ULTIMATE CAPACITY ASSESSMENT OF VVER 1000 CONTAINMENT STRUCTURE

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ABSTRACT

In the paper a direct approach is proposed for evaluation of an existing containment for internal accident loads, based on the comparison of capacity and demand curves. For that purpose, both parameters are plotted graphically in the coordinate system of pressure and temperature. In case the capacity curve is enveloping the demand then the capacity is considered sufficient. Since the procedure is based on series of non-linear analyses, essential parts are the detailed numerical modeling as well as the comprehensive model verification. The complete procedure is applied for capacity assessment of a typical VVER 1000 containment.

INTRODUCTION

An essential component of the nuclear power plant safety is the 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 during and after severe internal accidents.

The containment ultimate capacity is a complex parameter and cannot be considered as a constant number. Generally, it depends from 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 by them, the arrangement of the liner welding and anchors, etc. In addition, the actual pre-stressing force can be considered rather variable than constant; it can be influenced by many time depending processes as corrosion, relaxation, aging, etc. The loading conditions also vary and cannot be defined by a single set of loads; however, the most severe load conditions, relevant to the containment capacity, are the internal over pressure and the temperature loads. These two loads are acting simultaneously on the containment and in a very complex interaction. Therefore, we assume that the ultimate containment capacity is a rather complex function of the pressure-temperature interaction.

Many Nuclear Power Plants with VVER 1000 reactors were built during the 1980’s, mostly in Eastern Europe. During our experience on the assessment of the integrity of pre-stressed concrete vessels, mostly in the framework of the Probabilistic Safety Analysis of level 2 (PSA 2), we have found that the containment “capacity” can vary seriously depending on the temperature-pressure loading. There is a large number of accident scenarios, every of them described with different temperature-pressure time functions. Usually each capacity assessment finishes with a different value of the ultimate capacity as well as with a different failure mode. That means that a large number of analyses are needed in order to assess the ultimate capacity of the containment under all applicable load cases. The aforementioned problems, forced us to search a straightforward solution for containment evaluation against specified pressure-temperature levels and acceptance criteria, accounting both temperature and pressure, independently from the loading history. Further on this solution should provide clear classification of the possible failure modes, the level of damages and the possibilities of radioactive release for different accident scenarios.

Many investigators have been working on the subject of containment ultimate capacity assessment and serious progress has been achieved [1, 2, 3, 4]. One significant step forward has been the Cooperative Containment Research Program (CCRP) performed at Sandia National Laboratories (SNL) in New Mexico [2]. One of the main conclusions from the CCRP and ISP 48 projects is that the numerical methods and finite elements codes are capable to describe the post elastic behavior of containment structure subjected to severe loads. This conclusion can be considered adequate for other containment types, as well as the containment of the VVER-1000 reactors. It gives us the ground to concentrate our efforts on the numerical techniques as a major tool for ultimate capacity analyses.

DESCRIPTION OF VVER-1000 STRUCTURE

The VVER 1000 reactor building is a spatial structure composed by four main parts – foundation block, containment structure, inner RC structure and auxiliary surrounding structure. The four sub-structures are integrated by a thick reinforced concrete with thickness of 2.4 meters on level +13.20.

The foundation block is a rigid structure on three levels, from -4.20 to +13.20, closely spaced by lateral walls. Internally of the containment there is a heavy reinforced concrete structure starting from +13.20 aimed to support and protect the primary mechanical components and equipment. Externally, the containment is surrounded by reinforced auxiliary structure with plan dimensions 66.0 x 66.0.

An essential part of the reactor building is the containment. The containment structure of VVER-1000 reactor is composed by a pre-stressed reinforced concrete cylinder and a spherical dome, both connected by a massive ring. The containment is mounted on the thick plate on elevation +13.20. The main geometrical dimensions of the containment are:
height of the cylinder – 44m; diameter – 45m; relative elevation at the top of the dome - +66.45m; thickness of the cylinder wall – 1.2m (at the boundary rings and around the penetrations the thickness is bigger); thickness of the dome wall – 1.1m (at the boundary rings the thickness is bigger).

