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MATCH OF PREDICTED AND REAL LONG-TIME DEFORMATION OF PCCV

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ABSTRACT

The paper presents a retrospective view on the design expectations of the existing containment structure of VVER 1000 MW unit type. The comparison is focused on the real measured response of the structure with the response predicted by the design calculation, based both on the standard and laboratory tests.

INTRODUCTION

The continues decrease of prestressing level has a significant impact on long-time operation of prestressed concrete containment structure. Key role plays the time dependent material parameters, shrinkage and creep in case of concrete and relaxation in the case of tendons. For ordinary concrete structures, these changes of material parameters stabilize during the first years of utilization of structure. In case of robust concrete structures, as the containment is, the deformation changes are much slower and takes more time. Another factor, increasing the time need for stabilization, is a global change in temperature field after starting of unit operation. This change restarts the processes of shrinkage and creep of concrete and therefore the time of stabilization is even longer.

Calculations of containment structure, done in time of design, are based on material parameters and their time dependencies defined by standards. Due to significant dependence of concrete material parameters on mixture and aggregate origin, the short and long-term laboratory tests of concrete are accomplished as a part of design and construction process. These tests improve the prediction of long-time behavior of containment structure and help to select the most suitable concrete mixture.

After the completion of the construction of the containment structure, regular measurements on the structure begin. In the case of presented structure, the monitoring of deformation changes is ensured by more than 240 sensors (vibrating wire strain gauges) which have been installed at various levels inside the structure since the beginning of construction. Thanks to this long-term measurement, a comparison of the real response of the structure with the response predicted by the design calculation, based on the standard and the laboratory tests, is possible.

CALIBRATION BY LABORATORY TESTS

Concrete specimens for long-term laboratory shrinkage and creep tests were taken directly from the mixture at various levels of the structure during its construction. The locations covered the lower and upper part of the cylinder, the connection of the cylinder with the dome and the dome. The standard dimension of specimens for long-term laboratory tests is 400 x 100 x 100 mm. Along with the preparation of these specimens, additional specimens were taken to test the strength and modulus of elasticity.

The level of loading of the specimens intended for creep tests is at 30% concrete strength. The test program covered specimens loading at 28 days, 90 days, and 360 days. For each combination of concrete origin and time of loading, three specimens were placed inside one vertical steel frame for creep test and another specimen was intended to measurement of shrinkage. The loading is maintained by preloaded springs. The specimens are stored indoors at a temperature around 20°C and constant humidity, the parameters of the environment are monitored. A few specimens are preserved in a heated space with a controlled temperature of 40°C, but the number of specimens is really low and therefore it is difficult to generalise the measurement for the global structure. Drying of concrete is limited by wrapping of all specimens into plastic but no monitoring of the concrete humidity is provided. The measurement of deformation is performed by an external precise mechanical deformeter placed into metal marks glued on the surface of the specimen.

The original purpose of these laboratory tests was to obtain values of creep and shrinkage that better match the behavior of the real structure. Smooth measured values were used in the design calculations instead of theoretical values according to the design standard.

Due to the relatively low total number of specimens and the loss of some specimens during the long history of tests, only a limited number of combinations of concrete origin and time of loading have measured data for the all history. Therefore, measurements on two typical specimens (no. II and VI) have been selected as an input data for the calibration of the equations used in the standard. These specimens correspond to the lower and upper bounds of the measurement range of all specimens and allow to see the impact of test uncertainty on the results. As a representative of the current design standards, the standard EN 1992-2, Appendix B was selected for its ability to calibrate equations according to the tests.

In the first step, the default parameters of the equations according to EN 1992-2, Appendix B were used. Due to the unknown humidity of the specimens, the value of humidity was set in the way to have similar average results as measured on the specimens. In the second step, the optional parameters were changed step by step with the aim to fit the measured creep and shrinkage on each specimen. A comparison of theoretical and calibrated time histories is shown in Figure 1 to Figure 4. The measured shrinkage shows a slower increase at the beginning and slightly higher final values. The measured creep encloses theoretical results and the shape of curves is similar.

