Reliability Analysis of an Ignalina NPP Building Impacted by an Airliner

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ABSTRACT

In order to ensure that nuclear reactor systems are reliable and safe in case of external loading, it is very important to evaluate uncertainties associated with loads, material properties, geometrical parameters, boundaries and other parameters. Therefore, a probability-based approach was developed as the integration of probabilistic and deterministic methods using existing state-of-the-art software. The subject of this paper is the reliability analysis of an Ignalina Nuclear Power Plant building impacted by a commercial airliner, which is indigenous to Lithuania. The Monte Carlo Simulation, First Order Reliability Method, and the combined Monte Carlo Simulation and Response Surface method were used for the probabilistic analyses. During an airplane crash, the dynamic impact loading is uncertain and this uncertainty must be accounted for in determining the failure probability. The Response Surface/Monte Carlo method was used for the determination of such a relation expressed by the probability-loading function. With failure defined as concrete cracking and rebar rupture, the failure probabilities of the impacted wall were calculated as a function of the peak impact load. The conclusion is that a commercial airliner flying at the landing approach speed will cause the impacted wall to develop through-the-wall cracks, but no reinforcing bar failure will occur, and thus, no perforation by aircraft components should occur.

INTRODUCTION

The Ignalina Nuclear Power Plant (NPP) is located in Lithuania, close to the borders of Belarus and Latvia. The plant contains two RBMK-1500 reactors, which is the most advanced version of the RBMK reactor design series - actually the only two of this type that were built. "RBMK" is a Russian acronym for "Channelized Large Power Reactor".

After the terrorist attacks in New York and Washington D. C. using civil airliners, the structural integrity assessment of civil airliner crashes into civil and NPP structures has become very important. The interceptions of many terrorists' communications reveal that the use of a commandeered commercial airliner is still a major part of their plans for destruction. Therefore, human induced external events, such as the impact of a commercial airliner, were selected for analysis and reported in this paper. An airliner or other flying objects in the vicinity of a NPP represents a very large threat to the plant, including the reactor. An aircraft crash may damage the roof and walls of buildings, pipelines, electric motors, power supply cases, electric transmission power cables and other elements and systems that are important for safety. An aircraft crash is an important external event and was selected for detail deterministic and probabilistic analysis.

Previously, Dundulis et al [1, 2] reported the results of a deterministic analysis for the transient response of an Ignalina NPP building subjected to impact loading from a commercial airliner. Both global and local failures were considered. However, the values of material properties, the geometry characteristics of the structures and the loadings used in the structural integrity analysis all have a degree of uncertainty. Therefore, it is necessary to account for the uncertainty in these quantities when performing a structural integrity evaluation. This can be accomplished through probabilistic analyses to see if a combination of relevant parameters could lead to failure and to determine the probability of failure.

A finite element model of a representative Ignalina NPP building was developed. A Riera loading function [3] was determined for a commercial airliner traveling at its landing speed. The probabilistic analyses required the use of both a probabilistic engine and a deterministic engine. The ProFES code [4], a probabilistic engine, was used in conjunction with the NEPTUNE structural analysis code [5], a proprietary deterministic engine. ProFES determined the values for many combinations of the random variables and collected the values for the resulting response variables, and NEPTUNE performed the deterministic transient structural response calculations based on the ProFES determined values for the random variables. A special ProFes-NEPTUNE translator, *pn_glue* [6], was used to transfer information between the two codes. After the multitude of deterministic computer runs were performed, ProFES determined the structural reliability of the building subjected to the impact of a commercial jetliner.

MODEL FOR PROBABILISTIC ANALYSIS OF FAILURE OF A TYPICAL IGNALINA NPP BUILDING

The Ignalina NPP buildings are rectangular in form and composed of box-like rectilinear compartments. The selected building was a portion of the Accident Localization System (ALS), which has outside walls of the NPP. The impacted wall and the adjacent exterior and interior walls and ceilings are included in the FE model. The walls and slabs of the compartments of the NPP building are manufactured from reinforced concrete. The geometrical data on compartments of a typical Ignalina NPP building were obtained from drawings. The pipelines, which are located in this building, are not included in the FE model. This FE model was created using the ALGOR preprocessor [7]. The ALGOR/NEPTUNE interface program was previously developed to transform all input variables (nodal coordinates as well as element properties and loading) from ALGOR input format to NEPTUNE input format.

