Motivation

Structural elements like the post-tensioning of a containment structure of a nuclear power plant are currently reviewed on 30 year old partly destructive approaches. A reliability based control approach is desired.

Main Results

The feasibility of applying the IRIS Risk Paradigm to establish a consistent approach for reliability based control of post-tensioned containment structures has been demonstrated.
28-1 Introduction

The world’s nuclear power plants are, on average, 25 years old [IAEA, 2010] (F.28-1) and most plants are believed to be able to operate for 60 years or more. The design lifetime of a nuclear power plant is typically 30 to 40 years. This may be extended by 10 to 20 years or more provided that the plant operator can demonstrate by analysis, trending, equipment and system upgrades, increased vigilance, testing, ageing management and other means that licence renewal or permission to continue operation based on the original licence poses no threat to public health, safety or the environment.

Special emphasis should be put on the assessment of the aged status and ageing management of those safety-related systems, structures and components that limit the operating lifetime of the plant, i.e. those that cannot be replaced or readily reconstructed, such as the reactor pressure vessel and containment.

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 post-tensioned concrete for NPP containment structures. The design post-tensioning 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. The containment ultimate capacity itself is a complex parameter and cannot be considered as a constant value. 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 post-tensioning 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 post-tensioning force can be considered as

![Number of reactors in operation by age (as of 31 December 2009)](F.28-1)
variable rather than constant; it can be influenced by many time-depending processes as corrosion, relaxation, ageing, etc.

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

The aim of this paper is to develop an innovative approach for containment structural health monitoring of the stress state of the reactor building structure.

28-2 Description of the Structure of WWER-1000 Reactor Building

The reactor building structure of nuclear power unit type WWER-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, at elevation +13.20 m.

The containment structure is a post-tensioned 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:
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 post-tensioning 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 post-tensioning tendon is comprised of 55 cables with cross sections of 140 mm² each. The tendons are post-tensioned on both ends by a design force of 1000 tons (9810 kN). Cross section view of the containment building is shown in F.28-2.

The post-tensioning tendons in the cylindrical part are arranged in three rows of screw line with falling and ascending branch slope to the horizon 35°15'. Both ends of each bundle are anchored in one area – in a single anchor or adjacent niches as in the area of anchoring bundles are placed in four rows. Prestressing tendons in the dome are located in two rows in two perpendicular directions. Both ends of each tendon are anchored in a single block, as the tendon is folded at the opposite end of the dome. The arrangement of the post-tensioning tendons in the cylindrical part is shown in F.28-3 and in the dome part in F.28-4. The manufacture of post-tensioning tendons with lengths from 80 to 180 m is done by the method of continuous winding on custom-built production line. To introduce post-tensioning, anchoring devices are used at both ends of each tendon consisting of ear/koush/anchor screw and nut with pads. The area of the cross section of
Motivation for the Current Approach

In case of post-tensioned containments, the control and maintenance of post-tensioning systems is necessary for the safe operation of the nuclear power plant (NPP). Development of non-destructive examination (NDE) and monitoring techniques and methodologies is essential, especially for the control of the ageing process at the non-accessible locations and hidden defects (for example liners in hidden places, reinforcement in massive structures, etc.).

Continuous monitoring is implemented at the start of the nuclear power plant’s operation and will end when final shutdown takes place. It gives an accurate picture, throughout the lifetime of the structure, firstly of the phenomena which affect the tension of pre-stressing cables, and therefore the residual compression prevailing in the structure and, secondly, of the overall and relative settlement of the reactor building.

Monitoring of the tendon force by measurement of the cable forces at selected cables
There are basically two current approaches widely used for inspection/monitoring of the tendon post-tensioning 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 post-tensioning force is derived from the 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 in F.28-5.

**Limitations of the Currently Used Methods**

The current monitoring approaches mentioned above have a number of limitations. The sensors embedded in the concrete are subjected to ageing 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 demonstrated in the practice to have negative influence on the tendon and anchor durability.

