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UNCERTAINTIES OF MEASUREMENTS WITH METAL FOIL STRAIN GAGES

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ABSTRACT

Strain gages are often in use to obtain information about structures. They are used in transducers, which measure force, mass, pressure, strain and so on. The accuracy of transducers is often better than 0.05 %. Experimental Stress Analysis (ESA) with directly installed strain gages shows other results. The uncertainties of those measurements are approximately one hundred times higher than the uncertainties of strain gage transducers. The reasons are discussed in this paper. Formulas and calculation examples are given for non-zero and for zero-referenced stress measurements.

KEYWORDS

Stress measurement, strain measurement, measurement uncertainty, accuracy, metal foil strain gage.

LIST OF SYMBOLS

E	*Young´s Module*
F	*Force*
P_{el}	*Electric Power*
R	*Resistance*
R_0	*Nominal Resistance*
R_{SG}	*Resistance of Strain Gage*
R_S	*Shunt Resistance*
T	*Temperature*
V_A	*Bridge output Voltage*
V_B	*Bridge excitation Voltage*
h	*Thickness of (Glue + Measurement Grid Carrier + half Measuring Grid)*
k	*k factor, Sensitivity of Strain Gage*
l	*Length*
r	*Distance material surface to neutral axis*
t	*Temperature in °C*
t_{Ref}	*Reference Temperature in °C*
Δ	*Change, Deviation or Error*
α_E	*Temperature Coefficient of Young´s Module*
α_{SG}	*Thermal Expansion Coefficient which SG is adapted for*
α_{Mat}	*Thermal Expansion Coefficient of Material*
δ	*Relative Deviation, Error or Uncertainty*
ε	*Strain*
ε_{SG}	*Strain of Measuring Grid*
ε_{Mat}	*Strain of Material*
ε_{Rs}	*Strain, pretended by Shunt Resistance*
ε_{corr}	*Corrected Strain*
ε_{max}	*Maximum Strain*
ε_{meas}	*Measured Strain*
ν	*Poisson´s Ratio*
σ	*Stress*
σ_{SG}	*Mean Stress beneath Measuring Grid*
σ_{max}	*Maximum Stress*

φ *Alignment Failure*

INTRODUCTION

Strain gages have been in use for more than seventy years. The strain gage technology with its many possibilities for compensation of measurement failures was developed more and more over the decades. One important step was the development of metal foil strain gages. They are used for the construction of transducers and in experimental stress analysis (ESA). The technological progress can best be observed in strain gage transducers. The accuracy class of many types of strain gage transducers for the measurement of mechanical quantities now reaches 0.02 %. High precision force transducers even reach 0.005 %. On the other hand, the uncertainties of stress measurements with strain gages are worse than 1 %. This paper deals with the reasons for the vast difference.

MEASURES TO REACH A HIGH ACCURACY FOR STRAIN GAGE TRANSDUCERS

Strain gage transducers are designed to measure a distinct quantity. A spring body transforms the mechanical quantity into a high enough proportional strain. Four strain gages (sometimes even more) transform the strain into a relative resistance change. The output signal of well adapted self-temperature compensating strain gages is nearly independent of the thermal strain of the spring body material. Finite element software helps to optimize the shape of spring bodies. So the influence of mechanical disturbance quantities (e.g. transverse force) will be minimal. The spring body material (special alloy) has very good measurement characteristics and a well-known history. The very sophisticated strain gage designs are able to compensate a big part of the elastic after-effect, which occurs in the spring body material. The Wheatstone full-bridge circuit suppresses many disturbing effects, e.g. thermal effects. If this is not sufficient, individual adjustable resistors made of nickel are used within the bridge branches. Warm spring body material is less stiff than cold material. Nickel resistors within the voltage supply lines of the bridge compensate this thermal effect. Semiconductor strain gages are sometimes installed on the spring body and connected in serial in the voltage supply lines to improve the linearity. The protection of the measuring point is nearly hermetic. An Ingress Protection Rating IP67 is almost standard for industrially manufactured transducers. One can calibrate and adjust transducers very accurately. That suppresses the effect by uncertainty of Young´s module and tolerance of gage factor. Most of the above mentioned measures cannot be practically applied in ESA.

