The smart tendons – a new approach to prestressing

Peter FABO
Senior Lecturer
Comenius University
Bratislava, Slovakia

Milan CHANDOGA
PROJSTAR PK Ltd.
Bratislava, Slovakia

Andrej JAROSEVIC
Assoc. Professor
Comenius University
Bratislava, Slovakia

Summary

The EM method is a valuable tool in Civil Engineering for estimation of the real stress in the prestressing tendons, quality control during construction period, appreciation of the stress losses due to friction and relaxation, long-time monitoring of stress changes due to concrete creep, temperature changes, traffic load etc. Overview of EM technique with practical applications in the Civil Engineering is presented. The EM sensor can be an integral part of the cable sheath, cable duct or directly the anchor. Several examples of different „smart tendon "arrangements, from the single wire to large cables with capacity over 13 MN are presented. Selected examples of in-situ measurements illustrate usefulness of „smart tendons" and widely the „smart constructions" approach. The EM sensor is cost effective and the additional cost is negligible with the gain in the performance and safety.

Keywords: Cable stay ; elastomagnetic stress sensor ; EM sensor ; prestressing ; steel cable ; stress distribution ; stress measurement.

1. Introduction

The performance and safety of the prestressed concrete structure depends mostly on the real value of the prestressing force at any cross-section of the construction. The new sophisticated prestressing equipment enables to measure the total prestressing force and quite precise elongations during the prestressing work. This measurement can hard answer such questions, as:

What is the real stress distribution between the strands or wires in the tendon or stay during and after finishing the prestressing work? From the safety viewpoint it is very important in the case of cable stays that are subjected to substantial dynamic load.

What is the real stress distribution along the tendon after finishing the prestressing work? The designer uses the coded values of the friction coefficients and modulus of elasticity. But according our experience based on hundreds in-situ measurements, the real value of the friction coefficients depend often on several small details and the design value is sometimes very optimistic. In special situation only in-situ measurement gives real value of the friction coefficients (e.g. external tendons prestressed strand by strand, long grouted tendons etc.).

What are the short and long time stress losses? The resulting prestressing force in the tendon depends on anchoring loss due to wedge setting, elastic deformation of the construction due to acting force, relaxation of the steel and creep of the concrete. Monitoring of the real stress in the tendon can help to designer in calculation of real stress and deformation of the construction.

2. The Elasto – Magnetic (EM) method

2.1. The physical principle

The elastomagnetic sensor (EM sensor) [1], [2] is based on the elastomegnetic phenomenon – changing the magnetic properties of the steel under stress and temperature. Steel is the stress and temperature sensor itself. Magnetic properties carry even information about the fatigue of the steel.

Magnetic properties of the steel depend on the actual stress and temperature. The relationship between the incremental permeability of the steel, stress and temperature (Fig.1 and Fig.2) can be used for the estimation of the real average stress in the measured cross-section of the steel.

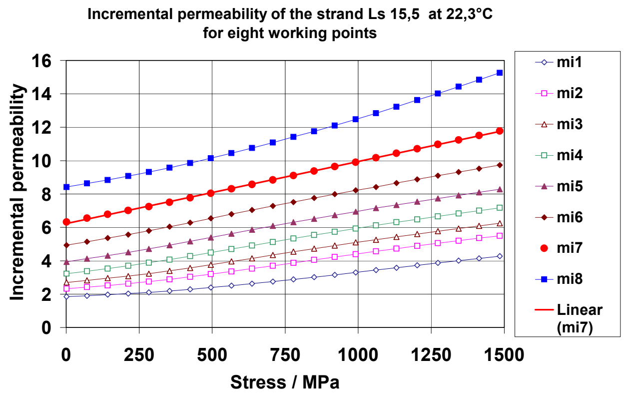

Fig.1 Elastomagnetic characteristics of the strand Ls15.5 for eight working points