The direct measurement of the post-tensioning force at the anchor is considered the most advanced method from those mentioned above. The disadvantage is that the installation or the replacement of the sensors requires dismounting the tendon where 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. However they could be performed only in an outage.

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**Distribution of the prestressing force along the tendon length**  

F.28-6

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![Diagram of prestressing force along the tendon length](image-url)
The described methods for post-tensioning force monitoring have one common disadvantage, that is measurement of the tendon force only at the anchor and that they 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 in F.28-6.

The equivalent external pressure as produced by the post-tensioning system and the containment confinement is a function rather of the average tendon force than the tendon force at the anchor. Therefore, the monitoring of the stress state of the containment structure should be based on the global tendon state, as tendon monitoring based only on anchor force readings might produce misleading conclusions.

Currently, there are many NPPs 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 of the structure that is successfully applied to a large number of bridges [Wenzel, 2009].

28-4 Methodology of the Current Approach

The proposed approach, applied on NPP reactor building structure can improve the control on the overall stress state of the structure, outline particular areas of the structure with altered stress state and improve the understanding of the structural global and local behaviour. The main idea behind the proposed approach is instead of directly measuring the post-tensioning forces in the tendons, to monitor the effects of the post-tensioning and thus indirectly the containment capacity and the overall NPP safety. The current approach is based on a permanent vibration monitoring system on the NPP reactor building structure, registering the ambient vibrations in different locations on the structure. Eventual changes in the stress state of the containment structure or eventual damage formations will be detected and indicated through alterations in the spectral distribution function.

The method of studying the stress state of a structure, considering alterations in the vibration amplitudes and subsequently in the spectral distribution function, is proposed by VCE [Tanaka et al., 2009]. The basis of this method is that any change in the energy distribution function is related to a particular change in the stress or damaged state of a location of the studied structure. 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. When isolating only the influence of the pre-stressing force on the structural vibrations it will be possible to evaluate the general stressed state of the structure, depending on the ambient vibrations recorded.

The proposed structural health monitoring approach is based on temporary and permanent ambient vibration measurements and finite element analyses. Firstly, numerical simulations should be executed for initial assessment of the structural modal characteristics. Attention should be paid when investigating the higher local modes of the dome and the cylinder, because they are likely to be strongly affected by the stress state of the
structure. Secondly, additional numerical analyses should be performed for studying the influence of the post-tensioning level on the modal behaviour of the main structural parts – dome and cylinder. The analytically obtained modal response is compared with the response obtained experimentally through ambient vibration monitoring and if needed the numerical model will be updated through a consecutive process of finite element model updating. This procedure is based on a mathematical optimization problem: the difference between the numerical and experimental data should be minimized through iterative modal analyses. The entire process should be finalized with specific thresholds and finally implemented into an early warning system. A general methodology scheme is presented in F.28-7.

The influence of the post-tensioning force on the containment dynamic response will be studied numerically. The level of post-tensioning is expected to affect mainly the higher modes of a structure, while the global modes should remain practically unchanged [Wenzel, 2009]. The amplitude changes increase predominantly in the high frequencies with increasing the post-tensioning force of the tendons (F.28-8). These amplitude changes will affect the energy distribution function and a further step in the investigation will be to study the influence of the other factors, influencing the ambient vibrations, in order to isolate the influence of the post-tensioning force itself.

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 the reactor building and the expected frequency and amplitude changes due to the factors indicated above. It is expected that the different temperature zones on the internal and external surface of the structure will affect the structural higher modes characteristics (amplitudes and/or frequencies) and thus the spectral distribution function.
The alteration in the energy distribution function will be independently investigated for each factor affecting it, by numerical analyses. The main tool for studying the influence of the various factors on the structural dynamic response will be the complex-harmonic analyses. They will be performed for different stress states and the resulting frequency spectra in different locations of the structure will be the base for studying of the correlation between the stressed state and the structural vibration behaviour.

