Suitability of subsequently installed vibrating wire sensors for direct stress measurement in concrete and mortar

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Abstract. Over the past decades, a major part of the building infrastructure has aged and is now in need of repair. In order to ease the repair backlog and to be able to distinguish between urgent and long-term repair needs, it is advisable to install a monitoring system to the structure. This monitoring is, among others, often based on periodical strain or deformation measurements, as they provide a direct indication of the effect of external loads on the structure (crack opening or heavy deformations). Still, most of the available monitoring systems cannot be installed subsequently or they are limited to measurements on the surface. For monitoring the structural behaviour inside specific components, the use of a sensor system based on the vibrating wire measuring principle appears promising. This sensor system has proven itself in geotechnical engineering. However, there is no profound experience of using this system in concrete structures. Therefore, the aim of the work presented in this paper was to investigate the suitability of these sensors for stress measurement in concrete and mortar. We will furthermore give an outlook on a possible application for monitoring reinforced concrete structures.

1 Introduction

Looking at the condition of German concrete transport bridges and parking garages, we see the result from decades of careless use of de-icing salts and its underestimated effect on the structure. A report of the German Federal Ministry BMVI [1] states, that only about 12 % of the surface of all bridges along trunk roads are in good condition.

An insufficient condition can thereby be attributed to two aspects: Either the bridge is already damaged and in direct need of repair or its load-bearing capacity does not fulfil the requirements of today's standards (due to increasing traffic loads) and it needs to be structurally redesigned and strengthened. Both aspects led to a massive repair backlog and the need for an immediate action for the major part of nearly 40,000 bridges. A European report about research and innovation in bridge maintenance [2] shows, that this aspect is not only relevant in Germany.

The states and the federal government as well as cities, municipalities and districts have to solve this enormous task. However, the financial possibilities are limited, which is why it has to be distinguished between urgent and long-term repair needs. The owner of a structure needs to be aware of its current and past condition to be able to estimate the occurrence of possible damage, either in order to set aside necessary funds or to order preventive maintenance measures at an early stage. A useful tool to gather information about the condition of a structure is to install a monitoring system that detects changes in stress, strain, humidity or temperature for example.

In case these monitoring options have to be installed subsequently, most of the available sensor systems are limited to measurements on the surface. Their measuring principle is usually strain based which is why stresses can only be determined indirectly. However, it would be of great interest to have a look at various points inside of existing structures, especially for monitoring load-induced stress redistribution due to damage, as well as for an in-situ check of calculated load assumptions made in the course of the redesign of bridges, e.g. [3-6].

In this paper, we investigated the suitability of subsequently installed vibrating wire sensors for stress measurement in concrete and mortar. This sensor system has proven itself in geotechnical engineering for monitoring of rock formations in past [7, 8] and present [9].

As the sensor is installed and pre-stressed into a previously drilled borehole, compressive or tensile stresses in the surrounding material will result in a change in prestress that can be transferred to absolute stress-values with the help of calibration curves given by the manufacturer.

However, there is no profound experience of using this system in concrete structures or on a laboratory scale. Thus, we prepared defined specimens from different concrete and mortar mixes, investigated the installation procedure and the associated analyses of the sensor readings and ran own calibration tests. We finally developed a model that enables the calculation of stresses within the elastic deformation behaviour independent from the mechanical properties of the concrete or mortar specimens and only from specific sensor values that occur before, during and after the testing process.

2 Materials and methods

2.1. Materials

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We used four different concrete and mortar compositions (**Table 1**). We selected these materials as they are in their composition equal or close to materials used in practice. Additionally we created a variation in compressive strength and stiffness to test the suitability of the sensors at a broad range of material properties.

Table 1. Mixture proportion of concrete and mortar.

