SAFETY ASSESSMENT OF A92 REACTOR BUILDING FOR LARGE COMMERCIAL AIRCRAFT CRASH

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ABSTRACT

The current paper presents key elements of the comprehensive analyses of the effects due to a large aircraft collision with the reactor building of Belene NPP in Bulgaria. The reactor building is a VVER A92; it belongs to the third+ generation and includes structural measures for protection against an aircraft impact as standard design. The A92 reactor building implements a double shell concept and is composed of thick RC external walls and an external shell which surrounds an internal pre-stressed containment and the internal walls of the auxiliary building. The malevolent large aircraft impact is considered as a beyond design base accident (Design Extended Conditions, DEC). The main issues under consideration are the structural integrity, the equipment safety due to the induced vibrations, and the fire safety of the entire installation.

Many impact scenarios are analyzed varying both impact locations and loading intensity. A large number of non-linear dynamic analyses are used for assessment of the structural response and capacity, including different type of structural models, different finite element codes, and different material laws. The corresponding impact loadings are represented by load time functions calculated according to three different approaches, i.e. loading determined by Riera’s method [1], load time function calculated by finite element analysis [11], and coupled dynamic analysis with dynamic interaction between target and projectile. Based on the numerical results and engineering assessments the capacity of the A92 reactor building to resist a malevolent impact of a large aircraft is evaluated. Significant efforts are spent on safety assessment of equipment by using an evaluation procedure based on damage indicating parameters.

As a result of these analyses several design modifications of structure elements are performed. There are changes of the layout of reinforcement, special arrangements and spatial reinforcement to increase shear resistance, as well as increase of the flexure reinforcement in most of the external protective structures.

Significant requirements are formulated regarding the equipment stability; some requirements for the passive safety systems are adjusted and spatial arrangement of equipment are improved. All the investigated scenarios show that there are sufficient margins to prevent a severe accident.

INTRODUCTION

The current paper describes the safety assessment process applied to Belene NPP reactor building for the case of a large aircraft collision. The Terms of Reference (ToR) for design and construction of Belene NPP are following the European Utility Requirements. According to the ToR the nuclear power plant shall be protected against a large commercial aircraft crash as DEC. The impact of a military aircraft (RF-4E Phantom) is taken into account in accordance with IAEA Safety Guide NS-G-1.5 [2] as design base condition. Additionally, an impact of a medium-size airplane (up to 100 tons) is considered in the design base loading.

The safety of the plant due to the postulated commercial aircraft crash is demonstrated by deterministic analysis. The assessment process and the acceptance criteria are as per DEC. The main goal of the assessment is to demonstrate that the effects of such a catastrophic event do not lead to a severe accident.

The detailed study of the air traffic over the NPP site and the surrounding territory has shown that only 5% of the planes that are crossing the sky over the plant belong to the group of heavy planes, i.e. above 300 tons. Nevertheless, for all further deterministic assessments, a commercial plane with a weight of about 400 tons and/or higher is selected. Both the Boeing 747 and Airbus A380 belong to that group of planes.

ANALYSIS APPROACH

Description of the A92 reactor building

The A92 concept of the reactor building includes a double shell RC structure with surrounding auxiliary structures. The external RC protective shell is made of concrete with several layers of high strength reinforcement
Transactions, SMiRT 21, 6-11 November, 2011, New Delhi, India

steel. The internal containment is post-tensioned RC containment with a steel liner. The Auxiliary Buildings are also reinforced concrete structures. A structural gap is provided between all external protective walls and the internal walls in order to avoid secondary interactions. A schematic 3-D visualization of the A92 reactor building is given in Fig.1.

![3-D visualization of A92 reactor building](image)

**Fig.1** 3-D visualization of A92 reactor building

**Numerical Models**

Two structural models are produced and used during the assessment process - Fig. 2. The main difference between the numerical models used is in the modeling of the external walls, namely only with shell FE in the first model and with solid FE in the second one. In both models non-linear material characteristics are used for concrete and reinforcement, taking into account the influence on the mechanical properties of the strain rate effects.