Another main tool used in the current study will be the spectral density function. This function reveals more clearly the fraction of energy transferred to different frequency ranges, resulting in the change of its pattern. The definition of the spectral density function is presented and explained in [Tanaka et al., 2009] and is defined as:

\[ E_i(f) = \sum_{k=0}^{i} F(k) \Delta k \text{, where} \]

Influence on the pre-stressing force (stressed state) on the modal behaviour of a structure

Zones with different temperature at the structure due to sun radiation
An Approach for Reliability Based Control of Post-Tensioned Containment Structure

\[ F_i(f) = \frac{G_i(f)}{\sigma_i^2} \] is normalized Spectral Density Function and \[ \sigma_i^2 = \sum G_i(f) \Delta f \] is Spectral Distribution Function.

\[ G_i(f) \] is the acceleration spectra, calculated by a conventional FFT routine.

The spectral density function \( E_i(f) \) varies from 0 to 1 and the observed tendencies in its pattern of the function will be used to indicate the alterations in the stress state [7]. Vibration investigations should be carried out for all disturbances from the external environment acting on the structure and affecting its stressed state.

**Expected Advantages of the Proposed Approach**

One of the main advantages is that the method offers continuous real-time monitoring of the containment, which in combination with appropriate thresholds and implemented into an intelligent warning system, could provide continuous information about the containment condition capability to serve as ultimate barrier. The estimated stress state could be used for subsequent containment damage detection potential in case of different accidents. 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 depending on, or disturbing the NPP operation. Furthermore, the proposed approach is based on measurement of the global effect of the post-tensioning system on the containment, rather than post-tensioning force at the anchor head, thus avoiding misleading conclusions.

**Summarizing the Main Goals of the Current Approach for SHM for the Containment Structure Are:**

- Control of the containment stressed state;
- Identification of relaxation in tendons;
- Location of existing damaged or relaxed tendon;
- Better understanding of the structural global and local behaviour.

**28-4-1 Change of Dynamic Behaviour because of Compression Stress**

Considering the geometric non-linearity of the structure (second order effects) could be noted basically in the following form: \([k] = [k_{ph}] + [k_{g}],\) total stiffness of a given structure is a sum of its physical and geometric stiffness. Geometric stiffness is in direct relation with internal (axial) forces of the system. In an elastic non-rigid body significant compressive forces decrease the total stiffness \((k_{geom} < 0),\) and significant tensile forces increase the total stiffness.
When loss of stability (buckling) is to occur $k_y \rightarrow -k_{ph}$ and the total stiffness is close to 0. This is shown with a simple example:

$$m = 5 \text{ t/m}$$

$$L = 6 \text{ m}$$

$$EJ = 162 000 \text{ kNm}^2$$

The equation for calculation of natural frequency of a beam subjected to axial forces (continuous model with neglected shear forces) is:

$$f_i = \frac{\lambda_i^2}{2\pi^2} \sqrt{\frac{EJ}{m}} ; \quad \lambda_i = i^2 \pi^2 \sqrt{1 + \frac{PL^2}{EJ\pi^2}}$$  

[Belvins, 1979]

In T.28-1 the first three natural frequencies are given for $P=0; P=0.1 \text{ Pcr}; P=0.25 \text{ Pcr}; P=0.50 \text{ Pcr},$ and $P=0.95 \text{ Pcr},$ where $P_{cr}=41123 \text{ kN}$ is the critical force (Euler buckling) of the beam.

The relation $f_i = \psi(P)$ is shown in F.28-10. There are analogical predictions for tendencies in eigenmodes of the containment for $f < 20 \text{ Hz}.$ Modes with $f > 20 \text{ Hz}$ for spatial vibrations of a relatively stiff structure are of greater interest, because they are difficult to predict with simple models. The concrete stresses due to post-tensioning are less than $0.1\sigma_{cr}$.