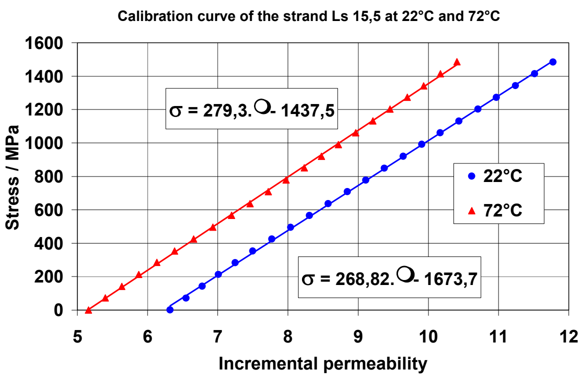

Fig.2 Calibration curves of the strand Ls15.5 for temperatures 22°C and 72°C

According the calibration curve Fig.2 from the known steel permeability µ(σ,T) and steel temperature T we estimate the actual stress σ. Important characteristics are the stress sensitivity $S_\sigma = 1/\mu(0,0).\partial\mu/\partial\sigma = 10^{-3}$ MPa^{-1} and the temperature sensitivity $S_T = \partial\sigma/\partial T = -2.4$ MPa °C^{-1}. In comparison with the resistive strain gauges the EM sensor is about 50 times more sensitive.

2.2. Stress estimation, accuracy and reliability

The EM sensor enables easily to measure changes of permeability with regard to the known load state, in the most cases the zero stress state. The primary winding magnetizes the cable and the change of the magnetic flux induces voltage in the secondary coil. The real sensor is the steel structure itself. The high tensile low carbon steel is very suitable for EM method application.

Each type of EM sensor must be calibrated (in the laboratory or on site) with the sample of the measured steel. During calibration the relationship between the output voltage of the measuring unit, temperature of the measured steel and the actual stress is estimated. To exclude the influence of the measuring unit parameters, the new generation of the measuring units performs before each reading autocalibration and calculates directly the magnetic flux through the sensing coil of the EM sensor. Precise measuring of the acting force (e.g. using annular dynamometer or calibrated prestressing jack) and the steel temperature is inevitable. Calibration curve of the EM sensor PS123 with cable 27xLs15,5 is shown on Fig.3, estimation of the temperature coefficient on Fig.4.

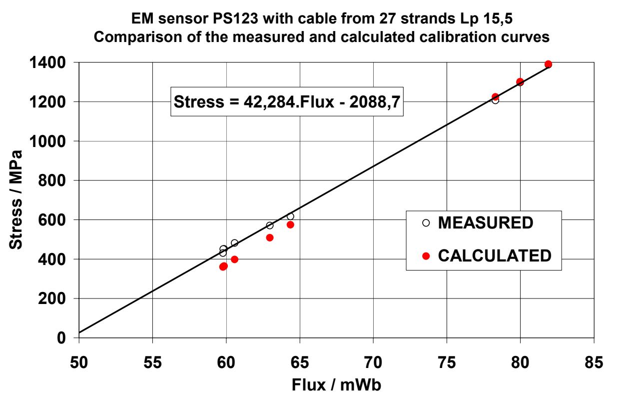

Fig.3 Calibration curve of the EM sensor PS123

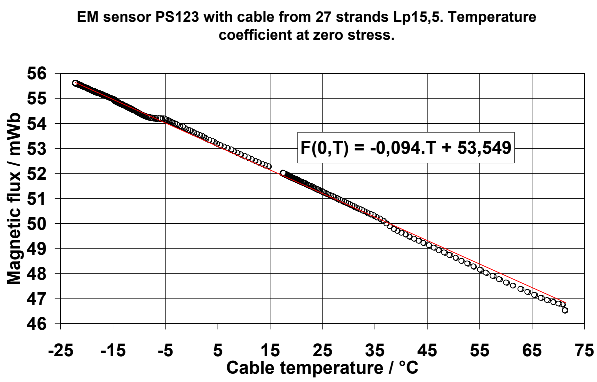

Fig.4 Estimation of the temperature coefficient

The more sophisticated approach to the EM sensor design and calibration calculates the magnetic field distribution using software for 2D or 3D nonlinear DC magnetic field modelling. Such software (e.g. Maxwell, Femm, etc.) is mostly based on Finite Elements Method and known BH characteristics of the all used magnetic materials. A comparison of the on site measured and from BH characteristics calculated calibration curves for EM sensor PS123 is shown on Fig.3.

The radial displacement of the cable inside the sensor duct changes the configuration of the magnetic field and acts virtually as the change of the stress. On Fig.5 is shown the influence of different cable arrangement inside the EM sensor duct. This problem arises at cables made from the single strands, protected by the steel or plastic tube. For the very precise measurements a special EM sensor arrangement with several sensing coils must be designed.