ACCURACY USING STRAIN GAGES AT EXPERIMENTAL STRESS ANALYSIS

Preface

It is practical to split the measuring tasks into non-zero related measurements and into zero related measurements. For non-zero related measurements it is possible to adjust the zero-point at distinct time points without any loss of information. E.g. one has to measure the amplitude or the frequency of an oscillating stress and the offset is not of any importance. The aim could be to detect the damping ratio or the natural frequency of a structural element. Zero related measurements are those for which any zero-shift is of importance. An adjustment of the zero-point during the measuring time would generate a loss of information. E.g. one has to measure the development of static stress in a construction element over a very long time. Zero related measurements are more critical because every zero point drift causes a measuring error. Structural monitoring tasks are often zero related measuring tasks.

Parts of Measuring Chain

Figure 1 shows the elements of a strain gage measuring chain which transforms stress (unidirectional stress field) into a measuring value.

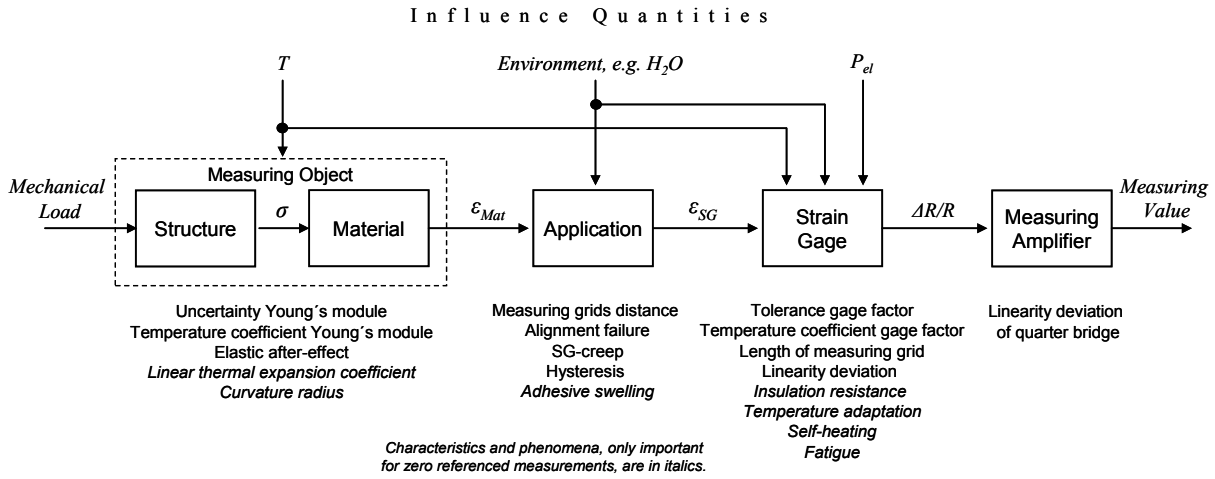

Figure 1. Signal flow stress measuring chain

Measuring object

A mechanical load causes stress in the measuring object. Hence, strain on the surface will occur. The proportion factor between stress and strain is called Young´s module (Eq. 1).

$$\varepsilon_{Mat} = \frac{\sigma}{E} \tag{1}$$

Unfortunately, Young´s module often has a high uncertainty. Extensive evaluations were made for many structural steels. Itoh (1984) determined a coefficient of variation of 4.5 %. Furthermore, Young´s module depends on temperature because it has a temperature coefficient. The following characteristics of the measuring object and phenomena can also cause measuring errors: elastic after-effect, linear thermal expansion coefficient, curvature radius. That means Eq. 1 has several sources of uncertainties.

