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VERIFICATION OF NUMERICAL MODEL OF EXISTING PRESTRESED CONCRETE CONTAINMENT STRUCTURE

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ABSTRACT

One of the instruments used for purpose of long-term evaluation of pre-stressed concrete containment structures of operated NPP is verificated numerical model. Such a model enables to evaluate agreement of design assumptions with reality as well as allows to simulate non-standard situation of structure which occurs during operation. Verification of the model is done against measurement of real pre-stressing forces and deformations of containment structure for several loading steps in history of structure – application of pre-stressing, structure integrity test, long term creep of prestressed structure.

INTRODUCTION

Since the beginning of construction of Temelin NPP containment structures the continuous process of measured data collection is running. Measurement gives information about pre-stressing of tendons as well as about deformation and temperature of structure. These measured data are primarily used for evaluation of containment safety including prediction of future pre-stressing losses. In case of existing numerical models, measured data are used as a direct input in models therefore stronger model simplifications are possible without decreasing of results accuracy.

Model, presented in this paper, is created with aim to simulate history of containment structure without direct connection to measurement. Model input are the same as in case of real structure – model is loaded by application of pre-stressing forces in place of anchors. Distribution of pre-stressing forces along tendons length and deformation response of structure is driven by friction and material models set according laboratory tests. Measurement is used only for verification of results – the agreement of measured and calculated parameters is evaluated and refining of the model is based on changing of model parameters of model extent with goal to reach the best equality as possible. Benefit of this more complex approach is the fact that deeper understanding of structure behavior is necessary therefore it can be expected that prediction done by this model will be more accurate.

CONTAINMENT STRUCTURE

Model, presented in this paper, represents containment structure of VVER 1000 MW unit placed at site Temelin NPP, Czech Republic. This unit has a PWR reactor and a containment of pre-stressed reinforced concrete. The containment structure is a part of reactor building and is placed on the reinforced concrete slab of thickness 2.4m at a level of +13.20m – see Figure 1. The containment consists of a cylindrical and a dome part. The wall thickness of cylindrical shell is 1.2m, the dome wall thickness is 1.1m. Connection between the cylindrical and dome parts is made with the help of a rigid ring beam in which the anchoring blocks of pre-stressing tendons are placed. There is a gap between containment structure and internal structures as well as between containment structure and external surrounding structures. The containment is made of concrete, grade B40 according to the Czech standards (CSN) – aprox. corresponds to 30/37 according EN 1992-1-1. The tightness of the containment is ensured by the steel liner of a thickness of 8 mm made of carbon steel.

The pre-stressing unbonded tendons are conducted in polyethylene tubes. The cylindrical part of the containment is pre-stressed by 96 tendons running in helical direction. The tendon anchors are installed in the upper part of the ring beam, the bending of the tendons takes place in the slab at a level of +13.20m. The dome part of the containment is pre-stressed by an orthogonal grid plan of 36 pre-stressing tendons. Always two tendons are conducted against each other, anchors of one tendon and bending of the other one are situated on one side. The tendons of the cylinder and dome parts are of the same structure and cross section. Every tendon is formed by 450 wires featuring a diameter of 5 mm. Low-relaxation wire was used for production, its yield point being 1620 MPa. The initial nominal pre-stressing force according to the design is 10 MN. Tendons preservation was made with grease during production, preservation of anchors was made after pre-stressing.

The containment function was verified during the structure integrity test (SIT) performed before a starting of unit operation. The test carried out on both the Unit 1 and Unit 2 was implemented as a combined test. The function was tested for strength at an overpressure of 460 kPa, the function was tested for tightness at an overpressure of 400 kPa. The SIT of the Unit 1 was carried out in 1998, the SIT of the Unit 2 was carried out in 2000.

