Concrete Stress Measurement – Device and Applications

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1. Abstract

This contribution deals with the development of an new sensor for measuring stress in massive concrete structures. It starts with an technical overview regarding the apparatus and its theory of operation. At least some application examples from building sites and results will be shown.

2. Introduction

Measurement techniques installations on building sites occurred in numerous projects. The objective was the assessment of the solicitation of concrete components resulting from own and restraint tensions during the hydration phase and further on. In this case usually a combination measurement with temperature and strain profiles was conducted.

The measured temperature and strain profiles did not finally permitted any quantitative statements to the tensions existing in the construction element. The results showed the temperature rise during concrete hydration with the typical deformation processes pending from the outside restrain of the construction element in tensile or compression. The direction change in the cooling phase relevant for cracking could also be seen. It is possible to deduce the tensile stress with well-known material parameters, in particular the young's-modulus development. However the substantial influence from concrete creeping and concrete relaxation cannot be considered in these computations. Cracks were often observed afterwards in the construction elements. But these cracks could not be explained on the basis the results of the measurements.

Due to this deficit the need for a measuring instrument rises for the direct measurement of the concrete stress. The measuring instrument should be applicable in the laboratory and on the building site.

3. Point of start

The idea to develop a measuring device for stress measurements in concrete is not new. Such an equipment was already developed in Japan at the beginning of the 90's. It consisted of a 5 x 5 x 50 cm large wire mesh basket, which is coated inside and outside with a humidity-permeable flow. At its end a load cell was installed. Such an device is described in /3/. This measuring instrument was installed by the MPA Braunschweig in a project in Berlin. The following problems resulted during field application:

- The dimensions of the device are too small. Concrete can only badly be filled into the wire basket. An effective compaction was hardly possible. Due to the small dimension the use of large aggregates was not possible.

- The measuring device is filled horizontally from the top. The cover can be locked only with difficulty in such a way that a vertical installation appears as unsuitable.

- The use of a load cell on classic strain gauges basis is unsuitable as numerous electromagnetic interferences occur on the building site.

In co-operation with Scanrock GmbH (Germany) and the measuring device manufacturer Geokon Inc. (USA) a new sensor design for the use under building site conditions was sketched. The basic operational principle has been maintained.

4. Theory of operations and structure of sensor

Figure 1 shows a schematic representation and a photo of the concrete stress meter. The stress meter essentially consists of the serial connection of a load cell and a concrete cylinder. Both are mechanically connected. Load cell and concrete cylinder are laterally surrounded by a humidity-permeable tube that is additionally coated inside and outside with a humidity-permeable foil. Tube and foil ensure that the stress meter is laterally force-decoupled by the surrounding concrete.

The tension sensor is filled with concrete directly before the installation. The installation of sensor and concrete of the construction element should happen at the same time, so that sensor and surrounding concrete have the same hardening conditions. It is presupposed that the concrete in the sensor and the environment concrete have the same quality. So it can be ensured that the concrete in the stress meter has same rigidity conditions as in the remaining construction element.

