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DETERMINATION OF STRUCTURAL DAMAGE TO BUILDINGS USING MICROSENSORS BASED ON STRAIN GAUGE TECHNOLOGY

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Abstract: In the supervision of buildings and structures, to guarantee the support strength and to detect structural damage due to ageing and varied utilisation at an early stage and at low cost, special measuring instruments are increasingly being developed. An important tool in the measuring techniques applied to determine loads and detect damage are strain gauge-based microsensors. These can protect the integrated precision resistance foils from the adverse ambient conditions prevailing in the vicinity of the structure and can easily be attached to the structure subject to supervision.

Investigations carried out within the scope of the project have so far concentrated on problems concerning the integration of the sensor into the structure. Work has been focused on both, a suitable design of the sensor and an appropriate selection of measurement points ensuring low impact on the structure, the possibility of subsequent attachment to existing objects, and high signal amplitudes in the case of changes in the built volumes. Investigations into potential applications of the sensors were carried out on the basis of a theoretical description and by practical experiments, simulating the structures' environment using suitable dummy structures and load transmitters. They are used to test the measuring method and, above all, to establish a matrix for the transfer of exactly defined states of external stress and strain to the strain gauges enclosed inside the sensor.

Keywords: multicomponent microsensor, strain gauge, monitoring of buildings, encapsulated measuring device, dummy structure.

1 INTRODUCTION

In the Federal Republic of Germany, sustainable structural change is apparent in civil engineering and building construction. With above-average growth, the proportion of reconstruction work is greatest in the building industry. In view of the fact that total building contracts amount to some 5 to 10 billion Euro, and assuming a service-life of 50 to 100 years, considerable funds will be required for future maintenance and reconstruction. It is, therefore, of great interest from the economic point of view that these costs be minimized.

Bearing this in mind, a collaborative research center has been created at Braunschweig Technical University, within the scope of which a novel structural supervision method is being developed aiming to minimize the reconstruction costs on the basis of early damage foresight. A partial project in this collaborative research center is being carried out at the Physikalisch-Technische Bundesanstalt in Braunschweig. Compact multi-component force transducers for integration into the structure will be developed to determine the stress situation inside the structure and, also, to identify structural weak points resulting from changed transmission conditions. Strain gauges will be used that are considered suitable according to the experience gained in conventional force transducer construction.

2 STATE OF THE ART

Strain gauges are currently only being used for short-term measurements, for the purpose of instantaneous analyses. The sensitive materials – particularly the adhesive layer – cannot withstand permanent chemical attack and climatic stress within the structure. The fact that application of the strain gauges requires much sophistication and must take place under laboratory conditions is an additional difficulty.

These problems can be solved by the use of encapsulated measuring units whose metal housings are welded onto the structure, or attached by means of purpose-made bonding agents. Suitable units are being used for the first time for the strain gauge-based supervision of an open-air structure: the Olifant River Bridge in the Republic of South Africa [1]. Here, each strain gauge has been enclosed in separate housing and glued to the structure.

3 CONCEPT OF THE ENCAPSULATED MULTI-COMPONENT SENSOR

The detection of several load components makes a complex application of encapsulated strain gauges necessary. A unit which can easily be fitted into a small bore orifice in the structure seems to be an obvious choice. The sensor can be specially adapted to several tasks: for example, it may be designed as a primary detector of load changes or as a two- or six-component transducer. The representation of states of plain stress is of particular importance in structures designed as girders with rigid and mobile bearings.

