On the Floor Response Spectra due to Aircraft Impact

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1 ABSTRACT

Assessment of the effects of a large aircraft impact on a NPP reactor building are the basic topics of the present work. The focus is on the dynamic response of the internal sub-structures, by means of floor response spectra. The factors influencing the floor response spectra, as the nonlinearities of the impact area, load time function shape and the impact velocity are pointed out and subsequent conclusions are made. Alternative motion parameters for assessment of the damage potential and procedure for indirect assessment of the equipment capacity are also discussed.

2 INTRODUCTION

The load case – aircraft impact, is not new in the Nuclear Power Plant design. It can be considered, that the starting point, has been the request of the US National Regulatory Commission in 1968 for safety evaluation of the Three-Mile Island nuclear power plant station against accidental aircraft impact, Riera (1980). Impact of commercial aircraft has been considered and as representative case, normal impact of Boeing 720 with velocity of 103m/s was investigated. As part of this project, the method for calculation of the load function of aircraft impact on rigid target has been developed and published, Riera (1968). The work is considered as pioneering study of the aircraft impact problem and the developed method developed for load function calculation, known later on as Riera’s method, is still used today.

Later, in the early 1970’s the aircraft impact problem was subjected of widening interest from both sides of the Atlantic, which resulted in large number of relevant publications. Two main trends were formed. The US concept, i.e. impact of commercial aircraft - Boeing 720 or 707 class at landing speed – and the German concept for impact of military fighter aircraft at flight speed. Based on the work of, Drittler and Gruner (1973), an official design load function of Phantom II was introduced by the German Department of the Interior in 1974, Henkel and Wölfel (1984). Consequently, several national regulatory agencies introduced the load case aircraft impact as design basis. Therefore, after 1974 several plants in Switzerland, Belgium and all nuclear power plants in Germany have been specifically designed to resist accidental aircraft crash.

Since, the first studies of aircraft impact on nuclear facilities in the seventies, the engineers’ attention was concentrated on both aspects from structural mechanics point of view: 1) the structural capacity to be assured and 2) all components within the structure must sustain the induced vibrations.

The second aspect leads to the calculation of the floor response spectra (FRS), thereafter used for equipment and components design. The standard procedure is to use deterministic approach. The time dependent forcing function is applied at several selected locations, usually assuming normal impact. The response of the structure is then calculated by numerical integration of the equation of motion, as it is in the classical structural dynamic. This is done for every loading condition, i.e. point of impact. Since, the accidental aircraft impact is considered as design basis loading and not serious damages are expected on the structure, very often the dynamic response of the structure is obtained with elastic time-history analysis. In order to account for some local non-linear response of the structure in the vicinity of the impact location, the load function has been modified by reducing the maximum impact force and extending the time, keeping the impulse unchanged, Henkel and Klein (2007). Finally, enveloping of the FRS at every location from interest obtained for different impact scenarios is performed. Generally the attention is concentrated on the acceleration FRS and on the absolute acceleration at the nodes with equipment location. It was found that the peaks of the acceleration FRS are generally in the 8-40Hz range and that above 10Hz it may be expected that
the peak values will exceed the spectral acceleration of the seismic FRS, Riera (1980). Also it was found that the obtained FRS were very sensitive to the analysis input parameters – FRS corresponding to reaction-time curves for the same aircraft and impact velocity, but obtained by different methods, may be quite different in the high frequency range: the corners of the polygonal approximation to the reaction-time curve introduce high frequency components that play a decisive role in the values of the floor spectral acceleration in the high frequency range; the local non-linear response will filter and modify the vibration loading on the internal structures and equipment. All this uncertainties together with high peak values of the acceleration FRS (AFRS), which may be several times larger than the acceleration of gravity may lead to expensive design requirements, which do not necessary lead to improvement of the plant reliability. Despite, the shortcomings of both, the “deterministic” approach and of the using of acceleration FRS (AFRS) only, were pointed out in the early beginning of studying the problem – aircraft impact, both concepts are still state-of-the-art today. Respectively, the same uncertainties are still valid.