Finite element modeling of the building

The wall of the building was modeled using the four-node quadrilateral plate element developed by Belytschko, et al. [8]. The element was further developed by Kulak and Fiala [9] by incorporating the features to represent concrete and reinforcing steel bars (rebars). Subsequently, additional failure criteria were added, and this enabled the modified element to model concrete cracking, reinforcing bar failure and gross transverse failure.

NEPTUNE calculates stresses at the centroid of the concrete element at five integration points, designated as IP1 through IP5, through the thickness and in each rebar layer. In the model, layers of individual reinforcing bars of the concrete walls are represented by smeared uniformly distributed layers of steel. The thickness of these layers is determined by assuming that the cross-sectional areas of the reinforcing bars are spread uniformly along the respective pitch of the layers. The direction of reinforcement is specified in each quadrilateral plate element in the model. Transverse wall reinforcement and liner are neglected in the analytical model.

Some composite metal frames, made from different steel components, are imbedded in the walls. These structures were modeled using separate beam finite elements [10] and were added to walls and slabs at appropriate locations along the edges of quadrilateral elements. The 3-D beam element is a three-dimensional uniform cross-section element capable of undergoing large deformations with elasto-plastic material response.

Boundary conditions of models and loads for analysis

A portion of a typical Ignalina NPP building was used in the analysis. The outside constraints consist of walls and floor-ceiling slabs of the adjacent structure. Most of the outer nodes of the Ignalina NPP building model would be connected to the adjacent outside structures. Because these external constraints would be primarily resisting the Ignalina NPP building deformation in the tension-compression mode, their stiffness would be very large. For simplicity, therefore, the locations of the external nodes, which would be in fact connected to adjacent structures, are assumed to be completely fixed in translation.

A two engine commercial airliner is one of the most common aircraft used in Lithuania and, thus, is most likely to fly over the Ignalina NPP. The aircraft is a short-to-medium range airplane and is used primarily for continental flights. The impact force loading history [2] for this airplane was determined using a Riera loading function. The impact area includes the frontal areas of the body, the engines and the wings.

Description of finite element model

The finite element model of the Ignalina NPP building part is presented in Fig. 1. One crash/impact location was considered in this paper. Arrows depict the assumed impact area of the airplane. The impact direction is assumed to be perpendicular to the selected wall of the building.

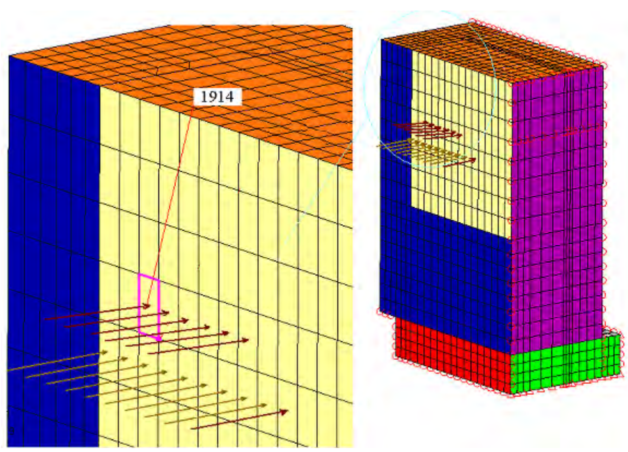

Fig. 1 Finite Element Model of the Ignalina NPP Building

The concrete reinforcement used has a unique design. The reinforcement consists of layers of vertical and horizontal reinforcing steel bars combined with embedded steel columns made from steel frames to provide additional strength. There were five (5) physical layers of reinforcing bars identified as LA, LB, LC, LD and LE. These five layers were represented as three smeared layers (L1, L2 and L3) in the appropriate quadrilateral RC plate elements of the FE model. Layer L1 is located in the inner half of the wall and is subjected to tension during the initial part of the impact loading. Layer L3 is located in the outer half of the wall (i.e., impact side) and initially experiences compression. The steel-frame columns embedded in the concrete walls were modeled using three-dimensional beam elements located along vertical edges of appropriate elements.

