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Numerical simulation of strain gages

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Introduction

Some people might find the title of this article disconcerting. Why should a sensor that is used in experimental stress analysis and in force measurement technology, be simulated numerically?

For us at TU Darmstadt, the reason was quite obvious. As users of strain gages for multicomponent force transducers and particularly for wind tunnel balances, we found it was a problem to use manufacturers' strain gages, but cannot influence their characteristics.

But developing wind tunnel balances for use in extremely low temperatures compelled us to take a closer look at strain gage characteristics, so that we could use strain gages with the same precision that was possible at ambient temperature in the required range of -180 °C to +60 °C.

At this point we got the idea of applying numerical methods to determine the properties of the strain gages and then, by specifically modifying the material and geometric properties, to change the strain gages so that they meet our requirements. We virtually created a tool that can be used to determine the influence quantities on the strain gage properties, without having to perform long series of tests to discover them. This proved to be a very demanding aim.

Firstly we produced a dissertation that looked at the possibility of using a finite element program to determine the resistance and sensitivity of a strain gage.

This involved modeling a strain gage measuring point and calculating the geometry of the strain gage in both its non-deformed and deformed state. There was no possibility of directly calculating the resultant change in resistance. So we used the analogy between heat conductance and electrical conductance to calculate the change in the electrical resistance of the strain gage.

Modules for calculating heat conductance with the aid of a FE method were already implemented in our program package. These findings about the calculation of the resistance and/or change in resistance on the basis of the deformation and thus the sensitivity of a strain gage, confirmed that our idea could be realized. But a lack of funding

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meant that the method could not be developed further and it was therefore put on ice.

But then, four years ago, we contacted HBM, who were interested in our work on wind tunnel balances, because we had succeeded in building force transducers with excellent zero point and sensitivity stability throughout the entire -180 °C to +60 °C temperature range. We also revived our idea about numerically simulating strain gages. HBM was so interested that we were able to fund Yu Tao as a doctoral student for three years. Yu Tao's task was to develop the numerical simulation of a strain gage measuring point so that its characteristics could be calculated.

The resistance, the gage factor and the transverse sensitivity were to be determined and the influence of the material characteristic quantities of the various layers and the geometry of the grid of a strain gage measuring point on the characteristics was also to be determined in a parameter study. Initially, the aims were more ambitious as calculations for the thermal behavior of the measuring point and the creep behavior were included. But these aims could not be realized with the requisite accuracy.

Method and modeling

The basis for numerical simulation was the ALGOR® finite element program, which includes calculating the deformation state as well as a module for calculating the local conductivity in a body. This made it unnecessary to use the previous method of heat conductance. First the model was used to determine the geometry of the deformed state. A conductivity calculation was then performed with the model in the non-deformed and deformed state. For the deformed state, it was necessary to use an intermediate step to determine the influence of the change in volume on the specific electrical resistance, which is not included in the conductivity calculation. This method resulted in the resistances for the two states and their difference enabled the sensitivity to be calculated. As the constraint for this calculation, a potential difference of 5 V was specified at the ends of the grid.

To determine the gage factor, a deformation of 1000 µm/m with homogeneous distribution was specified in the base body. This produces the global constraint which is satisfied by the purely elastic deformation of the grid material. The difficulty is to choose the constraints that ensure that the stress field below the strain gage is completely homogeneous and one-dimensional. This was resolved by modeling the test specimen for experimentally determining the gage factor **(Fig. 1)**.

