STRUCTURAL HEALTH MONITORING OF VVER-1000 CONTAINMENT STRUCTURE

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ABSTRACT

An approach for structural health monitoring of post-tensioned concrete containment structures is proposed and discussed. The approach is currently under development as part of the research project IRIS under the FP7 research program. The proposed structural health monitoring is based on permanent ambient vibration measurements and finite element analyses. Firstly, numerical simulations are used for assessment of containment ultimate capacity for accident loadings as well as for safety margin assessment to particular accident scenarios. Secondly, numerical analyses are used for studying the influence of the pre-stressing level on the containment capacity and its safety margins. And on third place numerical analyses are used for studying the influence of the pre-stressing level on the containment modal response. The analytically obtained modal response is compared, with this obtained experimentally through ambient vibration monitoring in the numerical model is updated through a consecutive process of finite element model updating. The main idea behind the proposed approach is instead to measure the pre-stressing forces in the tendons to monitor the effect from the pre-stressing and thus indirectly the containment capacity and the NPP safety. The entire process should be finalized, with specific thresholds and early warning system.

INTRODUCTION

An essential component of the nuclear power plant safety is the structural capacity of the containment structure. The containment has to prevent the reactor installation from external impacts as well as to provide a tight physical barrier against release of radioactive materials in case of severe internal accidents. Therefore, the containment structures are designed to resist to internal pressure and temperature loadings. Common practice is to use pre-stressed concrete for NPP containment structures. The design pre-stressing force is selected in such a way that the produced equivalent external pressure overlaps the expected internal pressure caused by Design Basis Accident (DBA) and thus provides elastic response of the containment structure. However, when severe internal accident conditions are considered, the internal pressure could exceed the design pressure and the response of the structure goes in the non-linear range. In both cases, the adequacy of the containment response, as well as its ultimate capacity, depends directly on the level of the pre-stressing. The containment ultimate capacity itself is a complex parameter and cannot be considered as a constant number. Generally it depends on a series of variables, e.g. the material properties of the concrete, the liner, the reinforcement and the tendons respectively as well as the structural composition – the structural system, the arrangement of the pre-stress tendon system, the presence of penetrations and openings and the measures to mitigate the stress concentrations caused thereof, the arrangement of the liner welding and anchors, etc. In addition, for the case of non-grouted tendons, the actual pre-stressing force can be considered as variable rather than constant; it can be influenced by many time-depending processes as corrosion, relaxation, aging, etc.

Therefore, an essential part of the maintenance of the containment structure is to implement regular monitoring on the tendons force and eventual additional pre-stressing if necessary. An important measure from reliability point of view is to set up criteria for minimal allowable pre-stressing force and thus to minimize the interventions on the tendons.

Currently, an innovative approach for containment monitoring, including the pre-stressing level, is under development, within the framework of the FP7 IRIS (Integrated European Risk Reduction System) research project as a common sub-task shared between Kozloduy NPP, Vienna Consulting Engineers GmbH (VCE) and Risk Engineering LTD.

DESCRIPTION OF THE STRUCTURE OF VVER 1000 REACTOR BUILDING

The reactor building structure of nuclear power unit type VVER-1000 is a space configuration system which could be considered as composed of four main parts – foundation structure, containment structure, auxiliary
structures, and inner structure. These four parts are integrated by a solid 2.40 m thick slab of reinforced concrete, on elevation +13.20.

The containment structure is a pre-stressed reinforced concrete structure composed of two parts – cylinder and dome, connected by a thick supporting ring-shaped beam. The containment is entirely separated from the auxiliary structures. The main geometric dimensions of the containment are: cylinder height 44 m, cylinder inner diameter 45.0 m, cylinder wall thickness 1.20 m, dome thickness 1.10 m. On the inner side of the containment shell there is steel liner, 8 mm thick, which ensures leaktightness.