The “shell” FE model consists of about 100,000 shell finite elements. The shell elements used for the external walls are with increased accuracy, e.g. seven integration points in thickness direction. The reinforcement is modeled as planar diaphragms within the shell finite element. The resulting model could provide accurate prediction of the global dynamic response of the structure and proper assessment of the bending failure modes of the external/impacted walls. The “shell” FE model is used mainly for assessment of the in-structure dynamic response for the needs of equipment assessment (induced in-structure vibrations).

The “solid” FE model consists of about 250,000 finite elements. The external walls are modeled by several layers of solid elements (concrete walls) and shell elements (flexure reinforcement). The shear reinforcement is modeled by truss elements. The “solid” FE model is used for the detailed assessment of the external protective wall resistance, i.e. shear or punching failures, stress-strain, and crack distributions.

![Isometric view of the structural models of the A92 reactor building](image)

**Fig.2** Isometric view of the structural models of the A92 reactor building – with shell elements on the left side and with solid elements on the right side.
Detailed FE models of the passenger airplanes are developed too, e.g. Boeing 747, Fig.3 [3, 4].

Fig.3 Isometric view and lateral cross section of Boeing 747-400.

The structural response is analyzed by two approaches – 1) force time history analysis using preliminary computed load time functions and 2) missile-target interaction analysis, with direct application of the crashing airplane FE model as loading. The force time history analysis is performed by using both implicit and explicit time integrations, while for performing missile-target interaction analysis only explicit time integration is used.

**Loading Definition**

For most of the performed analyses, the loading is represented by a load time function derived through the Riera method. For this purpose, a simplified model of Boeing 747-400 is developed and about 30 load time functions are calculated varying the impact velocity from 100 to 160 m/s and the fuel mass from 40 to 85%, respectively, as shown in Fig.4.

Load time functions for velocities of 110, 140 and 160 m/s are computed by finite element analyses of the aircraft model impacting a rigid wall, too. A load time function obtained by FEA for velocity of 140 m/s is given in Fig.5 as an example. The load is applied on an area representing the aircraft projected area and it varies with the time.
Crash Scenarios

According to ToR, the assessment of the effects for the plant safety due to a large aircraft crash shall be performed as for DEC and using best estimate approaches. Therefore, the crash scenarios in terms of impact locations and velocities are selected according to the plant layout and the realistic aerodynamic characteristics of a large passenger airplane. The reactor building is divided in three specific zones as height and structural type and the possible impacts in these zones are studied. The lowest zone is dominated by the flat walls of the auxiliary building. At this zone the reactor building could be affected only from one side, since the rest is protected by various additional buildings. Due to the low elevation of this zone and the presence of obstacles on the site it is assumed that flat wall cannot be impacted with a velocity higher than 120 m/s, which is still much higher than the landing speed of a large airplane. The impact in the lowest zone is referred as Crash Scenario N1. The medium height zone is dominated by the cylindrical walls of the external shell. At this zone, the reactor building can be accessed also only from one side, due to the physical obstacles which the surrounding structures provide. It is estimated that the impact velocity for crashes in this zone cannot exceed 140 m/s. The impact in the medium zone is referred as Crash Scenario N2. The high zone includes the dome of the reactor building. This zone can be accessed from a full 360º range and is the zone with highest probability of impact due to the “clear horizon”. It is assumed that the impact at this zone could be with velocities up to 160 m/s, which is approximately twice the landing speed of large airplanes. It is assumed that higher speeds at such low elevation will cause the airplane to be practically uncontrollable and thus impossible to be directed precisely at the target. The impact in the highest zone is referred as Crash Scenario N3. The analysed impact locations are given in Fig.6.

DIP and Failure Criteria for Structures and Equipment

Having in mind the complex stress distribution produced in the structure during an aircraft impact, several damage indicator parameters (DIP) are selected for the needs of the structural capacity assessment. The following parameters are monitored and the following failure criteria are analyzed:

<table>
<thead>
<tr>
<th>Damage Indicator Parameters</th>
<th>Failure Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage Index (damaged part of the cross section as % from the cross section);</td>
<td>Perforation and/or punching-cone failure;</td>
</tr>
<tr>
<td>Crack width and opening, residual crack width and opening;</td>
<td>Crossing through the section residual cracks;</td>
</tr>
<tr>
<td>Crushing in the compressive zone;</td>
<td>Crushing in the compressive zone (strains above 0.3%) deeper than the compressed reinforcement;</td>
</tr>
<tr>
<td>Maximum displacements and maximum residual displacements;</td>
<td>Plastic strains above 2% in the flexural reinforcement, plastic strains above 0.5% of the shear reinforcement.</td>
</tr>
</tbody>
</table>