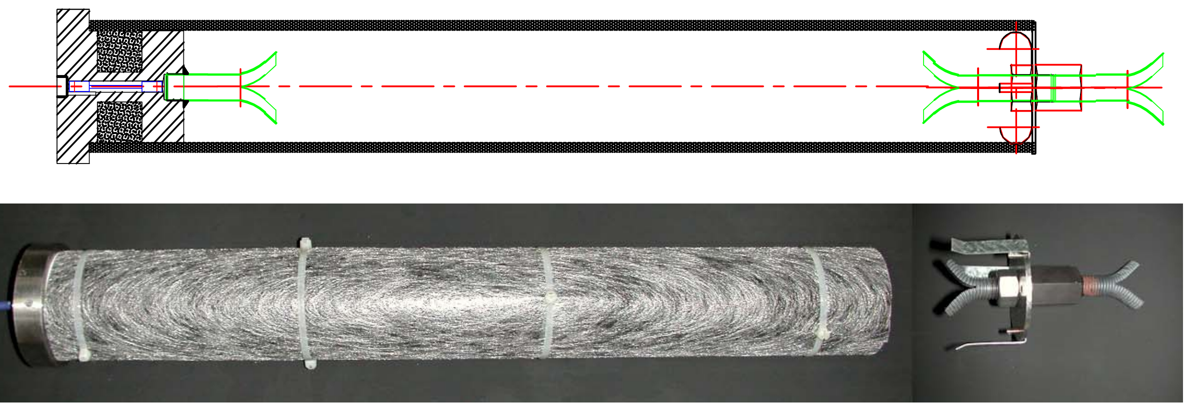


Figure 1 Schematic representation of the sensor structure and photo

Due to its construction, the concrete stress meter is affected with a systematic measuring error. The load cell is a rigid foreign body in the measuring medium with temporally variable rigidity characteristics. The order of magnitude of the measuring error only depends on geometrical conditions in the receiver. If the rigidity of the dynamometer is higher than the concrete ones, the measured tensions are higher than the real ones. With increasing concrete hardening the concrete rigidity exceeds the rigidity of the dynamometer and the measured tensions will be below the actual tension

It is meaningful to dimension the load cell in such a way that an effective young's modulus is reached by in approximately 30,000 N/mm^2, whereby the systematic measuring error for usual concrete is minimized after reaching the ultimate strength. The characteristic shown in figure 2 shows that the measured value deviations for concrete rigidities are less substantial for an concrete young's modulus lower then the one of the load cell.

In /2/ a relationship between the actual tension in the concrete and the tension measured with the stress meter is derived. This relationship can be transferred to the new sensor form examined by the MPA Braunschweig and was adapted to its geometry.

$$\frac{\sigma_m}{\sigma_C} = \frac{2{,}12 \cdot l_L + l_C}{l_C + l_L \dfrac{E_C(t)}{E_L \cdot}\left(1{,}12 + \dfrac{A_C}{A_L}\right)\left(\dfrac{1}{1+\varphi}\right)} \quad \text{with}$$

σ_m, σ_c: measured stress, real stress,

E_c, E_L: young's-modulus of concrete, young's-modulus of load-cell,

A_L, A_C: cross sectional area of active load-cell part, cross sectional area of concrete prism,

l_L, l_C: length of active load cell part, length of concrete prism and

φ: creep coefficient.

The curve, that results from this relationship for the stress meter is shown in figure 2. For low concrete young's modulus the systematic measuring error is up to + 9%. This value decreases with increasing young's modulus. With a young's modulus of 26,000 N/mm^2 the deviation vanishes. The range relevant for measurements at early age concrete ends approx. with an elastic module of 35.000 N/mm^2. Here the systematic measured value deviation is up to. 3%.