PROBABILISTIC ANALYSIS METHODS USED IN THIS ANALYSIS

Probabilistic methods provide a means to assess the effect of uncertainties of material properties, geometry data and loads on the prediction of structure reliability and performance. In order to achieve the probabilistic evaluation, the computer code ProFES was used. The NEPTUNE code was used for deterministic transient analysis. By default the NEPTUNE input and output data cannot be imported into the ProFES code. Thus, the special ProFES/NEPTUNE translator, *pn_glue*, was used [6]. The translator, written in Perl, has been developed to exchange information between NEPTUNE and ProFES. The Monte Carlo Simulation (MCS) method, the First Order Reliability Method (FORM) and the Response Surface (RS)/MCS methods for numerical probabilistic analysis were used in this analysis.

Probabilistic Analysis using the MCS Method

The MCS was used to determine the failure probability of the impacted wall resulting from an aircraft crash.

Selected Random Variables for analysis

The aim of the uncertainty analysis is to identify and quantify all potential important uncertainty parameters. Ranges and subjective probability distribution describe the state of knowledge about all uncertain parameters. In probabilistic analysis, uncertainties in numerical values are modeled as random variables. The following mechanical properties and geometrical parameters important to the strength of the structures were used as random variables:

- Mechanical properties: Concrete – Young's modulus, stress points of the compressive stress-strain curve of the impacted and support walls; Reinforcement bar – stress points of the stress-strain curve of the impacted wall and support walls.
- Geometry data: Concrete wall – thickness of the impacted wall and support walls; Reinforced concrete – rebar area of the impacted wall and support walls.

The logarithmic normal distribution for mechanical properties and geometry parameters was used in this analysis. The selected random variables, distributions and coefficients of variation are presented in Table 1 and Table 2. According to Russian design criteria, which should reflect the as-built conditions, the failure strain for reinforcement bars is 14%. It has been observed, however, that reinforcement bar failure may occur at splice connections, and for this case, the splice failure strain could be 4% [11], which should be a conservative value. So the 4% failure strain was used in some of the following analyses.

The points defining the load curve are considered to be random variables. These points represent the beginning/end points at which different components of the aircraft structure (e.g., fuselage, wings, engine, etc.) begin to contact or end contact on the building wall. Thus, in a sense, this approach takes into account the variations in loading from the individual structural components. The normal distribution for the load points was used in this analysis, Table 3.

Table 1. Random Variables for Reinforced Concrete Material Properties and Parameters

Material/ Location	Distribution	Property/Parameter	Mean	Std. Dev./ COV*	Comment
Concrete	Log. Normal	Young's modulus	2.7e+10	0.2*	Unit: Pa
	Log. Normal	Stress_point 1	4.35e+07	0.2*	Unit: Pa
	Log. Normal	Stress_point 2	5.16e+07	0.2*	Unit: Pa
Reinforcement bars	Log. Normal	Stress_point 1	4.27e+08	0.2*	Unit: Pa
	Log. Normal	Stress_point 2	4.36e+08	0.2*	Unit: Pa
	Log. Normal	Stress_point 3	7.03e+08	0.2*	Unit: Pa
	Log. Normal	Stress_point 4	8.50e+08	0.2*	Unit: Pa

Table 2. Random Variables for Geometry Parameters

Material/ Location	Distribution	Parameter	Mean	Std. Dev./ COV*	Comment
Concrete wall	Log. Normal	Wall thickness	1.00	0.1*	Unit: m
Reinforcement bars	Log. Normal	Rebar layer thickness (data is presented only for 1 rebar)	0.00196	0.1	Unit: m

Table 3. Random Variables for Load Curve Parameters (peak points)

