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Modelling of RBMK-Reactor Building for External Effects Analysis

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Abstract

This paper describes the IVO PE contribution to the research program co-ordinated by the IAEA investigating the extreme external load effects on RBMK -reactors. The program began in 1998 and it is co-ordinated by Dr. Gurpinar. The objective of the research project is to study the performance and safety of the nuclear power plants, which are of the type RBMK against the airplane crashes and gas explosions and to design measures to improve the safety of the plants. IVO PE has developed the 3D FEM model of the RBMK reactor building on the basis of plant layout drawings and apply the specified aircraft crash and gas explosion loads to this model. The results of the analysis are the plant response to the specified loads in form of response histories and response spectra.

1 INTRODUCTION

In this work the effects from aircraft crashes and gas explosion to the reactor building of Leningrad nuclear power plant Sosnovy Bor are studied. The external events described below are discussed in IAEA safety guide [1]. In the following section some key concepts concerning the man-induced external events are presented.

1.1 MAN-INDUCED EXTERNAL EVENTS AND THEIR EFFECTS TO NUCLEAR POWER PLANT

The sources of man-induced external events, that can affect the safety of nuclear power plant are classified as: 1) Stationary: such as chemical plants, oil refineries, storage depots and pipe lines; 2) Mobile sources such as means of road, rail, sea and air transport. When sources are identified the sreening process is initiated to eliminate those sources for which no further consideration is necessary. The screening procedure may be carried out by the use of screening distance value (SDV) or, where the data permit, by a statistical evaluation of the likelihood of an event. For some sources a simple deterministic study based on information on source, distance and characteristics alone may be sufficient to show that no significant interacting event can occur. It is therefore often possible by such analysis to select an SDV for a particular class of sources beyond which sources of this class may be ignored. In the SDV approach to aircraft crash the potential sources of crash, which exist within defined distances from the nuclear power plant should be considered. The SDV is determined on the basis that any potential hazard beyond the screening distance can safely ignored. The SDV is derived from the following information: 1)Distance from the nearest major airport to the plant; 2)Type of air traffic and number of movements; 3)Location of air traffic corridors and air route crossings; 4)Distance from the plant to military installations such as military airports and practice bombing ranges. The more detailed alternative for SDV in case of aircraft crash is an screening probability level (SPL) method. The screening probability level is determined such that it will not be necessary to consider events of that have lower probability of occurrence than SPL. The approach for selecting the design basis for aircraft crash is to establish a design basis probability value (DBPV) for the crash. The DBPV can be taken as an order of magnitude greater than the SPL, since it is recognized that the probability of occurrence of serious radiological consequences resulting from an initiating event is normally at least an order of magnitude less than the probability of occurrence of the initiating event itself. As for gas explosions which are also considered in this paper similar procedures are used.

2 DESIGN BASIS FOR RBMK PLANTS

2.1 Aircraft crash

All RBMK units in operation today are situated in the east European part of former USSR. They are far away from civil and military airports and from major air traffic routes. In the reference [2] it is stated that at least an area with a radius of 15-30 km around the RBMK sites is free of installations of this kind. Consequently the locations of the RBMK sites can be characterised as favourable with regard to risk of aircraft impact because the general flight density is very low there. For a fast flying military aircraft a value of 10^{-9}/a is given in [2] as a general crash probability in eastern Europe far away from military airports when considering a characteristic area of 104 m^2. When taking into account also light aircraft (weight < 6 t), values of about 10^{-8} -10^{-7}/a /104 m2 are reported for the total crash probability of all types of aircraft under these circumstances. From these numbers an average probability value of 5 x 10^{-8} /a /104 m2 (or 5 x 10^{-12}/a /m2) was deduced which shall be taken as a representative description of the aircraft risk at RBMK sites in Eastern Europe.

According to international practice adopted in 1990-92 the USSR Ministry of Defence, Civil Aviation Research Institute and Physics and Power Institute conducted researches on probability assessment of aircraft drop on the South Urals NPP Site [3]. Except for assessment of a particular flight situation close to the site this research comprised problems of assessing the general air flight situation in the European part of USSR. This is the part, where all operational RBMKs are located. These data comprise every type aircraft used today, both civil and military and also their debris separated in flight.