The internal surface of the containment and the integration plate on elevation +13.20 is covered by a steel liner, 8mm thick, to form a hermetic volume. The containment is pre-stressed by 132 tendons, arranged helicoidally in the cylinder and orthogonally in the dome. The design pre-stressed force is 9810 kN for each tendon. There are great number of penetrations and openings that are disturbing the continuity of the structure.

NUMERICAL MODEL

A detailed three dimensional numerical model is developed, Fig.1, fully representing the geometry of the prototype structure. The FEMAP software is used for building the geometry and the SOLVIA finite element code [6] for performing the analyses. The model takes into account the complexity of the structure by precise modeling of the foundation part and the soil bedding, the internal structures, the pre-stressed containment and surrounding auxiliary structures including local changes in the integrity and stiffness due to different penetrations and openings.

The fundament block, the internal RC structure and the auxiliary surrounding building are modeled with conventional shell elements with one integration point in thickness direction as those structure parts are not the main goal of the analyses.

On the contrary, the containment, the cylinder and the dome are modeled with shell elements with six integration points in thickness direction. For modeling the post-elastic material behavior, the CONCRETE material model of SOLVIA FE code is employed that corresponds basically to the Ottosen model. The material model is based on a non-linear uniaxial stress-strain relation, generalized to take into account the biaxial and triaxial stress conditions. The tensile failure (cracking) and compression failure (crushing) are modeled by failure envelopes. The smeared crack approach is adopted i.e., the cracked concrete is treated as a continuum. The steel liner and the reinforcement are modeled using the REBAR option, as continuum planar diaphragms, modeled as layers within the shell thickness and with equivalent thickness and location. Therefore, strain compatibility is required between the concrete and rebar “layers”. However, the rebar stress-strain law is independent. The PLASTIC material model in SOLVIA, based on elastic – perfectly plastic formulation, was used for modeling the rebar.

Conventional solid elements with elastic material were used for modeling the connecting ring.

Serious attention is paid to the proper and detailed modeling of the tendons, following the exact trajectory, including the irregularity around the openings and penetration as well as the variation of the tension forces. The tendons are modeled on the member by member basis, following their exact trajectory, including the irregularities around the openings. The tension force in each tendon is introduced individually. The relaxation and the friction are accounted in detail, the change of the tension force along the tendon is considered. Additionally the change of the tension force in each tendon due to change of geometry is considered as well.

The material properties are derived after a comprehensive investigation process including in situ and laboratory tests.

Fig.1. General view of the numerical model.
VERIFICATION OF THE MODEL

The numerical model is verified comprehensively by comparing the stressed conditions derived by the model analyses and the observed strains (stresses) in the prototype structure. The stressed conditions of the real structure and the actual pre-stressing tendon force are obtained directly from the permanent monitoring systems installed in the containment. Test data is kindly made available by Kozloduy NPP.

The containment structures of Kozloduy NPP are equipped with two permanent monitoring systems – System for Automatic Control of the Stressed Condition (SACSC) and System for Automatic Tendon Control (SATC). The SACSC system is built together with the containment construction and consists of three types of sensors – stress-gauges measuring the stresses in the inside and outside reinforcement, strain-gauges, measuring the strains in the inside and outside edges of the concrete and –temperature-gauges measuring the concrete temperature. Using this monitoring system, the stressed condition of the containment during the whole time span of operation has been recorded and has been used for model verification. The monitoring system, SATC, is used to monitor the level of the pre-stressing force in the tendons. The SATS data is analyzed to derive the actual (real) pre-stressing force in the tendons that is applied in the analyses. Additionally, in situ measurement campaign is performed to derive realistic mechanical properties of the structural elements. That includes aging and corrosion consideration, carbonization and erosion of outer surfaces, crack measurements, etc.