Distribution	Parameter	Mean	Std. Dev./ COV*	Comment
Normal	LoadUnit 1, pressure in impacted wall	-227000	0.2*	Unit: Pa
Normal	LoadUnit 2, pressure in impacted wall	-246700	0.2*	Unit: Pa
Normal	LoadUnit 3, pressure in impacted wall	-600200	0.2*	Unit: Pa
Normal	LoadUnit 4, pressure in impacted wall	-733300	0.2*	Unit: Pa
Normal	LoadUnit 5, pressure in impacted wall	-1165000	0.2*	Unit: Pa
Normal	LoadUnit 6, pressure in impacted wall	-1085000	0.2*	Unit: Pa
Normal	LoadUnit 8, pressure in impacted wall	-1557000	0.2*	Unit: Pa
Normal	LoadUnit 10, pressure in impacted wall	-1200000	0.2*	Unit: Pa

Selected limit states and system events for analysis

The objective of the transient analyses is to evaluate the effects of an aircraft crash on an Ignalina NPP building structure. The structural integrity analysis was performed for a portion of the ALS using the dynamic loading of an aircraft crash impact model caused by civil airplane traveling at a velocity of 94.5 m/s. The aim of the transient analysis was to evaluate:

- Structural integrity of the impacted wall of the building;
- Structural integrity of the building walls adjacent to the impacted wall.

Based on the objective of the transient analyses, the following limit states were selected:

- Limit States 1-5 – The concrete in element number 1914 (Fig.1) in the impact area reaches the ultimate strength in tension and a crack starts to open. This impacted wall is the outside wall of the ALS and a through-the-thickness crack should not develop. NEPTUNE calculates stresses at the centroid of the element at five integration points (IP1 through IP5) through the thickness of the concrete element. Integration point 1 is on the inside surface, and integration point 5 is on the outside surface. Therefore, the limit states were checked at all five integration points.
- Limit States 6-10 - The concrete element of the support wall of the building reaches the ultimate strength in compression and a compressive failure occurs. This neighboring wall is an inside compartment wall of the ALS and the cracks in this wall may open. Therefore, the strength of wall was evaluated for compression. The same limit states at all five integration points through the thickness were checked.
- Limit State 11- 13 – The splice failure strain limit of 4% for the rebars in element number 1914 (Fig.1) would be reached and the rebars would fail. All three layers (i.e., L1 through L3) of rebars were checked. Note, Layer L3 is on the impact side of the wall
- Limit State 14- 17 - The splice failure strain limit of the first layer of rebars in the interior concrete wall is reached and the splice would break. The same limit states at all four layers of the reinforcement bars were checked.

It is important to calculate the probability of concrete failure at all five integration points in the same computer run. Also it is important to calculate probability of reinforcement bar failure in all layers in same run. Therefore, the following four system events were used in the probability analyses:

- System Event 1 – Limit state 1 - 5. This system event is evaluated as true if all the limit states are true within the same run. This system event evaluated the probability of crack opening in concrete at all the integrated points of the impacted wall.
- System Event 2 – Limit state 6 - 10. This system event is evaluated as true if all the limit states are true within the same run. This system event evaluated the probability of concrete failure at all the integrated points of the neighboring interior support wall.
- System Event 3 – Limit state 11 - 13. This system event is evaluated as true if all the limit states are true within the same run. This system event evaluated the probability of rebar failure at all layers of the impacted wall.
- System Event 4 – Limit state 14 - 17. This system event is evaluated as true if all the limit states are true within the same run. This system event evaluated the probability of rebar failure at all layers of the neighboring support wall.

Probabilistic Analysis Results using MCS Method

Using the MCS probabilistic analysis method, the probabilities of limit states and the probability of failure for system events were calculated for both the impacted wall and the adjacent interior wall, which provides support to the impacted wall. The number of MC simulations was 3000. It should be pointed out that because of the small number of MC simulations performed, the probabilistic analysis using the MCS method was performed as a scoping study.