In order to enable the inspection of the level of the containment pre-stressing, measurement systems are installed permanently on the structure. These systems measure structure deformations and pre-stressing force in the tendons. The following measurement systems are permanently installed on the containment (distribution of sensors is showed in Figure 5):

- NDS and SDM systems – these two systems consist of vibrating wire strain gauges fitted during concrete pouring into the containment walls. The sensors are of four types and measure concrete deformation, temperature, horizontal displacement in the middle of the height of the cylindrical part of the containment. The containment includes more than 240 sensors which are installed in it (246 on the Unit 1 and 256 on the Unit 2).
- Hottinger system – this system is formed by strain-wire gauges stuck on the anchors of all tendons of the cylinder and of the dome, i.e. 264 anchors measured. The sensors measure force in the anchor of the pre-stressing tendons.
- MEM system – the system is formed by the sensors installed on the conduits of the pre-stressing tendons. These sensors measure force in the tendons by means of the magneto-elastic method. The sensors are placed on two tendons of the cylinder and of the dome. The sensors on the dome tendons are placed under the anchor and the tendon bend. On cylinder tendons they are placed under the anchor and at the middle of the cylinder height, on the Unit 1 the sensors are installed in the lower part of the cylinder as well.

The measurement is carried out once a month. Inspection of the measured values is carried out after each measurement, a complete assessment is made once a year at the end of outage time.

FE MODEL

Main goal of the model is to simulate long-term behavior of containment structure for which time dependent changes of material parameters are important. Model should also be able to simulate other changes of global loadings of structure such as temperature changes, an internal pressure loading or a rupture of tendon. One of the requirements for model capabilities was possibility to simulate free motion of tendon in a duct.

Model is created in Abaqus SW and represents whole containment structure. Due to the fact that the containment is a part of reactor building, the concrete slab at a level of +13.20m have been implicated into the model including main walls of one lower and one upper story. Boundary conditions are set at the edges of the walls. By this way, the flexural stiffness in the fixing of cylindrical part of containment should be well simulated. Global view of the model is in the Figure 2.

The basic principles used for model creation are follows:

- elastic behavior of materials are expected (but future expansion to non-linear material parameters is possible)
- model includes main openings in the wall and the changes of its thickness

- perfect connection between concrete surface and liner is expected and couplers are not included in the model
- elements modeling tendons respect real trajectory and enables free motion of tendons in a ducts including friction. Tendons are independent and their modeling enables individual changes of pre-stressing forces.
- concrete reinforcement is not modeled, contribution of reinforcement to the stiffness is included into modulus of elasticity of concrete.
- weight of cranes, installed on containment structure, is modeled by means of nodal masses, crane track is included in the model.

The principal part of the model is mass of concrete modeled by solid elements. Considering need of simulation of thermal changes, six elements across wall thickness is generated. Elements forming concrete of containment are used as a host elements for following additional part of containment structure:

- tendon ducts modeled by beam elements - Figure 3
- steel structure of formwork modeled by truss elements - Figure 4
- steel structure of crane track modeled by truss and shell elements
- liner and embedded plates modeled by shell elements

Tendons are modeled by beam elements. Connection between tendon and duct is provided by “Tube to tube” contact elements which simulates interaction between two tubes were one tube lies inside the other and is able to take into account the friction between tendon and duct. Application of pre-stressing is done by means of linear increasing forces acting at the end of tendons along with removing elements representing anchors. After reaching final level of pre-stressing, elements representing anchors are reactivated and forces are decreased to zero.

In the model, there are considered only time dependent parameters for concrete – shrinkage and creep. Relaxation of tendons steel have been neglected – according tests the majority of relaxation is done during application of pre-stressing force and pre-stressing losses due to relaxation of tendons steel after fixing of anchors are not significant. Shrinkage of concrete is incorporated by means of sets of independent strain time histories joined with individual parts of structure according their age. Creep is introduced by visco-elastic material parameters including dependence on temperature changes. Both, shrinkage and creep, are based on B3 concrete model – Bazant (1999) – modified according results of long term measurement on concrete samples in laboratory – for discussion of appropriate model of concrete shrinkage and creep see Stepan at al. (2003).

VERIFICATION OF FE MODEL

The containment structure is exposed to several different loadings during its life time. All loadings have been divided into two groups – instantaneous change of loading when effect of time could be neglected and intermediate time periods when there is a constant load level and only time dependent material parameters cause changes of deformation of structure.