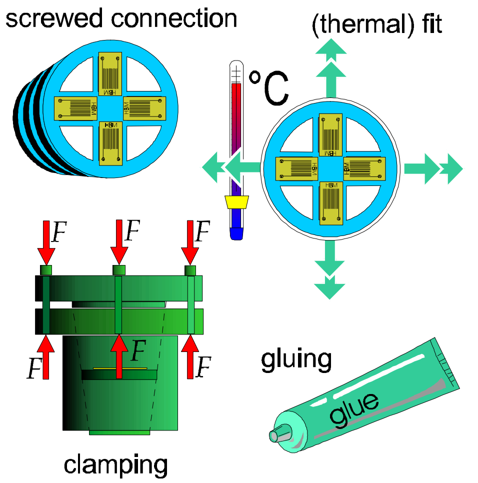


Fig.1: Potential fittings of encapsulated sensors

A wide spectrum of possible fittings is available; examples are shown in Fig. 1. Optimum coupling of the sensor housing to the surrounding structure is an important criterion for the choice to be made. No displacement of the contact areas may take place at the strain amplitudes which are to be measured and which are typical of the structures concerned.

Over a extended period of time, the fitting must remain unaffected by the chemical attacks and climatic stress factors to which the structure is typically subject. Fast mounting and dismounting with the aid of simple tools, without sophisticated pre-treatment of the structure, is another important aspect to be taken into account. Also, mounting must be possible without the assignment of specifically trained staff.

4 DUMMY STRUCTURES TO INVESTIGATE SENSOR CHARACTERISTICS

With the object of selecting and optimizing the fitting methods and establishing the matrix for the transfer of external strain on the strain gauges enclosed in the sensor, special dummy structures have been designed as load transmitters and calibration bodies, in a form similar to a bridge girder which allows realistic conditions to be simulated. These bodies were used to define the marginal conditions for the supervision of buildings and structures, to select and optimize the fitting methods, and to establish a matrix for the transfer of states of external stress to the measurement signal output.

5 ROD-SHAPED LOAD TRANSMITTER

A rod-shaped dummy structure has been developed to check the transmission properties for a possible simultanious six-component load application. It was manufactured from a round rod (outside diameter: 50 mm) and provided with various bores to which strain gauges can be directly fixed and which can also be equipped with sensors of different design

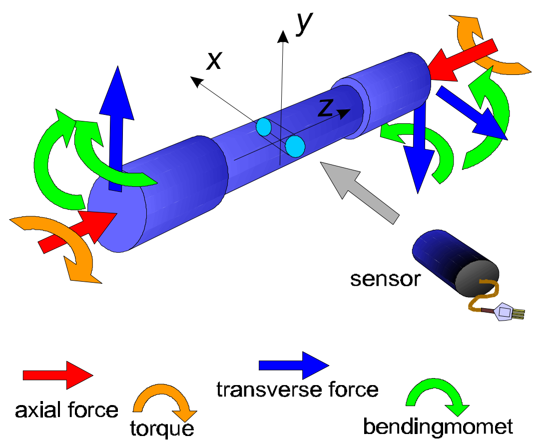


Fig. 2: Rod-shaped load transmitter for six-component load application

For the body represented in Fig. 2, the states of strain and stress generated in the force-applying mechanisms can be approximately calculated by FEM and by analytical considerations. The PTBs 1 kNm torque standard machine allows transverse components to be additionally applied to this load transmitter through movement of the thrust bearing. With the aid of the multicomponent transducers developed at PTB (Röske [2]), all six components can be measured and adjusted to the desired load values through changes in the thrust bearing position. A 100 kN force standard machine is additionally used to apply forces in the axial direction. For this kind of load application, besides the FEM analysis, an approximation formula has been determined from Airy's stress function according to Neuber [3]:

$$s_t = \frac{¶^2 V}{¶r^2} = \frac{F}{2pR^2 \cdot 8Rr(1-\sin j)}\left[1+\frac{a^2}{r^2}-\left(1+3\frac{a^4}{r^4}\right)\cos 2j\right] \qquad (1)$$

a and φ are the cylinder coordinates around the bore axis, r corresponds to the bore radius, R is the radius of the rod cross-section.