<table>
<thead>
<tr>
<th>Natural frequencies of pre-stressed simply-supported beam</th>
<th>T.28-1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>P=0</strong></td>
<td><strong>P=0.1 Pcr</strong></td>
</tr>
<tr>
<td>Mode No.</td>
<td>Frequency [Hz]</td>
</tr>
<tr>
<td>1</td>
<td>7.7543</td>
</tr>
<tr>
<td>2</td>
<td>63.221</td>
</tr>
<tr>
<td>3</td>
<td>152.07</td>
</tr>
</tbody>
</table>

Relation between compressive force and fundamental frequency  

F.28-10

\[ f_i = \psi(P) \]
28-4-2 Development of FE Model with FEMAP and SOLVIA

Cylindric Wall

The cylindrical wall is modelled with 4-node rectangular shell elements. The wall is meshed in such way that the tendon's path passes through existing nodes (F.28-11). Openings and penetrations are neglected.

Placement of elements and nodes in the cylinder [m]  

The diagram shows the placement of elements and nodes in the cylindrical wall with the tendon's path passing through existing nodes. The tendon is oriented at an angle of 37.5° with respect to the horizontal axis.

Boundary condition of the structure  

The boundary condition of the structure is shown in the diagram. The boundary area is marked and the mesh is visible, indicating the spatial distribution of the elements and nodes.
28-5 Results and Progress beyond the Current Practice

28-5-1 Dynamic Analyses of the Structure

Complex-Harmonic Analysis

Analysis of frequencies from 0 to 60 Hz, increment step 0.05 Hz. Acceleration load $a = a_0 \cdot \sin(\omega t)$, where $a_0 = 0.15 \, \text{g}$.

Various types of complex-harmonic analyses are performed, considering different levels of post-tensioning and thus different stress states of the structure:

// Analysis of the containment structure without post-tensioning;
// Analysis of the containment with design post-tensioning;
// Analysis of the containment with post-tensioning 80% from the design (long-term loss of stress during exploitation).

Frequency response spectra are created for displacement [m], velocity [m/s] and accelerations [m/s²] for some nodes of interest with respect to frequency [Hz]. The controlled nodes are shown in F.28-13.

28-5-2 Analysis of Results

As the permanent vibration monitoring system at the reactor building structure is installed only at the dome part, main attention will be given to this structural part. The significant local modes in the dome part are demonstrated by comparison of the frequency
response functions from two dome locations – top of the dome and base of the dome (ring beam). In F.28-14 the frequency response spectra are presented for displacements in vertical direction. The analysis is performed with design values of the post-tensioning force. The peaks in the frequency response spectrum appear exclusively at the top dome location, therefore all of them represent local modes of the dome structure. The range of the local mode frequencies at the dome start at approximately 14 Hz.

The local modes of the dome part of the structure are presented in F.28-15. The modes at 13.9 Hz and 20.25 Hz can be classified as first local modes of the dome. The rest of the observed local modes are of higher orders – 25.5 Hz, 29.7 Hz and 34.1 Hz.

After the series of complex-harmonic analyses with different post-tensioning force, the obtained general results could be summarized as follows:

// Change in deformed shapes of vibration of the structure due to post-tensioning
// Shift of natural frequencies of the structure for different states of post-tensioning
// Excitation of additional natural frequencies in post-tensioned state
<table>
<thead>
<tr>
<th>Local mode of dome</th>
<th>F.28-15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local mode of dome at 13.9 Hz</td>
<td>Local mode of dome at 16.6 Hz</td>
</tr>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>Local mode of dome at 20.2 Hz</td>
<td>Local mode of dome at 25.5 Hz</td>
</tr>
<tr>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>Local mode of dome at 29.7 Hz</td>
<td>Local mode of dome at 34.1 Hz</td>
</tr>
<tr>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
</tbody>
</table>

// Amplitude change of the structural response for different states of post-tensioning
// Change of normalized spectral density function \( \psi(f) \)

The complex-harmonic analyses of the containment structure are performed for design post-tensioning load, 80% of the design post-tensioning load and for a case without post-tensioning load.
Change in Deformed Shapes of Vibration of the Structure due to Post-Tensioning