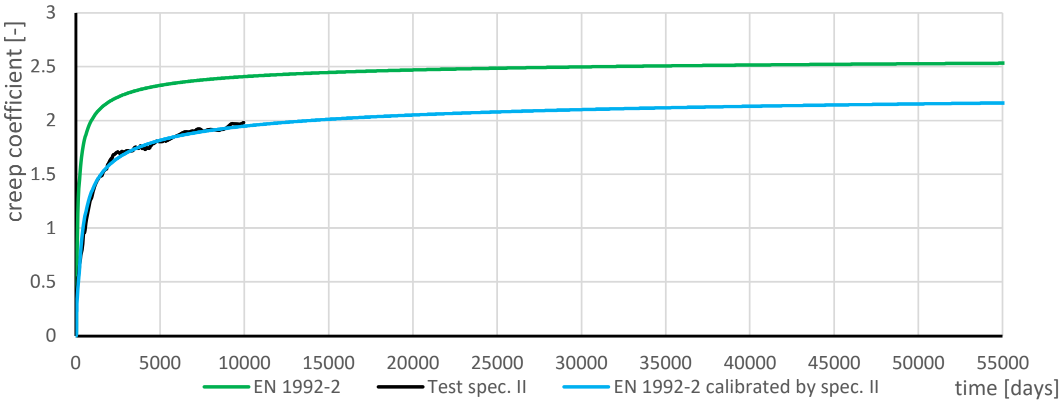

Figure 1. Comparison of creep according to EN 1992-2 and calibrated by test of specimen II

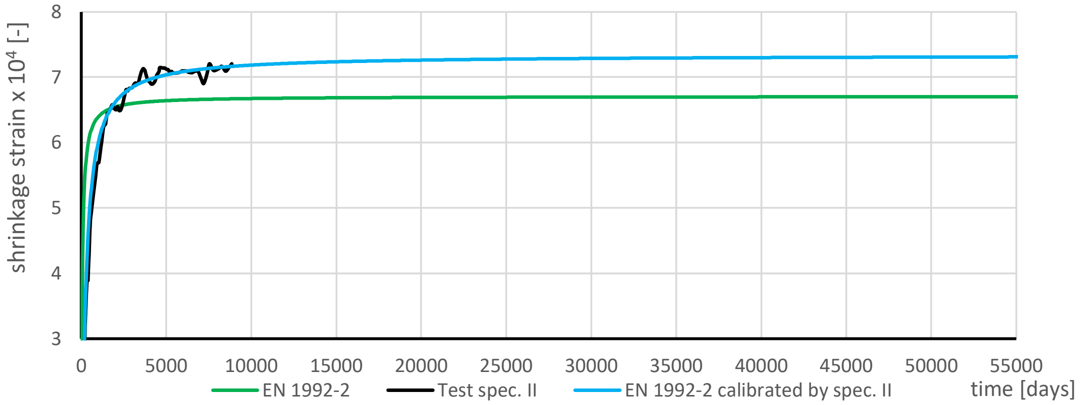

Figure 2. Comparison of shrinkage according to EN 1992-2 and calibrated by test of specimen II

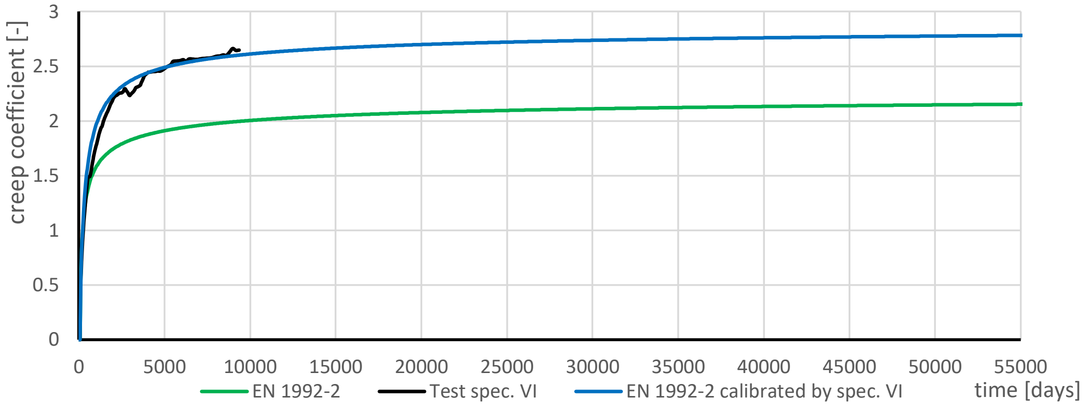

Figure 3. Comparison of creep according to EN 1992-2 and calibrated by test of specimen VI

