conical bodies such that the envisaged measuring range covers the range of elastic deformation of construction steels. Suitable calibration procedures as well as measurement methods for the early detection of structural damage in buildings were developed for this adaptation model. A strain-gauge layout was devised for the sensor that is adapted to the specific local conditions, and the strain gauge is protected by a plastic seal. In order to be able to assess the lifetime of the sealing materials, which in part were being employed for the first time, the chemical/climatic building environment was simulated under forced conditions in the laboratory.

1 Introduction

Within the Republic of Germany a sustained structural change in building policy may be observed. An above-average increase in building restoration has cornered the most important part of the construction market. With the total value of current buildings in the Republic rated at almost 20 billion Euro, having an assumed lifetime of 50 to 100 years, the future bodes a substantial financial outlay for restoration and maintenance. Political economy demands that these costs be minimized. This was the underlying reason for the establishment of a collaborative research centre (SFB) of the German research corporation (DFG), at the Technical University of Braunschweig, to develop innovative building supervision to support early damage prognosis, in order to minimize restoration costs. An SFB sub-project is underway at PTB. To determine the load situation in buildings and also to recognise vulnerable spots by changes in transfer states, compact multicomponent force transducers will be developed for implementation in a structure. Strain-gauge adhesive measuring strips (strip gauges) are suitable for this purpose, as experience in conventional force transducer construction shows.

2 Mechanical simulation of the structural environment

The development and optimization of the adaptation model that describes the mechanical coupling between the strip gauge (DMS) and the inner surface of the borehole, was carried out with the help of so-called simulation transmitters. These represent the structural environment and, in the interest of greater reliability of the subsequent model, they were designed to create worst-case conditions. With their help the following problems were to be solved:

- determination of a suitable adaptation type under simultaneous multicomponent loading;

- specification of boundary conditions such as measuring range and measurement uncertainty;
 - development and testing of a measurement method for damage detection;
 - simulation of the chemical and climatic characteristics of a building environment.
- The simulation methods developed for these problems will now be briefly described.

2.1 Experimental transmitter for the optimization of the adaptation model

Various rod-shaped load transmitters were designed to determine a suitable adaptation model and to optimize the transfer characteristics for multi-component loading. The representation of different stress components at the measuring borehole was effected during the first experimental phase by the installation of diverse force and torque standard measuring devices. Simultaneous loading shall in future be realized by a multi-component reference device, specially developed for the purpose. The rod-shaped load transmitters allow the analysis of the circumferential strain in the measuring borehole, for axial loading. The precise knowledge of the circumferential strain from analysis, numerical simulation and metrological examination using strain gauges in the borehole, is also used to verify the transfer matrix for the experimental transmitters, determined using the calibration procedure described below. Various rods were adapted for certain examination purposes, e.g. a Z-shaped variation was made to demonstrate high shearing deformation, or rods of high-quality spring steel alloys were used to realize extremely high strains.

2.2 Calibration transmitters and calibration methods

For the calibration, the transmitter shown in Fig.1 was built to realize plain stress states. The mechanically most suitable adaptation model described below shows crosstalk between the individual measuring stages on the borehole circumference.



Fig.1: Rotatable calibration body with bearing

The crosstalk effects were determined using the disc-shaped calibration transmitter which can be turned in its bearings round the centre axis of the sensor borehole. The fitted sensor was rotated in 5° steps with the rotation transmitter in the bearings and loaded to 100 kN. The calibration in various rotation planes of the primary strain, oriented relative to the sensor, thus occurs without dismantling the sensor.

The tangential strain states in the borehole were derived according to [1] from the Airy strain function:

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

Here a and φ are the polar coordinates around the drilling axis, r is the drilling radius. The result is a function that has a constant term and a cosine term revolving round the borehole circumference at twice the locus frequency. The measured values, determined using the adaptation model described in section 3, also show a function similar to the tangential strains in the borehole circumference. Figure 2 shows the measured values of a sensor with 8 individual strain gauges as an example.