Main load steps, used in calculations, are follows:

- building-up of containment structure:
  - concreting of lower cylindrical part
  - concreting of upper cylindrical part
  - concreting of ring beam and dome
- pre-stressing – divided into several steps according real process of application of pre-stressing (each tendon was pre-stressed in two step levels and there were different groups of tendons of cylinder and dome pre-stressed step by step)
- structure integrity test
- start of operation (considerable change of global temperature of structure)

Next load steps have been selected for verification of FE model:

- structure integrity test – containment is loaded by internal overpressure therefore there is clear definition of load. In addition, duration of load is relatively short and influence of time-dependent parameters is low. This loading is used as a base load for verification of instantaneous elastic response of structure.
- application of pre-stressing – due to need of simplification of process of pre-stressing and crucial importance of this loading for stress-deformation state of structure, verification of calculation results for this loading is important.
- long term response of structure after application of pre-stressing – this time period is significant because causes loss of pre-stressing force in tendons during period of unit operation. Due to temperature dependency of material parameters of concrete, the calculation have been divided into two steps – period before starting of operation and operation period.

Examples of time histories used for verification of model are presented in enclosed figures:

- Figure 6 – pre-stressing of Unit 2: measurement of horizontal displacements in the middle of cylinder height , individual pre-stressing steps are notable.
- Figure 7 – SIT at Unit 2: measurement of internal overpressure and changes of pre-stressing forces in cylindrical tendon no.68 measured by MEM system.
- Figure 8 – long-term measurement of deformation of Unit 2: measurement of strain in the middle of cylinder height (horizontal and vertical), effect of increasing of global temperature of structure is in evidence after year 2001 when operation of the Unit 2 started.

The process of model verification consists of comparison of measured and calculated deformation, strain and pre-stressing forces. Verification starts with comparison of strain in the middle areas of cylinder and dome (middle of height of cylinder and center of dome). In these areas the effect of moments on measured strain is reduced and the wall acts in compression through whole thickness therefore local inhomogeneities and accurate location of sensors are not so fundamental. Based on measurement of all sensors of NDS system, placed in the middle areas, the “characteristic” response of structure has been defined and results of calculation is evaluated against this characteristic response. The long-term changes of pre-stressing forces are checked by comparison of time histories of average forces in anchors of cylinder and dome. Distribution of pre-stressing forces along tendon length is verified by comparison with measurement of MEM system.

In the second step, comparison of strain measured in moment areas (areas close to fixing of cylinder and dome into connecting rigid structures) and individual evaluation of pre-stressing forces in tendons are done. In the moment areas, there is difficult to find “characteristic” response and it is necessary to evaluate individually measurement of each sensor. Reason is a presence of cracks in concrete and high sensitivity on location of sensor in cross-section. Very good instrument for evaluation of correctness of measurement is results of measurement during pressure tests. Thank to knowledge of expected response during these tests, it is possible to assign whether sensors are able to measure real values or not.

Based on results of these verification steps, the input parameters of models are adapted with aim to reach the best possible agreement of simulated and measured response of containment Unit 1 and Unit 2 (models and calculations are carried out independently for both structures). These verified models are then used in case of occurrence of non-expected loading (i.e. rupture of tendon or significant thermal loading) and for prediction of future losses of pre-stressing forces in tendons. Annual re-verification of models is expected – new measurement of structure response will be implicated and possible changes of structure configuration will be incorporated into model (i.e. replacement of tendon).

CONCLUSION

Presented process of model verification, based on comparison of simulated and measured response of real structure, demonstrated that in case of existence at least of basic long-term monitoring of response of simulated structure it is possible to refine the model enough to be able to closely simulate the real structure and help with understanding of the structure behavior and predict future behavior of the structure.

REFERENCES

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Bazant, Z.P. and Baweja, S. (1999). "Creep and Shrinkage Prediction Model for Analysis and Design of Concrete Structures: Model B3", ACI Special Publication, in press.