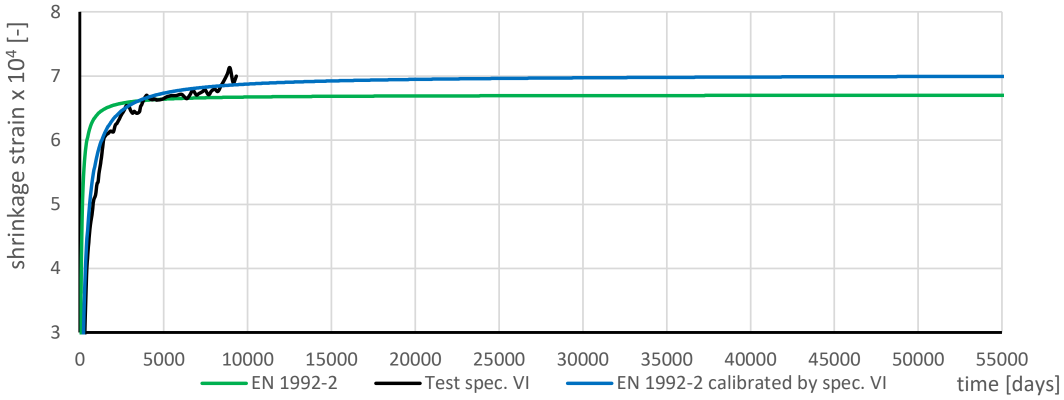

Figure 4. Comparison of shrinkage according to EN 1992-2 and calibrated by test of specimen VI

CALIBRATION BY MEASUREMENT ON EXISTING STRUCTURE

The time histories of shrinkage and creep of concrete of the existing structure are determined using the FE model. A detail description of the model including its verification is presented in Stepan (2013). The model represents a concrete containment structure including tendons and steel structures placed inside the concrete. The entire history of the structure is simulated, starting with the concreting in several steps to the today's state. The distribution of prestressing forces in the individual tendons is set according to the measurement on the tendons with sensors. The global stiffness of the structure is set according to its deformation response during the structure integrity test. Changes of temperatures are based on the measurement of temperature sensors inside the concrete and the measurement is idealised for each typical part of the structure.

For a complete description of the time-dependent behavior of the structure, three additional parameters are necessary – relaxation of tendons and shrinkage and creep of concrete. The relaxation of tendons is calculated according to EN 1992-1-1, Section 3.3.2, steel class 2. The relaxation after 1000 hours and the temperature dependence of the relaxation are determined according to the material tests. In the case of shrinkage and creep of concrete, the determination of the most representative parameters is based on the assumption that the shape of time-histories and the mutual dependency of shrinkage and creep are controlled by the theory presented in EN 1992-2, Appendix B. The dependency of shrinkage and creep of concrete on the temperature is calculated according to EN 1992-1-1, Appendix B, Section B1.

The process of calibration of the shrinkage and creep of concrete using the FE model started by the application of the coefficients recommended by the standard. After that, an iterative set of sequential steps was then performed, including calculation of the entire lifetime, comparison of the results with the measurement and appropriate adjustment of the coefficients. The basic criterium for evaluation of the results of the calculation was the matching with the time histories of the measured forces in tendons and with the time histories of the deformation in the central part of cylinder and dome, where the effect of the moments on the stress distribution is limited. As a result, this reverse search of the suitable input data for shrinkage and creep of concrete shows the difference between the initial theoretical data according to the standard and the final data corresponding to the real behavior of the structure.