The cylindrical part and the dome are connected by a solid ring-shaped beam which serves also as a base for anchoring the pre-stressing tendons. The pre-stressing is implemented by a total of 132 tendons whereby 96 of them are arranged helicoidally in the cylinder part, and 36 are arranged orthogonally in the dome part. Every pre-stressing tendon is comprised of 55 cables with cross section 140 mm² each. The tendons are pre-stressed on both ends by design force of 1000 tons (9810 kN). Cross section view of the containment building and arrangement of the pre-stressing tendons is shown on Fig.2.

**Fig.1 Cross section view of typical VVER 1000 reactor building and arrangement of the pre-stressing tendons.**

**ASSESSMENT OF THE CONTAINMENT CAPACITY**

**Numerical model**

Finite element model has been developed describing the reactor building structure, including all its elements – containment shell, foundation structure, auxiliary structures and inner structures. In this way, all possible interactions of the structure elements are taken into account, and a more realistic picture of the structure behavior under the loads considered is achieved. The model is composed of 56682 nodes and 81766 elements – see Fig.2.

**Fig.2 Isometric section cut view of the structural models of VVER 1000 reactor building (left) and composition of the implemented finite element, together with the material constitutive laws (right)**
For modeling the containment, finite elements with increased accuracy have been used, taking into account all cross section elements – concrete core, steel liner and reinforcement. The finite elements applied are SHELL elements [5] with seven integration points in the cross section depth for the concrete core. The steel liner and the reinforcement are modeled by the REBAR option [5], as plane disks with cross section equivalent to the reinforcement. The composition of the finite elements used is shown on Fig. 2 (right side).

Non-linear models of the materials are used. The concrete core is modeled by CONCRETE material model [5], corresponding basically to the Ottosen model. Bi-linear elastic-plastic material is assigned to the steel liner and the reinforcement. The material constitutive laws are shown in Fig. 2 (right side).

The tendons are modeled on member by member basis, following their exact trajectory, including the irregularities around the openings. The relaxation and the friction are accounted for in detail, the change of the tension force along the tendon is considered.

Assessment Approach

The assessment procedure is based on graphical comparison between the structural capacity and the loading intensity by plotting both parameters in the same “temperature gradient – overpressure” coordinate system. For the purpose the pressure vs. time and temperature vs. time loading functions are integrated in one loading diagram using a common time axis. The limit bearing capacity of the structure is determined based on a series of non-linear static analyses whereby the function of the assumed load (internal pressure or equivalent temperature gradient) is monotonously increasing until it reaches the collapse criteria. The level of damage in the cross sections is determined based on damage index (DI), which is the ratio between the cross section, which has endured plastic deformations, against the whole cross section. The DI index may have values from 0 to 1, where 0 designates entirely elastic cross section, and 1 designates entirely crushed one. Different limit states are considered from structural capacity and leaktightness point of view, based on current code prescriptions [2; 3]. Shortly they can be summarized as follows:

<table>
<thead>
<tr>
<th>Structural Capacity</th>
<th>Leaktightness</th>
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<tr>
<td>Level Ia: elastic response. The structural integrity is ensured with large margins.</td>
<td>Level Ib: leaktight structure. Radionuclides leakage is below the design value.</td>
</tr>
<tr>
<td>Level IIa: Limited damages. The structural integrity is ensured.</td>
<td>Level IIb: limited increase in the leakage rate, whereby the leakage may exceed the design value.</td>
</tr>
<tr>
<td>Level IIIa: Excessive damages. The structural integrity is still ensured.</td>
<td>Level IIIb: Large, or very large increase of the leakage rate.</td>
</tr>
<tr>
<td>Ultimate capacity: Loss of structural capacity and integrity.</td>
<td></td>
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The acceptance criteria correlate the load combinations considered with the permissible stress state in the structure. According to the code prescriptions the stress state due to load combinations caused by severe accidents is limited to Level IIia. And Level IIib, as far as this is reasonably achievable.