According to this data if there are no military installation close to the NPP, probability of a high-speed aircraft drop P_0 is equal to $1*10^{-8}$ /year. The most contribution to probability P_0 is done by the so-called local aviation (aircraft weight up to 6 tons), but total probability of drop does not exceed $1*10^{-6}$ - $1*10^{-7}$ /year on the effective area 1000 square miles. Further the $5*10^{-7}$ /year value is adopted as an average probability assessment of aircraft drop on 1000 square miles area.

2.2 Gas Explosion

According to the building codes valid today for nuclear construction in Russia the design pressure of the frontal shock wave to be considered for newly designed NPPs amounts to 10 kPa with a compression phase of 1 second. An other value is used for the Leningrad plant, where a design pressure of 7 kPa is considered. The level of pressure waves considered for other RBMK plants should be similar to that of Leningrad NPP. The NPP site locations are chosen so, that they are far away from traffic lines (railways, main roads) and they are also located in sufficient distances from rivers and other navigable waters. Particular attention is given that there exists no dangerous industrial installations in the vicinity of NPP-site and especially that the hazard from gas pipelines can be excluded.

2.3 Assessment of Aircraft Drop Aftermath on the RBMK Site

The impact of an aircraft is a local character. The engineering experience shows that major aircraft drop aftermath is following: 1) Direct hit of an aircraft, its debris or structure parts at equipment of safety important systems and its damage; 2) Fire due to fuel ignition; 3) Equipment failures, that are caused by oscillations of structures or oscillations transmitted through ground to structures and equipment. In this case important are such factors as physical separation of systems in one building, remoteness of one building from one another etc., when assessing an aircraft aftermath.

Recently some Russian organisations have carried out researches on analysis of probable aircraft catastrophe aftermath for nuclear and/or radiation dangerous installations of different type VVER-440 and VVER-1000 NPPs, research reactors, spent fuel facilities, fast reactor NPPs, RBMK NPPs, NDHP-500 etc. references [2] and[3]. Summarising these researches it is possible to come to following conclusions: 1) Aircraft drop directly on the ground within installation area or on a nearby structure causes fast decaying high frequency oscillations. Intensity of these does not exceed by amplitude an earthquake of intensity grade 4-5 in MSK scale; 2) Dynamic high frequency oscillations of monolithic reinforced structures also are fast decaying and their possible effect is measured at distance of 25-40 m; 3) According to valid domestic Russian regulatory documents impact resistance of concrete structures even by a high-speed military aircraft for materials used in the industry is ensured with reinforced concrete thickness 1,2-1,5 m.

Probability of which structure dropping aircraft hit, is determined by relationship:

$$P = P_0 * F_3/F_0 \qquad (1)$$

where F_3 - effective area which is a projection of the structure component area onto the plane perpendicular to the aircraft travel trajectory, F_0 = 1000 square miles and $P_0 = 5 * 10^{-7}$ /year for RBMK-units. The effective area F_3 for typical RBMK designs without spherical or cylindrical containment is determined by relationship:

$$F_3 = F_b * \cos B + F_k * \sin B \qquad (2)$$

where F_b = vertical wall area; F_k = roof area; B = aircraft trajectory angle relative horizon. This relationship can be considered as assessment from above as strength and reliability margin is concerned, since it is true for assumption of equal danger of every aircraft flight direction to a structure. Taking in consideration recommendations on equal probability of aircraft trajectory angles from 10 to 45 degrees it is possible to adopt

$$F_{ap} = F_b * \cos 10^\circ + F_k * \sin 45^\circ \qquad (3)$$

as preliminary calculation value for F_{ap}, which is deliberately conservative irrespective of relation of F_b and F_k areas.

3 FEM-MODELING OF THE LENINGRAD NPP

3.1 Description of the structure

In this work the reactor building of Leningrad NPP Sosnovyi Bor has been modelled. The reactor building is at bottom 70,5 m wide at wider part and 52,5 m wide at narrower part in longitudinal cross-section. In transversal cross-section it is 66,9 m wide at wider part and 23,5 m at narrower part. The building from different directions is depicted in Figures 4, 5 and 6. The origin of global system of co-ordinates is at grade level of the reactor axis. The x-axis is parallel to longitudinal axis of the building; y-axis is parallel to transversal axis of the building and z-axis vertical. The building contains 10 walls at longitudinal cross-section and 8 walls at transversal cross-section.