Materials	C.MS	C.LS	M.3	PM.0.8
Sand [kg/m³] (max. particle size [mm])	406 (2)	41 (2)	1,255 (3)	942 (0.8)
Ground Limestone / Filler [kg/dm³]	-	-	100	130
Gravel 2/8 [kg/m³]	555	162	-	-
Gravel 8/16 [kg/m³]	687	1,273	-	-
CEM I [kg/m³] (type)	365 (42.5 N)	400 (32.5 R)	600 (52.5 N)	487 (blended)
Water [kg/m³]	195	280	270	276
w/c-ratio [-]	0.535	0.700	0.450	0.567
VMA [M.-%]	-	0.192	-	-
Superplasticizer [% bwoc]	-	-	-	0.3
Additives/ PP-Fibres [kg/dm³]	-	-	-	65

The concrete C.MS served as a reference mix in the tests as it represents a standard concrete often used in practice with a compressive strength of 45 MPa and a maximum aggregate size of 16 mm, see **Table 2**. C.MS stands for a concrete (C = concrete) with medium strength (MS = medium strength). This mixture is also representative of an old concrete A4 according to [10].

The mixture C.LS is based on the C.MS recipe. We only used a higher w/c-ratio and a different grading curve in order to lower compressive strength and Young's modulus. At the same time, we added a viscosity-modifying agent (VMA) to stabilize the mixture and avoid segregation and bleeding. The abbreviation LS stands for low strength. C.LS can be classified as old concrete A2 according to [10].

The materials M.3 and PM.0.8 are repair mortars (M = mortar and PM = polymer-modified mortar) with a maximum aggregate size of 3 mm and 0.8 mm, respectively. While we developed the formulation of M.3 for this investigation, the composition of PM.0.8 is a commercially available bagged product, i.e. its composition not fully known.

The hardened properties after 120 d of curing (20°C and 65 % RH) of the latter three formulations can also be taken from **Table 2**.

Table 2. Hardened properties of the materials (age 120 ± 7d).

Material	Bulk density [g/cm³]	Young's modulus [GPa]	Compressive strength [MPa]	Bending tensile strength [MPa]
C.MS	2.31	30.5	45	---
C.LS	2.09	16.1	20	---
M.3	2.16	27.1	70	7.1
PM.0.8	1.93	11.0	35	7.1

2.2. Vibrating wire sensors (stressmeters)

The product range of manufacturers for available vibrating wire sensors [11-14] shows a wide variety of sensor types, most of which are used in the field of geotechnics and civil engineering. External installation on surfaces or direct installation inside a component (subsequently or embedded) offer numerous possibilities for deformation and stress monitoring of an entire structure.

The measuring principle of a vibrating wire sensor can be vividly explained by comparing it to a guitar string. In both, a wire is firmly clamped over a defined length, excited by an impulse and caused to vibrate. The frequency of the oscillation generated in this way is called the natural frequency f [15]. It depends on the clamping length l, the pretension σ and the density of the wire ρ (see equation (1)). [16]

$$f = \frac{1}{2l} \cdot \sqrt{\frac{\sigma}{\rho}} \qquad (1)$$

In a guitar, the tension is adjusted via the tuning pegs so that the natural frequency of the string produces the desired tone. The natural frequency of the vibrating string in the sensor is defined by the manufacturer (dimensions of the sensor casing, the wire and the pre-tension).

While the tensioned guitar string is excited (plucked) manually, this is done inside the sensor by an electronic impulse from a magnet placed next to the string. In this way, the string is briefly deflected sideways and thus set into heteronomous vibration. [15] A receiver, also located next to the string, records the vibrations and sends them to the associated data logger. [17]

Since pre-stress and density of the wire are invariant in such a system, frequency changes can be attributed purely to strain-induced length change ε in the surrounding material. A direct correlation between length and frequency changes can be expressed according to equation (2) with the help of a specific gage factor Q [-]. [18]

$$\varepsilon_1 - \varepsilon_2 = Q\,(f_1^2 - f_2^2) \qquad (2)$$

For the investigations presented in this paper we used vibrating wire sensors 4300 EX (Softrock version) from GEOKON® (**Fig. 1 top**), which were developed for monitoring rock formations. These sensors can be inserted directly into a borehole in the rock. Due to their cylindrical shape (borehole stressmeters), they can be spread against the rock wall in the borehole. The fixed coupling to the surrounding rock enables the direct and spatially resolved measurement of stress changes or absolute stresses in the surrounding rock.