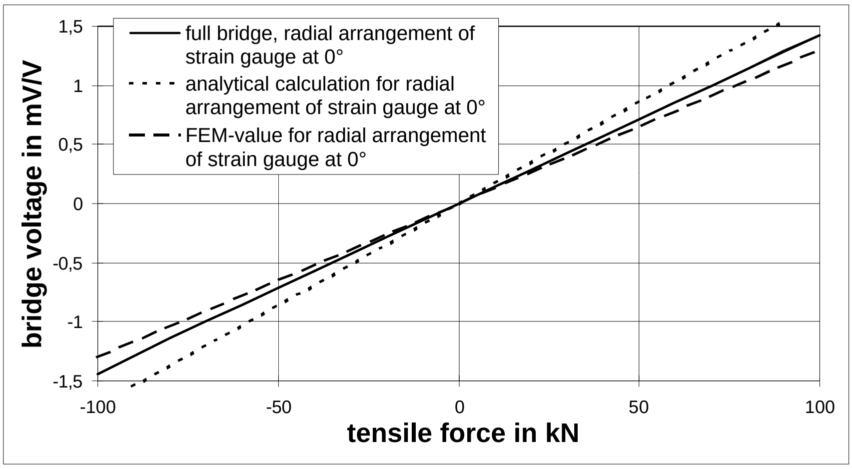


Fig. 3: Comparison between FEM analysis, analytical calculation and measured values

The approximate tangential states of stress in the bore's inner surface are obtained with r = R. For a full bridge provided with four strain gauges arranged at 0°, 90°, 180° and 270° in relation to the rod's longitudinal axis, Fig. 3 shows a comparison between the strains which were obtained from FEM simulation and analytical consideration and converted into signal voltages, and the measured values. There is good agreement between the data determined theoretically and those measured experimentally.

The measurement shown here as an example for a bore 20 mm in diameter was also carried out for other bore diameters and individual strain gauges, at different positioning angles and applying all load components. The data obtained provide exact information about the circumferential extension of the bore and are to serve as a basis for the establishment of the transfer matrix.

The rod-shaped load transmitter also plays an important role in the functional checking for potential errors in the different fitting possibilities and in the selection and optimization of the latter.

6 DUMMY STRUCTURE

In cooperation with the *Deutsche Bahn AG*, dummy structures have been designed by the institutes involved in the described collaborative research center. Into this objects such weak points have been integrated as are typical of bridge construction, according to the experience gained.

Parallel to the dimensioning of the dummy structure, the concept of differential measurement has been devised, which allows cracks to be reliably detected with the aid of two sensors, even nascent cracks less than 1 mm in length. Fig. 4 shows the dummy structure used and illustrates the basic concept of the method: There are two variable parameters of state for the point of load application to be supervised: the state of stress and the crack length. A so-called reference sensor is to be integrated into the stress pattern, at a selected point of application and in such a way that it is not affected by the development of the crack but nevertheless provides information about the state of stress in the area to be supervised. A second sensor is to be installed so that it will measure strong signal variations if there is a defect at points where cracks could possibly occur.

The dummy structure was calculated using several FEM models. The dimensions – in particular those of the recesses – were deliberately chosen so that they determine the limits of the differential measurement concept as a „worst case“ simulation and provide information about the required accuracy of the multicomponent sensor.

This calculation also proved that the regions beside the recesses are suitable for crack detection, in particular at 1/3 and 2/3 of the recess height. The general placement measurement points are independent of possible curvatures, or of the ratio of recess length to recess width.