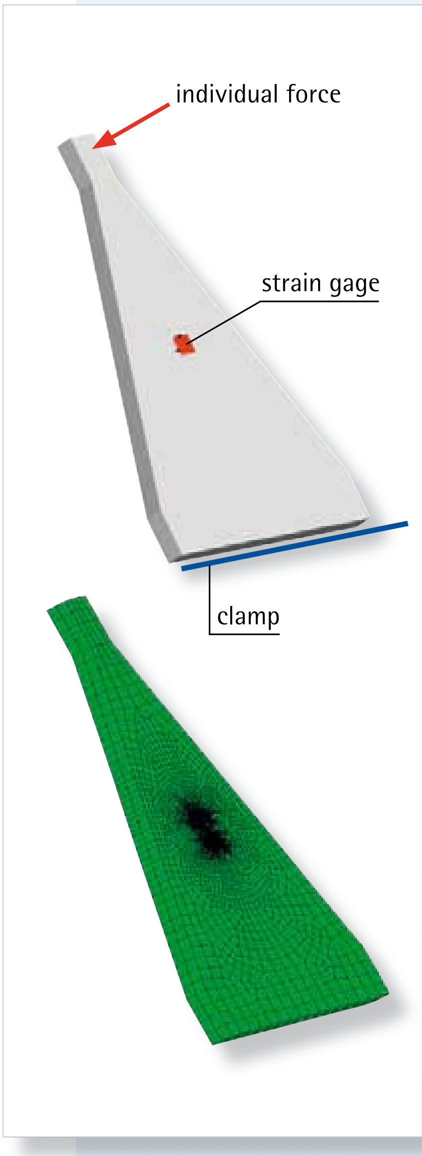

*Fig. 1:
Constant stress carrier for experiment and FE analysis*

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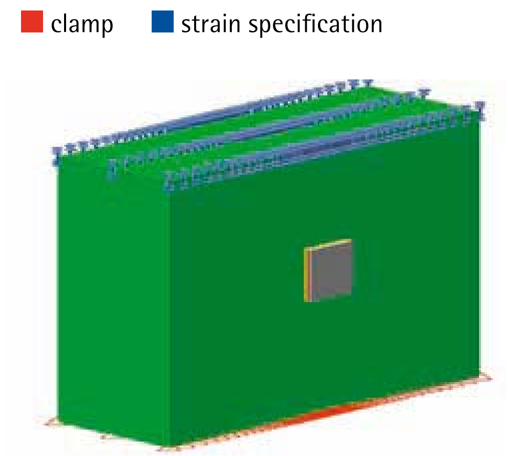

Fig. 2: FE model with strain specification over the displacement constraints

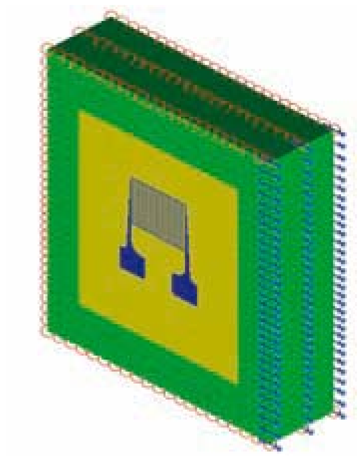

Fig. 3: Model for calculating transverse sensitivity

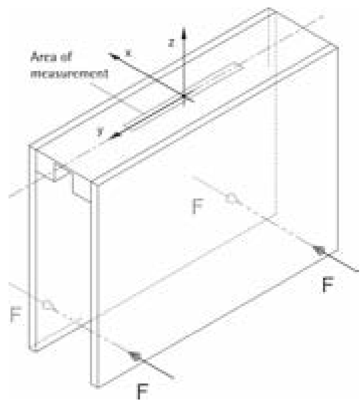

Fig. 4: Apparatus for experimentally determining the transverse sensitivity of strain gages

When loading the tip of the test specimen with a force, a completely homogeneous one-dimensional stress field and the required two-dimensional strain field were also produced numerically in the area of strain gage application without a strain gage. After the virtual application of the strain gage and its different layers, the field is no longer as homogeneous because the strain gage itself has a stiffening effect. To reduce the complexity of the calculation, a smaller model **(Fig. 2)** was subsequently introduced. The field of strain in the base body is generated by specifying the displacement constraints.

When calculating the transverse sensitivity, a deformation state had to be created similar to that used in the experiment in the base body, where only one strain component occurred in the transverse direction under the strain gage. It was far easier to specify the corresponding edge strains, as shown in **Figure 3**, with the numerical simulation than in the corresponding experiment apparatus **(Fig. 4)**.

Modeling the structure of the strain gage application caused a lot of discussion and a real strain gage was first modeled with a nominal (rated) resistance of 350 Ω. The layer structure comprised the following layers: base material, adhesive layer, carrier foil, grid adhesive layer, strain gage grid, grid embedding and measuring point covering agent **(Fig. 5)**.

The networking of the overall structure in finite elements is shown in **Figure 6** in various section magnifications.