The verification process is performed on three levels with increasing detailing. The first level includes comparison of the dynamic properties of the real structure and the numerical model in order to verify the global mass and stiffness distribution. The natural frequencies of the real structure are obtained by full scale dynamic tests performed in 1995. The results from this verification process are not closely relevant for the analyses results discussed hereafter and therefore they are not be presented here. The second level of verification involves a comparison of the global stressed conditions. By series of analyses the values of the pre-stressing force and the friction coefficient are adjusted. For this purpose the “mean integral stress” is used as a parameter of comparison. This parameter is equal to the sum of the stresses, measured in all gauges, divided to the number of the gauges. In Figure 3 is shown the graphical comparison between the measured values of the mean integral stress (the broken line), and the ones computed (straight lines) with the numerical model including different input parameters – pre-stressing force and friction coefficient.

The results of the second level verification show that the percentage difference between measured and analytical values varies between 0 and 25 percents, depending on the chosen tendon system parameters. The results also show that the numerical model with pre-stressing force of 8600 kN in the cylinder, and 8850 kN in the dome as well as a friction coefficient of 0.05 have to be used as the closest analog of the prototype structure.

The third and last step in the verification process is the verification of the local stressed conditions. For that purpose the stress history measured from the internal and external gauges in 32 cross sections are compared with the stresses at the same locations in the numerical model. In Fig. 4 an example of the results is shown comparing hoop stresses in the central part of the cylinder.
Fig. 3. Comparison between measured and analytical values of the “mean integral stress”.

It can be seen that the measured results vary significantly, depending mostly on the actual gauge technical condition. In the general case, the analytical stresses are always inside the envelope of the measured results that can be considered as an evidence for realistic numerical assessment.

CAPACITY ASSESSMENT

A typical time function for pressure and temperature build-up due to design base accident used for evaluation of a VVER-1000 containment are shown in Fig. 5 [5]. These functions are also used for the presented capacity analyses.

Based on the time functions a joint load curve for pressure and temperature build-up due to a specific accident scenario can be developed.

The temperature time history is used for a transient temperature analysis of the containment wall. Special attention is paid on the proper interpretation of the obtained temperature gradients. The temperature profiles in Fig. 6 show rapid decrease of the temperatures within the wall thickness in the first hours of the accident (the thermal inertia of material). As in the further analyses a static temperature interpretation is used, the temperature gradients of the transient analyses are converted into a linear static gradients. The static gradient is the difference between the inner wall surface temperature and the outer wall surface temperature considering the irregular temperature penetration. The static temperature gradient is obtained after scaling the absolute gradient (due to transient temperature analyses) with the ratio...
of the area under the temperature profile into consideration (non-uniform) and the steady state temperature profile (nearly linear). So the entire effect of the temperature loading on the section forces and moments will be proportional only on the temperature acting on the internal wall surface and the wall thickness, which means to scale the temperature loading curve and convert it into an effective linear static gradient.

The containment ultimate capacity is evaluated by series of non-linear analyses. On every step of analysis the structure is subjected to constant internal pressure and monotonically increasing static temperature gradient. The computed capacity curve in the coordinate system of temperature gradient and pressure is shown in Figure 7.

Fig.6. Effective temperature profiles - absolute temperature profile minus the steady state temperature profile caused by a design base accident

It is important to note that a specific representation of a real crack trough the containment wall and a consequent leak/break can not be simulated analytically, since a smeared crack approach is employed and the structure is treated as continuum even after complete cracking/crushing of the cross-section appears. Therefore for the aim of the analyses presented here the criterion for failure is the appearance of extremely large strains at any location of the structure, i.e. the failure criterion is analytically based insofar the computed strains are compared to appropriate “realistic” limits. In many cases the physical criterion can not be fully reached as the numerical instability of the solution appears first. In such cases the numerical instability or the computation failure is considered as a structure failure.

There are three distinct zones in the capacity envelope curve that can be outlined as far as there are different failure modes observed:

Low pressure zone – this is the zone with pressure up to 200 kPa. The thermal gradient varies between 50 and 66 °C. The failure mode is characterized with high compression stresses and crushing in the internal layers of the cross-section and cracking of the external layers. Since there is a sufficient zone with medium compression, the tension cracks are restricted on the external layers and they are not crossing the whole cross section, i.e. there are no penetrating cracks and a leak to the atmosphere. Despite that, due to the high compression on the internal layers, plastic strains occur at some zones of the steel liner. In the real structure, the steel liner is connected discretely to the reinforced concrete wall of the containment and it is not restrained out-of-plane. Therefore, local buckling and/or welds failures may occur but an eventual leak is not highly credible.