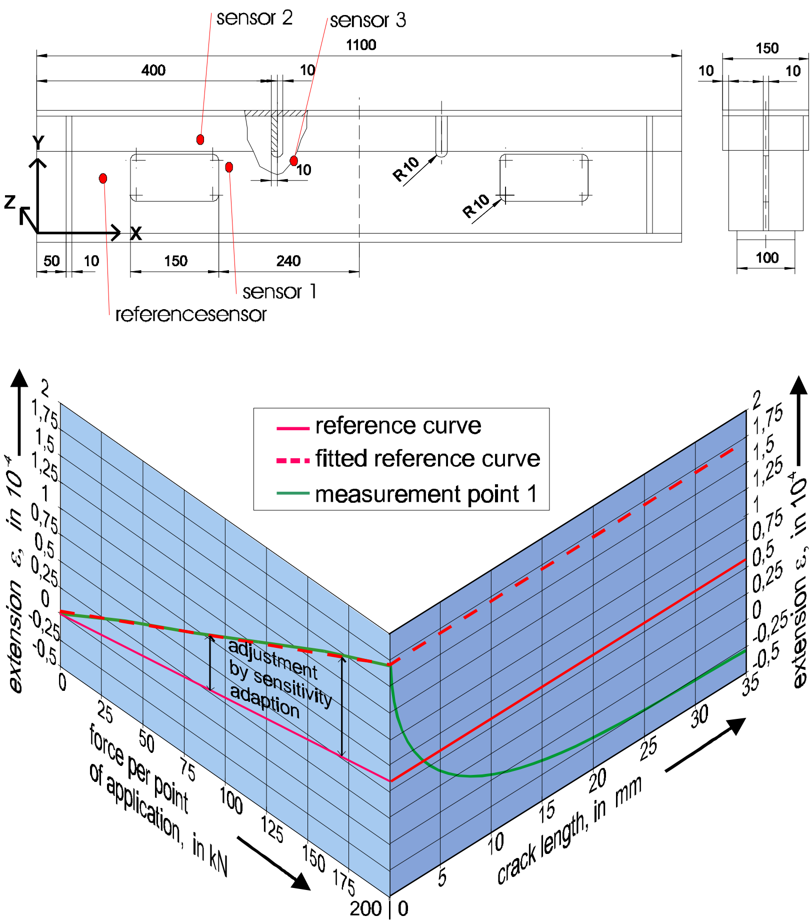


Fig. 4: Concept of differential measurement method

The enlargement angle of cracks at the recesses of the dummy structure was investigated in experiments and by FEM simulation using refined models. Such an enlargement angle cannot, however, be determined by computer-aided analyses. This is analogous to microcracks between the grain boundaries in metal crystal structures, and precise prediction is therefore impossible. For the cracks serving as a basis of the calculations for the dummy structure, a crack therefor was simulated by an acute angle, and was adjusted to the line bisecting the angle at the corner concerned. As shown in Fig. 5, cracks 1 to 10 mm in length were produced by introducing a cut using a saw.

For the measurement the dummy structure was fitted using a hydraulic loading mechanism by means of a facility**.** Local variation of the point of force application was integrated between the upper bars active in the load application.

The concept of the differential measurement method was checked with regard to the computing model and the measurability of the anticipated signals by comparing the calculated extensions with the values measured with the strain gauges directly applied to the sensor measuring points not yet provided with a bore.

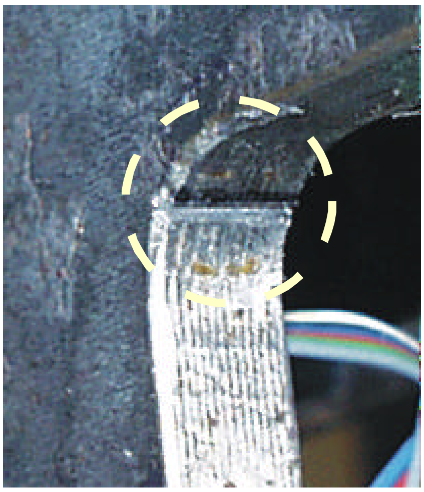


Fig. 5: Crack simulated by introducing a sawed cut

Fig. 6 shows as an example the measurement signal at the reference position in comparison with the same component at measurement point 1 in Fig. 7. The displacement of the point of load application between the two upper bars active in load application has been plotted on one axis, i.e. a locally variable load has been represented. The second dimension represents the crack length. A signal independent of the crack can clearly be seen at the reference point of measurement; a dependence of the signal on the crack length is found at the sensor measuring point. The differential measuring method, together with the load values and the data of the point of load application, is thus suited to provide information about the initiation of small cracks.