To prove the method in principle, it seemed sensible to compare a real strain gage with the simulation. However, the model was far too complicated for the parameter study of the material influence quantities and we had to drastically reduce the number of finite elements to keep the computing time within acceptable limits. For these calculations, the model was reduced to one strain gage with two grid wires, as in **Figure 7**.

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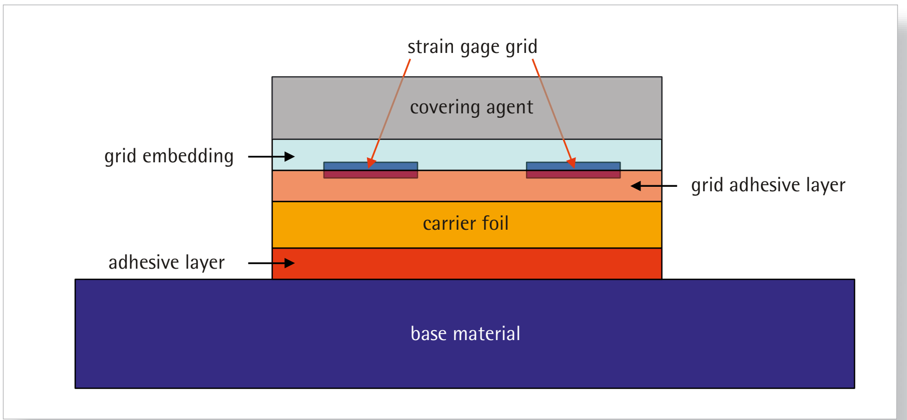

Fig. 5: Layer structure for the FE simulation (section)

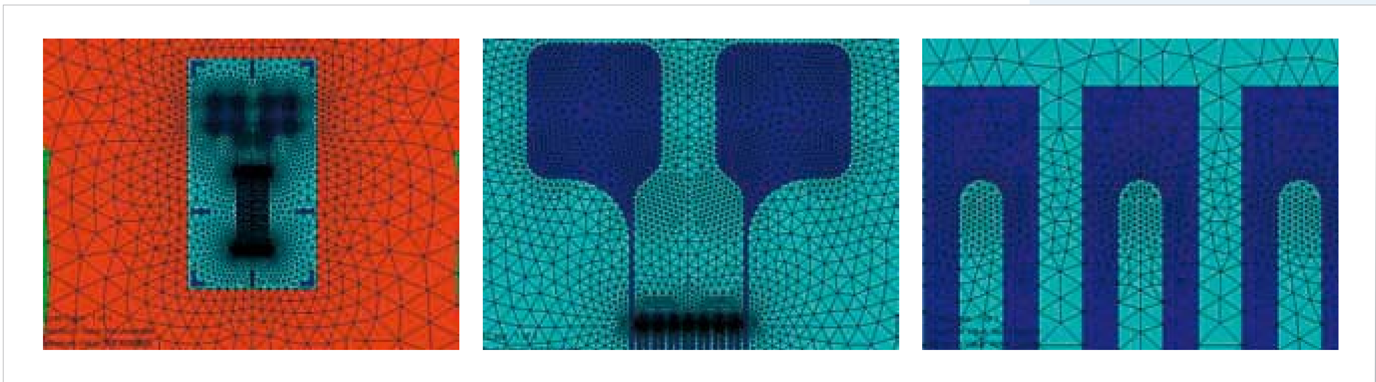

Fig. 6: FE network in various section magnifications

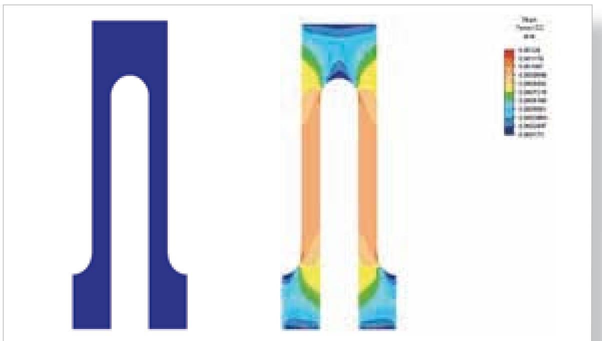

Fig. 7: Simplified strain gage grid for the parameter study, geometry and calculated longitudinal strain ε_z