For the impacted wall, the calculated probability of ‘Limit states 1 -3’ is from 0.645 to 0,964. These probabilities indicate that the tensile failure surface of the concrete element within the impact area will be reached at three of the five integration points and a crack could develop in these three layers. The calculated probability of ‘Limit states 4 -5’ is very small, i.e., at the fourth integration point it is 0.007, and at the fifth integration point it is 0. These values indicate that the probability of a crack opening in the fourth and fifth layers of this concrete element is very small.

The probability of a crack opening at all five integration points in a concrete element within the impact area during the same run was calculated. The system event was used to analyze this probability of failure. The calculated probability of 'System event 1' is 0. This indicates that, within the same run, the tensile failure surface of the concrete at all the integration points of this element is not reached, and the probability of crack opening in the concrete element of impacted wall is very small.

The calculated probabilities for 'Limit states 11 - 13' and of 'System event 3' are also 0. This indicates that the splice failure strain of the rebars within the impact area will not be reached in any of the rebars, and the probability of rebar splice failure is very small. For layers 1, 2 and 3 of the impacted wall, the probabilities for concrete failure are near 1. In contrast, for concrete layers 4 and 5 and the rebars of the impacted wall, the probabilities are near 0.

Based on these results, only very small probabilities of failure exist in several layers of concrete and in all layers of rebars. Therefore in the next section, the FORM method was used for additional evaluation of failure probabilities of the impacted wall.

For the interior support wall, the calculated probabilities of 'Limit states 6 -10' and of 'System event 2' are 0. Thus, the compressive failure surface of the concrete of the support wall will be reached with a probability of 0 for all the integration points of this element, and the probability of compressive failure is very small. The calculated probability for 'Limit states 14 - 17' and of 'System event 3' are also 0. This indicates that the splice failure strain for the rebars in the support wall will not be reached for any of the rebar layers, and the probability of a rebar splice failure is very small.

For the interior wall, the probabilities of failure are 0 for all concrete layers and rebar layers. Since this wall is an inside wall of the building and is not very important for leak tightness of the ALS, no additional evaluation of the probability of failure of this wall was carried out.

Probabilistic Analysis using FORM Method

FORM was used to study the probability of failure of the impacted wall of the Ignalina NPP building due to the effects of an aircraft crash onto the building. FORM is the preferred method for evaluating small probabilities because for the same precision as MCS it requires the least number of finite element model runs. With FORM, the computational effort is proportional to the number of random variables and limit states.

The same mechanical properties and geometrical parameters used in the MCS analysis of the impacted wall were used as random variables in the FORM analysis. Also, 'Limit states 1-5' and 'Limit states 11-13,' defined in the MCS analysis (see 'Probabilistic Analysis using the MCS Method'), were also used here. It is important to calculate the probability of concrete failure at all five integration points of the element within the same run. Similarly, it is important to calculate the probability of reinforcement bar failure in all three layers within the same run. Therefore, the two system events were used in the probability analysis, i.e. the 'System event 1' and 'System event 3' defined in the MCS.

The number of simulations performed was 1419. The probabilities of limit states and system events were calculated. The results of the probabilistic analysis are presented in Tables 4 and 5.

Table 4. Failure probabilities for Limit States in Element 1914

Name	Definition	Probability	Beta
Limit State 1	Concrete Failure at IP1: Stress Equivalent > 3.79e+06	0.501644	0.00412009
Limit State 2	Concrete Failure at IP2: Stress Equivalent > 3.79e+06	0.510365	0.0259852
Limit State 3	Concrete Failure at IP3: Stress Equivalent > 3.79e+06	0.506571	0.0164719
Limit State 4	Concrete Failure at IP4: Stress Equivalent > 3.79e+06	0.497763	-0.00560789
Limit State 5	Concrete Failure at IP5: Stress Equivalent > 3.79e+06	0.497695	-0.00577722
Limit State 11	Reinforcement Bar Failure in L1: Strain Equivalent > 0.04	0.229597	-0.740173
Limit State 12	Reinforcement Bar Failure in L2: Strain Equivalent > 0.04	0.00287634	-2.76156
Limit State 13	Reinforcement Bar Failure in L3: Strain Equivalent > 0.04	5.3236e-171	-27.8545