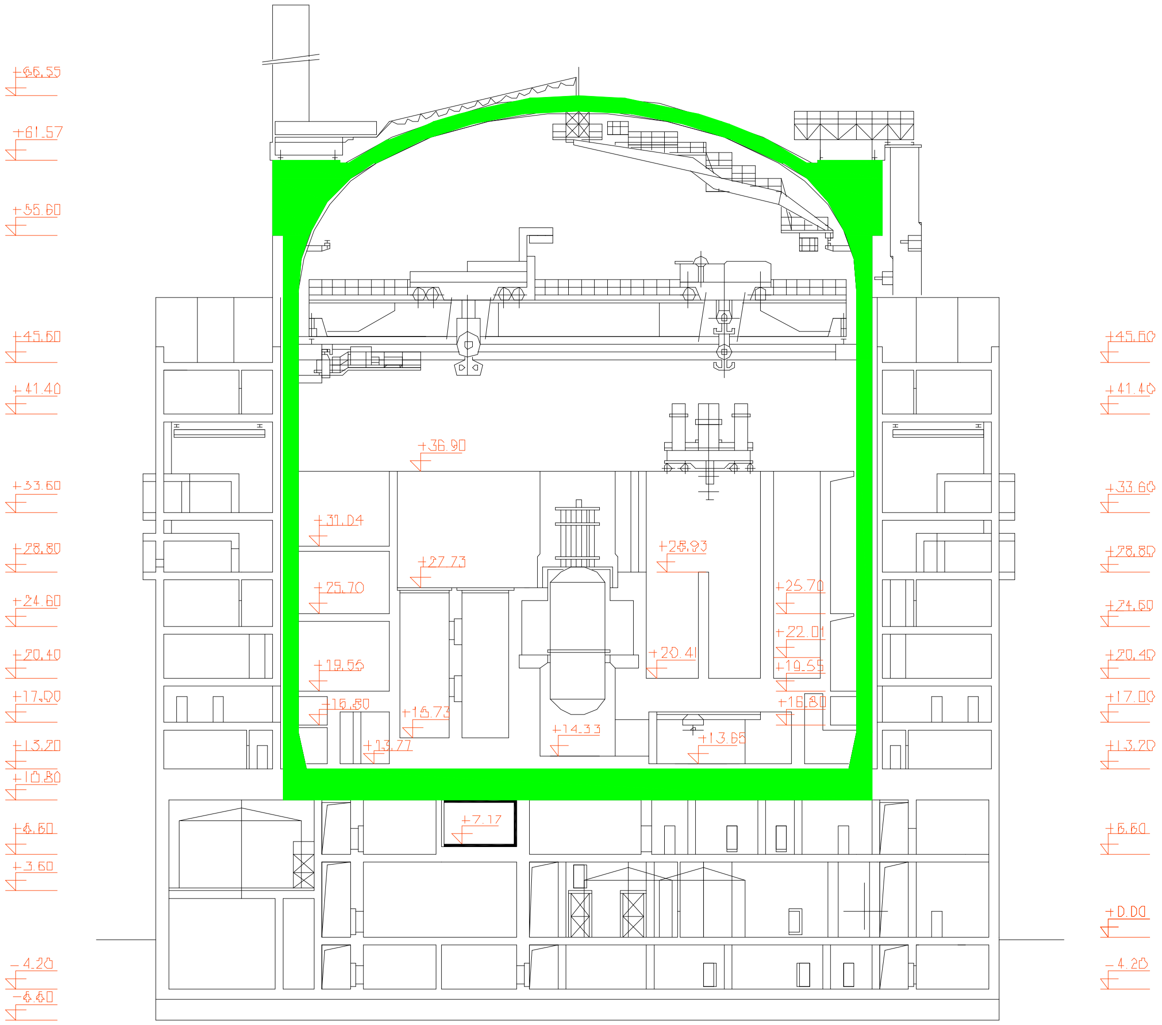

Figure 1. Section view of VVER1000 Reactor building, concrete containment is marked by green filling