The sensor consists of a cylindrical stainless steel housing with a diameter of 29 mm and a length of 41 mm. Inside, perpendicular to the subsequent direction of loading, the wire is stretched across the sensor's diameter. It is then excited by an electrical impulse during the measurements according to the measuring principle. The sensor is connected to a GK-403 Readout Box via cable. [19]

Fig. 1. Body of the GEOKON® borehole stressmeter 4300 EX (top) and pretensioning tool (below).

Associated with the measuring body are a wedge and a load introduction plate (both made of steel, **Fig. 2**), which are placed on the top of the sensor for installation in a drilled hole (diameter 38 mm = 1.5"). A pretensioning tool (**Fig. 1** bottom) can be mounted via an eyelet at the flat end of the wedge, which consists of a guide rod with an impact weight. As the sensor is placed in the desired position in the borehole, the wedge on the sensor is pulled via the impact weight on the rod, pressing the load introduction plate upwards against the borehole wall. After reaching a prescribed clamping value (see point 3. in following enumeration), the guide rod can be removed from the sensor and the borehole.

In the associated instruction manual [19], the manufacturer recommends the following procedure for the installation of a sensor in a borehole:

1. fix the sensor to the guide rod and position it in the borehole (apex of load plate perpendicular to direction of measuring).
2. measure the digit value of the sensor after a short resting phase
3. apply 2000 digits of preload to the guide rod with an impact weight
4. detach the guide rod from the sensor, pull the pretensioning tool out of the borehole
5. note: the preload value will decrease within the first 2 days.

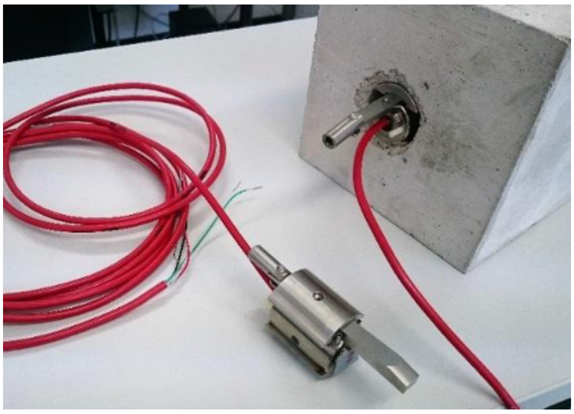

Fig. 2. Vibrating wire sensor 4300 EX before and after exemplary installation in a 150 mm cube.

According to [19], the stress can be calculated from the displayed digit-values (R-values) of the sensor as given by equation (3).

$$\sigma_M = \left((R_M - R_0) \cdot G + (T_M - T_0) \cdot 2G\right) \cdot 6{,}895 \cdot 10^{-3} \quad (3)$$

with:
σ_M = change in stress at level of the measured value [MPa].
R_0 = Zero value at the beginning of the investigation [digits].
R_M = measured value at the time of later readings [digits].
T_0 = Temperature at the beginning of the examination [°C].
T_M = Temperature at time of later readings [°C]
G = Sensitivity factor [psi/digits]
6.895 = constant for conversion from psi to GPa

While all required measured values are given by the sensor, the sensitivity factor G has to be chosen depending on the Young's modulus of the rock in place according to **Fig. 3**. Note, to convert Young's moduli from GPa to $1 \cdot 10^6$ psi (as shown on the x-axis), the values have to be divided by 6.895. For a measurement with the GEOKON® sensors, the Young's modulus of the rock (and any scattering) must therefore be sufficiently known.

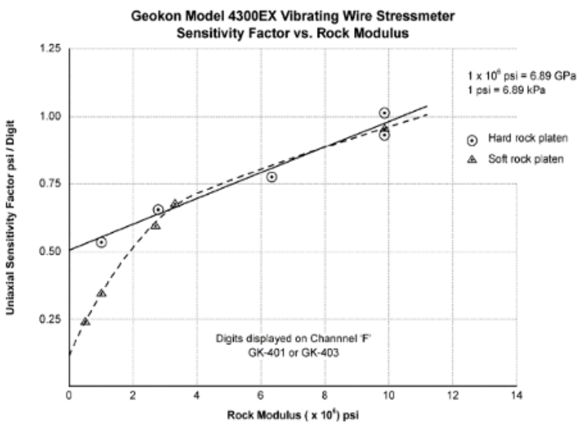

Fig. 3. Diagram for determining the sensitivity factor as a function of the Rock-Modulus in situ [19].