Sine functions were fitted to the output signal using the least squares method. The relative deviations were less than 10^{-4} . A corresponding calibration equation resulted for each $\frac{1}{4}$, $\frac{1}{2}$ or full bridge from the comparison of the respective balancing function of the measuring signals with the appropriate primary voltages and their orientation. Similar to the tangential

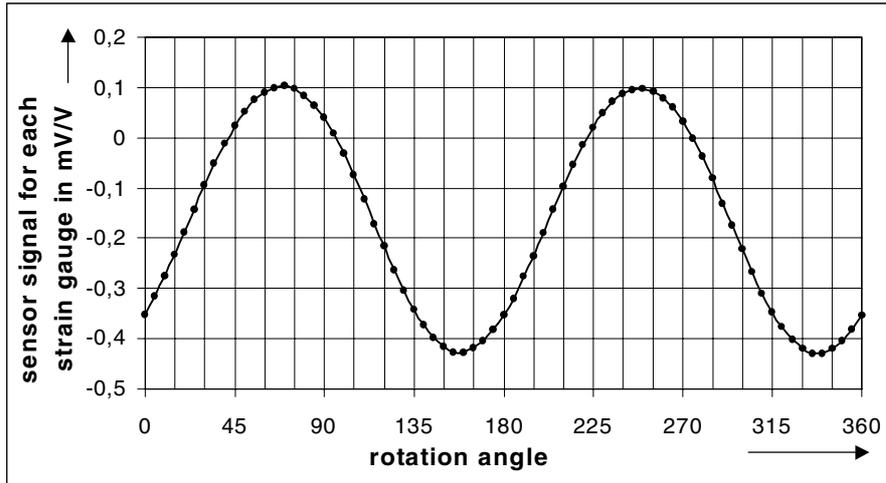


Fig. 2: Signals at a rotation of the first principal of stress

voltage function (1) for the drilling edge, the equation contains a constant term and one alternating at twice the locus frequency. For plain stress a transfer matrix can be derived from these equations. For the representation of spatial voltage components a multi-component force and torque

standard measuring device [2] is currently being set up in PTB, as outlined in Fig.3. It is to be used in the calibration of sensors that record all spatial load components. To do this, a rod-shaped load transmitter, with the incorporated sensor, is fitted between two plate systems. The upper level is managed by individual drives arranged in a hexapod system. The lower hexapod system has reference force transducers integrated in it which determine the load on the test object.