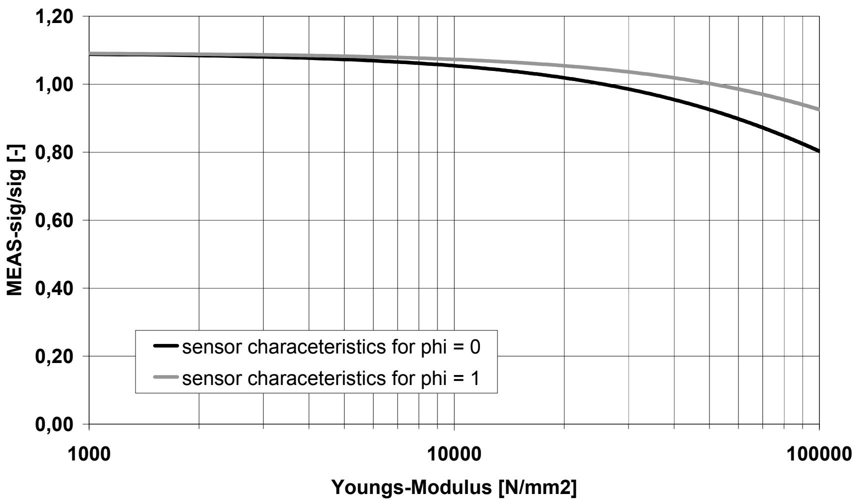


Figure 2 Accuracy of sensor depending on young's-modulus development

5. Calibration

Some calibration experiments were conducted with the developed concrete stress meter for the investigation of its operability. For the calibration with defined loads tension and compression test specimens were manufactured in the laboratory of the MPA Braunschweig.

The long term testing should document the stability of the measured values of the sensor under fatigue solicitation. This experiment was conducted particularly regarding the problems expected due to creeping and relaxation. Further investigations to this topic are following.

Load tests on concrete bodies were conducted in order to improve the use of the tension sensors within a further project described below regarding force measurement in excavation-rigid. The accuracy of the measuring sensor during defined loading of the test specimens was to be determined. Experiments were run on tensile and compression elements.

The test specimen for the compression test has the dimensions w x h x l of 50 x 150 x 100 cm. Concreting took place perpendicular to the load direction. It was equipped with two stress meters and five further strain meters for stress and strain measurements. The load was applied 28 days after concreting. The modulus of elasticity was up to 27,000 N/mm^2.

Figure 3 shows the measured stress and strain values. The measured stress and the applied stress resulting from loading are depicted vs. the average value of the strain measured in the test specimen. Compression stresses up to approx. 4 N/mm^2 were congruent with the actual values. For higher loads the curves separate, whereby the measured tension is higher than desired value with increasing tendency. A deviation of + 8 % results for applied stresses of 10 N/mm^2.

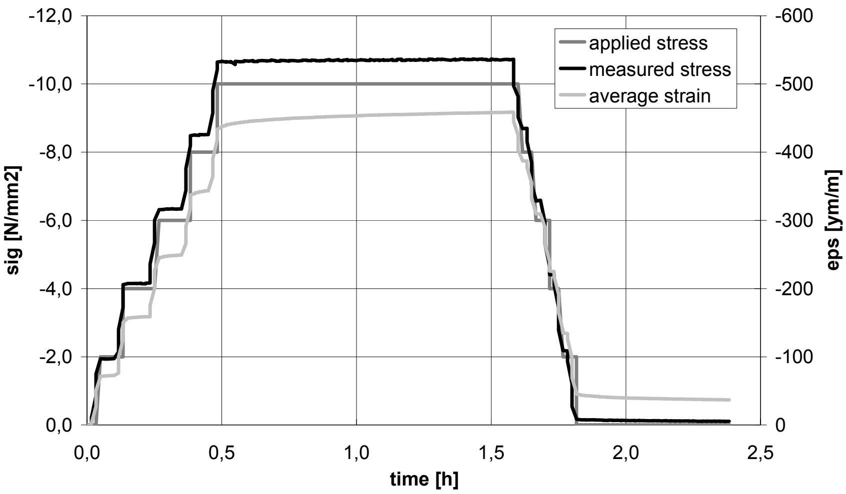


Figure 3 Result of the compressive load tests

The operability of the stress meter in tension was examined in an extra test regarding the special interest in the measurement of tensile stresses as a consequence of thermal restraint solicitation at early concrete age. The stress meter was built into a horizontal testing frame, which was designed for the investigation of creeping and relaxation behaviour of young concrete. The load was applied in several stages at the age of 1d, 2d, 8d, 15d. The body was loaded with 0.5 f_{ct} at the time the load step was applied. The sample had a constant temperature of 20°C during the experiment.

The results of this test are shown in Figure 4. In the early load stages the measured values higher than the applied stress. This was expected regarding the background of the sensor characteristic developed in section 4. The deviation is within the range of expected accuracy.