Another dummy structure has been provided with bores for the sensors. First, strain gauges were directly applied. Similar to the values obtained from direct strain gauge application to the rod-shaped load transmitter, the values obtained here were compared with the sensor's measurement values and will be made use of for the verification of the transfer matrix.

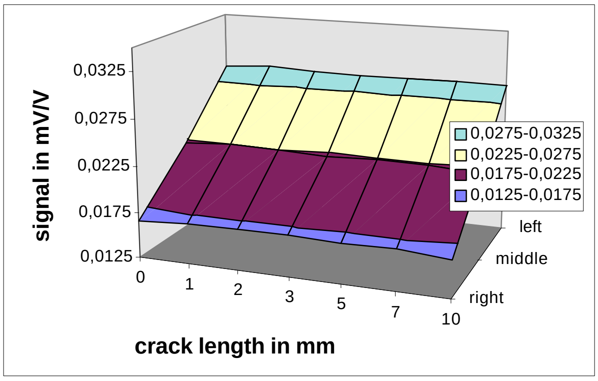


Fig. 6: Measurement signal generated by horizontal strain at the reference sensor

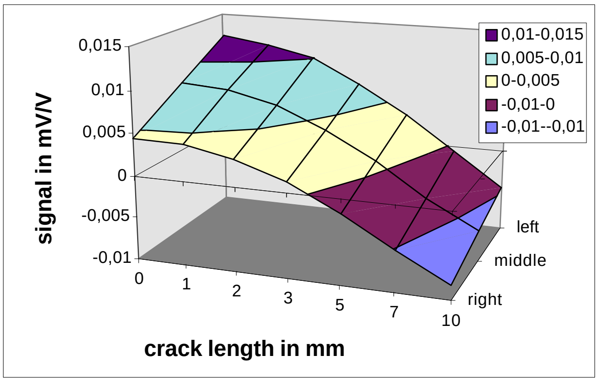


Fig. 7: Measurement signal generated by horizontal strain at sensorpoint 2

The experience gained with the dummy structure allows requirements for the fundamental sensor properties to be formulated. For the supervision of buildings and structures, the sensors are integrated into low-load areas for which, according to the experience gained, extensions of not more than 0.05% are to be expected. The effects of cracks developing in high-load areas are usually of a local nature. To allow the insignificant effects at points further away to be measured, a reproducible resolution of the sensor signals of $1*10^{-4}$ should be aimed at, with ε equal to 0.1% as the maximum extension. With the strain gauges applied around the bore, the effect which these strain gauges have on the structure was investigated. As in the case of the simulated strain values, these investigations allowed the general conclusion to be drawn that the web width between fractures and bores should be approximately equal to the sensor diameter. In connection with the one-third arrangements in the recesses, found by FEM analysis, points have been identified which are suited for crack detection and involve only very low stress for the structure.

7 CALIBRATION BODY

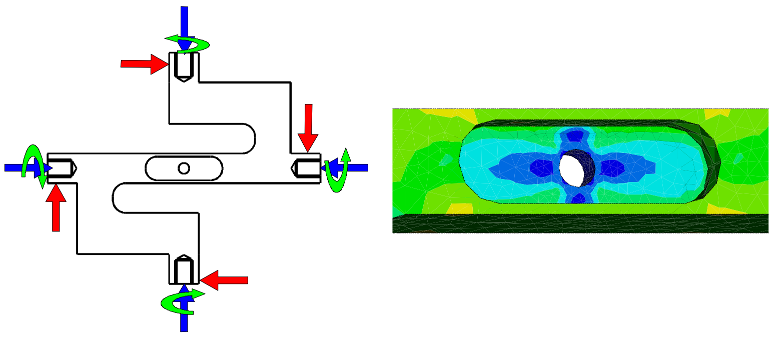


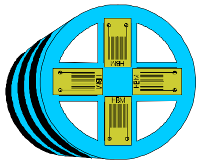
Fig. 8: Calibration body and FEM analysis of shear strain under 100 kN load