Table 5. Failure probabilities for System Events in Element 1914

Name	Probability	Beta
Through-the-thickness Concrete Failure (i.e., Failure in Limit States 1 through 5)	0.02664	-1.93307
Failure of all Reinforcing Bar Layers (i.e., failure in Limit States 11 through 13)	0	-4.01317

The calculated probabilities for 'Limit states 1 - 5' are from 0.498 to 0.510. This indicates that the tensile failure surface of the concrete in the impact area could be reached at each of the five integration points (IP1 through IP5) but not during the same computer run. Thus, a crack in each layers of this concrete element could open. The probability of a crack occurring at all five integration points in the concrete element during the same run was calculated (i.e., System Event 1), and the value was 0.0266. This indicates that the probably of the ultimate strength for tension being exceeded through the thickness of the concrete element in the impact area is 0.0266. Recall that the MCS indicates that the probability for System Event 1 was 0.

The probability for 'Limit State 11," which checks for failure of the first rebar layer (L1) in the concrete wall at the location of impact, was found to be 0.2296. The calculated probabilities for 'Limit States 7 and 8' are very small; the probabilities for the third and fourth rebar layers were 0.007 and 0, respectively. These limit state values indicate that the probability for splice failure of the rebars in the third and fourth rebar layers is very small. The probability of exceeding the splice failure strain in all rebar layers of the impacted wall (i.e., System Event 2) was 0. Thus, the aircraft should not penetrate the reinforcement in the impacted wall.

Probabilistic Analysis using RS/MCS Method

During an airplane crash, the dynamic impact loading is uncertain. Therefore, it is important to estimate the dependence of the failure probability of the building due to the uncertainty in loading. The RS/MCS method was used for the determination of such a relation expressed by the probability-loading function. Also, because this approach is not compute intensive, failure probabilities for two values of the rebar failure strain were obtained: the conservative value of 4% and the Russian design value of 14%. Thus, insight into the affect that rebar failure strain has on the probability of failure for the rebars.

First using the full finite element model of the building, a limited number of MC simulations were performed to determine the response surfaces, i.e., the probability functions for failure of the walls of the Ignalina NPP building. Then the MCS method was used on the response surfaces to study the probability of failure of the building walls as indicated by concrete cracking and reinforcement bar rupture. In this analysis the probability function was used as an internal function in ProFES to determine the failure probability, which greatly reduces computational effort.

The same mechanical properties and geometrical parameters used in the MCS and FORM analyses were also used as random variables in the RS/MCS method. Also, the same limit states used in the FORM analysis were used in the RS/MCS analyses.

Surrogate Impact Loading Function

The available loading function for a civil airplane traveling at 94.5m/s was used in this analysis. The peak load of 58MN occurred at 0.185s [2]. The loading is seen to be a nonlinear function consisting of a series of straight line segments. Because of limitations on the number of random variables imposed by ProFES, it was necessary to use a surrogate loading function that was a linear function starting at 0 MN at the instant of impact and reaching a peak value of 58MN at 0.185s. It is noted that this surrogate function provides a larger impulse than the original function. For this part of the analysis, which is to do a preliminary study of the effect that the loading has on the probabilistic analysis, the peak load was varied, arbitrarily, from 0MN to 700MN, and the time at which the peak load occurred was kept constant at 0.185s. The probability distribution function for the loading was chosen to be uniform distribution.

Probabilistic Analysis Results using RS/MCS Method

Using the full FE model, two hundred (200) MC simulations were performed to determine the probability functions for Limit States 1 and 11. The distribution for the loading was assumed to be uniform. The range of loading was from 0.022 MPa to 2.2 MPa. The maximum point of loading used in the deterministic transient analysis of civil airplane traveling at a velocity of 94.5 m/s crash is 1.557 MPa (correspond to 58 MN). Using the Response Surface Method, the dependence functions for the response variables based on the input random variables were calculated.