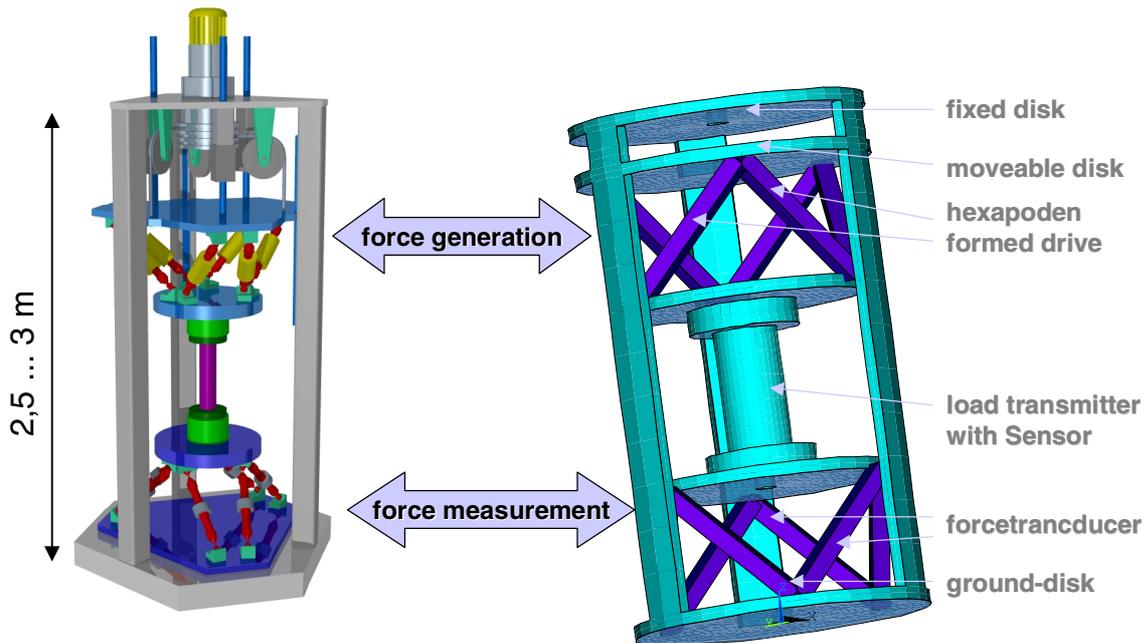


Fig. 3: Multicomponent force and torque reference-machine

Investigations in [3] showed that customary force transducers are subject to large deviations for dynamic excitation. To be able to describe these effects for building sensors, they are mounted in a load rod and dynamically calibrated on an oscillator. The multi-component accelerator standard measuring device presented in [4] is employed here; it can produce dynamic forces of up to 10 kN. The dynamic calibration shows that the sensors, described by the adaptation model below, do not deviate from the static sensitivity or measuring uncertainty within the range of building eigen-frequencies. The reason for this is the micro-mechanical solid bond with the building, as well as the low mass in proportion to the rigidity, tending to resonance only at very high frequencies. The effects of this higher frequency or impulse-type of incitation shall in future be observed using the force-pulse calibration device described in [5].

2.3 Dummy structures for damage simulation in buildings

The investigation of typical damage in buildings and the development of a measuring method for damage detection was carried out on dummy structures in the laboratory. These were designed in the form of a girder and given the vulnerable spots typical of bridge construction: e.g. cutouts, windows or welding seams. Typical structural changes and cracks can be detected early by using a differential measuring method. Here the signal characteristics of two sensors are compared. The adaptation side should be chosen such that the load-dependent output signals in the damage-free state only differ by a constant factor. Using a sensitivity fit at the measuring amplifier, the signal difference is balanced to zero. Since damage in the initial phase only results in local effects, at first the voltage matrix of just the closest sensor is affected, showing a change in signal. The other sensor remains unaffected and the consequence is a signal difference between the two sensors. FEM simulations show that universally suitable adaptation sites may be found for special vulnerable points requiring surveillance. Collated in standard tables, these would allow one to dispense with individual FEM analysis for every sensor application. This procedure also enabled the permissible measurement uncertainty for the developed sensor to be derived.

3 Adaptation model

The adaptation model describes the mechanical interface between the inner drilling surface in the building and the strain gauge applied in the sensor. Some 50 models were developed and tested. They are variations of four different basic modes: clamping, screwing, adhesion and moulding. Of these only the clamped version proved suitable. The conical surfaces of an inner and outer component are clamped together under stress. The inner component forces the outer to expand, so fixing the sensor in the borehole. The strain can be applied by an external or a central inner screw. The conic angles chosen are less than 4.3° which ensures auto-arrest. Improvement of diverse construction details was achieved through several development steps. The inner component touches the outer only on a confined contact surface lying deep within the borehole. The outer component has several slits alternating between top and bottom, such that its circumference can expand uniformly. The crosspieces remaining between the segments are not in contact with the inner component. This is effected by inserting appropriate slittings into the inner circumference of the outer component. The thickness of the outer component wall is chosen to be as thin as possible. The minimum thickness is limited by the necessary material strength of the transition area to the flange segments for the introduction of the initial clamping force. The value of the tightening force was optimised in several experiments and taken into account regarding the number and strength of the clamping screws. Finally extensions of up to 1‰ could be measured at the drilling edge with almost negligible hysteresis and good linearity. The decisive improvement was achieved by an angular design as in the cross-section sketched in