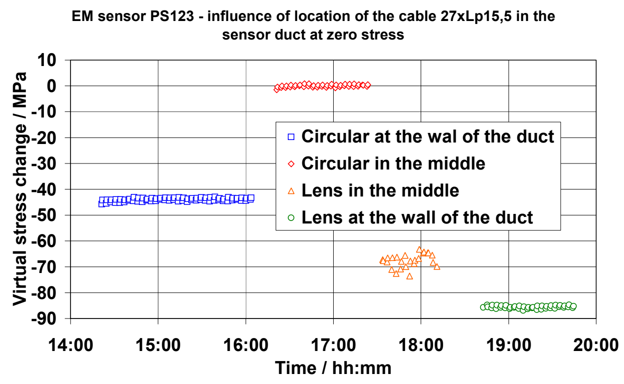

Fig.5 Influence of radial displacement

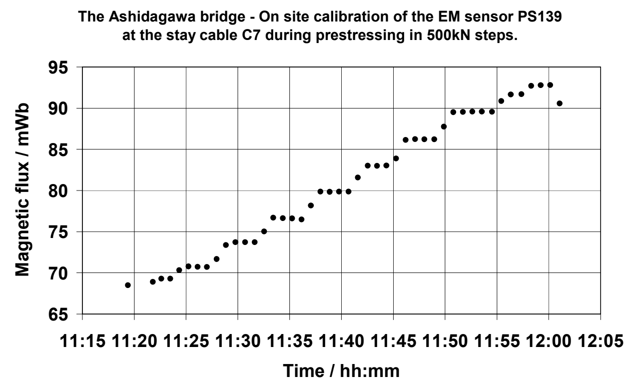

Fig.6 On site EM sensor PS139 calibration

An example of on site EM sensor calibration is shown on Fig.6. EM sensor PS139 was installed on site at the compact stay cable with PE sheath diameter 135 mm (Fig.7). During the cable installation and prestressing in the 500 kN steps (according the hydraulic pressure and prestressing jack calibration curve) the magnetic flux through the sensing coil was continuously recorded. Measured calibration curves for the both EM sensors installed at the two stay cables are shown on Fig.8.

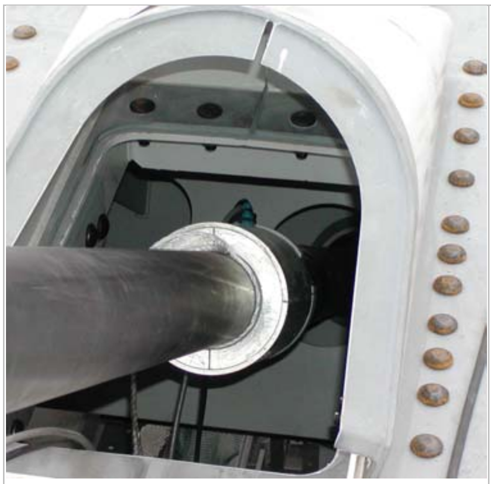

Fig.7 EM sensor PS139 at the stay

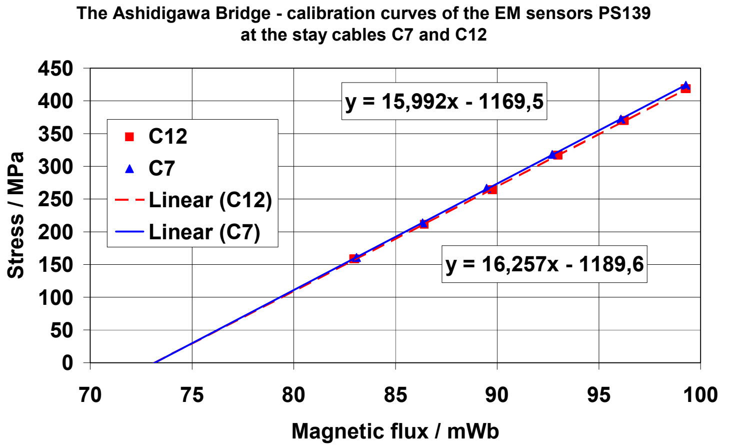

Fig.8 Calibration curves of the EM sensors PS139

An example of the accuracy test is shown on Fig.9 and Fig.10. At the Jiangyin Yangtze River Highway Bridge was installed the EM monitoring system [3] including not only the active EM sensors but also the reference EM sensor (like the dummy strain gauge) with the sample of the unloaded steel cable. On Fig.9 is shown the time history of the force (zero reading) during the one month. Fig.10 shows statistics of more than 4600 readings. The standard deviation is 1.73 kN, the average measured force is 1250 kN (see Fig.12) what gives the error 0.14%. In the case of Gaussian distribution the extended uncertainty of the force estimation equals to 0.27%.