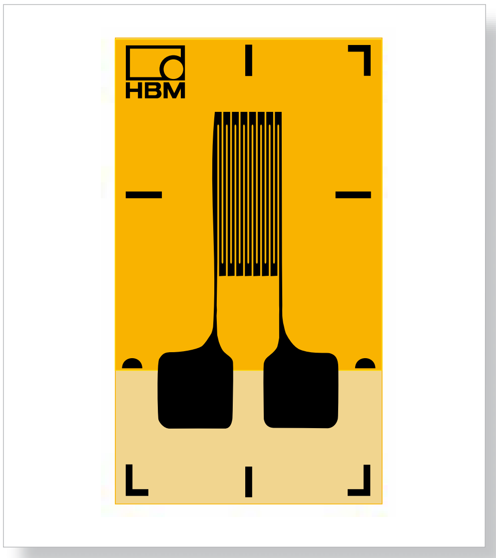

Fig. 8:
Special strain gage for validating the finite element calculation

It soon became apparent during the calculations that precise knowledge of the geometry of the measuring point and the material properties of the different materials used is the limiting factor for comparability between the simulation and the experimental results. Nevertheless, to provide adequate validation for the method, HBM produced a special strain gage **(Fig. 8)** whose geometry was measured with the utmost accuracy. The resistance, gage factor and transverse sensitivity were first calculated for this strain gage and only then were standard tests for the experimental determination of these characteristic values performed. So a genuine forecast of the data took place.

Results

The results of the FE simulation and a comparison with the experimentally determined values are shown in the table below:

	Minimum measured values	Maximum measured values	Average measured value	Uncertainty σ_{n-1}	FE simulation results	Relative deviation between measurement and simulation
Measuring grid thickness [µm]	4.95	5.13	5.047	0.036	5.047	-
Resistance [Ω]	144.219	144.9875	144.65	0.28	146.45	1.24 %
Gage factor [-]	2.041	2.055	2.0502	0.0061	2.042	0.4 %
Transverse sensitivity [-]	-	-	0.06 %	-	0.15 %	-

Table:
Comparing measured values with values from the FE calculation

As can be seen from the comparison, the forecasts for the resistance and the sensitivity can be described as very good. On the other hand, the transverse sensitivity forecast is relatively inaccurate. The reason for this is that relatively small differences in the Bridgeman constant of the grid material cause major changes in transverse sensitivity. The Bridgeman constant indicates the ratio of the specific electrical resistance to a volume change in the grid material.

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We know, from earlier theoretical considerations, such as those by Rohrbach and Czaika [1] that the transmission of strain from the base material to the grid basically takes place in the end loops. The later experimental investigations of Stockmann [2], performed with the Moiré interferometry method on original strain gages, allowed accurate metrological acquisition of the two-dimensional displacement fields on the surface of the strain gage measuring grids. The calculation using the finite element model now virtually represents a second verification of the facts and can initially be documented by the following image. **Figure 9** shows the difference between the longitudinal strain on the surface of the grid and the longitudinal strain in the base carrier. There are no visible color differences where the strain in the grid is the same as the strain in the base material. It becomes very clear that the application of strain to the measuring grid takes place in the end loops and in a small part of the grid, as this is the only place where there are visible color differences. But at the same time, this also means that this is where the effect on the specific strain gage quantities can be felt.

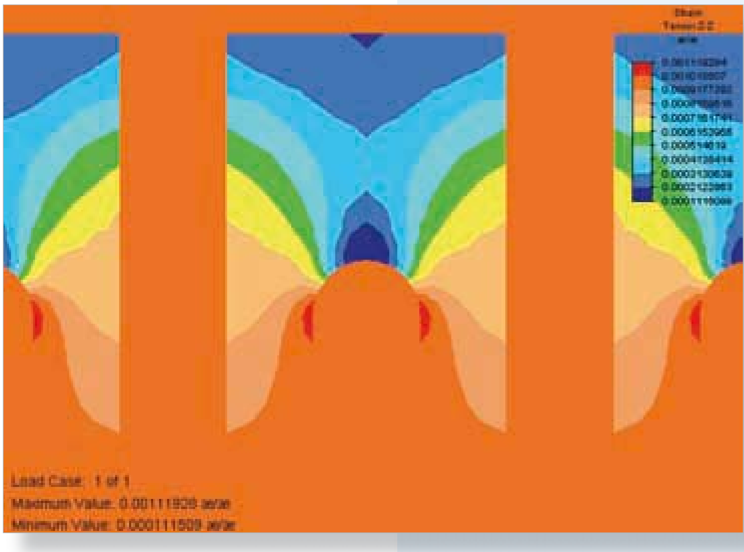

Fig. 9: Longitudinal strain difference (grid surface, base body)