Due to the complex dynamic response of the structure when subjected to large impact and due to the absence of analytical and experimental data several DIPs are used for the needs of the equipment safety assessment:

<table>
<thead>
<tr>
<th>Damage Indicator Parameters</th>
<th>Failure Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration Floor Response Spectra;</td>
<td>Loss of integrity Primary Circuit;</td>
</tr>
<tr>
<td>Displacement Floor Response Spectra;</td>
<td>Loss of integrity or functionality of the equipment</td>
</tr>
</tbody>
</table>
- Maximum accelerations, for maintaining of sub-critical condition;
- Maximum relative displacements of the equipment restraints (drift);
- Cumulative Absolute Velocities (CAV) for core cooling;
- Intensities of Japan Meteorological Association (I_{IMA}) for spent fuel cooling;

Acceptance Criteria

The safety of the plant due to the postulated large commercial aircraft crash is demonstrated through assessment process and acceptance criteria applied as per DEC. It has to be demonstrated that the effects of this event do not lead to severe accident conditions. Therefore, the assumed acceptance criteria in this study allow the development of damages in the civil structures and the safety equipment, provided that they do not lead to severe accident conditions. The following acceptance criteria are adopted:

**Structural Capacity**
- Impact induced hazards do not penetrate the external protective shell
- There is no secondary impacts due to contact between external and internal walls
- The internal containment should be intact
- The spent fuel pool should be intact (no leakage)
- Global stability is assured

**Equipment Safety (Heat Removal Capacity)**
- The primary circuit should be intact
- The available set of active and passive equipment should be enough to provide safe shut down, core cooling and spent fuel cooling

STRUCTURE ASSESSMENT

The structure assessment is performed regarding the presented assumptions and models. The three scenarios that are shown correspond to impact on a flat wall, cylinder wall, and on the dome, respectively. The dome impact seems most likely to occur. The biggest structural effects in terms of damage are caused in the first scenario: flat wall impact.

It should be marked that there are several iterations needed for improving the reinforcement arrangements and dimensions of structural elements in order to achieve acceptable results, e.g. no penetrations and acceptable deformations (displacements).

It is demonstrated that, although there is a difference in the material models and in the finite element techniques, all methods and models provide comparable results, e.g. maximum displacements and stress-strain distributions at impact are evaluated with confidence.

Table 1. Comparison of maximal computed displacements at impact location

<table>
<thead>
<tr>
<th>Max.Displ. [cm]</th>
<th>SOLVIA SHELL ELEMENTS Riera’s Load Function</th>
<th>SOLVIA SOLID ELEMENTS Riera’s Load Function</th>
<th>ABAQUS SOLID ELEMENTS FEA Load Function</th>
<th>ABAQUS SOLID ELEMENTS Crash analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario N1</td>
<td>38</td>
<td>21</td>
<td>23</td>
<td>36</td>
</tr>
<tr>
<td>Scenario N2</td>
<td>8</td>
<td>6</td>
<td>6</td>
<td>25</td>
</tr>
<tr>
<td>Scenario N3</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>15</td>
</tr>
</tbody>
</table>

The results show that the development of cracks at impact is significant; however, the concrete section will preserve enough integrity in order to prevent penetration of fuel and crash debris inside the outer protective shell. Results of the development of cracks in the cylinder wall at impact are shown in Fig.7.
EQUIPMENT SAFETY ASSESSMENT

The equipment safety assessment is performed through a multi-step procedure. The assessment approach includes evaluation of CAV and I_{JMA}, assessment of Sa, assessment of Sd, and finally a detailed (non-linear) analysis of the equipment of interest. The procedure requires development of in-structure response, including in-structure response spectra, in-structure CAV and I_{JMA}. The thresholds are best estimate values derived from the statistics of the European Strong Motion Data Base [5] and the equipment capacity as presented in the experience database by DOE [6]. Statistics of some of the parameters and more detailed descriptions of this approach are presented in [7, 8, 9, and 10].