After, the events from September 11, a new load case was born – intentional impact of large passenger airliner. The loading parameters – peak force, load function shape, impulse – will vary significantly by changing the aircraft size (mass) and impact velocity. From structural engineer’s point of view, the aircrafts can be divided in three groups: Group A – large aircrafts with weight more than 330t (A380, A340, B747, B777); Group B – intermediate aircrafts with weight between 150t and 330t (A300, A330, A350, B767, B707); Group C – small aircrafts with weight less than 150t (A321, B737).

Figure 1, is qualitative comparison between the normalised load time functions of Phantom II and Boeing 707 describing accidental crash and available in the literature, Henkel and Wolfel (1984) and the load functions of or Group B aircraft and or Group A aircraft describing malicious impact. It is obvious that this new loading is from completely different scale, therefore can not be treated as the design basis load cases of aircraft impact. To satisfy the new high demands, raised from this new load case, new activities and investigations of airplanes impacting nuclear power plants were prompted. Presently the research is concentrated mostly in three fields – 1) coupled analysis taken into account the missile-target interaction, 2) refined modelling and dynamic analysis of the target structure considering the material non-linearity and 3) alternative procedures for assessment of the damage potential of the induced vibrations additionally to the classical approach of using AFRS. With the present work, the authors hope to add some contribution to the last two fields.

![Figure 1. Selected load time functions for different aircraft impacts](image)

## 3 METHOD OF INVESTIGATION

The presented work is concentrated on the assessment of the floor response spectra due to impact of large commercial aircraft. The analysis is decoupled, therefore the aircraft is presented by load function according
to the Riera method, Riera (1968). The reactor building is represented by detailed spatial model taking into account the non-linear material behavior and soil-structure interaction. The basic goal is to perform parametric study of the factors influencing the floor response spectra and to propose alternative approach for assessment of the damage potential of the induced vibrations. For the purpose series of non-linear time history analyses of complex spatial model are performed varying some significant parameters.

3.1 Object of the investigation

Representative structure of typical double shell reactor building, designed to resist impact of military jet is object of investigation in the present study. The structure includes all basic elements of modern reactor building. Double-shell containment concept is used to meet the safety requirements. Pre-stressed reinforced concrete is used for the inner containment. The outer protective shell is constructed of non-stressed reinforced concrete, aimed at protection against external hazards. Inside the containment the Accident Localization Area (ALA) is situated where all the basic equipments of the primary circuit is positioned. At two sides of the containment two adjacent annexes are located and all the structures are supported by a common foundation part. A vertical cut of a typical reactor building structure used in the present analyses is given in Figure 2.

Several aircraft crash scenarios are analysed in the present work of impacts with different speed on the cylindrical part of the protective shell. The floor response spectra evaluation is performed for two levels from ALA. The impact location and the response levels are shown in Figure 2.

![Figure 2. Schematic view of typical reactor building employing the double shell concept.](image)

3.2 Loading

According to the today state-of-the-art, the aircraft impact loading can be presented as load function, Riera (1968), with corresponding impact area or by direct numerical simulation of collision of two bodies, Henkel and Klein (2007), Jovall (2007) and Stepan (2007). At the present study the first approach is used. Representative aircraft from Group A, is modelled as a stick with mass distribution \( m(x) \) and crushing strength \( Re(x) \), where \( x \) denotes the distance along the fuselage from the nose up to the current section that undergoes crushing. The force acting on the target, according to the Riera’s formula, Riera (1968), can be calculated using eqn (1):
\[ F(t) = Re[x(t)] + |x(t)|V^2(t) \]  \hspace{1cm} (1)

Furthermore, with some modification of the original method, separate load functions are calculated for all distinct structural parts of the aircraft – fuselage, wings and engines. Afterwards, the calculations are repeated with different velocities from 100 to 160 m/s and different fuel quantity as percent of the fuel capacity. Generally, the impact of the wings together with the central reservoir, control the shape and the intensity of the load function. Figure 3 illustrates the influence on the impact velocity over the normalised wing’s load function shape and intensity. Generally, with increasing the velocity, the load function becomes sharper – higher peak loading, steeper loading slopes and shorter duration. Except on the structural capacity, these effects have also serious effect on the shape and intensity of the AFRS. The impact area is based on geometrical considerations.