The structure stress state is controlled in 32 cross sections. Four cross sections each have been considered for eight different elevations of the containment structure. The containment ultimate capacity as well the containment response to different accident scenarios is assessed, based on the values of the damage indexes and the deformations in the liner, reinforcing grids and pre-stressing tendons, as well as on the acceptance criteria as described above. Detailed description of the assessment procedure can be found in [1].

Containment capacity and response to design and beyond design accident loadings

The ultimate containment pressure capacity is assessed via non-linear static analysis with monotonically increasing pressure loading. Based on the obtained results the following conclusions are made regarding the containment structure behavior: 1) the structure performs entirely in elastic mode (Level Ia) up to overpressure ~650 kPa (~1.67xPd – design pressure), and the first cracks occur in hoop direction (vertical cracks) in the middle part of the cylinder. At pressure values of about 760 kPa (~1.95xPd), the structure reaches Level IIa. At pressure 920kPa (~2.4xPd) the structure reaches Level IIIa; 2) The steel liner and the reinforcement perform entirely in elastic mode (Level Ib) until pressure of 920kPa is reached, then plastic deformations occur in hoop direction in limited areas of the cylinder middle part – elevation +32.40. In the range 1000-1050 kPa (2.6-2.70xPd) the liner deformations in the most heavily loaded areas in the cylinder middle and in the boundary with the base slab reach values of the order of 1.0-1.2%, therefore, a conservative assumption could be made that at pressure values above 1000 kPa (~2.6xPd) the structure leak tightness cannot be ensured anymore i.e. Level IIb has been reached; 3) At
pressure values above 1050 kPa (2.7xPd) the deformations in the most heavily loaded tendon reach 1.5%, therefore, with further increase of the pressure, brake of the tendons and exhaustion of the structure bearing capacity could be expected.

In order to determine the effect of the temperature load, a series of non-linear static analyses have been conducted. Based on the obtained results, it can be stated that the temperature loading, with equivalent temperature gradient up to 200°C, does not have negative effect on the ultimate bearing capacity and leak tightness of the structure, but it causes an increase of the damage intensity (on the external side of the cross sections) in the containment structure for the same pressure values. More detailed description of the influence of the temperature loading on the containment pressure capacity can be found in [1].

The obtained results allow an integral assessment to be made on structure capacity as function of the containment inner pressure and temperature gradient, whereby the capacity is presented in graphic form as capacity envelopes in a coordinate system "temperature gradient - pressure". The structure response on the impact of specific accident scenario is assessed by graphic comparison of the capacity and load parameters, plotted in the same coordinates - see Fig. 3.

It can be seen that the VVER 1000 containment structure possess significant capacity and fulfill the code prescriptions for the accepted containment response to different design and beyond design accidents.

**Influence of the pre-stressing force on the containment response**

The containment capacity is directly dependent on the level of the containment pre-stressing. The influence of the pre-stressing force on the containment capacity is studied numerically. For the purpose, two analyses with constant pressure, corresponding respectively to DBA and BDBA, and monotonically decreasing pre-stressing force are performed, until the structure reaches the appropriate limit states. The results of the second analysis are presented in Fig.4, where the Damage Index evolution is function of the pre-stressing force reduction in tons, compared to the design force of 1000t (9810kN).

**Fig.3 Graphical comparison between the structural capacity (corresponding to different limit states) and particular loading acting on the structure**

![Graphical Comparison](image)

**Fig.4 Influence of the pre-stressing force at the tendons on the containment response to severe accidents.**

![Influence of Pre-Stressing Force](image)
Based on the obtained results, it can be concluded that the VVER 1000 containment could satisfy the acceptance criteria for structural response (Level IIIa and Level IIb), with overall pre-stressing level reduced up to 25%.