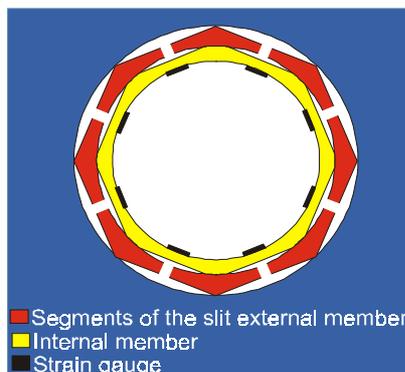


Fig.4.

For surface contact at the borehole circumference, the casting between sensor and building sets a relatively low limit for the hysteresis-free measuring range. The radial initial stress caused by the bracing results in tangential casting which may not be interrupted at any point on the borehole inner surface, otherwise hysteresis will occur. The

Fig. 4: Concept of the square-formed, clamped sensor

axial, line-shaped contacts of the angular sensor ameliorate the restrictions in the measuring 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 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. Figure 5 shows a comparison of the measuring results obtained with the diverse circular designs (1-3) and with the angular construction.

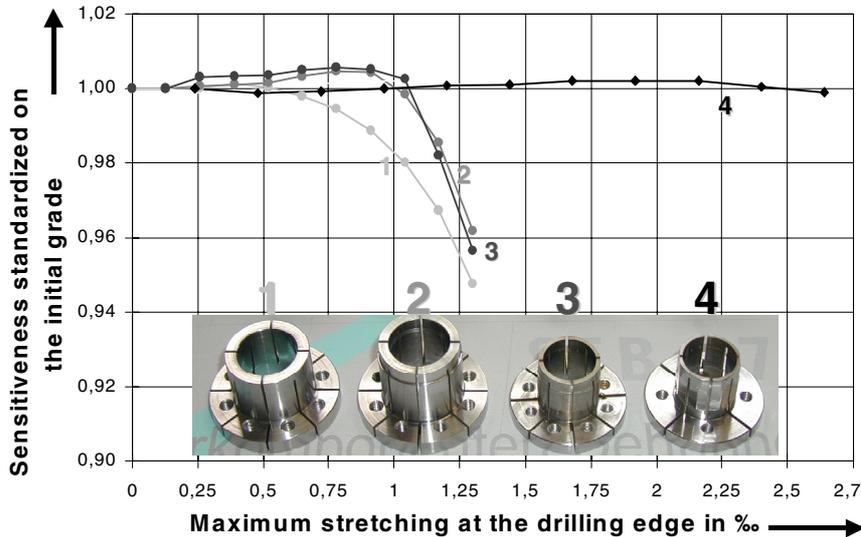


Fig. 5: Comparison between round and edge-shaped sensors

designed that integrates several measuring grids with the required circuit connections, the size of the measuring surfaces being optimally fitted to the sensor geometry. A strip of this kind can be fixed in position at a point on the inner circumference, unrolled and stuck on. In this way a clearly more accurate positioning of the measuring grids is achieved. The strip gauge shown in Fig.6 contains three full bridges; from their measuring signals both the two axial components and the shearing component may be derived.

4 Encapsulation of the strain gauge

The permanent encapsulation of the strain gauges to protect them from external influence must be safeguarded in order to realise a life expectancy compatible with that of the building. Since thermally produced air pressure fluctuations can have consequences for the measuring result in the interior, this is sealed with an air and moisture permeable PTFE membrane. The essential protection of the strain gauge itself from undesired moisture is realised by a plastic layer. But since the majority of plastic materials allow a considerable degree of diffusion - a 20 g sample of normal silicon rubber can absorb up to 0.5 g of water - various plastics were tested in a thermal water bath. Strain gauges were stuck onto a refined steel plate and different protective layers were applied. In similar fashion, such plates and sensors incorporated in load-rods were tested in climate chambers. DIN IEC 68 2-30 was used for reference. Currently we have been testing plates exposed to the elements on the roof of a building to determine the correlation with forced ageing, particularly in a water bath, to be able to predict