A comparison of input data for shrinkage and creep of concrete corresponding to different methods of input data calculation is shown in the following Figure 5 to Figure 10. The three most representative parts of the structure are shown – the lower part of the cylinder surrounded by another building (the outer surface is exposed to indoor conditions), the upper part of the cylinder (the outer surface is exposed to outdoor conditions) and the dome (the outer surface is covered with water proofing). For each case, the curves for shrinkage and creep according to the default design standard, the design standard calibrated by laboratory tests and the data calibrated according to the measurement on the existing structure are presented. In the case of the lower part of the cylinder surrounded by another building, where the outer surface is exposed to indoor conditions closed to the exposure of specimens in laboratory, the measured values on the specimens are also presented.

The comparison of the results for all three parts of the structure shows the following findings:

- calculation according to the standard with default parameters gives a slow initial increase of values, especially for shrinkage. In contrast, the final values are close to the values measured on the existing structure.
- calculation according to the standard with parameters calibrated by laboratory tests shows a better shape of the curves, closer to the existing structure, but the final values remain significantly lower. An attempt to improve the calculation by calibration according to

laboratory tests of the specimens resulted in less representative shrinkage and creep values for the existing structure.

- direct application of measurement on specimens to the analysis of structure gives a conservative response.

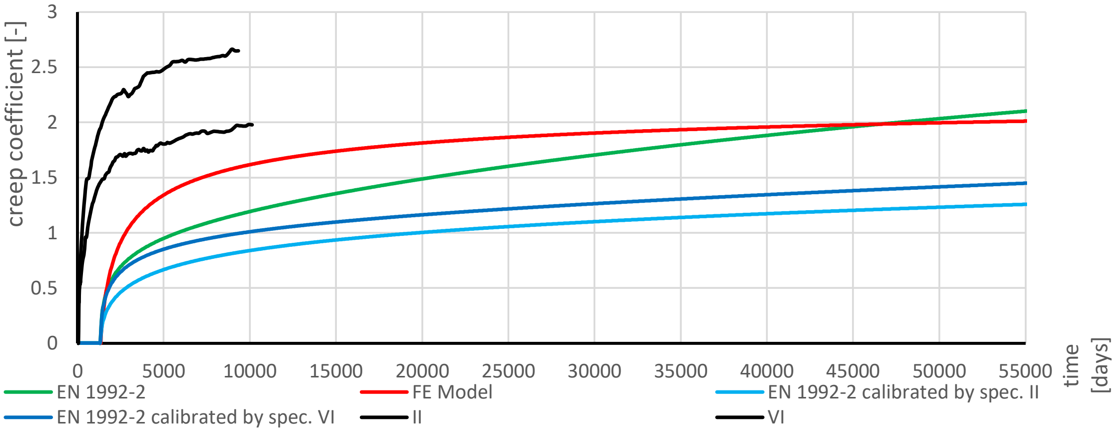

Figure 5. Comparison of creep for the cylindrical part in indoor environment

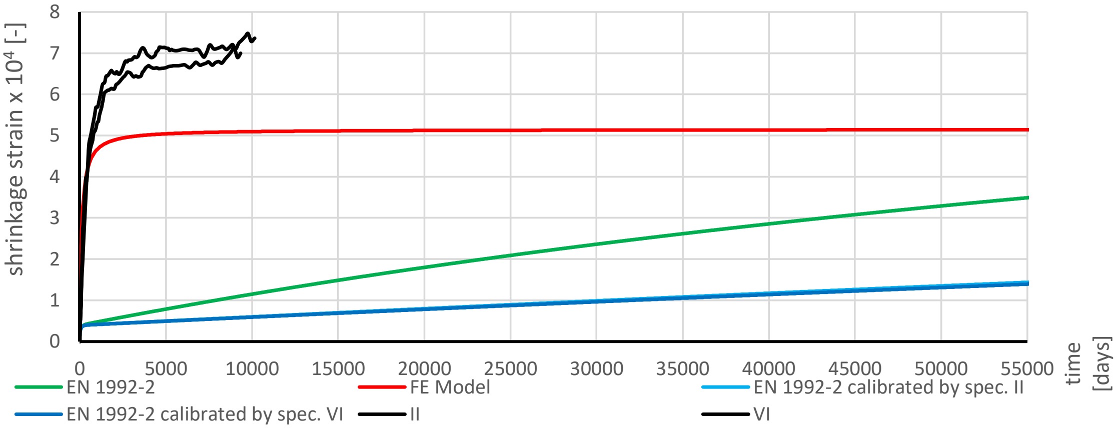

Figure 6. Comparison of shrinkage for the cylindrical part in indoor environment

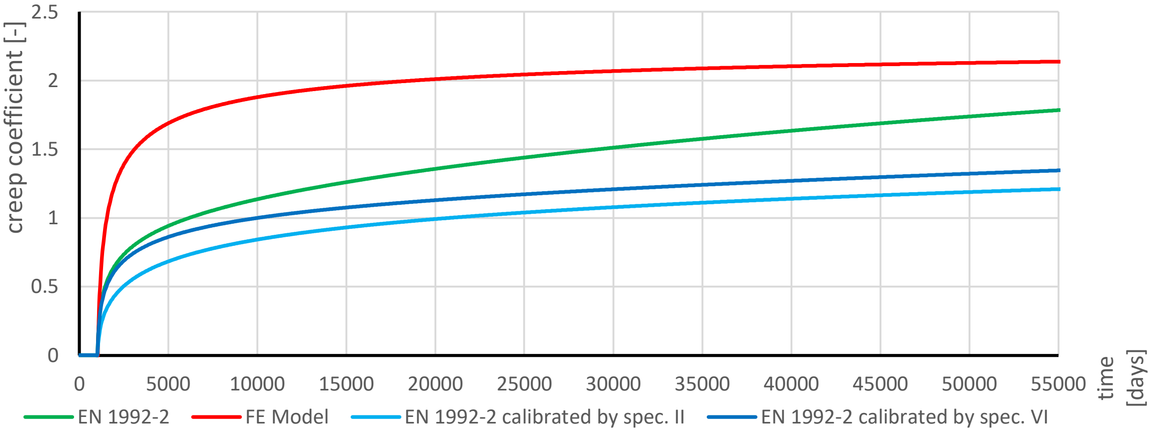

Figure 7. Comparison of creep for the cylindrical part in outdoor environment

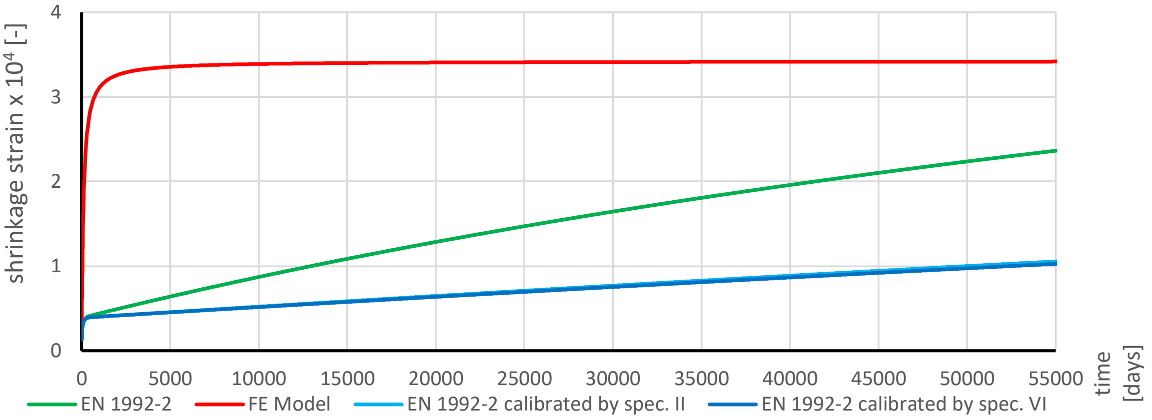

Figure 8. Comparison of shrinkage for the cylindrical part in outdoor environment