Accuracy of the EM sensor is after calibration in the full range of forces and temperatures typically better than ±1%. Without calibration (using the average magnetic properties of the measured kind of steel) accuracy is typically within ±5%.

An example of the EM sensor long time reliability is shown on Fig.11. The EM measuring system was installed in the year 1993 in the nuclear power plant. EM sensors with inner diameter 225 mm were embedded in the envelope of the nuclear reactor and monitoring the prestressing force in the elliptic tendons prestressed to 10 MN. Frequency of the measurements was during years 1994-1999 once in the month, Slight influence of the temperature variations during the year is clearly visible.

The EM monitoring system is a part of the complete envelope health monitoring system. On Fig.12 is shown force change due to rising and falling pressure inside the envelope during the integrity test.

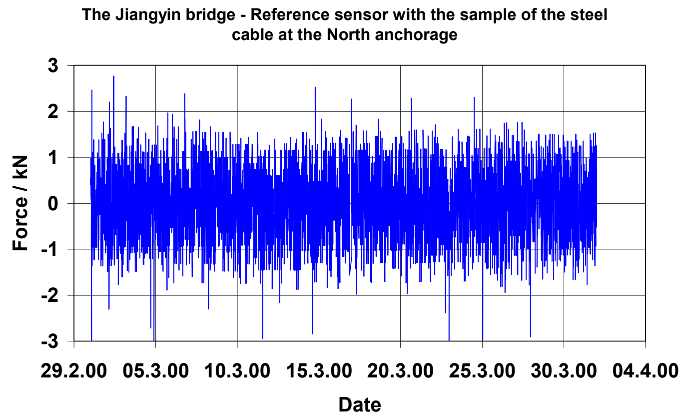

Fig.9 Time history of the zero reading stability

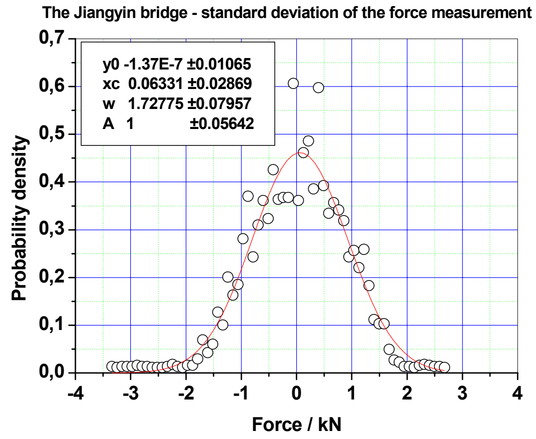

Fig.10 Standard deviation of the zero reading

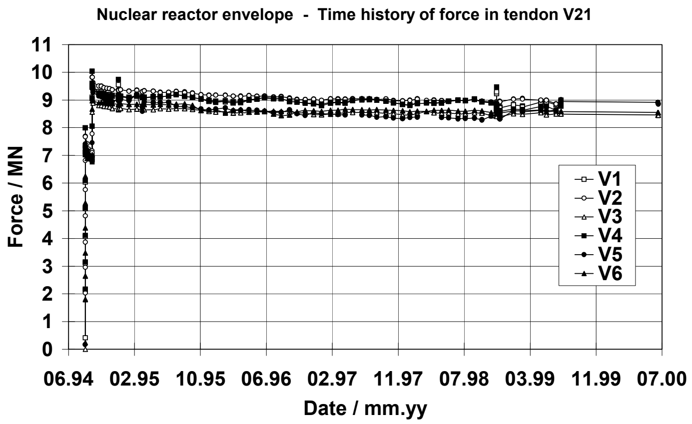

Fig.11 Time history of the force in the tendons of the nuclear reactor envelope

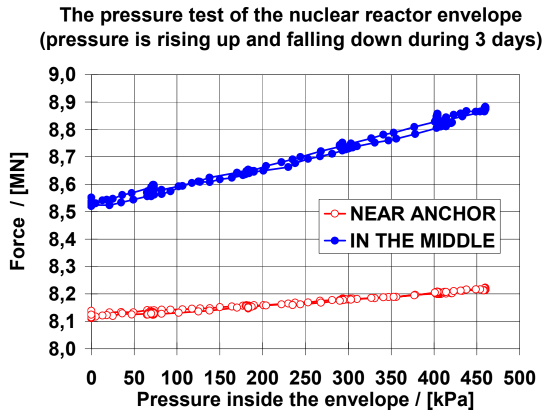

Fig.12 Force in the tendons of the nuclear reactor envelope during the integrity test