2.3. Specimens and testing procedure

For preliminary testing we used a monolithic and prismatic specimen of C.MS (b = h = 150 mm, length = 264 mm). For the main test series, we cast cubes with side length of 150 mm from every material listed in **Table 1** resulting in a total number of four cubes. After 100 to 150 days of curing at 20°C and 65 % RH we ground two sides plane parallel for later loading and extracted a core with a diameter of 38 mm (1.5“) from the middle of each specimen to place the sensor inside.

All specimens were loaded in a testing machine (Zwick Roell type 1498) up to a load level of approx. 30 % of the maximum compressive strength with 10 kN step profiles and a speed of 0.5 kN/sec. We thereby noted the digit values of the sensors displayed on the readout box GK-403 for further analysis.

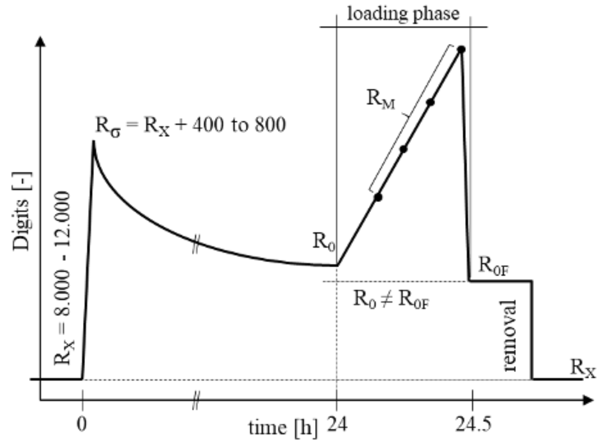

Fig. 4. Visualisation of point in time and magnitude of sensor values in digits

3 Results and discussion

3.1 Preliminary investigations, analysis and advancements

To investigate the suitability of the vibrating wire sensors for the use in concrete structures, as a first step we ran extensive preliminary investigations on the handling of the sensors during installation, the interpretation of the measured values and the multiple use of the sensors under laboratory conditions.

For the calculation of the stresses from the noted digits, we used equation (3) and a G-factor of 0.75. This value corresponds to the Young's modulus of C-MS (30.5 GPa, i.e. $4.42 \cdot 10^6$ psi) according to **Fig. 3**. We compared the calculated stresses with the theoretical stresses inside the specimens resulting from the applied load of the testing machine (applied load F over surface of the specimens (150 mm · 264 mm = 39,600 mm²)).

As a first result from the investigations, we had to define the following sensor values that we additionally visualised in **Fig. 4**.

- Resting value $\mathbf{R_X}$: uninstalled
- Pre-stressed value $\mathbf{R_\sigma}$: directly after installation
- Zero value $\mathbf{R_0}$:
  directly before loading, 24h after installation
- Measured value $\mathbf{R_M}$: at a certain load level M
- Final zero value $\mathbf{R_{0F}}$: immediately after unloading but still in place

The main findings from the preliminary tests and the recommendations developed for the use of the sensors in concrete (in italics) can be summarised as follows:

- The stresses calculated according to equation (3) did not equal the theoretically calculated stresses resulting from load over surface of the specimen.
  a new model is needed for the calculation of stresses for laboratory testing
- According to [19] the resting value R_X of every sensor is 10,000 digits. In fact it varies between 8,000 and 12,000 digits, as confirmed by the manufacturer
  An effect of the magnitude of the zero value on the measurement cannot be excluded without doubt.
- The applied pre-stress R_σ decreases to varying degrees in dependency on the Young's modulus of the concrete or mortar. Measurements should be taken at the earliest 24 h after the installation. Longer waiting times do not improve the stability of zero value R_0.
  We conducted all measurements 24 h after the installation of the sensors
- When using small-sized specimens (e.g. 150 mm cubes) with a compressive strength below 30 MPa, the application of 2,000 digits to the sensor can lead to direct failure of the investigated material.
  Pre-stress should be limited to 400 - 800 digits
- The precision when adjusting the pre-stress with the impact weight strongly depends on the experience of the person installing the sensor. Since the setting options are relatively coarse, deviations from the desired pre-stress value happen easily.
  The finally applied pre-stress value should be included in the equation for the calculation of the stresses as it directly affects the measured value.
- The sensors lose parts of their pre-stressing throughout the testing (zero value before loading ≠ final zero value). This might be due to a certain slip between wedge and platen. The height of this loss depends on the height of the applied load and the Young's modulus of the surrounding material.
  The loss in pre-stress results from R_0 - R_{0F} . It needs to be included in the equation for the calculation of the occurring stresses.

- If various sensors are installed close to each other in one borehole, stiffness of the tested materials and the measured values are affected in this area. This will lead to higher stresses compared to the same test set-up with only one sensor installed. *Values measured with two or more sensors in one borehole cannot be compared to values measured with one sensor in one borehole.*
- The duration of the experiments we conducted was between 30 and 45 minutes. The changes in temperature logged in this time were in the range of maximum 0.5 Kelvin due to the stable climatic conditions in the laboratory. That affected the calculated stresses by less than 0.1 %. *The temperature correction is negligible for experiments conducted in a laboratory.*

As a result, equation (3) and the diagram for determining the sensitivity factor as a function of the Rock-Modulus (**Fig. 3**) cannot be used for the calculation of stress in laboratory testing of concrete and mortar specimens, which is why we conducted calibration tests in a main test series to develop a customized calculation model.

3.2 Main test series

The goal of the main test series was to calibrate the sensors installed in a cube of 150 mm side length to the load of the testing machine for all materials investigated, see **Table 1**. We thereby considered the aspects regarding the installation of the sensors in concrete as discussed before.

A calibration test consisted of five single measurements on one cube with the sensor installed in the middle of the specimen. For all specimens we used a pre-stress of 750 digits (±50).

3.3 Development of a customized model to calculate stresses from the digits given by the sensors

With the data obtained in the main test series, we developed a model to calculate stresses from the sensor values installed in a concrete or mortar specimen at any desired load step within the elastic deformation behaviour, see equation (4). We included all five sensor values (R_X, R_σ, R_0, R_M, R_{0F}) to capture the effects on the measured values as discussed in chapter 3.1. These values also indirectly express the Young's modulus of the tested material, as it directly affects the development of the pre-stress applied to the sensor. The change in temperature is not taken into consideration due to the negligible influence in a temperature-controlled environment. We compared the calculated stresses with the theoretical stresses inside the specimens resulting from the applied load of the testing machine related to the area of one side of the cube of 22,500 mm².

$$\sigma_M = \underbrace{\left(R_M - (R_0 + F_M \cdot C)\right)}_{1} \cdot \underbrace{\left(\frac{R_\sigma}{(R_M - F_M \cdot C)}\right)}_{2} \cdot \underbrace{\frac{R_X}{R_\sigma}}_{3} \cdot \underbrace{0.0069}_{4} \cdot \underbrace{m}_{5} \quad (4)$$

where:

σ_M = stress at a certain load level M related to R_M [MPa]
R_M = measured value at load level M [digits]
R_0 = zero value [digits]
F_M = load applied by testing machine resulting in R_M [kN]
C = correction factor [-] ; calculated from $\frac{(R_0 - R_{0F})}{F_{max}}$
where:
R_{0F} = final zero value [digits]
F_{max} = max. load of testing machine [kN]
R_σ = Pre-stressed value [digits]
R_X = Resting value [digits]
m = material factor [-] (cementitious materials *m* = 1.0, polymer modified mortar *m* = 0.82).

The model consists of five terms (noted above the equation).