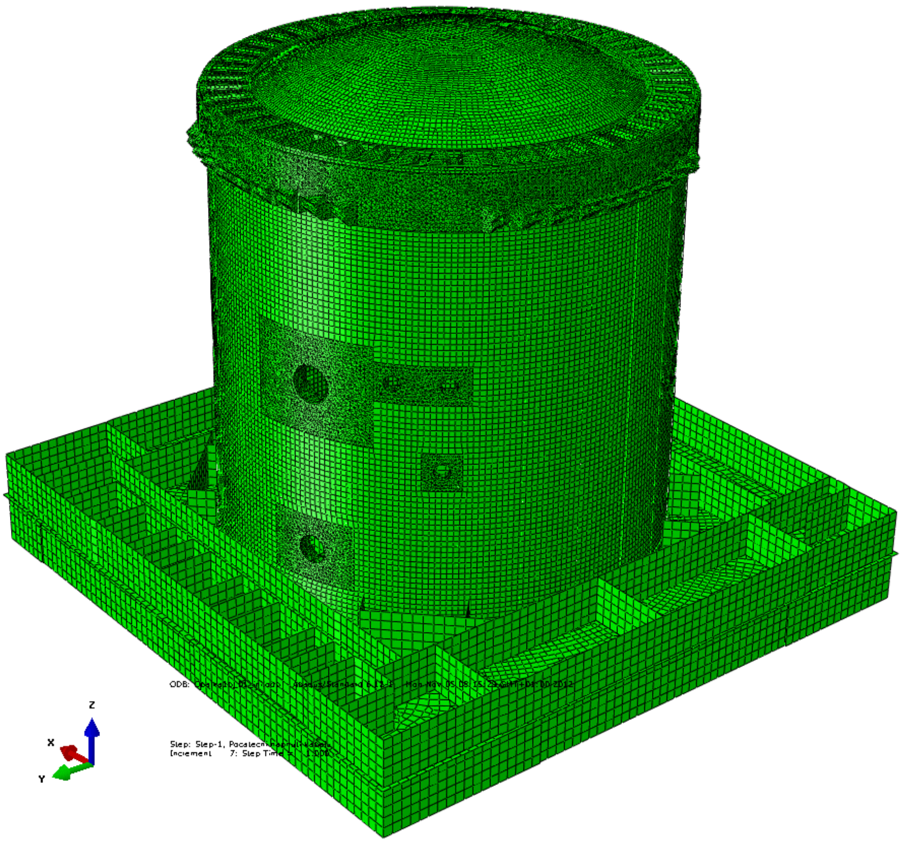

Figure 2. Global view of presented model

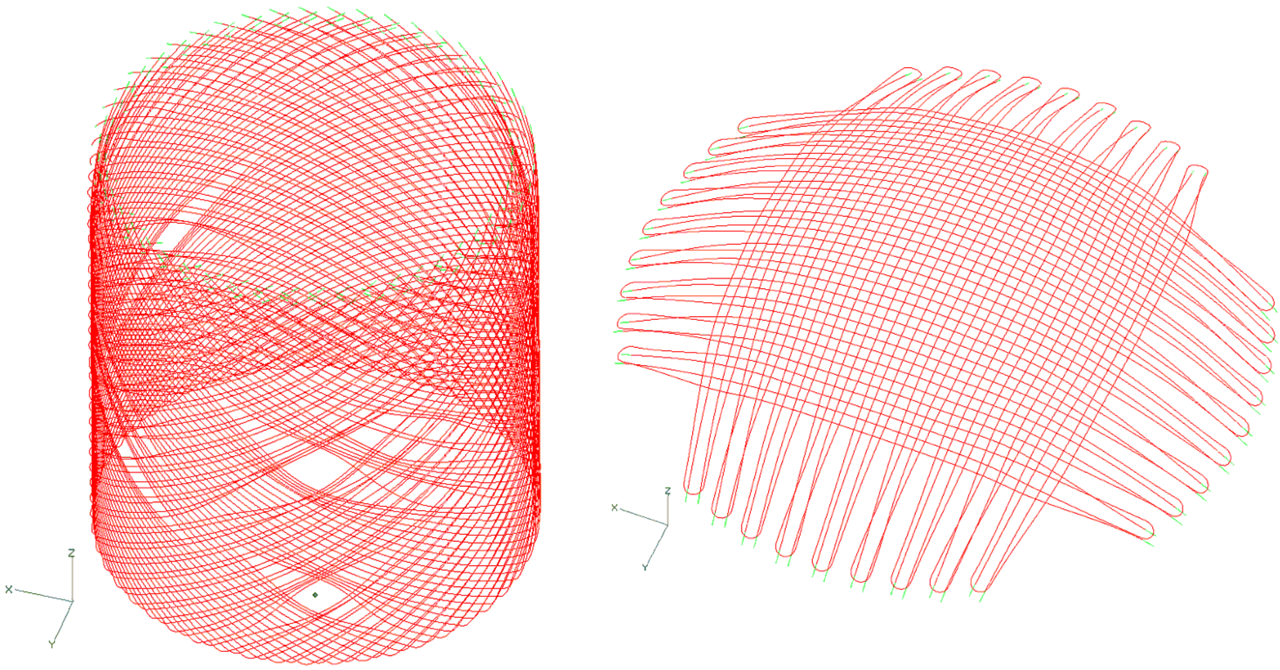

Figure 3. Layout of cylindrical and dome tendon ducts

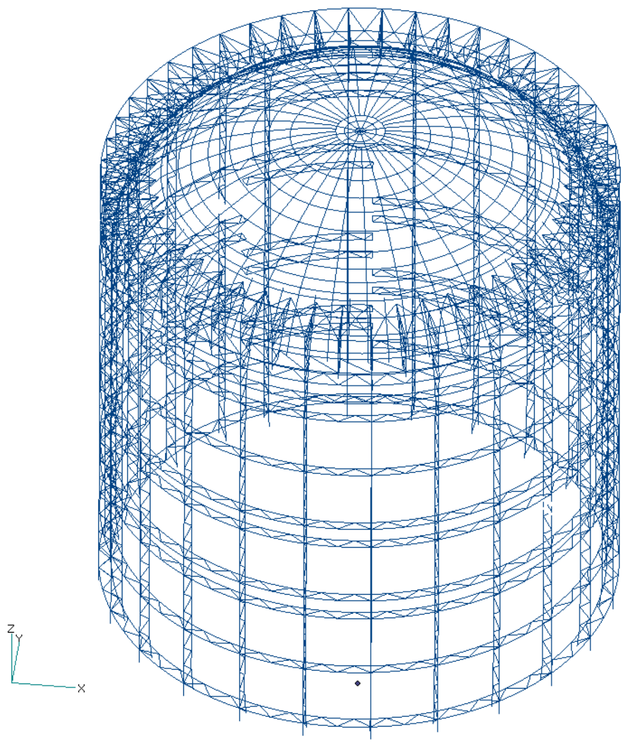

