Reconstruction of Accident Localization System of Units 3 and 4, NPP "Kozloduy"

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ABSTRACT

The presented structure analysis is performed within the accident localization system modernization program of Units 3 and 4, Kozloduy Nuclear Power Plant. The purpose is to involve a pressure-suppression system, so-called "Vortex (Jet) Condenser" and to improve the reactor compartment abilities to sustain large LOCA. The Vortex Condenser function is to restrict pressure in steam generator box below the limits for accident condition.

Detailed structural analysis of main building is performed for all loading conditions. Structure behaviour under following load cases is examined:

- Normal operation loads;
- Design base accident loads;
- Beyond design base accident loads;
- Seismic loads.

Structural capacity is evaluated; reconstruction in the reactor building is performed in order to mount new equipment. Conclusions for the safety of reactor building structure are presented.

The presented project has been successfully implemented for both units in 2001–2002.

KEY WORDS: accident localization system, vortex condenser, static and dynamic analyses, nuclear power plant, probabilistic safety assessment.

INTRODUCTION

The units 3 and 4 of Kozloduy Nuclear Power Plant (KNPP) are of type VVER 440/V230. As known that type of reactor unit does not poses containment. There is a reinforced concrete compartment originally designed for relatively small loss of coolant accident. The recent safety requirements raised the problem for a complete requalification of the reactor compartment. The goals are to prove integrity and seal function of the reinforced concrete compartment in case of primary circuit pipe break (pipes DN200 and DN500). In order to realize that task the Accident Localization Systems was modernized by introduction of new equipment, i.e. the so-called vortex (jet) condenser. The vortex condenser is a passive safety system aimed to avoid overpressure or vacuum in containment.

The Accident Localization System is intended to avoid or to restrict the radioactive waste release beyond the established limits. Its modernization has been performed in compliance with the requirements of new Bulgarian, Russsian and IAEA regulations [1-3]. The containment structure was upgraded in order to mount the vortex condenser.

The reconstruction of the Accident Localization Systems consists of following activities: accident analyses and definition of accident loads (definition of new design base accident); analytical qualification of the reactor compartment for the new loads and load combinations; detailed design for installation of vortex condenser. The aim of the report is to present the main steps and assumptions of the structural analysis.

LOADS AND LOAD COMBINATIONS

One of the shortcomings of the original design concept of these units is the relatively low level of the anticipated design base accident: pipe break with DN32 (insertion). A new design base accident is defined by the modernization of the accident localization system:

- Design base accident is break of the primary circuit pipe DN100 wit insertion DN32 or guillotine break of stem line;
- Beyond design base accident is break of the primary circuit pipes DN200 or DN500.

Both design and beyond design accidents cause additional loads [4,5] to the normal operation loads and civil structure (reactor compartment) is checked for capacity to sustain them. Based on performed accident evaluations the following additional loads are applied to the reactor compartment in case of design base accident:

- Air temperature in steam generator box is changed from 60 °C to 144 °C
- Overpressure in steam generator box is 0,0035 MPa or vacuum load is 0,026 MPa
- Air temperature at the outlet is 90 °C
- Water temperature in vortex condenser is 80 °C
- Water shock to cover plate over the vortex condenser due to the moment of vortex condenser start-up is 250 kN at 25 m^2 area;

- Torsion moment acting on the vortex condenser support structure due to fluid rotation is 2500 kNm.

The following additional loads are considered in case of beyond design base accident:

- Air temperature in steam generator box is changed from 60 °C to 120 °C
- Overpressure in steam generator box is 0,10 MPa or vacuum load is 0,0305 MPa
- Overpressure in recycled chamber, situated over the vortex condenser is 0,05 MPa;
- Air temperature at the outlet is 90 °C
- Overpressure in the room over the ejecting valves is 0,01 MPa
- Water temperature in vortex condenser is 80 °C
- Water shock to cover plate over the vortex condenser due to the moment of vortex condenser start-up is 250 kN at 25 m^2 area;
- Torsion moment acting on vortex condenser support structure due to the fluid rotation is 2500 kNm.