CURRENT PRACTICE FOR VVER 1000 CONTAINMENT INSPECTION AND MONITORING

Usually the containment inspection and monitoring is based on Designer prescriptions and include different periodic activities, such as inspection of the concrete surface, non-destructive concrete strength tests, inspection of the liner coating, inspection of the tendon anchors for corrosion and damages, checks of the pre-stressing force by lift up tests and etc. Also, the VVER 1000 containment structures are equipped with various permanent monitoring systems using sensors fitted in the cross sections prior to concreting. Usually this includes sensors measuring the concrete and rebar deformations, temperature and horizontal shift in the middle of the height of the containment cylindrical part. In some VVER 1000 containment structures there are also permanent monitoring systems measuring the pre-stressing force in the tendon anchors. Loss of pre-stressing force in the tendons (non-grouted) of post-tensioned concrete containment is a common problem, especially in newly built structures, where the processes of shrinkage and relaxation are still active. The loss of pre-stressing force in tendons of post-tensioned concrete structures is considered as first priority technical issue by the Committee on the Safety of Nuclear Installations (CSNI) of the OECD-NEA.

Lift-up tests and real-time monitoring at the anchor head

There are basically two current approaches widely used for inspection/monitoring of the tendon pre-stressing force. The first one is based on lift-up tests. During the lift-up process, the pressure in the test press is continuously increased and recorded until the anchor is released, i.e. lifted from the supporting block. The pre-stressing force is derived from the press pressure.

Another, widely used monitoring approach is constant measurement of the tendon force on the anchor by strain gauge or pressure cell installed between the anchor and the supporting block. Alternatively, the tendon force can be monitored by measuring the force in few tendon cables and after that estimating the total tendon force, as shown on Fig.5.

![Fig.5. Monitoring of the tendon force by measurement of the cable forces at selected cables](image)

Limitations of the currently used methods

The mentioned above current monitoring approaches have some limitations. The sensors incorporated in the concrete are subjected to aging processes which affect their reliability and they cannot be replaced. Therefore, it is not expected from such monitoring systems to be operable during the entire reactor building life.

One of the main limitations of the lift-up tests is that the test can be performed only during an outage that is usually once a year. Additionally, the lift-up test is considered relatively subjective, due to the uncertainties during detection of the anchor lift. Also, the lift-up tests are considered to have negative influence on the tendon and anchor durability.

The direct measurement of the pre-stressing force at the anchor is considered the most advanced method from the mentioned above. The disadvantage is that the installation or the replacement of the sensors requires dismounting the tendon onto which the sensors will be installed. Having in mind that the expected life of such
sensors will be significantly shorter than that of the reactor building, such operations should be expected and could be performed again only in an outage.

The described methods for pre-stressing force monitoring have one common disadvantage, which is that they measure the tendon force only at the anchor and do not take into account the tendon force distribution along the tendon length. Typical distribution of the tendon force at one regular and one irregular (around an opening) tendon is presented on Fig.6. The equivalent external pressure as produced by the pre-stressing system and the containment confinement is a function rather of the average tendon force, than the tendon force at the anchor. Therefore, tendon monitoring based only on anchor force readings might produce misleading conclusions.

![Fig.6 Distribution of the pre-stressing force along the tendon length](image)

**THE PROPOSED APPROACH FOR MONITORING**

Currently, there are many reactors applying for license extension or already licensed to year 2030. Therefore, it is necessary to develop long term solutions for containment monitoring procedures, which would overcome the above mentioned limitations of the current approaches. One possible solution is monitoring based on ambient vibrations that is successfully applied to a large number of bridges [6].

The method of studying stressed state of a structure, considering alterations in the energy distribution function, is proposed by Vienna Consulting Engineers GmbH (VCE) [8]. The basis of this method is that any change in the energy distribution function is related with a particular change in the stressed or damaged state of a studied structure location. Based on a permanent vibration monitoring it is possible to follow every potential change in the frequency or the amplitudes which will subsequently affect the energy distribution function.

The proposed approach, applied on a NPP reactor structure can improve the control on the overall stressed state of the structure, outline particular areas of the structure with altered stressed state and improve the understanding of the structural global and local behavior.