Application (installation)

The strain gages measuring grid should have the same strain as the material beneath it (Eq. 2).

$$\varepsilon_{SG} = \varepsilon_{Mat} \tag{2}$$

But we have to deal with several imperfections in measuring practice. These are distance between measuring grid and material, alignment failure, strain gage creep, hysteresis, strain gage carrier and adhesive swelling. The resulting measuring errors are influenced by the applicator skills and environmental conditions, especially humidity. The standard ASTM E1237 (2009) provides guidelines for installing bonded resistance strain gages.

Strain gage

The strain gage transforms its own measuring grid strain into a proportional relative resistance change (Eq. 3). The sensitivity is called gage factor or k factor (VDI/VDE/GESA 2635 in 2007).

$$\frac{\Delta R}{R} = k \cdot \varepsilon_{SG} \tag{3}$$

Many strain gage characteristics and phenomena disturb an ideal transformation: tolerance of the gage factor, temperature coefficient of the gage factor, length of active measuring grid, linearity error of the strain gage, insulation resistance of the strain gage and its leads, temperature adaptation of the strain gage, self-heating, fatigue due to many load changes. Influence variables are temperature and other environmental conditions, e.g. humidity, RMS value of excitation voltage.

Measuring amplifier

The measuring amplifier transforms the relative resistance change into a measuring value for stress or strain.

The resistance change is very low (0.2 % at 1000 µm/m and gage factor of 2). That is why Wheatstone bridge circuits are applied. The measuring amplifier supplies the excitation voltage and processes the bridge output voltage. In ESA, it is common to use only one active strain gage in the bridge circuit. Eq. 4 is in use to describe the interconnection between the relative resistance change and the bridge voltage ratio of quarter bridges.

$$\frac{V_A}{V_B} = \frac{1}{4}\frac{\Delta R}{R} \tag{4}$$

Eq. 4 generates linearity errors at high relative resistance changes, because the true interconnection is non-linear. This paper does not consider measuring errors which may occur due to long electrical lanes, disturbing electric and magnetic fields, thermo voltages and errors of the measuring amplifier itself. All these errors are nearly fully avoidable by application of suitable measuring technologies, such as senses wires, shielding techniques, modern carrier frequency measuring amplifiers.

Uncertainty of Non-Zero Referenced Measurements

For such measuring tasks the zero-point is not of any significance, because only changes in the measuring quantity are of significance or the zero-point is stable during the measurement (typical for short time measurements, e.g. crash tests, short time loading tests).

Uncertainty of Young´s module

Young´s module shows an uncertainty which often has more than one percent. The relative uncertainty of Young´s module causes a relative uncertainty of stress with the identical amount in ESA (Eq. 5).

$$\frac{\Delta\sigma}{\sigma} = \frac{\Delta E}{E} \tag{5}$$

That means, in the case that the Young´s module of the material under test is known with an uncertainty of 5 %, then a minimum uncertainty of stress of 5 % will occur, even if it were possible to measure the strain without any error.

Temperature coefficient of Young´s module

We must note the temperature dependence of Young´s module. E.g. the temperature coefficient is approximately $-2 \cdot 10^{-4}\ K^{-1}$ for steel. The relative change of Young´s module is shown by Eq. 6:

$$\frac{\Delta E}{E} = \alpha_E \Delta T \tag{6}$$

That means an additional uncertainty of stress (Eq. 7).

$$\frac{\Delta\sigma}{\sigma} = \alpha_E \Delta T \tag{7}$$

E.g. Young´s module for a steel type is given at a temperature of 23 °C. The measurement is done at 33 °C. Young´s module will be decreased by 0.2 %. An additional error of 0.2 % for the measured stress will occur. Compensation would be difficult because the temperature coefficient of Young´s module is dependent on the temperature itself.