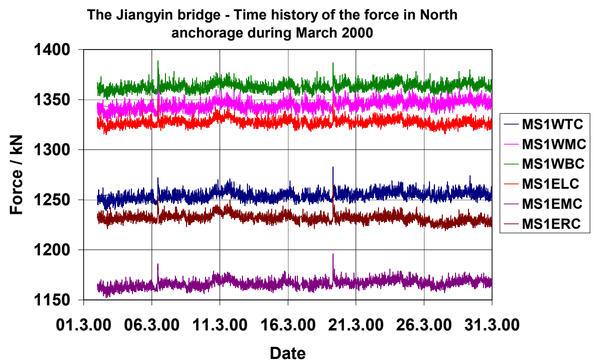

Fig.13 Time history of the force in the cables

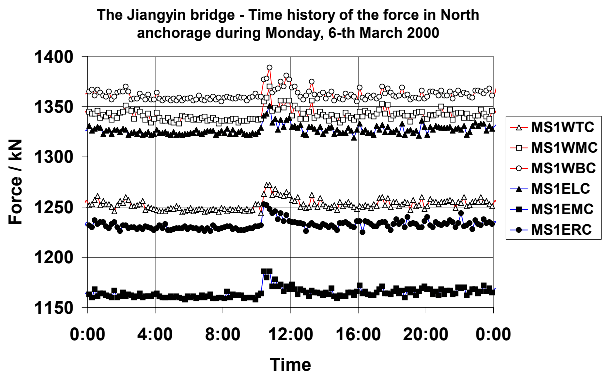

Fig.14 Detail of the Fig.13

The next example of the accuracy and reliability is shown on Fig.13 and Fig.14. EM sensors were installed on site at the six from 177 hexagonal cables, creating the main cable of the Jiangyin Yangtze River Highway Bridge. The automatic measuring system measures continuously (every 10 minutes) the force in all six cables with installed EM sensors. The EM monitoring system was installed during bridge construction in year 2000 [3] and is also a part of the complete bridge health monitoring system.

2.3. The EM sensor and the measuring unit

PSS (Projstar Smart Sensor) is a new generation of very reliable and accurate annular EM sensors for determining of stresses in all kinds of prestressing steel (wires, cables, bars) and prestressing tendons or stay cables up to 15 MN capacity. Construction of the EM sensor is very simple and reliable. On a plastic bobbin are wound the primary and secondary coils. Direct measurement of temperature is provided through the precise digital temperature sensor. The non-volatile ROM contains the unique EM sensor number and enables automatic communication with the measuring unit and utilization of calibration data. The steel cover protects sensor against any damage and poured polyurethane resin against moisture and even salt water. It can be embedded into the concrete and its lifetime is practically unlimited. The first EM sensors were installed in 1986 and have been working. On Fig.15 and Fig.16 are shown the standard EM sensors for single strands.

Fig.15 EM sensor PSS16 for strand 0,6”

Fig.16 EM sensor PSS20 for MONOSTRAND

The measuring unit energizes the primary winding and processes the voltage induced in the secondary coil. The new generation of the measuring units uses for permeability measurement the current pulse obtained by discharging a large capacitor through the primary coil. Typical duration of the pulse is 50-200 ms and the peak current reaches 25 A. This approach minimizes the heating of the measured steel and the EM sensor itself.

The measuring unit suitable for all EM sensors is a portable, four channels, computer controlled and 24 V battery powered. It works in the local or remote mode and can be extended using multiplexor units up to 64 channels. After sensor installation and taking the zero reading it is possible at any time connect the portable measuring unit and measure the actual force and temperature or build the standalone measuring system for continuous monitoring (e.g. rock and soil anchors).