3.2 Used finite element programs and element types

Modelling has been made by 3-D finite element modelling programs MSC/PATRAN, MSC/NASTRAN and FEMAP. FEMAP is an application inside MSC/NASTRAN FOR WINDOWS -program [4], [5]. Elements used in modelling were rectangular shell element QUAD4 with four nodes and two node, straight beam element with standard I-cross section. The co-ordinate system used was rectangular, Cartesian XYZ-co-ordinate system. The QUAD4 surface elements were flat shell elements, which were used to model the middle surfaces of floors and walls in two dimensions and their thickness was given as element property. Beam elements were used to model one-dimensional structures and their cross-sectional shape and dimensions were likewise given in element property table. In whole structural model there were 5605 nodes and 7510 elements. Each node in the model had six degrees of freedom, translations in the X-, Y- and Z-directions and rotations around these directions. The number of degrees of freedom in whole model was 36630. The thickest shell element in model is 2,04 m thick and the thinnest is 0,23 m thick. The thickest elements were in two internal walls. The thinnest elements were in various internal floors. The thickness of I-beam webs is 10 mm at the centroid. The base slab of the building was modelled to be fixed in all six degrees of freedom at all nodes. Consequently, there can not be any translation or rotation on those nodes. It is important to point out also the directions of the local co-ordinate system of the shell elements, because stress resultants and loads are given in local co-ordinate system. In FEMAP the positive x-axis of local co-ordinate in an element has the same direction as the side one of the generating surface. The direction of local y-axis is determined by the direction of side two of the generating surface. The positive direction of z-axis of generating surface as well as element is then determined by right hand-rule. The top side of the element is on the side of positive z-axis and the bottom side of the element is in the side of negative z-axis.

4 APPLIED LOADS

4.1 Aircraft crash

The sample load time functions used in this study and corresponding to the definition in IAEA safety guide [1] are: 1) the load/time-function for the crash of a military aircraft General Dynamics Phantom RF-43E with a velocity of 215 m/s, whose impact area is assumed to be 7 m2. This load/time-function covers a wide range of military and civil aircraft; 2) load/time-function is for Cessna 210 crash at 360 km/h. Averaged impact area is assumed to be 4 m2. These load time functions are depicted in following figures

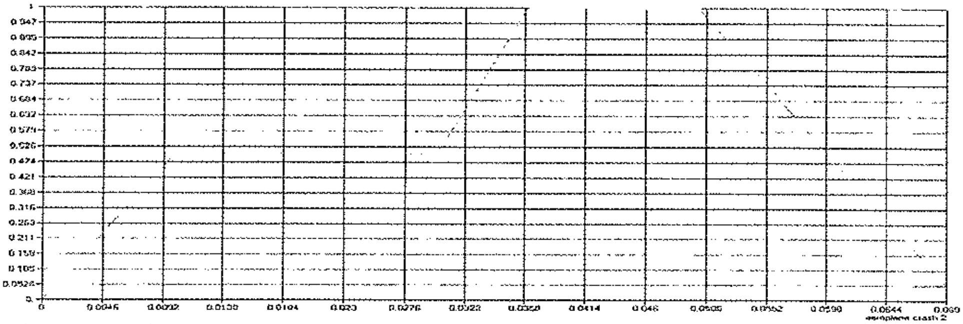

Figure 1 Load/time function for Phantom RF-43

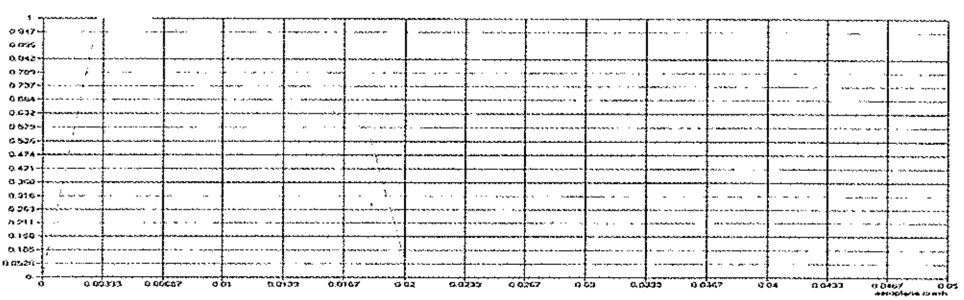

Figure 2 Load/time function for Cessna 210

4.2 Gas Explosion

The gas explosion load analyzed in this study is a deflagration of gas cloud, whose load/time-function is shown in the following figure. It is from deflagration of spherical cloud with about 50 m diameter. The velocity of pressure wave is 350 m/s. The load determination corresponds to IAEA guide [1].