By showing the lines of constant displacement (isothets), the findings of the numerical simulation can be directly compared with the experimental findings from the moiré interferometry measurements. **Figure 10** shows the isothetic fields for the longitudinal direction from the Stockmann [2] investigation and from Tao's FE calculation [3]. The experimental investigations show that there are only considerable bends in the lines in the end loop area, whereas the lines in the grid run virtually parallel. This behavior is even more pronounced in the FE simulation, as an extremely symmetrical state can be assumed here.

Fig. 10: Isothetic fields for the end loops and links under longitudinal strain from the experiment (Stockmann [2]) and from the FE calculation (Tao [3])

The conformity shown by the images of a strain gage under transverse stress **(Fig. 11)** is also good in comparison.

Fig. 11: Isothetic fields for the end loops and links under transverse strain from the experiment (Stockmann [2]) and from the FE calculation (Tao [3])

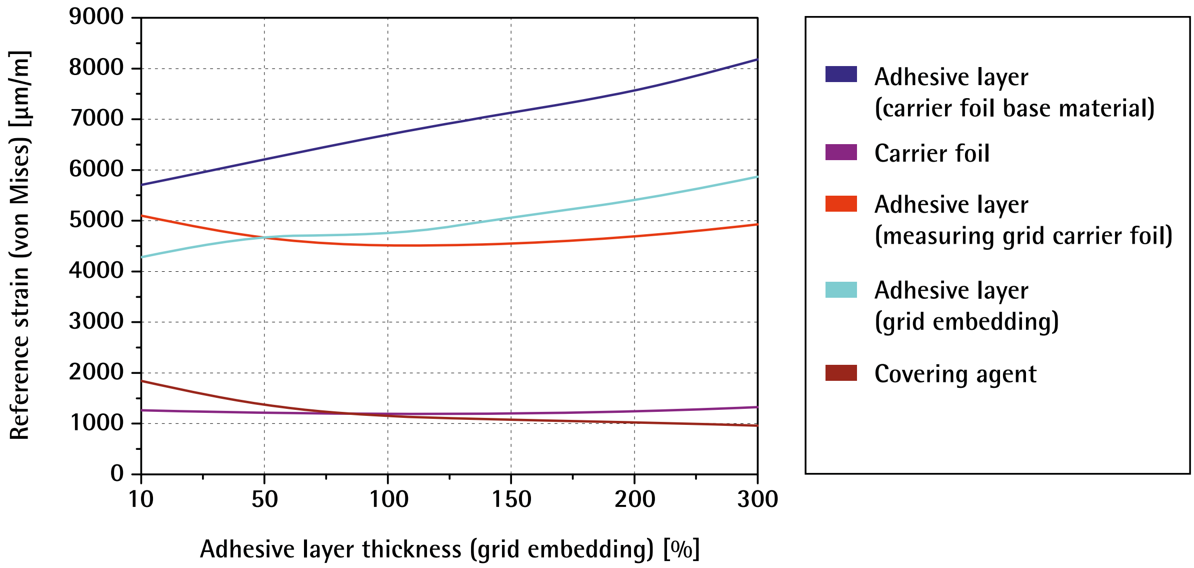

Fig. 12: The effect of the grid embedding thickness on the maximum reference strain (von Mises) occurring in the layer structure (100 % thickness corr. to 25 µm, strain in the base material is 1000 µm/m)

These examples clearly show that the findings of known experimental investigations of the deformation behavior of strain gages can be readily confirmed by numerical simulation. A considerable advantage of the finite element simulation for investigating and developing strain gages is that unlike experiments, where only the top layer of the composite can be investigated, here the deformation states can be visualized in any of the layers. This makes it possible to carry out the parameter study mentioned above.

The measuring grid properties were kept constant and the layer thicknesses and the modulus of elasticity of the other layer materials were varied for a given model (see **Fig. 6**). There were plenty of results from these studies and these are shown in [3].

As an example, **Figure 12** shows the effect of the thickness of the grid embedding on the maximum reference strain occurring in the different layers.

References

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