Figure 4. Layout of steel structure of formwork

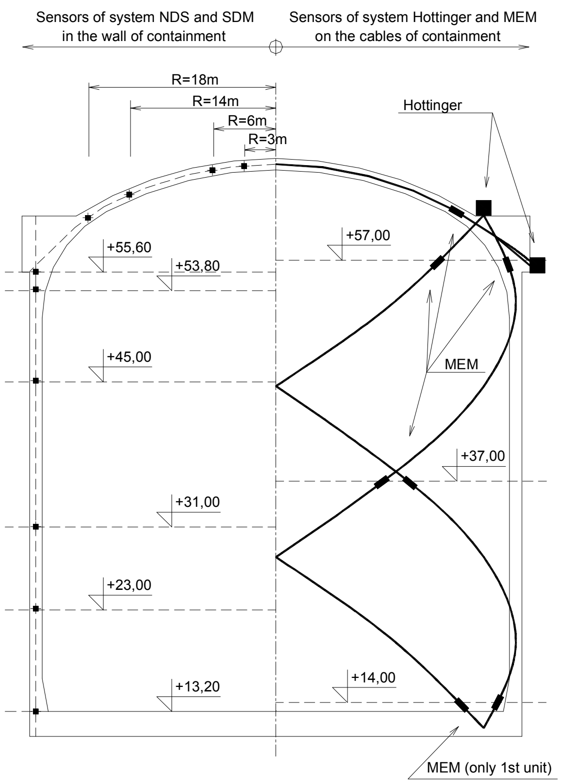

Figure 5. Distribution of sensors on the containment structure

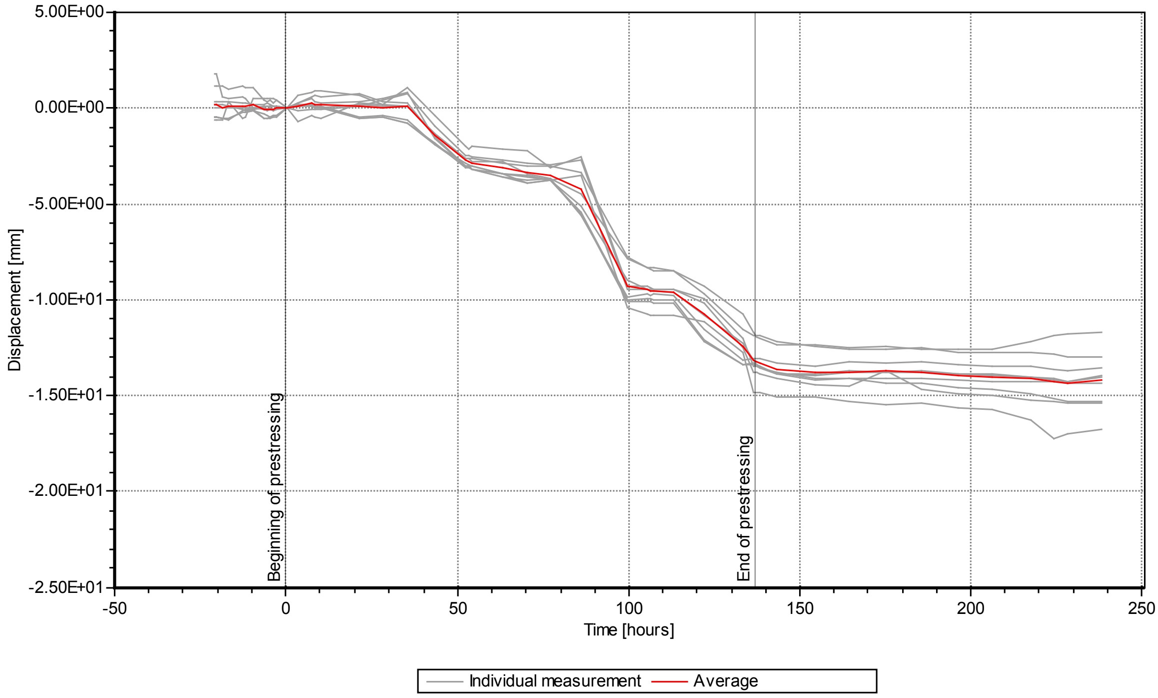