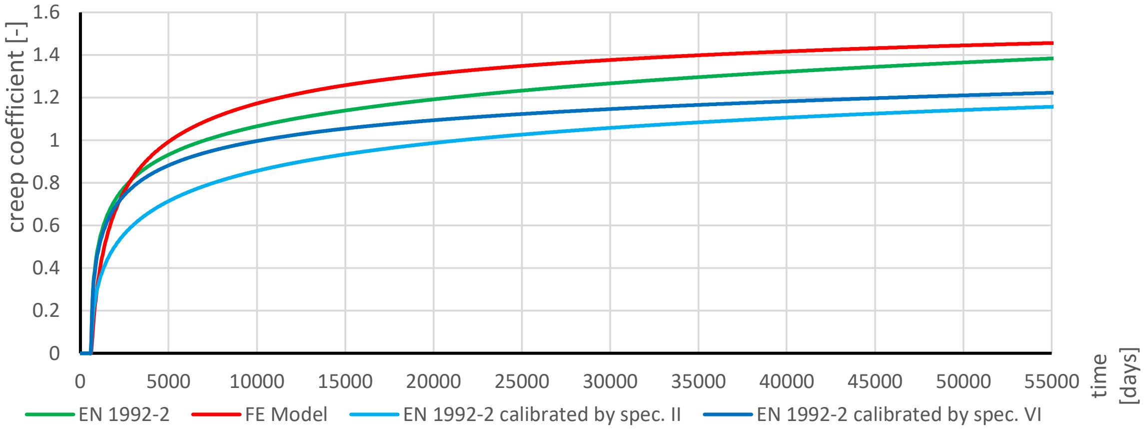

Figure 9. Comparison of creep for the dome part

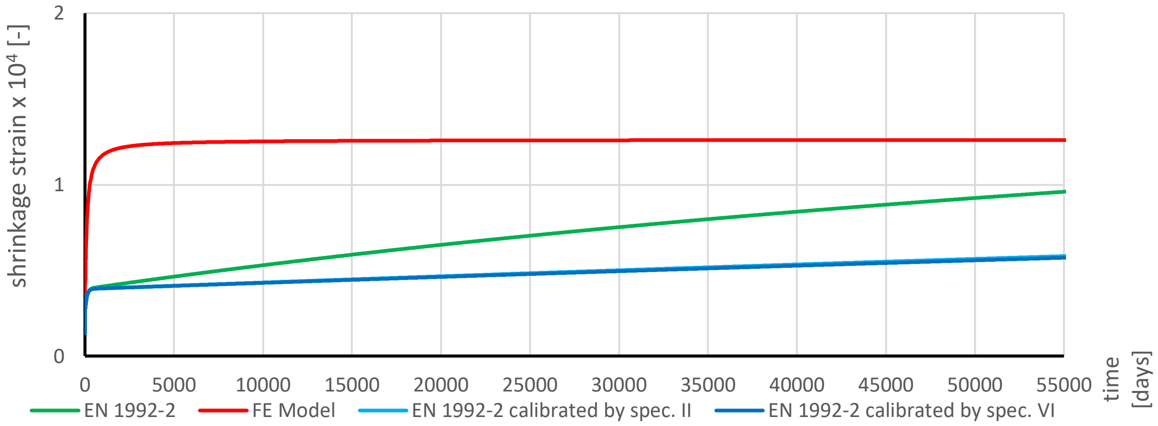

Figure 10. Comparison of shrinkage for the dome part

CONCLUSION

Time histories of the calculated deformations of structures with conventional dimensions and using the material input data according to the standard show rapid initial increase of the deformation with fast stabilization. This corresponds to the fact that the standards are calibrated for usual concrete structures in dry conditions, not for thick concrete walls with slow drying of concrete. Laboratory tests performed on specimens of similar in size to conventional structures help to slow-down the initial increase of deformation and correct the final level of deformations but there is still uncertainty in the transfer from the size and conditions of the test specimens to the size and conditions of the real structure. In the case of a massive structure with thick walls, the calculation with the default parameters specified by the standard gives unrealistic results with a very slow increase of deformation. Calibration of parameters in the standard according to measurements on specimens in the laboratory does not solve the transfer of results from the size of the specimen to the size of the real structure. The transfer is based on the equations given in the standard and does not work properly for a wall of such high thickness as the containment wall is. Therefore, the calibration of the numerical model according to the long-time monitoring of the real structure seems to be the only way to include all external conditions and specifics of the structure into the material input data. This approach also overpasses other incompleteness of material models and boundary conditions in the FE model.

REFERENCES

Stepan, J. (2013). “Verification of Numerical Model of Existing Prestresed Concrete Containment Structure” *Proc., SMiRT 22 Conference*, IASMiRT, San Francisco, California, USA.