3. Examples of the EM sensors application in the Civil Engineering

The EM method is a very reliable and cost effective way for stress monitoring especially on prestressing tendons (grouted or external) and stay cables. The EM sensor can be integrated as a part of the cable during its construction or installed on site at the existing cable. The integral EM sensor over the whole cable measures the total force or average stress in the measured cross-section. The MULTISTRAND sensor measures the force in each single strand, the total force and the force distribution between the strands. Several examples of EM sensors arrangement are given in papers [4], [5], [6]. An example of using the PSMS-13 (Projstar Smart Multistrand Sensor) jack head is shown on Fig.17 and Fig.18. The grouted cables made from 12 strands Ls 15.5 mm were monitored during the prestressing using the PSMS-13 head (Fig.19) designed for the PAUL TENSA 3000 kN prestressing jack. Cables were pushed strand by strand to the cable duct (steel tube). Obviously the initial lengths of the strands are not equal. A simple calculation shows that for the designed initial length 80 m and modulus of elasticity 195 GPa the difference in initial lengths 36 mm yields to the difference in stresses 88 MPa. The statistics of measurements performed during year 2003 on 59 grouted cables is shown on Fig.20. The resulting stress distribution is Gaussian with the average value 1447 MPa and the standard deviation 88 MPa. It is impossible to detect overloading of the single strand in the cable from the standard elongation - hydraulic pressure plot.

Instead the MULTISTRAND EM sensor at the jack head it is possible to install such sensor under the anchor head or build it directly inside the anchor head. Such arrangement enables to know the real stress in the cable at any time during cable prestressing, after wedge setting, during the whole construction period and during the all lifetime of the cable. The EM sensor can be calibrated directly during the cable prestressing, provided the prestressing force is known with the sufficient accuracy and the sensor is installed near the active anchor. This approach guarantees the uncertainty of force measurement under 1% and resolution under 1MPa.

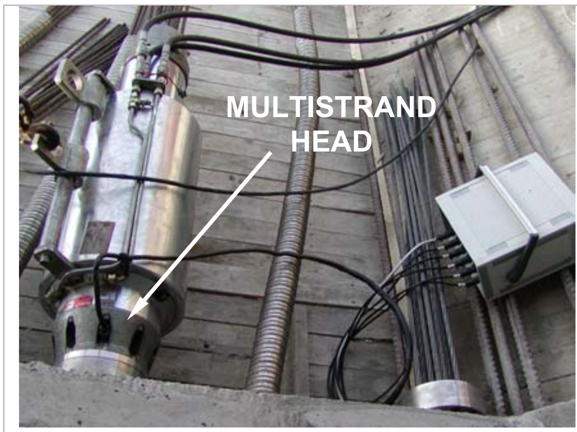

Fig.17 PAUL TENSA 3000 kN jack with the MULTISTRAND head

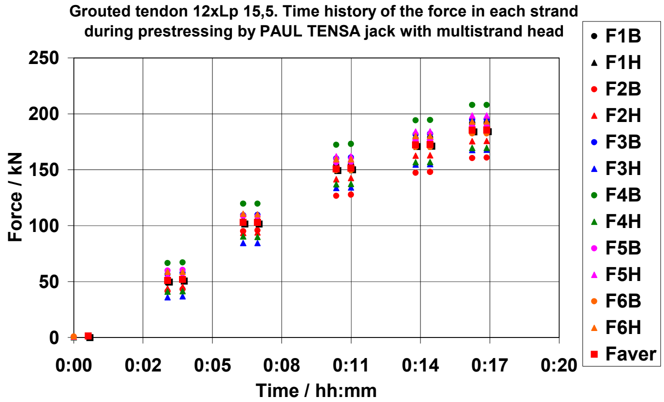

Fig.18 Force distribution between the strands in the long grouted cable from 12 strands Ls 15.5

Fig.19 MULTISTRAND head

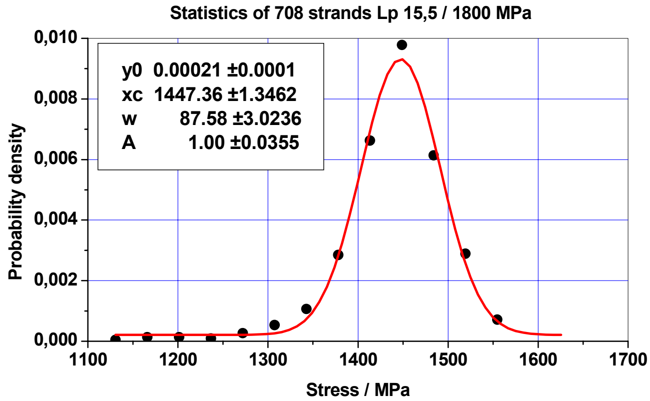

Fig.20 Stress distribution in 59 grouted cables

4. Conclusion

Our experience over the past 15 years confirms that the EM method is reliable, accurate and generally applicable for many structural monitoring situations when other measuring methods (especially the resistive strain gauges or vibrating wire gauges) are inapplicable.

5. References

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