Distance measuring grid to material surface (test objects bended under load)

If the strain gage is bonded on a structural element which will bend under load, the measuring grids strain will differ from the strain of the measuring object surface. The measuring grids strain will be higher than the strain of the measuring object. The effect is determined by the distances between measuring grid, material surface and neutral axis. This phenomenom causes multiplicative strain deviations with a positive sign.

$$\frac{\Delta\varepsilon}{\varepsilon} = \frac{h}{r} \tag{8}$$

Eq. 8 gives a strain extension of 0.001 with a distance between measuring grid and material surface of 100 µm at a distance between material surface and neutral axis of 100 mm. For this example, the true strain is 0.1 % lower than the measured strain. That means the measured stress would be 0.1 % too high.

Elastic after-effects

A spontaneous strain will occur after a spontaneous load according to Hooke´s Law. However, an additional, much smaller strain will follow after the spontaneous strain. This is due to relaxation processes of the micro particles in the test material. The amount of the after-effect depends on material, temperature and time. A strain error of approximately 1 % can occur after waiting half an hour before taking the measuring value.

Alignment failure

If the strain gage is not bonded exactly in the direction of the material stress (unidirectional stress state), a negative measurement deviation occurs. Then the measured strain is smaller than the material strain. The relative strain error is given by Eq. 9:

$$\frac{\Delta\varepsilon}{\varepsilon}(\varphi) = \frac{1-\nu+(1+\nu)\cos 2\varphi}{2} - 1 \tag{9}$$

For an alignment error of 5 degrees and a Poisson´s ratio 0.3 (steel), a strain error of -1 % will occur. The true strain and the true stress will therefore be 1 % higher.

Strain gage creep

After a spontaneous material strain, the measuring grid will nearly instantly be strained and than creep back a little bit. This creep process depends on the shape of the strain gages (short measuring grids are more critical, strain gages with very big end loops do not creep), the characteristics of adhesive and on the temperature. In consequence, the strain of the measuring grid will often be a little bit smaller than the material strain after a while. Example: The strain gage type LY11-6/120 (HBM), often used for ESA with its active measuring grid length of 6 mm bonded with adhesive Z70 (HBM), creeps 0.1 % back within one hour at a temperature of 23 °C. That causes a measurement deviation of -0.1 % regarding the true strain or stress. Strain gage creep partially compensates the elastic after-effect in the material and can be ignored for most applications. But in the special application case using the glue X60 (HBM) at strains of 2000 µm/m and a temperature of 70 °C, a deviation of -5 % will occur after one hour.

Hysteresis of strain gages

Short measuring grids are more critical and glue has an influence, too. The hysteresis is only 0.1 %, when a strain gage of type LY11-6/120 is bonded with glue Z70 for a strain of ±1000 µm/m. In most cases, the hysteresis error is negligible. Under special circumstances, if a strain gage LY11-0,6/120 is in use (active measuring grid 0.6 mm), the hysteresis error rises to an uncertainty of 1 % for strain and stress measurements.

Tolerance of gage factor

The measuring chain must be adjusted in accordance with the gage factor (printed on the strain gage envelope). It describes the connection between relative resistance change (output) and strain (input). The uncertainty of the gage factor is usually 1 %. The gage factor uncertainty causes an equal amount of relative uncertainty for strain and stress measurements.

Temperature coefficient of gage factor

The gage factor depends on temperature. Sign and amount is determined by the measuring grid alloy. Constantan measuring grids show temperature coefficients of approximately 0.01 % per Kelvin. That means a temperature rise of 10 K causes a gage factor rise of 0.1 %, which is not significant for ESA. But, under special conditions, if the measurement takes place at 120 °C, the measured strain and stress values would be 1 % too high.

Length of measuring grid

The strain gage transforms the average strain under its active measuring grid into a relative resistance change. If the stress field is not regular, average strain will be measured. But the maximum local strain is usually of more importance. To avoid the measurement of average stress instead of searched peak stress, short measuring grids must be installed. This is well known. Therefore, errors with significant amount occur very seldom and will not be discussed further in this paper.