Term 1 considers the change in digits between the zero value and a certain load step, what is comparable to the approach proposed by the manufacturer acc. to equation (3). However, we implemented a factor C [-] for the correction of the loss in pre-stress at a certain load level F_M during the test (possible slip between wedge and platen). It results from the quotient of R_0 - R_{0F} and the maximum applied load F_{max}. The factor C has further to be divided by the load applied on a certain step.

Term 2 considers the aspect that the height of the measured value at a certain load depends on the height of the applied pre-stress R_σ. Again, the factor C is introduced to correct the loss in pre-stress.

Furthermore, we implemented term 3 as it expresses the influence of the resting value R_X (sensor dependent) and the applied pre-stress R_σ on the measured values.

Term 4 represents the transformation of the calculated stresses from psi to MPa

Finally, we implemented a material factor *m* [-] (term 5). It became necessary, as the model overestimated the stresses for the PM.0.8 mortar by around 20 % whereas the stresses for the other three, pure cementitious materials perfectly fit the theoretical stresses (load over surface). This might be due to the PP fibres contained in PM.0.8 and the related difference in deformation behaviour. Thus, *m* has to be set to 1.0 for cementitious materials whereas we defined an *m* of 0.82 for the polymer-modified mortar to fit the model. This factor needs further investigations as it might be related to the amount and type of fibres in the mixture and the resulting deformation behaviour.

In **Fig. 5**, we visualised the mean stresses for the M.3 (dashed lines) and PM.0.8 (dotted lines). We calculated them from equation (3) given by Geokon (grey colour, G for M.3 = 0,70 ; G for PM.0.8 = 0,45 acc. to **Fig. 3**) as well as from the customized model according to equation (4) (black colour) and compared them to the stresses resulting from the load applied by the testing machine on the 150 mm cube (grey continuous line).

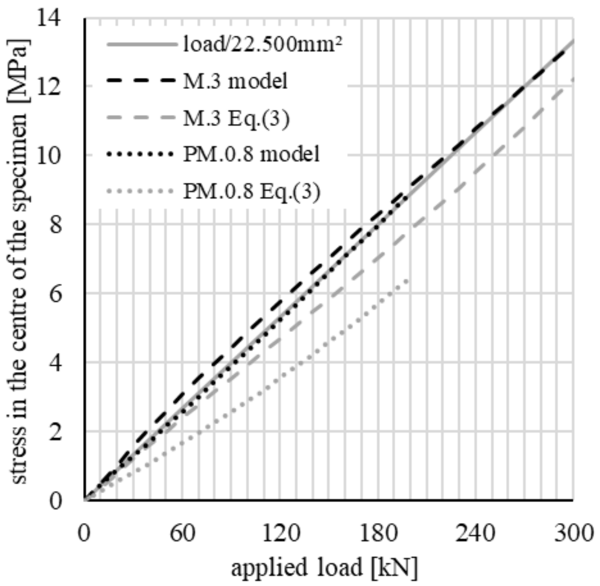

Fig. 5. Stresses in M.3 and PM.0.8 calculated from the digits measured by the sensor according to equations (3) and (4) compared to the stresses resulting from the load applied by the testing machine on the 150 mm cube.

The visualisation shows, that the calculation according to the manufacturer underestimates the occurring stresses whereas the calculations according to the developed model equal the stresses in the specimen.

4 Conclusion and outlook

From the investigations presented in this paper, we were able to show a general suitability of the vibrating wire sensors (borehole stressmeters) for the use in concrete. We thereby revealed some interfering influences and gave solutions that have to be taken into consideration when using these sensors to measure stresses inside concrete specimens under laboratory conditions.

We developed a model for the calculation of the stresses inside a 150 mm cube that is independent of the installation method of the sensors and the Young's modulus of the material.

However, further investigations are necessary to prove the model suitable for the calculation of absolute stresses in varying specimen geometries. We assume that a calibration and the development of a geometry factor is necessary to cover certain deviations from the stresses calculated with the presented model. In addition, we see further need for investigations on the introduced material factor m to prove the value we set for investigations on polymer-modified materials.

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