The rod-shaped load transmitter and the dummy structure allow statements to be made on the function mechanisms and possible applications. The exact establishment of a matrix for the transfer of states of stress - which is typical plain in building construction - to the strain gauges inside the sensor requires that a precise calibration body be available for these states. The rod-shaped load transmitter is particularly unsuitable for the precise representation of high shear components. A calibration body has been developed for this purpose to which loads can be applied in the existing 100 kN force standard machine where the body can be mounted in two positions. The design of the Z-shaped body has been optimized through analytical and FEM calculations so that maximum shearing strain occurs around the sensor bore. Prior to sensor installation, strain gauges were directly applied to the bore of this calibration body as well, to verify the states of stress determined by calculation. On the basis of the states of stress thus known, the transfer matrix for the values determined by the sensor was established for plain stress application.

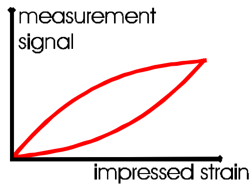
8 SELECTION OF THE SENSOR FITTING METHOD

The facilities described above were used to examine the different fitting methods and to optimize them in various designs. The results presented below were obtained by the respective fitting method for all kinds of load application, the behaviour being similar.

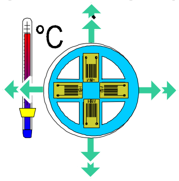
Screwed connection



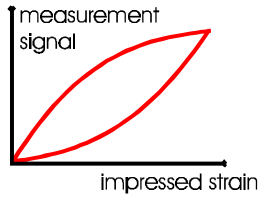
unsuitable because of hysteresis properties as a result of sliding in all types of screw threads, also conical ones; small signal



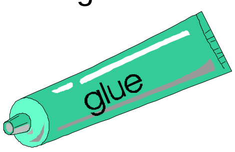
(Thermal) tight fit



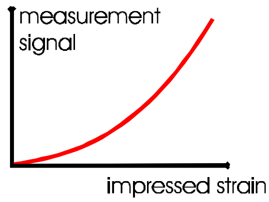
unsuitable because of too low initial stresses in all types of mechanical or thermal tight fits. The ratio of assembling force to body rigidity is unfavourable.



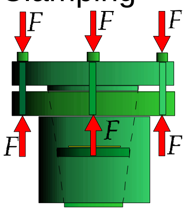
Gluing



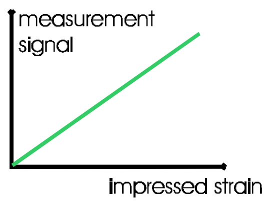
unsuitable because of strongly non-linear characteristics, the reason being that the elastic properties of the different bonding agents are not constant over the extension. Very progressive signal, strong creep.



Clamping



linear behaviour over very wide extension ranges, good reproducibility, easy mounting as a sensor for inside or outside clamping; complete metal enclosure also possible.



For the selection of the optimum fitting method, the sensors have been designed as hollow bodies, with strain gauges applied to the inner surfaces. This application to the inside periphery is optimum for the measurement of states of plain stress. A special strain gauge is being developed for this purpose, which is composed of several full bridges. Investigations for an extended six-component representation are currently being carried out using different inside designs. In addition, optimum sealing of the sensitive strain gauges is being investigated in climatic chambers and thermally stable water baths. For this purpose, a procedure was required which simulates time-dependent ageing of the epoxy resins preferably used for encapsulation.

9 SUMMARY

The first phase of the project has allowed the efficiency of the sensors based on the strain gauge technique to be proved. It has been possible to get a view of the necessary and actual accuracy, and with this to choose the kind of fitting and suitable dimensions to determine the fundamentals of this sensor technique. With the sensors suitable for clamping, a design has been identified in several development steps, which achieves the required accuracy without hysteresis in extended ranges by more than 0.1% of extension. The states of plain stress typical of civil engineering and in building construction can be determined with only a single special strain gauge. The sensors can also be of the metal-enclosed type suitable for inside clamping, which makes cavity mounting possible, for example inside a large concrete girder.

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