Linearity deviation of strain gages

Strain gages with measuring grids made of Constantan, Karma, Nichrome V, Platinum-Tungsten show an excellent linearity. Nevertheless, errors are known for Constantan strain gages at high strains. The true characteristic curve is given in good approximation with the empirical Eq. 10 (Hoffmann 1989):

$$\frac{\Delta R}{R} = k(\varepsilon + \varepsilon^2) \tag{10}$$

If the strain would be calculated with Eq. 11, the non-linearity would be eliminated.

$$\varepsilon = \sqrt{\frac{1}{4} + \frac{1}{k}\frac{\Delta R}{R}} - \frac{1}{2} \tag{11}$$

But in measurement practise, the quadratic part of Eq. 10 is usually ignored. Hence the measurement error is given as follows. The relative deviation of the measured strain value is as high as the strain value itself (Eq. 12).

$$\delta = \varepsilon \tag{12}$$

That means for strains up to 1000 µm/m, the relative strain error (respectively stress error) does not exceed a value of 0.1 %. It is equivalent to a strain of 1 µm/m. This is negligible for ESA. But deviation rises for special applications with very high strains: 10 000 µm/m causes 1 %. 100 000 µm/m causes 10 %. Fortunately, this error is rare and will be largely compensated by using quarter bridges.

Linearity deviation of the quarter bridge

Only one active strain gage is usually in use at a measuring point in the field of ESA. Therefore, the other resistors are not influenced by strain. The correct formula for the voltage ratio is (Eq. 13):

$$\frac{V_A}{V_B} = \frac{\Delta R}{4R_0 + 2\Delta R} \tag{13}$$

Though the true connection is non-linear, in practise the linear Eq. 14 is in use:

$$\frac{V_A}{V_B} = \frac{\Delta R}{4R_0} \tag{14}$$

The relative deviation, which is caused by the simplification, can be calculated by Eq. 15:

$$\delta = \frac{1}{1 + \frac{\Delta R}{2R_0}} - 1 \tag{15}$$

A strain of 1000 µm/m (gage factor = 2) generates a relative resistance change of 0.2 %. A calculation of the relative measuring error with Eq. 15 delivers -0.1 %. It is equivalent to a negligible strain error of -1 µm/m. But at higher strains, significant linearity errors occur: 10 000 µm/m causes -1 %. 100 000 µm/m causes -9.1 %. When Constantan strain gages are in use, this non-linearity will be mainly compensated due to the non-linearity of the strain gages. Hence this error will not be discussed further in this paper.

Uncertainty of Zero Referenced Measurements

In case of zero referenced measurements, additional uncertainties must be added to the above mentioned uncertainties. The zero point is of significance for zero referenced measurements. Typical examples are long time measurements at structures and fatigue tests of structural elements. Any displacement of zero point causes additive strain (or stress) deviation. These deviations are independent of the actual measuring value. The relative error δ is the quotient of absolute error and measuring value (Eq. 16). Expressed as a percentage, it is good comparable with the deviations discussed in the previous section.

$$\delta = \frac{\Delta\varepsilon}{\varepsilon} \tag{16}$$

It is obvious and important that the relative uncertainty will assume high values at a small strain or stress.

Linear thermal expansion coefficient, curvature radius, temperature adaptation

The temperature influence is mostly not eliminated by an additional temperature compensating strain gage in the Wheatstone bridge circuit. The material under test shows a thermal expansion. We do not like to measure thermally induced strain in the field of structural monitoring. We have to measure strain which is influenced only by load, because we have to evaluate stress. Therefore strain gages are used which are adapted to the linear thermal expansion coefficient of the material under test. Unfortunately, the compensation is not perfect. The residual temperature response is given by manufacturers. Eq. 17 shows an example for a strain gage type LY-6/120 (HBM):

$$\Delta\varepsilon = -13.8 + 1.58\,t - 4.88\cdot10^{-2}t^2 + 2.21\cdot10^{-4}t^3 \tag{17}$$

The temperature value (°C) must be inserted without a unit. The formula delivers the residual strain deviation in the unit µm/m. For a temperature of 30 °C, we get a strain deviation of -4.4 µm/m. But we would get higher errors for bigger differences between structure temperature and reference temperature (20 °C) or for incorrectly adapted strain gages. These errors are systematic and should be compensated by calculation (Eq. 18). Ambient temperature and linear thermal expansion coefficient of the material must be known.