Medium pressure zone – this is the zone with pressure between 200 and 800 kPa. At ultimate condition, the cross section stress distribution is governed by compression in the internal layers and tension on the external ones (Fig.8, Fig.9, Fig.10). With increasing of the pressure level, the crushing of the internal concrete is delayed or avoided. The presence of compression zone prevents the crack penetration through the whole section. The tension stress component from the pressure loading prevents the internal liner from failure and subsequent bypass of the hermetic shell. This zone of the curve corresponds to a relatively favorable loading that allows maximum use of the available structure capacity.

High pressure zone – this is the zone between 800 and 1030 kPa. At ultimate condition the whole cross section is subjected to tension stresses. The failure mode is governed by penetrating cracks through the whole section. There are possible failures on the liner around the welds, because of lack of sufficient ductility, and thus bypass of the hermetic containment appears.
Fig. 7. Capacity envelope curve of a VVER-1000 containment

a) Pressure 200 kPa, temperature gradient 66 °C  
b) Pressure 300 kPa, temperature gradient 66 °C

Fig. 8. Crushing (in red) in the internal layers of the cylinder.

a) Pressure 200 kPa, temperature gradient 66 °C  
b) Pressure 300 kPa, temperature gradient 66 °C

Fig. 9. Cracking (in green) in the external layers of the cylinder.
As it is shown in Fig.7 the loading curve of a typical design basis accident in a VVER-1000 (temperature-pressure curve) is completely enveloped by the capacity curve of the containment structure. Any other accident that could be presented by a similar loading curve should easily be evaluated by putting the loading curve in the same graph. Although the capacity curve is developed under a number of simplification assumptions, it remains representative for a significant number of scenarios that usually are evaluated within accident analyses or probabilistic safety analyses.

![Stress distribution through a cross section (central part of the cylinder)](image)

**CONCLUSIONS**

A straightforward solution for containment capacity evaluation for internal accident conditions is proposed in the presented paper. It is suitable for structural evaluation of existing containments in a probability safety assessment of a nuclear power plant; it can be used for design of new ones as well. The main advantage of the presented techniques is that once the capacity envelope is estimated, as many as necessary accident scenarios that are described by a temperature-pressure curve can be assessed without performing additional structural analyses. Further, the method offers clear, graphical comparison between the capacity and the demand and gives opportunity to develop recommendations for managing an accident condition in a way to avoid crossing of the curves or to “guide” the load curve to cross the capacity envelope in a desired location (the medium pressure range).

The calculation procedure comprises the following major steps:

- Estimate “pressure versus time” and “temperature versus time” curves from an internal accident analyses (thermo-hydraulic analyses);
- Using an appropriate and verified model of the containment wall, perform series of transient analyses to convert the “temperature versus time” curve into “temperature gradient versus time” curves;
- Using the common “time” axis, convert the pressure and temperature gradient curves into a temperature gradient versus pressure curve;
- Perform a non-linear static analysis with monotonically increasing pressure to derive the maximum pressure capacity of the containment;
- Perform series of non-linear analyses with constant pressure (equidistant steps from 0 to the maximum pressure capacity) and monotonically increasing temperature gradient, to obtain the temperature gradient capacity for different levels of overpressure;
- Plot the capacity envelope of the containment in temperature gradient versus pressure coordinate system;
- Plot the capacity and the load diagrams on the same graph and check if there are any crossings.

The proposed method has a few critical issues. It is of great importance to use a detailed enough and comprehensively verified numerical model in order to obtain realistic and reliable capacity envelope. However, sensitive analyses have to be performed, varying the input parameters to obtain a family of capacity diagrams. Moreover capacity envelopes with a different shape can be developed for different limit states (acceptance criteria). Regarding, the load curve calculations, the most critical element is the estimation of the effective temperature gradient, for that purpose additional verification efforts may be required.

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