The probabilistic function for Limit State 1, which is the development of a crack on the initial tension side of the wall, is given by:

$$Y1=2.726e+6+ -2.816*\boldsymbol{L}+ -2.743e+6*\boldsymbol{T}+ 0.043*\boldsymbol{c1} + 0.012*\boldsymbol{c2} + 0.005*\boldsymbol{c3} + *\boldsymbol{R1} + 1.320e+9*\boldsymbol{R3} + -1.775e+9*\boldsymbol{R4} + -0.004*\boldsymbol{s1}+ -0.007*\boldsymbol{s2} + -0.004*\boldsymbol{s3} + 0.008*\boldsymbol{s4} \quad (1)$$

where Y1 - Limit State 1, i.e. Y1 > 3.79e+6; (the value 3.79e+6 is the concrete experimental ultimate strength in tension); ***L*** - maximum force loading (pressure) point in impacted wall; ***T*** - wall thickness of the impacted wall; ***c1, c2*** and ***c3*** – stress points 1, 2 and 3 for concrete respectively; ***R1, R3*** and ***R4*** – thickness of reinforcement bars in the first, third and fourth layers, respectively; ***s1, s2, s3*** and ***s4*** – stress points 1, 2, 3 and 4 for the steel reinforcement bars, respectively.

The equations obtained using the RS method were used as internal response functions in the subsequent MCS analysis. The number of MCS simulations was 1,000,000. The probability function (1) was used to determine the relationship between the probability of 'Limit state 1' being reached and the applied load, i.e. peak value of the impact force. The force loading was applied to the assumed airplane impact area in the form of pressure in the transient analysis of Ignalina NPP building. The pressure value was recalculated to a force value and the probability results were presented as the relation between probability and force. The results of the probabilistic analysis are presented in Fig. 2. The probability of failure for Limit State 1 (concrete element reaches ultimate strength in tension) is zero (0) up to 10 MN, and the probability of failure is 1 at the resultant force approximately equal to 80 MN. Note, the maximum force used in the deterministic structural integrity analysis of the Ignalina NPP building for an airliner impacting into the building at 94.5 m/s is approximately equal to 58 MN.

The same approach was used for Limit State 11, which is the rupture of the outermost reinforcing bar on the initial tension side of the wall, which would be the first rebar to fail. Using the MCS/RS method, the probabilistic function for

Limit State 11 was calculated based on two values for the failure strain of the reinforcing bars (4% and 14%). The probabilistic function for Limit State 11 is given as:

$$Y2 = 0.403 + -2.281e\text{-}008*\boldsymbol{L} + -0.337*\boldsymbol{T} + -1.773e\text{-}009*\boldsymbol{c1} + -4.220e\text{-}010*\boldsymbol{c2} + 5.740e\text{-}010*\boldsymbol{c3} + 69.109*\boldsymbol{R1} + -35.895*\boldsymbol{R3} + -38.157*\boldsymbol{R4} + -2.151e\text{-}010*\boldsymbol{s1} + 3.140e\text{-}010*\boldsymbol{s2} + 6.618e\text{-}011*\boldsymbol{s3} + -1.227e\text{-}010*\boldsymbol{s4} \quad (2)$$

where Y2 - Limit State 2, i.e. Y2 > 0.04/0.14 (the value 0.04 is the splice failure strain of the rebar, and the value of 0.14 the failure strain of the rebar per Russian design failure strain). Other symbols are explained in equation 1. The results of the probabilistic analysis are presented in Fig. 3.

According to this result, the relation between the probability of 'Limit State 2' and the applied load was defined. For the failure strain limit of 0.04 (i.e., conservative splice failure strain), initiation of failure will occur at a peak force approximately equal to 20MN, and the probability of failure will reach 1 (i.e., 100%) at a peak force of about 370MN. For the failure strain limit of 0.14 (i.e., rebar failure at the Russian design failure strain) initiation of failure will occur at a peak force approximately equal to 110MN, and the probability of failure will reach 1 (i.e., 100%) at a peak force of about 580MN. The maximum force used in the structural integrity analysis of the Ignalina NPP building is approximately equal to 58 MN. Thus, it is seen that no rebar failure should occur at the Russian design failure strain.