Step One: CAV and I_{JMA}

Step One of the evaluation is in-structure response evaluation in terms of CAV and I_{JMA}. This requires spatial response analyses of the structure under impact. For each location where there is a critical structure system or equipment CAV and I_{JMA} are evaluated. If each component of CAV<0.16g*s or I_{JMA}<4.5 then no damage is expected and operation should not be affected. Further if each component of CAV<0.3g*s or I_{JMA}<5 safety is not going to be affected, i.e. structures and equipment are in a safe state. A sample of the obtained results from Step One is given in Fig.8. For all structures and equipment for which the conditions are not fulfilled Step Two of the evaluation is required.

Fig.8 Influence of the impact velocity (from 100 to 160m/s) on the CAV values for one of the controlled locations and the interdependence between the CAV and I_{JMA} values for the controlled locations for an impact with 160m/s.
Step Two: Acceleration FRS

For all locations where Step One is not satisfied, the acceleration FRS (AFRS) for 2% damping are calculated and compared with the “design ultimate capacity spectrum”. The latter is represented by AFRS obtained by enveloping the design seismic and impact (military jet) acceleration FRS multiplied by a factor of the available design conservatism (safety factor). The “safety factor” is derived as $SF = FR \times FD \times FL \times FA \times FS$, where each partial factor accounts for different conservative assumptions in the design stages. The “capacity” is assessed in each direction of excitation separately and compared with the corresponding demand. A sample of the results from Step Two is given in Fig. 9.

![Fig. 9 Comparison between the scaled design AFRS and the aircraft impact induced spectrum for one of the controlled locations.](image)

Step Three: Displacement FRS

It is widely recognized that under high frequency excitation the displacement (drift) estimated capacity is by far more realistic than the force (acceleration) based estimates. For all equipments where AFRS are not enclosed by the “ultimate capacity” AFRS in Step Two, the DFRS for 2% damping are computed as shown in Fig. 10. Using the spectral displacements in the equipment frequency range, the drift of the equivalent “center of mass” is estimated. The drift in each direction of excitation is compared with the threshold values of 0.001 and 0.01 for active and passive equipment, respectively. Equipment with drift below the threshold value, is considered safe. For the other locations Step Four is performed.

![Fig. 10 Comparison between the scaled design DFRS and the aircraft impact induced displacement spectrum for one of the controlled locations.](image)

Step Four: Detailed Non-Linear Dynamic Analysis

For all locations where the criteria from Step One to Step Three are not satisfied, a detailed numerical analysis of the equipment under consideration is performed. Depending on the equipment under consideration, the analysis could be pseudo-static or dynamic, linear or non-linear.

CONCLUSION

As a result of these analyses several design modifications of structure elements are performed. There are changes of the layout of reinforcement, special arrangements and spatial reinforcement to increase shear resistance, increase of the flexure reinforcement in most of the external protective structures too.
Significant requirements are formulated regarding the equipment stability; requirements for the passive safety systems are adjusted and spatial arrangement of equipment are improved. All the investigated scenarios show that there is sufficient margin to prevent a severe accident. In particular, some of the important conclusions are:

- The external protective structures possess enough strength and ductility to prevent penetration; therefore, the intrusion of aircraft parts, debris, fuel, and other external hazards inside the external protective structures due to the crash is not possible.
- The global stability of the reactor building in terms of overturning, sliding, and maximum stresses under the foundation plate is assessed to be adequate and safe.
- Damage and falling of the polar crane is not expected. The integrity of the internal containment is assured and its function as a physical barrier is guaranteed.
- The integrity of the primary circuit is assured for all investigated scenarios and no leakage or functional disturbances are expected.
- The functionality of the reactor control systems is assured for all investigated impact scenarios.
- For the use of multiple trains and spatial separation of active safety systems, more than a minimum set of equipment is functionally available for core cooling (more than one full train).
- All hydro-accumulators remain available in each investigated crash scenario.
- The PHRS should be considered non-functional mainly due to the post crash fire.
- For all investigated scenarios the available set of passive and active equipment is enough to provide safe shut down and core cooling.

ACKNOWLEDGEMENT

The presented analyses are performed under contract with Atomstrojexport JSC. The professional support and review of methodology and results by Dr. J. Riera and Dr. A. Guerpinar are deeply acknowledged.

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