Seismic analysis is performed for both seismic levels SL1 (Operational Basis Earthquake) and SL2 (Safe Shutdown Earthquake) [3]. The SL2 free field response spectra for 5% damping are shown on the Fig.1

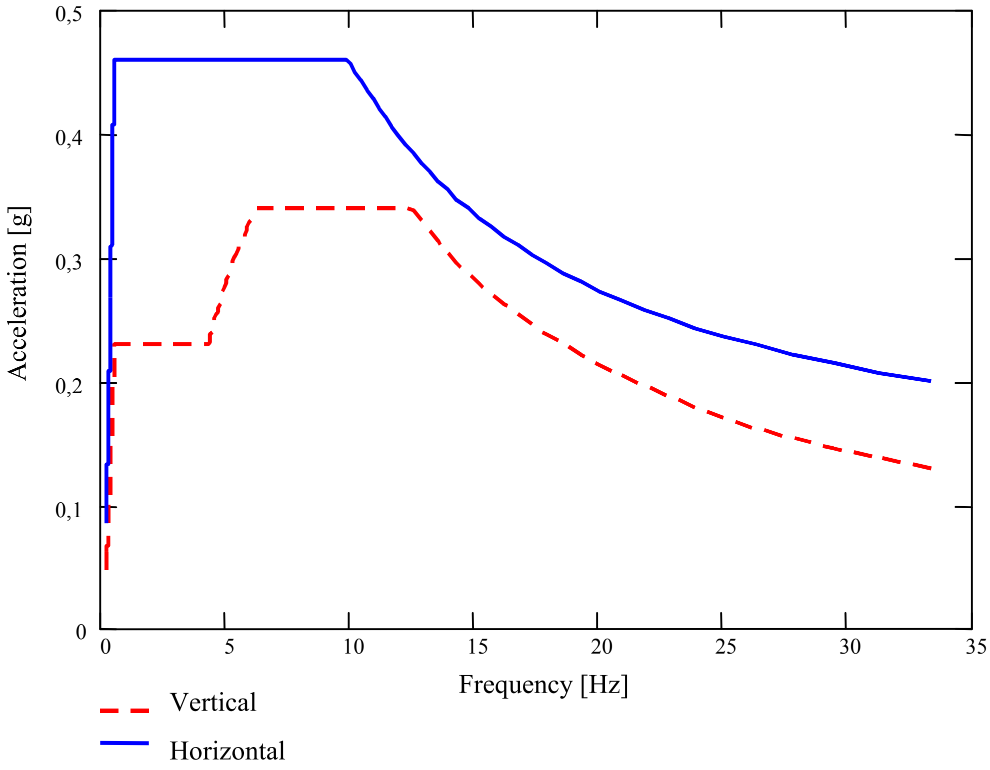

Fig.1 SL2 Free-Field Response Spectra

According to Russian code [1] the loads are divided into permanent loads, live loads with long duration, live loads with short duration and special loads. Permanents loads include the dead weight of the structure, plaster, steel liner, and slabs' and roof insulations. Live loads with long duration consist of hydrostatic pressure in vortex condenser, dead loads of permanent equipment and pipelines. Live loads with short duration include snow load on the civil structure. The special loads are seismic loads, pressure in case of design base accident, pressure in case of beyond design accident, water shock to cover plate over the vortex condenser due to vortex condenser start-up, torsion moment in the vortex condenser support structure due to fluid rotation and temperature change during an accident.

Since the project was executed in 2001 load combinations were originally performed according the valid at that time Russian code from 1987 [6]. After replacement of this code by a new one in 2002 [2], additional load combinations have been considered and sufficient structural capacity has been demonstrated. In this report are shown results from the 2001 analyses. Load combinations used in the analyses, including design accident and beyond design accident conditions are:

- Normal operation + seismic level SL2
- Normal operation disturbance + seismic level SL2
- Normal operation + Design base accident + seismic level SL1
- Normal operation + design base accident
- Normal operation + beyond design base accident.

The combination coefficients for each load type and load combination are assumed in accordance with [1]. Seventeen load types and eleven loads combinations are analysed.

STRUCTURE MODEL

The main building of the Kozloduy NPP Unit 3 and 4 is a complex spatial structure, which consists of two main parts – Turbine Hall and Reactor Building. These two parts are connected with Longitudinal Electrical Building (cable spreading rooms), situated between them. There are also two additional substructures of Ventilation Centre and Transverse Electrical Building.

A detailed finite element model of modified structure is developed in order to perform static and dynamic analysis (Fig.2). It consists of 4549 shell elements and 1380 beam elements. The vortex condenser has to be installed in a triangle box at the right reactor side (see Fig. 2). A sub-model of vortex condenser structure, supported at the mounting elevation (+2.70) is added to the general model [7,8]. The FE mesh size in the reconstruction area is made finer in order to account better the change in the stress-strain state of the modernized structure.