Figure 6. Unit 2 - Measurement of horizontal displacements in the middle of cylinder height during pre-stressing

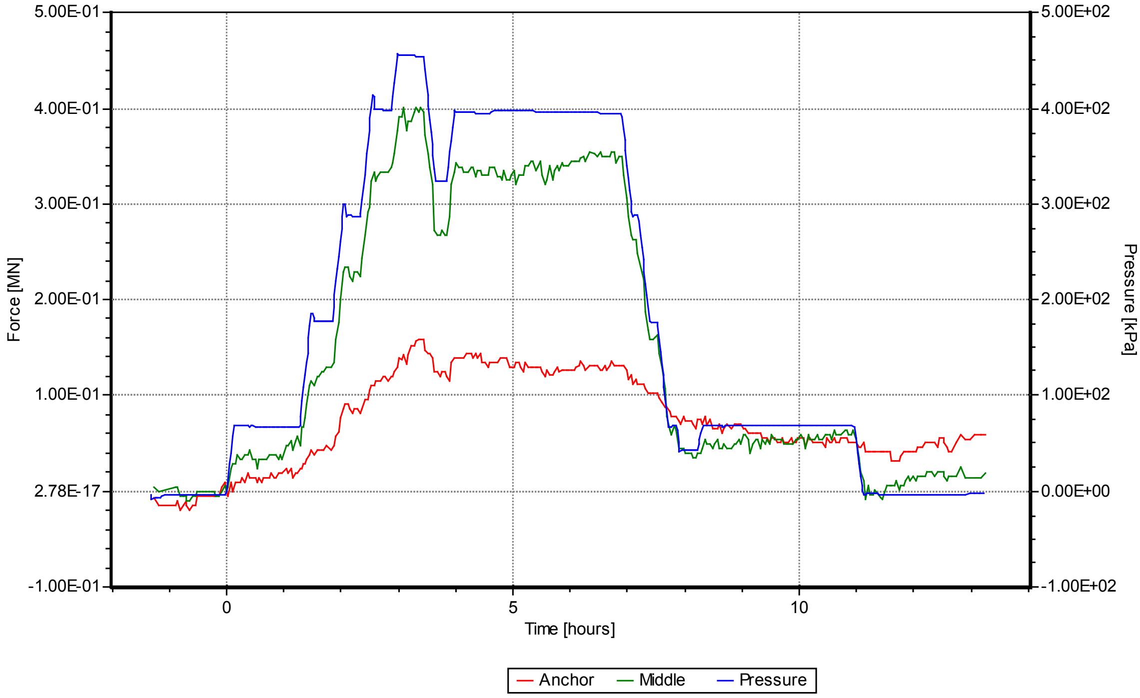

Figure 7. Changes of prestressing force along cylindrical tendon length during SIT at Unit 2