In case of the NPP reactor structure, the relations between energy distribution function and the stressed state due to pre-stressing are investigated by means of numerical simulations in order to look for threshold values as indicators of a warning stress state. The changes in the frequencies and amplitudes of the ambient vibrations and respectively in the energy distribution function are influenced by various other factors:

- Stressed state (global or local);
- Containment temperature;
- Equipment vibrations;
- Failed or Missing tendons;
- Environmental conditions (wind, sun radiation etc.).
The influence of most of the factors affecting the structural ambient vibrations can be studied both through numerical analyses and by monitoring data. Therefore an important step of the analysis is the comparison of the monitoring data and the results of the numerical simulations, where essential conclusions will be obtained regarding the structural mode shapes of reactor building and the expected frequency and amplitude changes due to the factors indicated above. For the purpose, the finite element model should be firstly synchronized with the experimental results by the so called Finite Element Model Updating (FEMU) [6]. The FEMU procedure is based on a mathematical optimization problem: the difference between the numerical and experimental data should be minimized through iterative modal analysis.

Currently, this approach for containment monitoring of NPP reactor structure, based on ambient vibrations and energy distribution function, is under development within the IRIS research project as a common task between Kozloduy NPP, Vienna Consulting Engineers GmbH (VCE) and Risk Engineering LTD. Due to the initial stage of the project, limited amount of results is available. However, some preliminary results are presented herein for better description of the proposed approach.

In Table 1 an exemplary comparison between the monitored and numerically investigated results are presented. The first two local mode shapes of the dome part of the reactor building were distinguished after processing the data of various monitoring sessions and consequently compared with the results of a complex harmonic analysis.

<table>
<thead>
<tr>
<th>MONITORING</th>
<th>HARMONIC ANALYSIS</th>
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<tbody>
<tr>
<td>1-st local dome frequency (Hz)</td>
<td>13.7</td>
</tr>
<tr>
<td>16.57</td>
<td>17.88</td>
</tr>
<tr>
<td>2-nd local dome frequency (Hz)</td>
<td>19.7</td>
</tr>
<tr>
<td>16.32</td>
<td>19.78</td>
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On Fig. 7, the frequency spectrum of vertical vibrations of the dome part, obtained during the experimental campaign performed by VCE, is presented. As can be seen from Fig.7, the amplitude peaks are concentrated in the range in 15 to 45 Hz, where also most of the local containment modes are expected. Such high order local mode is presented on the right side of Fig.7.

The influence of the pre-stressing force on the containment dynamic response is studied numerically. The amplitude frequency spectra for vertical vibrations at selected location at the dome, for different pre-stressing forces
are presented in Fig.8. In the same figure it is also presented the calculated energy distribution function based on the same frequency spectra. It can be seen that the level of pre-stressing affects mainly the high order modes, while the global modes remain practically unchanged. The amplitude changes increase predominantly in the high frequencies with increasing the pre-stressing force of the tendons. This amplitude changes affect the energy distribution function, shown again in Fig.8. Further step in the investigation will be to study the influence of other factors, influencing the ambient vibrations, in order to isolate the influence of the pre-stressing force itself.

![Fig.8 Frequency spectra for vertical vibrations at specific location on the dome for different pre-stressing forces. Computed Energy Distribution Function based on the frequency spectra.](image)

**DISCUSSION AND CONCLUSION**

Due to the initial phase of development of the monitoring concept, final conclusions cannot be drawn yet. However, some advantages of the proposed approach can be pointed out and discussed. One of the main advantages is that the method offers continuous real-time monitoring of the containment, which in combination with appropriate thresholds could provide continuous information about the containment condition to serve as ultimate barrier. Another advantage is that the proposed approach is totally non-destructive and delicate with respect to the containment structure, as far as the accelerometers can be installed and/or replaced at any time, without to disturb, or to be dependent on the NPP operation. Furthermore, the proposed approach is based on measurement of the total effect of the pre-stressing system on the containment, rather than pre-stressing force at the anchor head, thus avoiding misleading conclusions.

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