The last load stage, which was applied at a concrete age of 7 days, shows a very good agreement between desired value and actual value.

The calibration experiments show that the sensor achieves good results in the practically relevant measuring range of +/- 2 N/mm^2.

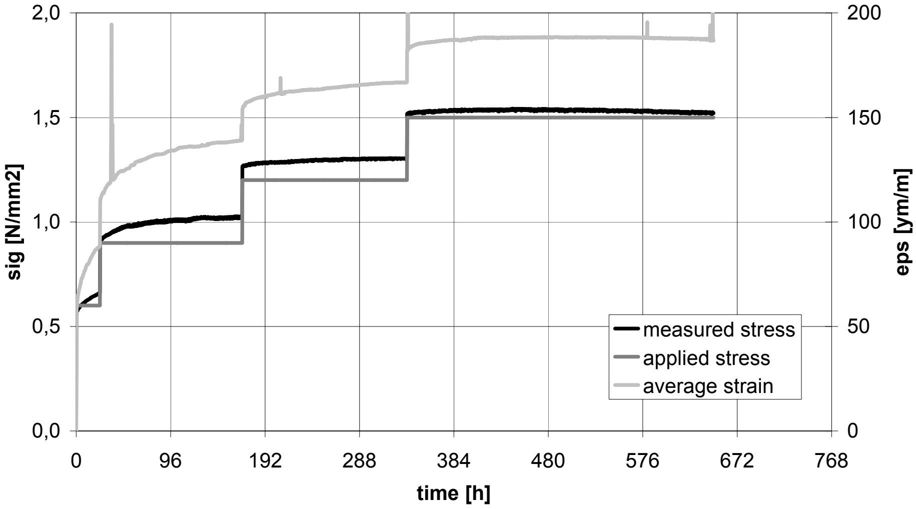


Figure 4 Results of the tensile test

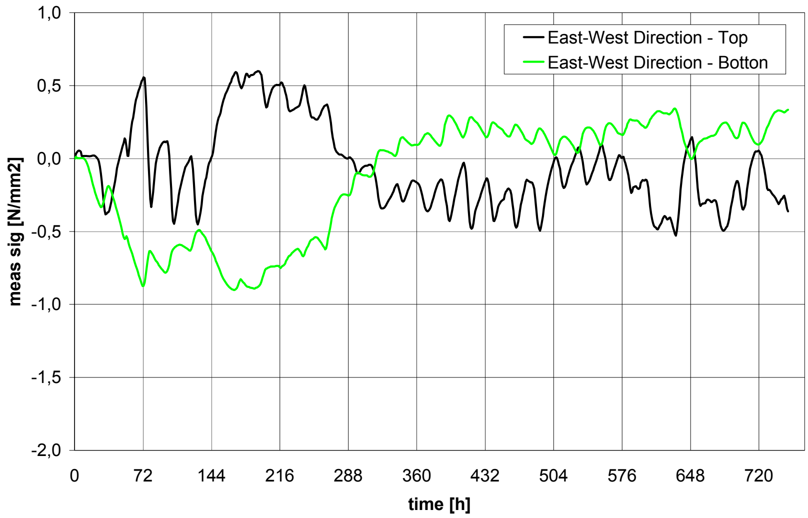
6. Applications

6.1 Foundation slab

For a building project in Berlin investigations were started regarding concrete compositions with low heat development. The objective was to reduce the heat development and thus the stress development in the concrete so that the installed reinforcement quantity could be substantially reduced. For this extensive simulation calculations with several parameter sets were run.

For the verification of the simulation results stress measurements on site were conducted. The measurements were run in two directions on the upper and the lower surface of the foundation slab. Figure 5 shows the results. It could be recognized that the processes on the upper and lower surface in the two measuring directions qualitatively correspond to each other. Compression stresses first developed on the upper surface, which decrease during the process and flow into an easy tensile level. In addition the process at the lower surface is opposite. Moderate tensions developed here firstly, which changed with increasing hardening progress over into compressive stresses.