**Figure 3.** Normalised impact load functions of representative aircraft from Group A, for impact velocities ranging from 100 to 160 m/s.

### 3.3 Numerical model and analyses

A detailed 3D model of the reactor building is developed. Shell elements are used for the model creation and different element integration orders were applied depending mainly on the significance of the area. Also the main equipment units are considered in the model, taking in account their geometry, mass and connection with the structure. The soil-structure interaction is represented by spring elements.

All analyses are executed with the SOLVIA finite element code and direct time integration method is used with a basic time step of 0.0005s as it is varied in specific places of each analysis.

In the containment shell model finite elements have been used simulating all cross section elements – concrete core, steel facing and reinforcing grid. In order to increase the solution accuracy, the containment shell is simulated by plane SHELL elements with increased number of integration points in the cross section depth,–which is 7. To these 7 integration points in the concrete core, additional integration points have been added for the rebar layers. Thus one could analyse the stressed state and degree of concrete damage within the depth of the containment structure wall together with the stress condition of the reinforcement. Principal composition of the finite elements used is shown on Fig. 4 (left upper corner).

Non-linear models of the materials are used; in this way the stiffness of the elements is being continuously modified during the computation process, depending on the deformations accumulated in the structure and the constitutive stress-strains of the materials used. The steel liner and the reinforcement are modelled, as plane disks with cross section equivalent to the reinforcement. Bi-linear elasto-plastic material is used. The material constitutive laws are shown on Fig. 4.
Figure 4. Composition of the finite element used, together with the material constitutive laws.

4 RESULTS

To describe the sensitivity of the calculated AFRS depending on the different input parameters, comparison of AFRS for different load functions was made. The influence of the type of the load function used (discrete for particular velocity or enveloped) and the influence of the impact velocity were investigated.

4.1 Influence of the load function shape

When analysing several impact scenarios as locations and with several impact velocities for each direction, one can be tempted to reduce the input load functions by enveloping 2 or 3 load functions with close velocities. Doing so, the engineer will be on the safety side when evaluating the structural capacity, since the enveloped load function will increase the impulse and thus the input energy. However, such enveloping modifies the dynamic parameters of the impact loading and can eventually lead to incorrect calculation of the FRS and eventually underestimation of the maximum spectral acceleration. On figure 5, an example of AFRS computed on response level 2 for load function with impact velocities 120, 130 and 140, together with the AFRS from load function which envelopes the mentioned load functions.

Figure 5. Influence of the load function shape/type on the AFRS.

According Figure 5, the AFRS from the enveloped load function, cover the spectral acceleration corresponding to the fundamental mode of the internal structure, but underestimate the high frequency response therefore can lead to non conservative assessment of the equipment.
4.2 Influence of the impact velocity

Another interesting topic for investigation is the effect of the impact velocity on the internal structure response. There is no doubt, that most damages on the structure will be produced by the impact with the highest velocity (If all other conditions are the same). However, this can be not so straightforward regarding the floor response spectra. With increasing the impact force and therefore the damages of the structure, the dynamic response will be modified due to the non-linearity and thus will modify the input motion of the internal structure, both as frequency content and intensity. Figure 6, describes comparison of the AFRS at response level 2 for different impact velocities from 100 to 140 m/s.

![Floor Response Spectra](image)

**Figure 6.** Influence of the impact velocity on the AFRS.

The AFRS due to the highest velocity impact is dominant in the low frequency range since the total input energy is generally higher. However, due to the strongest non-linear response the high frequencies are damped out. Furthermore, the highest spectral acceleration is actually produced from the slowest impact. This is because the structure resists the impact nearly elastic and transmits most of the energy directly to the internal substructures.

5 DISCUSSION ON ALTERNATIVE ASSESMENT OF THE DAMAGE POTENTIAL OF THE INDUCED VIBRATIONS

There is continuing trend in the earthquake engineering community to look for a better evaluator of seismic motion damage potential. Most specialists agree that the peak acceleration and the acceleration response spectra are not always efficient as indicators of the potential damage although they are simple for use and lead to direct estimation of the inertia forces. The standard seismic design still relies on classical spectral theory and on acceleration. It is out of the scope of the present work to investigate all available parameters for calculation of the damage potential of the seismic or other dynamic motion. However, example of using the cumulative absolute velocity as indicator of the damageability potential is given. Also, alternative representation of the FRS in acceleration-displacement coordinates is given.