Deformed shapes at design post-tensioning and close levels (80%) differ from low post-tensioning levels. In case of the cylindrical part the reason is the shape of the tensioned containment – the cylindrical wall changes shape to rotational hyperboloid. In case of the dome part – the deformed dome has less curvature. In addition there are local effects from post-tensioning, particularly in the dome. This is clearly observed at frequency 5.25 Hz – in the 0% level the deformed shape is global translational in horizontal direction. At levels close to design post-tensioning in the dome symmetrical vertical displacements appear. For the rest of the natural frequencies up to 60 Hz clear secondary effects in the dome do not appear, because vertical displacements prevail.

Shift of Natural Frequencies of the Structure for Different States of Post-Tensioning

T.28-2 shows all matching natural modes and their frequencies.

At frequencies up to 20 Hz the deviation is smaller than accuracy of analysis $\varepsilon = 0.05$ Hz (the increment step in the complex-harmonic analyses). At frequencies higher than 25 Hz, an increase of natural frequencies due to post-tensioning is observed, also mentioned in [Wenzel, 2009]. The absolute value of deviations is close to the accuracy of the analysis. The reasons for the small deviations are the significant spatial stiffness of the containment structure and the fact that it is linear elastic. The current results show that frequency shifts due to different post-tensioning forces is insignificant for the containment structure.

Excitation of Additional Natural Frequencies in Post-Tensioned State

In complex-harmonic analyses with post-tensioning additional natural frequencies are excited. They are related to local vibration modes, typical for the changed geometry of the post-tensioning containment and there is also relation to secondary effects from the post-tensioning. The additionally excited natural frequencies are higher than 30 Hz (high-frequency range) and they could be an appropriate base for studying the influence of the post-tensioning force and the overall stress state on the local mode characteristics.

Amplitude Change of the Structural Response for Different States of Post-Tensioning

The increase of post-tensioning force in the tendons changes the shape of the cylindrical and dome part of the structure and as a consequence its geometrical stiffness is increased. This leads to changes in the amplitudes of the natural vibrations at lower and higher frequencies. The following effects are observed:

For frequencies up to 20 Hz in horizontal direction (vibrations in the cylindrical part) the amplitude values are lower for the post-tensioning structure. The reason is the increased geometrical stiffness of the structure mentioned above. The affected vibration modes are global – with significant mass excitations.

For frequencies over 20 Hz in horizontal direction (vibrations in the cylindrical part) and over 10 Hz in vertical direction (vibrations in the dome part) the amplitude values are higher for the post-tensioned structure. The affected vibration modes are mainly local high-frequency modes. The comparison between the amplitude values for 80% and
100% post-tensioning shows that an increase of 20% in the post-tensioning force results in an amplitude increase of 10 to 20% in the higher order modes. In some cases the amplitude increase is higher for the higher frequency modes than it is for the dome part of the structure.

**Change of Normalized Spectral Density Function $E(f)$**

The increase of post-tensioning alters the shape of the normalized distribution function $E(f)$. The relative participation of frequencies less than 20 Hz, in the formation of the spectral density function, decreases. For structures without post-tensioning, these frequencies (less than 20 Hz) have the main influence (80%) of the integral value for $E(f)$. As a conclusion the spectral density function is negligibly affected by the post-tensioning force for frequencies up to 20 Hz, for both structural parts – cylinder and dome.

With increase of post-tensioning forces the participation of the lower modes in $E(f)$ decreases and the main weight comes from frequencies in the range of 20 to 45 Hz, where post-tensioning effects on the higher frequency modes are stronger. The alterations in the spectral density function vary from 2% to 10% depending on the location of the observed location. Locations in the cylindrical part of the structure demonstrate higher increase of $E(f)$ than locations in the dome part of the structure. The values of $E(f)$ for full post-tensioning are higher than values of $E(f)$ for 80% post-tensioning.

For frequencies over 50 Hz, particularly in acceleration spectra, there is a reverse effect – higher amplitudes for the post-tensioning structure at lower frequencies.