$$\varepsilon_{Corr} = \varepsilon_{Meas} + 13.8 - 1.58\,t + 4.88\cdot10^{-2}t^2 - 2.21\cdot10^{-4}t^3 - (\alpha_{Mat} - \alpha_{SG})(t - t_{Ref}) \tag{18}$$

However the formula itself has an uncertainty. This error increases proportionally to the difference between ambient temperature and reference temperature. The uncertainty is 0.3 µm/m per Kelvin temperature difference. That means the polynomial has an uncertainty of 3 µm/m at ambient temperature of 30 °C. In the case that a strain gage with a wrong adaptation is used (e.g. an adaptation error of $12\cdot10^{-6}$ K^{-1}, strain gage for ferritic steel is bonded on aluminum), the temperature response would be 120 µm/m for 10 K temperature change. Such big systematic errors are avoidable! But errors also occur if the application surface is curved, because the temperature compensation can not work optimally when the application surface is not flat. A curvature radius of 10 mm causes a deviation of approximately 10^{-6} K^{-1} (Hoffmann 1989). That means 10 µm/m for a temperature change of 10 K.

Self-heating

The electrical power will heat the strain gage (Eq. 19):

$$P_{el} = \frac{U_B^2}{4R} \tag{19}$$

The power is 52 mW for a bridge excitation voltage of 5 V and a strain gage resistance of 120 Ω. A strain gage bonded with a very thin adhesive layer on metal will dissipate the heat into the material. A very small strain gage bonded on material with a bad thermal conductivity will have a higher temperature than the material. This temperature difference causes a deviation (Eq. 20):

$$\Delta\varepsilon = \left(t_{Mat} - t_{SG}\right)\alpha_{Mat} \tag{20}$$

If the strain gage temperature is 1 K higher than the material temperature, a strain error of -11 µm/m will occur if the measuring object consists of ferritic steel. Low excitation voltages of 1 V or less are strongly recommended for very small measuring grids (e.g. 0.6 mm) bonded on materials with low thermal conductivity.

Swelling of adhesive and measuring grid carrier

The reason for swelling (and shrinking) is due to the hygroscopic characteristic of adhesive and measuring grid carrier. The effect exhibits a slow zero point shift, which is not distinguishable from material strain or stress changes. How fast the zero point shifts depends on the ambient conditions and on the protection of the measuring point against water molecules. The time constant can be several hours. Under very bad conditions even the bonding can fail! High humidity change rates and high temperature are critical conditions and need an excellent measuring point protection. There is no possibility of providing any numbers for zero point displacement without experimental evaluations under special conditions of high moisture load.

Insulation resistance

Water molecules which penetrate up to the measuring point will influence the insulation resistance. Low insulation resistances causes zero shifts, because they are acting as shunts connected parallel to the measuring grid or measuring leads. The resistance of the shunt can not be measured. By its nature, it will have a value in the similar scale of the insulation resistance, which can be measured between a strain gage contact and the test object. Eq. 21 exhibits the connection between strain error $\Delta\varepsilon$ and shunt resistance R_S.

$$\Delta\varepsilon = \frac{1}{k}\left(\frac{R_S}{R_{SG}+R_S}-1\right) \tag{21}$$

The formula shows that the influence is smaller with bigger strain gage resistances. Table 1 shows deviations with a 120 Ω strain gage (gage factor $k = 2$) at several shunt resistances:

Table 1 Deviations due to shunt resistances

R_S in MΩ	$\Delta\varepsilon$ in µm/m
50	-1.2
5	-12
0.5	-120

Well performed strain gage measuring points show insulation resistances of more than 1 GΩ. Most of the insulation resistances are higher than 50 MΩ. The strain errors of 1.2 µm/m are negligible. But for a poor insulation of 500 kΩ and a measuring value of 1000 µm/m, we would get a zero point deviation of -12 %. Hence insulation resistances that are too low cause instability in measurements and can lead to total failure of the measuring point. As mentioned before, comprehensive protective measures are necessary for high moisture load.