The results of the simulations confirmed that actually no critical tensile stresses remain in the slab. Cracks could not be recognized on the basis of the measured values and even by optical control at the building.



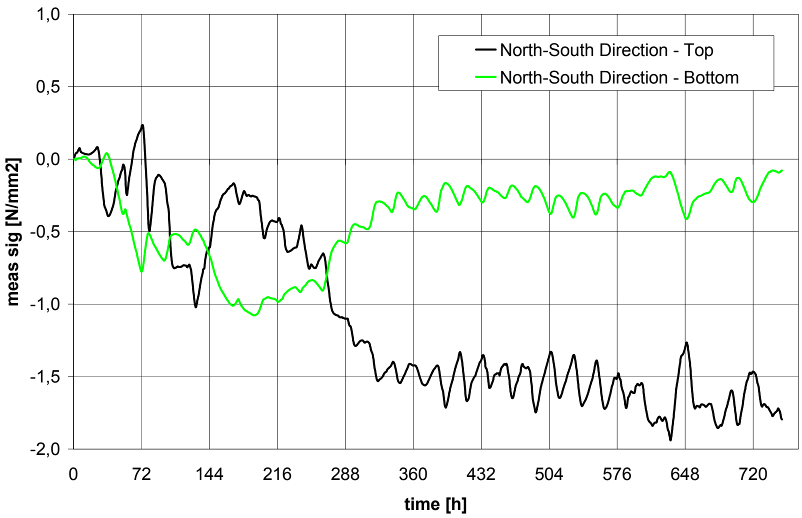


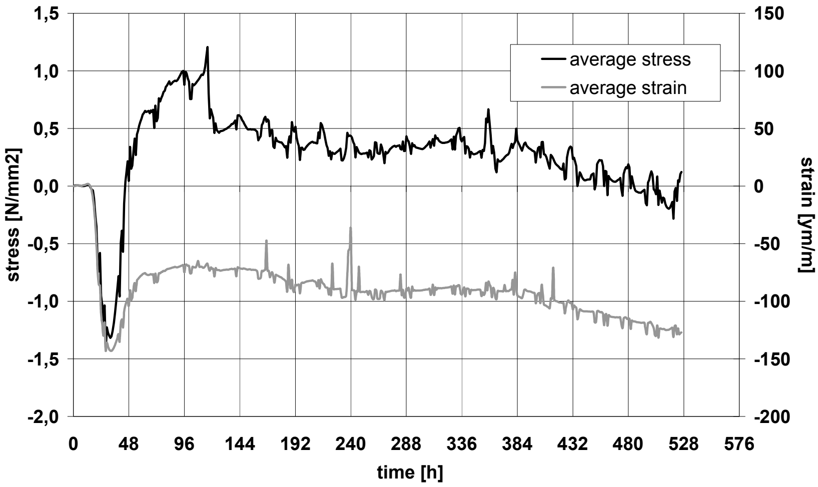
Figure 5 Results of the stress measurements

6.2 Concrete hardening in an excavation safety device

The excavation safety device during building of a Watergate installation was implemented by means of stiffening elements build in the excavation. The stiffening elements were implemented in two layers. In this case the application of the stress meter was the measurement of the stiffening forces during the excavation. Six stiffening elements were equipped with stress meters. Additionally strain transducers were installed as a parallel measuring system. The stiffening elements measurements were directly started after concreting during the hardening process.

In figure 6 the results from stress and strain measurements are compared each other. The results of the parallel measurement of stress and strain show the difficulties of a derivation of the construction element needs from the deformation measurements only. Stresses and strains run first parallel during the heating phase in compression. According to the direction change during the cooling phase the courses of the curves change. The deformations remain all in the compressive range. Against that, the stress measurement shows clearly tension of up to 1 N/mm^2 in the construction. Cracking is clearly to be recognized in the stiffening element after approx. 120 hours. After cracking the measured residual stress shows again that the fracture occurred somewhere outside of the measuring basis.