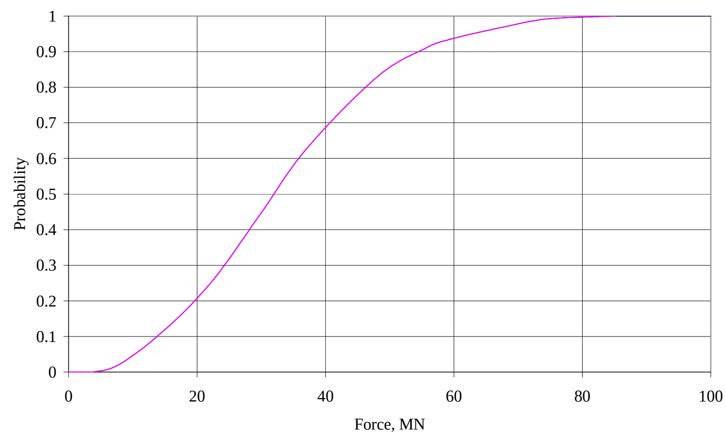

Fig. 2 Probability of a crack developing in the initial tension side of the impacted wall

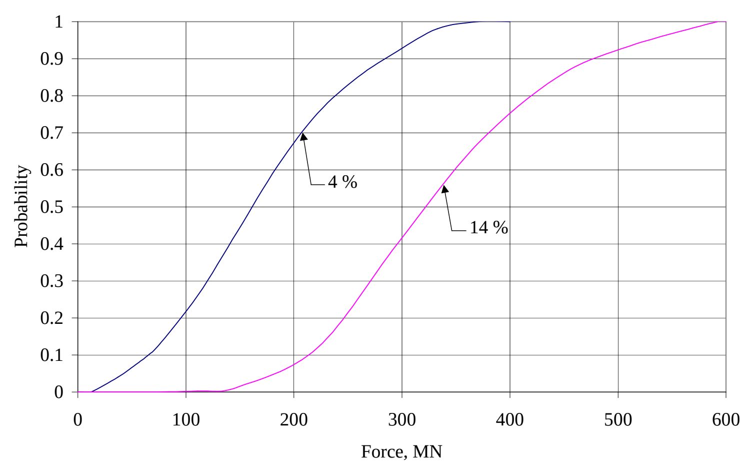

Fig.3 Probability of Reinforcing Bar Failure in the Initial Tension Side of the Impacted Wall for Failure Strains of 4 and 14 percent

SUMMARY AND CONCLUSIONS

Probabilistic analyses were performed to evaluate global damage to an Ignalina NPP building wall due to the crash of a civil airplane traveling at the approach speed of 94.5m/s. The Monte Carlo Simulation, First Order Reliability and combined Monte Carlo Simulation/Response Surface methods were used for the probabilistic analyses.

The results of the probabilistic analyses show that the MCS method is more conservative than the FORM method when determining large values for failure probability. The MCS method is not conservative for determining small values for failure probability.

The results of the probabilistic analyses of failure of the impacted wall show that:

- The ultimate tensile strength of concrete will be reached at all integration points of the concrete element located in the impacted area during the same run and a through-the-wall crack in the concrete element of the impacted wall may open with a probability of 0.0266. Note, this is in contrast to a mean-value deterministic analysis that indicated a crack would only form through about 38% of the wall thickness.
- Based on a coefficient of variation of 0.2 for the nominal impact load curve parameters and a rebar splice failure strain of 4%, which is conservative, the probability of failure for rebar layers one, two and three are, respectively, 0.23, 0.003 and 0.0. Thus, the probability of failure of all rebar layers is zero.
- Using the Russian design value failure strain of 14%, which should reflect the as-built condition, the loading study showed that the probability of rebar failure is zero up to a peak impact load of 135 MN, which is 2.3 times the nominal peak load of 58 MN generated during impact at the normal landing speed of the aircraft

Based on reliability analysis, which takes into account uncertainty, the conclusion is that a commercial airliner flying at the landing approach speed will damage the impacted wall of an Ignalina NPP building. However, the extent of the damage will be through-the-wall cracks, but the rebars should not fail. Thus, no perforation of the impacted wall by structures of the airliner should occur.

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