Fatigue

Where the test object is under dynamic loads, the strain gages can show fatigue in their measuring grids. The fatigue causes an increasing strain gage resistance, i.e. a zero point displacement. For vibratory strain less than 1000 µm/m, the shift of zero point is negligible. Higher magnitudes are critical. A 10 µm/m zero shift must be expected at the following conditions (all values are taken from Hoffmann Figure 3.3-20):

1500 µm/m and approx.	2 000 000 load cycles
2000 µm/m and approx.	100 000 load cycles
2500 µm/m and approx.	4 000 load cycles
3000 µm/m and approx.	100 load cycles

For such applications, optical strain gages (Fiber Bragg Grating) should be preferred.

The Human Factor

We must be sure that the measuring point is well planned and the strain gages are proper installed and protected. If it is not (inexperienced application engineer), vast measuring errors may occur up to a total failure of the

measuring point. Especially for zero referenced long-term measuring, the measuring point protection is of very high importance. There is probably no other measuring method with such a high significance for the human factor (knowledge, experience, skills of the engineers). Therefore, application engineers should have taken part successfully in certificated strain gage courses (VDI/VDE/GESA 2636 in 2000). A good example for successful strain gage measurements at very difficult conditions is shown by Figures 2 and 3. 44 measuring points are installed at the offshore research platform FINO 1 (height 129 m) in the North Sea. The strain gages are located between 5 and 25 meters below sea level. The purpose was to measure strain respectively stress at the jacket, which were caused by ramming, waves and wind. After two years, 42 measuring points still worked.