On the basis of the curves of measured values the crack is not to be recognized in the strain measurement. A change in strains is also visible In the direct confrontation to the stress gradient. This change taken alone would have been classified as caused by daily temperature fluctuation.



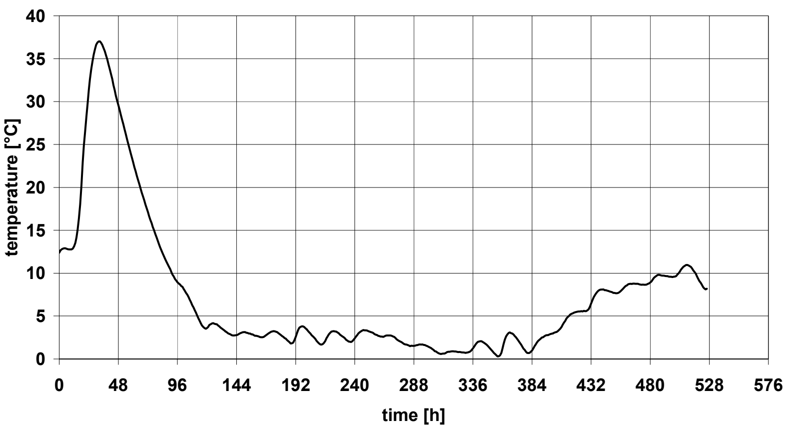


Figure 6 Stress, strain and temperatur process into excavation rigid during the confirmation

7. Conclusion

The MPA Braunschweig and the Geokon Inc. started a cooperation with the Scanrock GmbH. An existing realization of a tension sensor of Japanese origin was revised and improved regarding its applicability in practice.

In relation to the Japanese model modifications in size and form were made. Volume increase now makes the processing of stressing possible with a maximum aggregate size of up to 32 mm in diameter. Due to the vertical position when concreting in the tube allowing better compaction, the material properties in the sensor are approximately similar to the surrounding concrete. A dynamometer was used as active element according to the principle of vibrating wire gauges, which are characterised by a high robustness.

All modifications made lead to an improvement of the practical applicability of the measuring instrument for on-site use.

The operability and the accuracy of the equipment were examined in several experiments. Load tests in test equipments and measurements were conducted in massive concrete construction elements under building site conditions.

The investigations have shown that the measuring instrument is suitable for the special of the assessment of the tensile stress of concrete construction elements in the hardening phase. The direct comparison with strain measurements showed that meaningful statements about the construction element needs regarding tensile stresses are only possible with a stress measurement. The part of the creep deformation during the expansion phase considering the heat of hydration is so large that the tension in the following cooling phase can not be measured with strain sensors as decrease of the compressive strains. The stress measurement shows these tensions. In some test specimens the cracking and the following unloading could be proven.

For measurements in the relevant hardening phase the sensors shows an accuracy up to +/- 10 % of the measured value. Including all factors of uncertainty of the installation like the different concrete compression between the surrounding concrete and the concrete in the sensor this accuracy is to be classified as high. The validity of the results of a stress measurement is substantially higher than that of a strain measurement, even if the accuracy of the strain sensor with +/- 3 % is better.

The improvement of the tension sensor represents a practice-suited measuring instrument. The higher costs of the measuring instrument related to strain sensor are compensated by the higher expression of the results and thus that fewer measuring instruments are necessary for a meaningful measurement. Further investigation and optimising surely are needed from the point of view of the error minimization due to creeping. The basic principle of the sensor however shows that a complete elimination of errors by creep influences is not possible. Therefore the development of force sensor without own deformation may be necessary.

8. Literature

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/3/ Kawaguchi, Thoru; Nakane, Sunao: "Investigations of Determining Thermal Stress in Massive Concrete Structures"; ACI Materials Journal; Titel no. 93-M12; January – February 1196