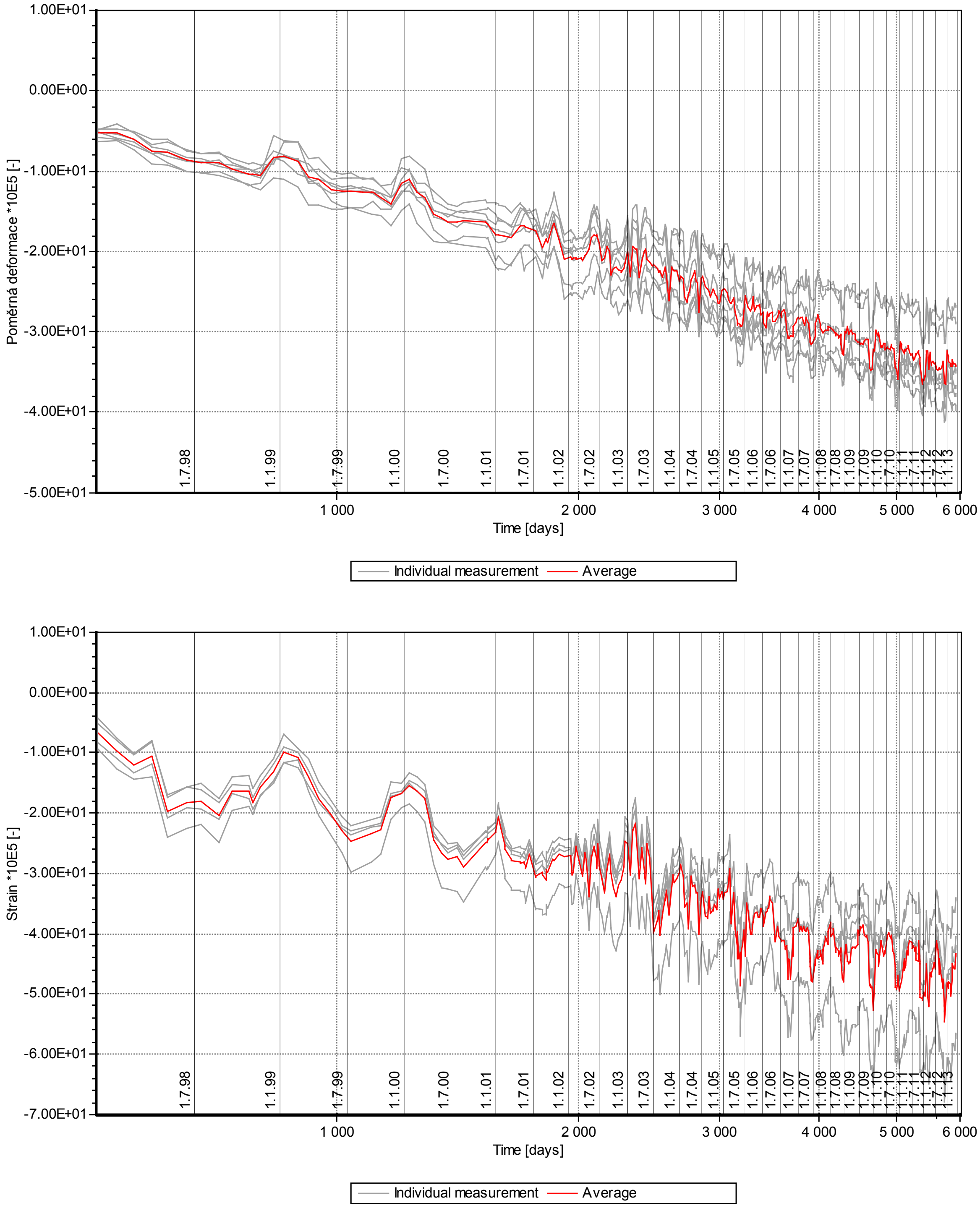

Figure 8. Unit 2 - Measurement of vertical strain in the middle of cylinder height and in the middle of dome during operation