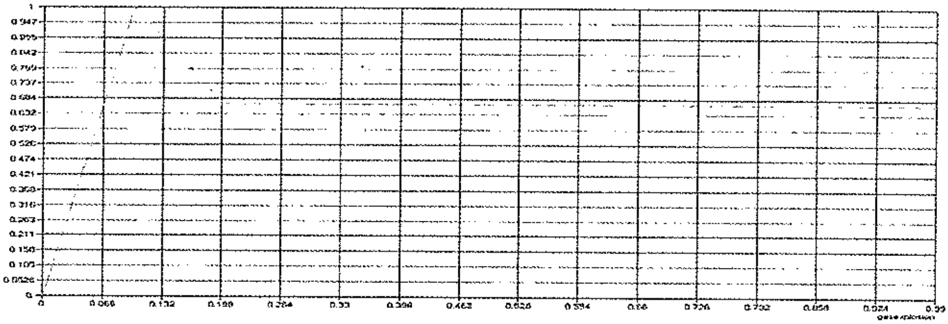

Figure 3 Load/time history of the gas explosion pressure wave

5 RESULTS

The analysis for both load types was carried out using direct time integration method. In aircraft crash analysis time step was 0,003 s and time range 0,3 s, so 100 displacement and stress states were available from analysis. In gas explosion analysis time step was 0,01 s and time range 1,0 s, so 100 displacement and stress states were available from this analysis, too. In all six hypothetical Cessna and two Phantom crashes were investigated. One direction for the incident gas explosion shock wave was investigated. In the following figure displacements from own weight are depicted

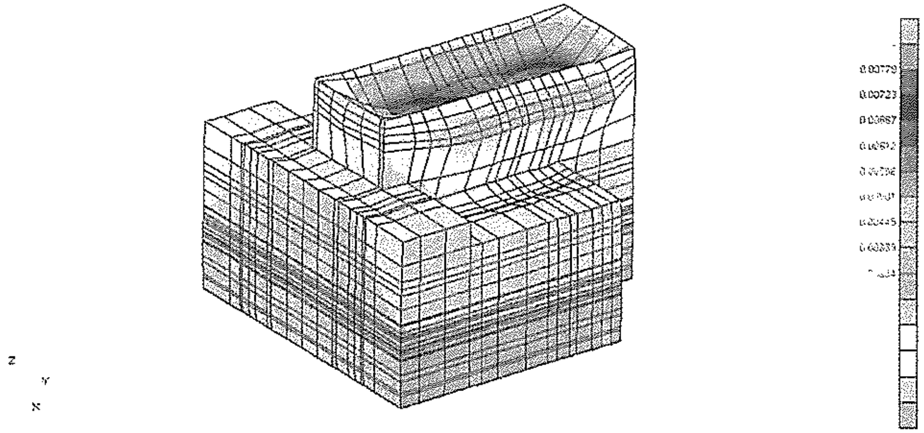

Figure 4 The finite element model for Leningrad NPP and displacements from own weight

The impact displacements and displacement time history from one typical Cessna crash are depicted in following figures