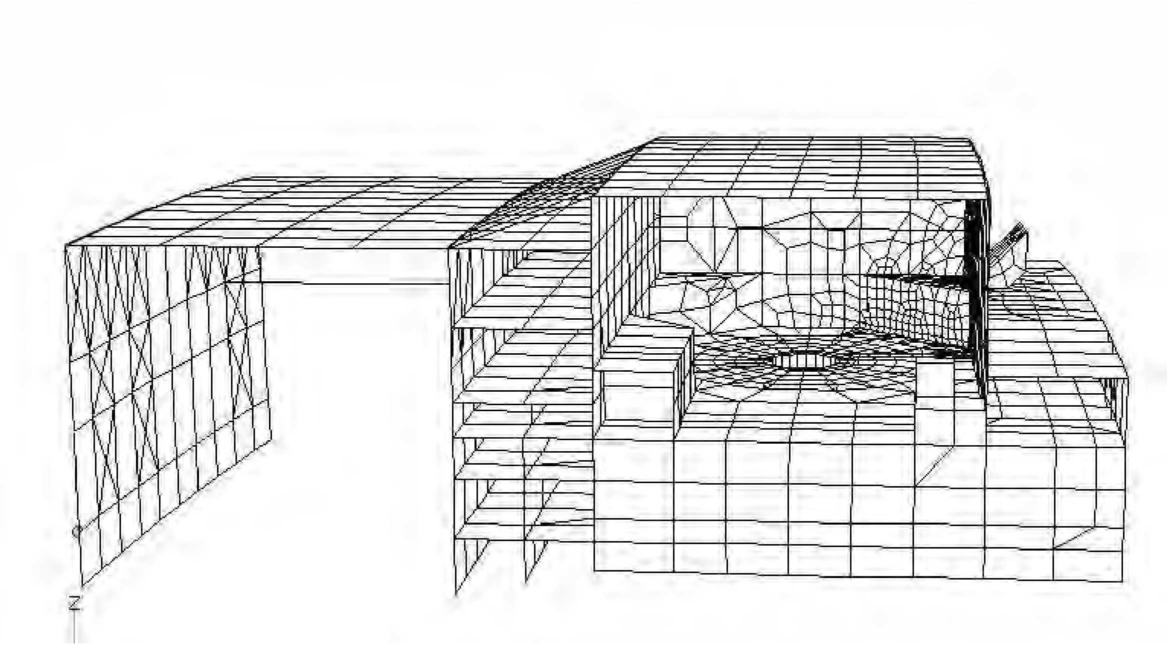

Fig.2 General view of the calculation model

Soil-structure interaction is taken into account by spring-dashpot supports attached to the corresponding model joints, restricted displacements and rotations respectively. Spring-dashpot assessment is performed for the real geological profile of the site and strain compatible soil properties. The general model analysis is performed by the FE computer program STAAD III – Release 23W.

As known the temperature loads are very important for a realistic capacity analyses of a massive concrete structure. In order to refine the temperature effect assessment an additional 2D model for temperature transient analysis of steam generator box contour walls (see Fig. 3) is developed. Both reinforced concrete wall and steel liner are considered. Temperature transient analysis is performed with computer program NISA-Heat.

ANALYSIS RESULTS

All load combinations are analysed and the governing forces and moments for each structural element (i.e. the worst load combination) are determined. Capacity check is performed and it is demonstrated, that the considered modification has only local effect on the structural stress states. The temperature transient analysis shows that temperature effects only skin-deep layer (2-3 cm) of the walls (see Fig. 3).

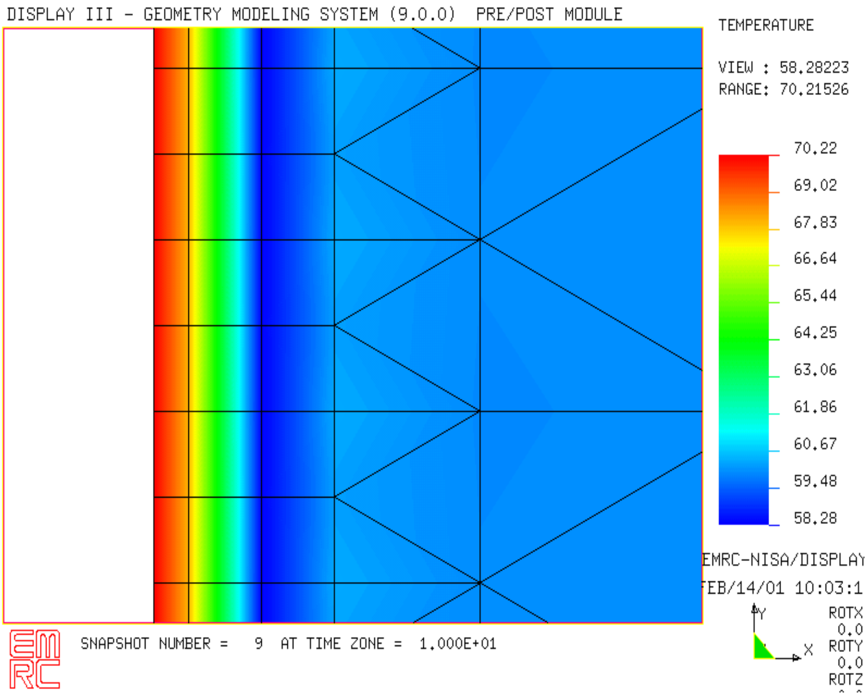

Fig. 3 Temperature distribution in the wall at 10 sec after accident

Two types of checks are performed for reinforced concrete elements according the Russian code [9]: capacity checks and crack check. Steel liner is checked according USA code [10].