5.1 Cumulative Absolute Velocity

The cumulative absolute velocity (CAV) is considered as a complex indicator of strong motion damageability. The CAV is estimated as an area under absolute accelerogram, therefore in indirectly take into account the frequency content of the record – high frequency accelerogram will generally give lower area than low frequency record, if the peak values are the same. The CAV is defined by the following equation:
\[ CAV = \int_0^{T_d} |a(t)| dt \]  

(4)

Where, \( a(t) \) is the acceleration, and \( T_d \) the total duration. Standard methodology for CAV calculation is developed in US NRC RG 1.166 (1997), where CAV is incrementally calculated in one second intervals, where at least one value exceed 0.025g. The threshold of 0.025g is a significant assumption for definition of standardised CAV and any change of the threshold will change the CAV value of the record. If the threshold is assumed zero, as in equation (4), than the CAV will depend from the duration definition.

On Figure 7, the CAV values computed on response levels 1 and 2 from impacts with different velocities are plotted together with the limit of 0.16\(^*\)g, given in US NRC RG 1.166 (1997). One should expect that under that limit, the damages in engineered structures are limited.

![Figure 7](image)

**Figure 7.** Influence of the impact velocity (from 100 to 160 m/s) on the value of CAV.

The decrease of the CAV, with increasing the velocity from 100 to 110 m/s is due to the beginning of the non-linear response of the structure, which damp the induced vibrations. Thereafter, the intensity of the vibration in the equipment locations will depend from complex interaction of increasing loading intensity, increasing damping due to non-linear response, change of the dynamic characteristics of the sub-structures etc. This can lead to smooth (nearly constant) or sharp increasing of the strong motion damageability, here measured as CAV, depending on the response location.

The computed values of CAV can be compared with seismic ones or with some appropriate limit, as showed as example on Figure 7. Similar procedure, based on CAV with appropriate upper limit, can be used as additional tool for indirect or preliminary assessment of the damage potential of impact induced vibration.

5.2 Acceleration Displacement Response Spectrum

The standard response spectra contained in the building codes is a plot of the acceleration vs. period (or frequency) domain which is convenient for the code design procedure, based on forces (strength). However, both forces and deformation are important in the dynamic response. Therefore it is convenient to plot the spectra in an acceleration vs. displacement domain which has been termed Acceleration Displacement Response Spectrum (ADRS). The ADRS is utilized by the capacity spectrum method, Freeman (1978), which is based on direct graphical comparison of the ADRS with the capacity curve of particular MDOF structure converted also in spectral acceleration – spectral displacement coordinates. The force-deformation capacity curve is converted in spectral acceleration-spectral displacement coordinates using the modal properties of the structure presented as equivalent SDOF oscillator. The intersection point of the capacity curve and the ADRS is called performance point, ATC 40 (1996), and gives the maximum response acceleration and displacement.

Example for comparison between seismic ADRS and ADRS computed for impacts with different velocities is given on Figure 8.
Figure 8. Influence of the impact velocity (from 100 to 160 m/s) on the ADRS and comparison with seismic spectrum.

The spectral acceleration from the impact response spectra exceed the seismic ones only in the range of extremely small spectral displacements (high frequency range), which should produce considerably smaller damage potential of the impact produced ground motion. Also, the ADRS can be used under the capacity spectrum method for simplified indirect assessment of the equipment response and capacity.

6 CONCLUSION

Series of non-linear dynamic analyses of impact of large commercial aircraft with different impact velocities are performed and floor response spectra at representative locations are computed. The results lead to the conclusion that the highest impact intensity (peak force) does not necessary produce conservative results, in form of floor response spectra. Also, the enveloping of several load functions with similar velocities, despite that is conservative for the evaluation of the load bearing capacity and that can decrease sufficiently the time cost for analysis of many impact scenarios, can lead to underestimation of the high frequency response.

The applicability of alternative “ground” motion parameter for assessment of the vibration damage potential is discussed, together with procedure for indirect assessment of the internal structures, based on code provisions for seismic design/assessment of conventional structures.

REFERENCES