**28-5-3 Comparison of the Results Obtained by Ambient Vibration Monitoring with the Results from the Finite Element Model**

The basic measurements with BRIMOS® on the dome were taken in May 2010 by a team of [VCE, 2010]. For the dynamic assessment of the structure itself five sensors have been placed. The main idea of BRIMOS® is rather simple. The dynamic characteristic of a structure is recorded by acceleration sensors and the signal in time range is changed into a frequency response by use of an FFT (Fast Fourier Transformation). In doing so the
results of this calculation are the natural frequencies of the structure represented in the ANPSD and the raw-spectrum.

Since the methodology of the current approach uses the results from the complex-harmonic analyses in this comparison the obtained eigenmodes and eigenvalues are used. The following conclusions could be done:

// There is general compatibility between the deformed shapes obtained by the ambient vibration monitoring and the finite element analyses.
// The frequencies obtained through the finite element model are generally higher. This could be due to overestimation of the stiffness in the computational model or due to other effects that have not been considered in the numerical simulation.

28-5-4 Conclusions and Possibilities for Future Development of the Investigation

The current study puts the basic steps and reveals tendencies in the structural vibration behaviour of the post-tensioned containment of a WWER-1000 type nuclear reactor that should be more deeply investigated. The tendencies of the spectral density function should be further studied and special emphasis should be given to specific structural lo-
<table>
<thead>
<tr>
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<table>
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<table>
<thead>
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<th>Eigenmode at 16.32 Hz</th>
<th>Eigenmode at 16.60 Hz</th>
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<tr>
<td><img src="image5.png" alt="Eigenmode at 16.32 Hz" /></td>
<td><img src="image6.png" alt="Eigenmode at 16.60 Hz" /></td>
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<tr>
<th>Eigenmode at 16.57 Hz</th>
<th>Eigenmode at 17.00 Hz</th>
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<tr>
<td><img src="image7.png" alt="Eigenmode at 16.57 Hz" /></td>
<td><img src="image8.png" alt="Eigenmode at 17.00 Hz" /></td>
</tr>
</tbody>
</table>
An Approach for Reliability Based Control of Post-Tensioned Containment Structure

Cations, higher variety of post-tensioning force and assumption of specific limited with decreased post-tensioning force.

The comparison of the numerical results and the monitored data showed very close proximity of the results. Outlining the essential structural local modes of both parts of the structure – dome and cylinder, allows the further development of the study by focusing on these particular structural modes of interest. Their behaviour and their influence on the spectral density function should be studied again by both manners – numerically and experimentally.

To obtain statistically stable numerical results further analyses are required – a wider set of output data to summarize, reduce simplifications, include openings and penetrations, where local effects are expected. In a further study these should be included because of the non-regularity of the tendon trajectories and the concrete wall around them.

Another further step should be assessment of the effects of other factors influencing the vibration behaviour: equipment forced vibration, containment temperature and environmental conditions. An FE model with solid elements could be used for analyzing the influence of non-uniform solar heating on the dynamic behaviour.

The limited amount of the study allows rough numerical evaluation of the changes, and focuses on the directions of the spectral density curve shifts. The obtained results are very close to the theoretical, which is an indication for the correct assumptions in the model and the analyses. Improvement of NPPs safety is a main issue for the nuclear in-
dustry. With twenty WWER-1000 type reactors across the world and a number of reactors to be designed and built (of modern technological generation but with similar building structures) spending time and resources for a better understanding of their behaviour is justified.

With rapid improvements of monitoring instrumentation it is possible to apply systems, monitoring permanently the condition of the building structure and based on specific thresholds to evaluate the current state of the structure. In areas with limited access (for example the tendons of the containment) these systems could be used for warnings about internal malfunctions (relaxation or tendons, deterioration of material properties due to ageing etc.) These systems will effectively serve as permanent monitoring tool, presenting the current stress state of the structure and as a warning system, alerting when the structural safety is at risk.

References