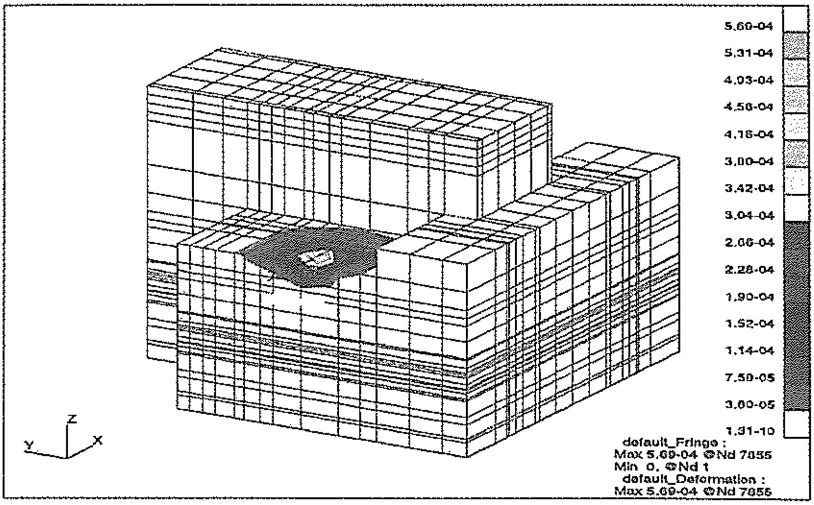

Figure 5 Displacements from Cessna 210 crash

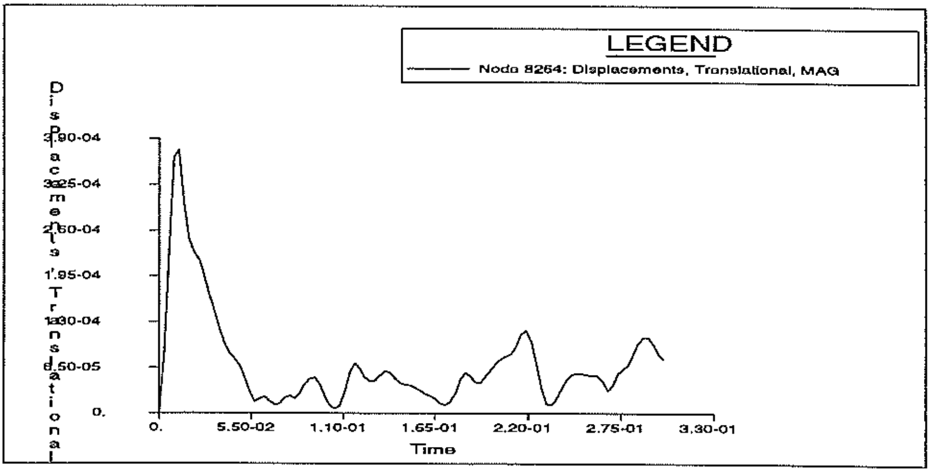

Figure 6 Displacment time history for Cessna 210 crash

In the following figure the displacement distribution for the gas explosion load is given. The approach direction of the shock wave is the negative global x-direction. The largest values of displacement occur in the upper portion of the sidewall of the reactor hall as can be seen from the figure.

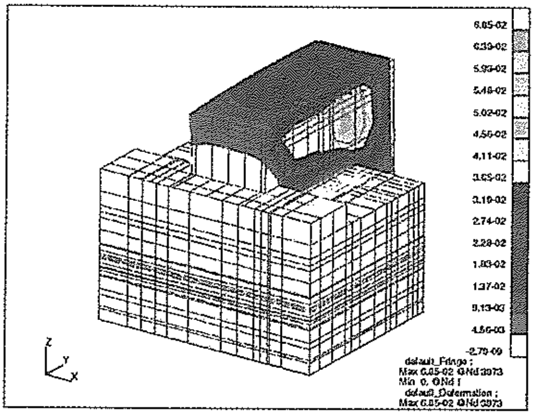

Figure 7 The displacement distribution from gas explosion shock wave

6 CONCLUSION

Nine aircraft crash locations were investigated. Only one direction for incident gas explosion wave was investigated. The modelling in this study contains following simplifications. The impacting load in airplane crash analyses is modelled to affect only one node point in the model. In reality the force is distributed to a larger area and affects the structure more like a distributed pressure load. The cracking of concrete is not taken into account. The non-linear effects, whatever is their cause, are not taken into account. Airplane crashes caused by Cessna 210 did inflict quite small displacements and stresses in cases when the load affected intersection points in the model, where two or more walls or floors met. The greatest displacements obtained in investigated cases was 11 mm in the case when load was located in the span between intersections and minimum displacement was 0,4 mm when load was located exactly at intersection. Similarly, in the case of gas explosion load, the displacements and stresses were greatest at areas, where no intersections were present. Those areas were mostly in upper part of reactor building and the greatest displacement about 7 centimeters appeared there.

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