During the experimental phase of adaptation model testing, commercial strip gauges were used. Insertion of the numerous individual strip gauges into the inner component with a 13.8 mm drilling diameter proved to be laborious. For this reason, after the final decision was taken in favour of the adaptation model for plane load states, a measuring strain gauge layout was

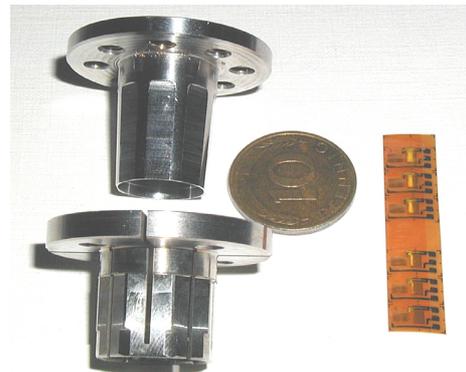


Fig. 6: Internal and external parts of the sensor, multi-grid strain gauge

their lifespan. First results indicate a factor larger than 150. To protect a strain gauge from moisture, a combination layer of polymethylmethacrylate (PMMA), a moisture-resistant adhesive used in dentistry, and a surface layer of butyl rubber proved suitable. Figure 7 shows the comparison of this sealant with silicon rubber seals.

The boundary layer between the refined steel and the sealant is particularly significant for the permanent encapsulation of the strip gauge. PMMA reacts primarily with the metal oxides.



Fig. 8: Detachment of an acrylate-sealing

Refined steel contains only few of these. The binding of the adhesive thus mainly depends on Van der Waals forces. However, these are sensitive to the highly polar water molecule and are undermined in the long term. A direct application of PMMA on refined steel submerged in a 50°C water bath was able to resist for a period of 100 days. The scaling off caused by the water can be clearly seen in Fig.8: the region still in contact allows the metal to shine through, the detached area causes refraction of light at the air gap and appears white. In order to achieve a permanent, chemically stable compound between refined steel and PMMA, special adhesion enhancing substances are introduced which contain a mercapto group for the refined metal and a vinyl group for the sealant as the reactive partner.

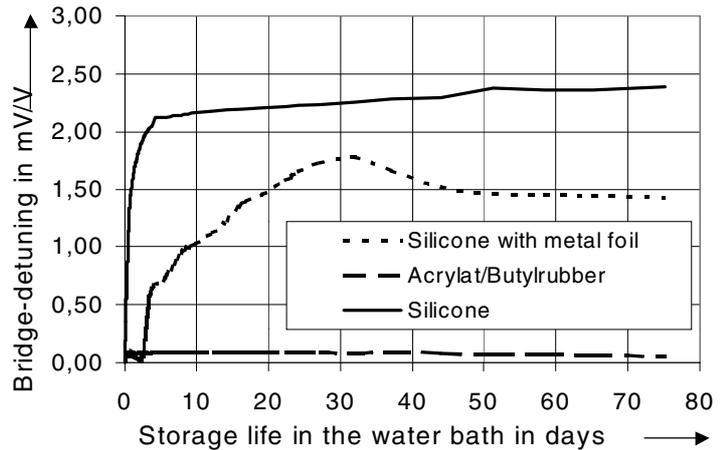


Fig. 7: Comparison between different sealing compounds

5 Conclusion

The operational suitability of a sensor based on strain gauge technology has been demonstrated. Questions concerning the adaptation model, calibration and measurement procedures were elucidated. For the future, the sensor and particularly its encapsulation shall have to prove their worth in real buildings. The stress measurement will be extended to all six spatial components with the help of a new loading device.

6 References

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