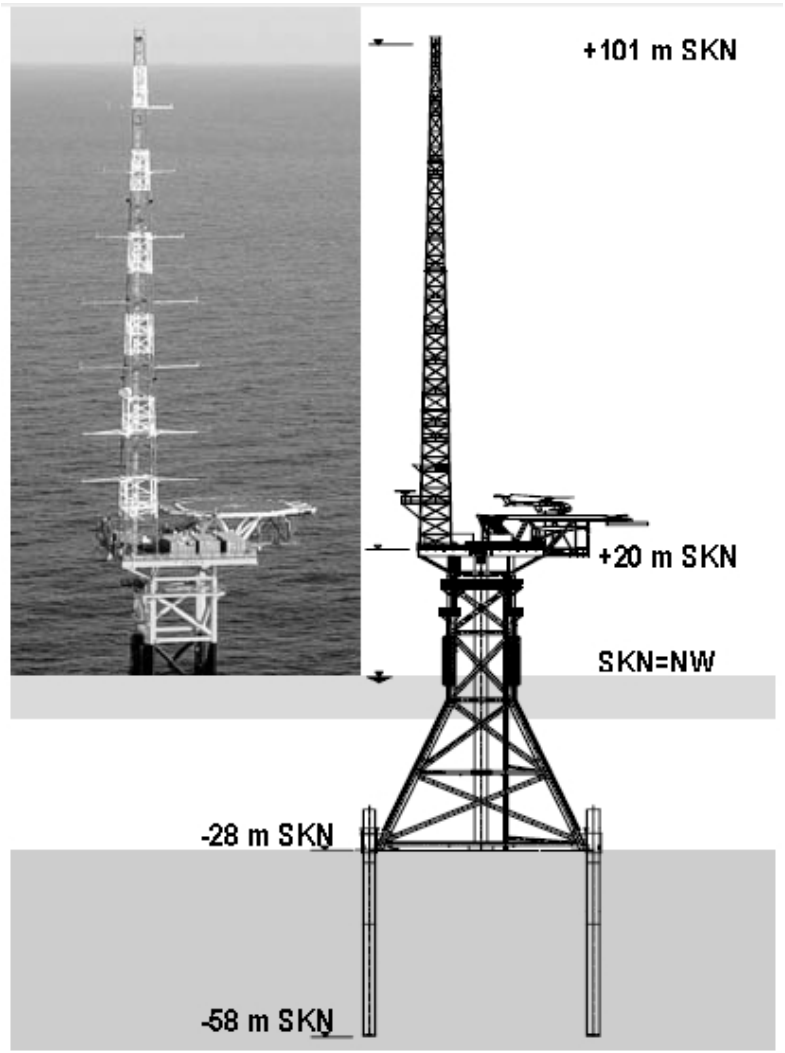

Figure 2. Off shore platform FINO 1 by kind permission of GL Garrad Hassan

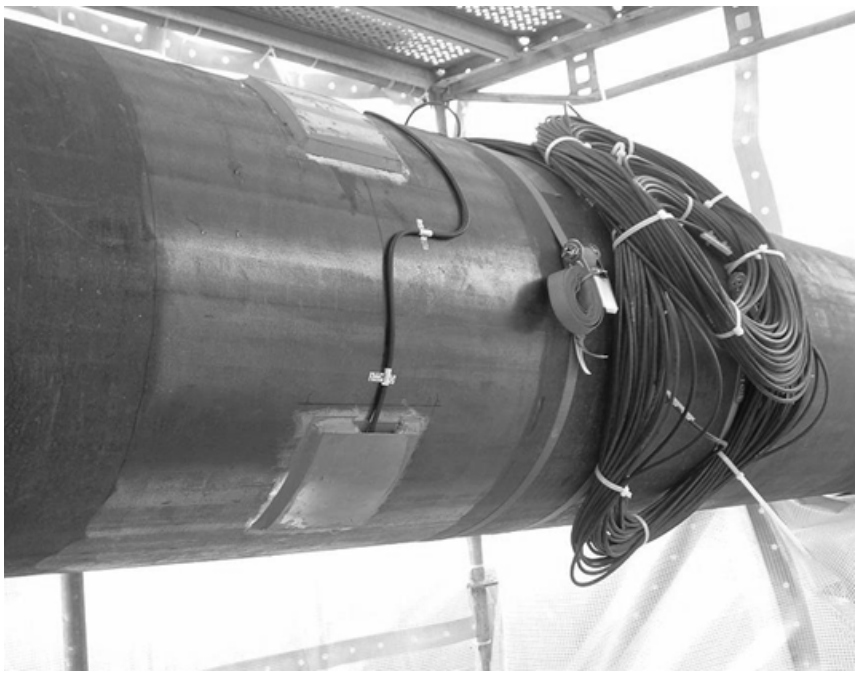

Figure 3. Two strain gage measuring points at jacket structure of off shore platform FINO 1

Final Remarks about Uncertainty using Strain Gages

Of course there are special applications, where other unmentioned errors may occur. E.g. Young´s module of some stainless steels (often in use for connecting elements) is considerably dependent on the measuring quantity stress. This paper does not attempt to be a guide for the calculation of the measurement uncertainty. The aim is to give hints to the test engineers about where sources of errors may be hidden and what values of uncertainty occur approximately. Mostly formulas or numbers are given. When the biggest possible error (worst case) is needed, all part errors have to sum up. Because the appearance of the worst case (all errors have the same sign and appear with their biggest value) is very rare (nearly impossible) in practise, it is mostly sufficient to sum up in Pythagorean manner. With strains around 1000 µm/m, approximately 4 % uncertainty is possible for strain measurements and 7 % for stress measurement. Uncertainties not far below 20 % must be estimated if strains are smaller than 100 µm/m strain.

CONCLUSIONS

The reason for the far better uncertainty of strain gage transducers instead of strain gages is made clear. In the practice of structural health monitoring, it is not possible to reach uncertainties smaller than 1 % for strain measurements. More likely are uncertainties of more than 4 %. By the way, the coefficient of variation of the yield point of structural steel is approximately 8 %. This paper should initiate a discussion about uncertainties for strain gage measurements at structures. The authors are grateful for every feedback, especially if colleagues gained different experiences or have different opinion about some aspects.

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