A summary of capacity check results are shown in Table 1.

Table 1 Capacity check results

Structural element	Type of check (load)	Unit	Capacity	Maximum internal force (moment)	Safety coefficient
Plate at elev. +2.70	Flexural load	kNm	375,0	267,7	1,40
	Shear Force	kN	737,7	408,9	1,80
Plate at elev. +11.35	Flexural load	kNm	688,6	477,3	1,44
	Shear Force	kN	661,5	267,0	2,48
Plate at elev. +16.80	Flexural load	kNm	375,0	73,3	5,12
	Shear Force	kN	303,7	220,0	1,38
Wall in axis “G”	Flexural and axial compressive load	kNm	1172,8	281,9	4,16
	Flexural load	kNm	1520,0	267,7	5,68
	Shear Force	kN	945,0	665,7	1,42
Wall in axis “12”	Flexural and axial compressive load	kNm	1917,0	650,0	2,94
	Flexural load	kNm	1520,0	460,3	3,30
	Shear Force	kN	945,0	729,6	1,30
Steel liner	ASME	MPa	1890,0	1055,0	1,79

The calculated minimum safety coefficient for walls is 1,30 and for plates 1,40 respectively.

Crack appearance checks are performed for the critical elements using load combination excluding temperature loads. The results of crack appearance checks show a minimum safety coefficient equal to 2,17 (Table 2).

Table 2 Cracks appearance checks

Structural element	Capacity M_{crc} , kNm	Maximum section moment, kNm	Safety coefficient
Wall in axis “G”	99,98	26,77	3,73
Wall in axis “12”	99,98	46,03	2,17

Liner checks demonstrate sufficient capacity and leak tightness in all load cases, including combinations with abnormal temperature loads (see Table 1).

SAFETY ANALYSIS

A probabilistic safety assessment of the civil structure elements is performed for evaluation of the conditional probability of failure. The central assessment of the conditional failure probability is evaluated according eq.:

$$P_r = \int F_R(x) f_S(x) dx ,$$

where $F_R(x)$ is a distribution function of resistance (capacity) and f_S is a probability density function of loads. Probability is evaluated under the assumption for lognormal distribution of loads and capacities. 20% uncertainty is used for sensitivity assessment of results. Safety analysis results for conditional probability of element failure u_s are summarized in Table 3.

Table 3. Conditional probability of element failure

Scenarios	u_s	$0.8u_s$	$1.2u_s$
1. Plate at elev. +2.70 – flexural load	4,2E-5	4,9E-7	8,1E-4
2. Plate at elev. +2.70 – shear force	5,0E-6	1,6E-8	1,0E-4
3. Wall in axis 12 – shear force	1,7E-5	1,9E-7	3,2E-4
4. Wall in axis 12 – flexural and axial (compressive) load	3,9E-6	2,2E-8	1,5E-4
3. Wall in axis “G” – shear force	2,6E-6	1,2E-8	8,8E-5
4. Wall in axis “G”– flexural and axial (compressive) load	3,4E-7	8,3E-10	2,2E-5

SPECIAL IMPLEMENTATION FEATURES

The present analyses are implemented in the time period 2001 -2002 for both units. More than 60 m^3 concrete is cut and removed for preparation of vortex condenser mounting. Technological transportation openings are designed for moving of vortex condenser parts to the mounting place. After these parts are assembled the mounting openings are closed monolithically again.

CONCLUSIONS

The analyses and the reconstruction of reactor building structure are made in order to prove adequacy of the accident localization system and to ensure suitable conditions for vortex condenser implementation. Static and dynamic analyses of modified structure are performed for the newly defined design base and beyond design base accident loads. All existing structural elements are checked. New structural elements are designed for vortex condenser installation.

The main results of performed analysis and design are:

- Design base of KNPP Unit 3 and 4 is changed and the reactor compartment capacity is demonstrated for the new conservative formulation of design base accident and beyond design base accident conditions;
- Reconstruction has only local effects on the structure behaviour;
- Reactor compartment structure has sufficient capacity to sustained all load combination;
- Safety analysis shows that structure modification imposed by the vortex condenser installation demonstrate sufficient safety.

The reconstruction provides solution of one important safety problem of the original VVER 440/V230 design and leads to substantial increase of plant safety.

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