Transactions, **SMiRT-22**
San Francisco, California, USA - August 18-23, 2013
Division V

FRAGILITY ASSESSMENT OF A PRE-STRESSED CONCRETE CONTAINMENT FOR AIRCRAFT IMPACT

Anton Andonov[1], Alexander Iliev[2] and Marin Kostov[3]

[1] Chief Expert, Risk Engineering Ltd., Sofia, Bulgaria (anton.andonov@riskeng.bg)
[2] Specialist, Risk Engineering Ltd., Sofia, Bulgaria
[3] Professor, Dept. of Earthquake Engineering, Bulgarian Academy of Sciences, Bulgaria

ABSTRACT

The paper describes the procedure and the results from the assessment of the vulnerability of a generic pre-stressed containment structure subjected to a large commercial aircraft impact. Impacts of Boeing 767 and Boeing 747 have been considered. The containment vulnerability is expressed by fragility curves based on the results of a number of nonlinear dynamic analyses. Three reference parameters have been considered as impact intensity measure in the fragility curve definition: peak impact force, peak impact pressure and momentum over area. Conclusions on the most suitable reference parameter as well on the vulnerability of such containment vessels are drawn.

INTRODUCTION

Aircraft crash has been considered in the design of nuclear facilities since the late 1960's. Initially its definition was based under the assumptions for accidental crash of military or commercial aircraft. Later on, after the events from September 11, 2001 the malicious impact of large commercial aircraft also emerged as load case. The necessity to include the accidental aircraft crash within the design basis of the nuclear facility is usually based on probabilistic estimation of the hazard. Probability of 1.10^{-7} or 1.10^{-6} has been used in various countries as screening value. The inclusion of malicious impact of large commercial aircraft usually depends on the regulatory requirements in each specific country. In both cases, the structural assessment is usually deterministic. The impact resistance of the target structure is usually assessed using predefined load time function, which in some countries is supplied directly from the regulator. More recently, the use of direct crash simulation (missile-target interaction method) also emerged as a tool for analysis of the aircraft impact resistance of nuclear structures which are also purely deterministic, i.e. the structural response and resistance is assessed under specified initial conditions.

However, the aircraft impact load can vary significantly in scale depending on the assumed boundary conditions – aircraft type/class, fuel quantity and impact speed. Furthermore, for the case of accidental crash it is very difficult to precisely define and justify these boundary/initial conditions and for the case of malicious impact it is practically impossible. Therefore the aircraft impact load is associated with tremendous uncertainty, as can be seen also from the results of a recent research work on this topic, Kostov et al., 2013.

Therefore, both in the design of new and for assessment of existing power plants, it is reasonable to estimate the structural capacity to impact loads in a probabilistic manner, usually presented by fragility curves. If the aircraft impact hazard is clearly defined the probabilistic capacity can be used to estimate directly the risk for structural failure. Furthermore, the structure can be designed/assessed to satisfy different acceptance criteria for different aircraft impact intensities with different probability of occurrence. In case of postulated malicious impact, the fragility curves can be used to estimate the limiting capacity of the structure as well the probabilities of failure under different impact scenarios, i.e. different combinations of aircraft types/classes, masses and impact speeds. This approach for multi-level aircraft impact assessment is in line with some current draft guidelines of the Agency, IAEA (2012) and IAEA (2013).

SCOPE OF THE PROBLEM

It is widely accepted to represent the vulnerability of a structure to fail under any arbitrary load through a fragility curve. The fragility curve describes the conditional probability of failure as a function of external load level and expresses the capacity of the investigated structure to resist the applied load as well the uncertainty in evaluating the capacity. Essential element in the fragility curve calculation is the selection of appropriate parameter describing the load level/intensity, which in the case of impact of large commercial aircraft is not as straightforward as for other loads considered in the design/assessment of nuclear facilities. The aircraft crash will produce several effects: soft impact of the fuselage and the wings, hard impact of the engines and the landing gear, internal vibrations and fire. While hard impact is usually associated with local damage, i.e. perforation, the soft impact is usually associated with global structural failure due to excessive deformation in a wide fragment of the impacted structure. Therefore, the aircraft impact intensity depends on the aircraft type (geometry, stiffness, mass) considered and the impact velocity, which makes it difficult to express by a single parameter. The currently available technical literature also does not advice about the most suitable parameter expressing the aircraft impact intensity.

The fragility curves for hard impact can be reasonably expressed by the impact speed, since the other parameters – shape/diameter, stiffness and mass can be easily restricted within narrow borders. There are also a significant number of empirical formulas for assessing the resistance of RC plates to perforation, penetration, scabbing and spalling. However, the use of fragility curves referred to the impact speed for soft impact will require to constrain the other aircraft parameters: type and mass (including fuel quantity), which restrict these fragility curves to be representative only under this boundary conditions, i.e. for specific aircraft under specific initial conditions (fuel mass and payload). This means that any change in the boundary conditions will require the definition of a new fragility curve, which besides being not practical, also does not correspond to the “physics” of the fragility curve which shall depend solely on the mechanical properties of the structure under consideration. Therefore if fragility curves based on speed are used, they shall be calculated per strictly defined impact scenario, which includes impact location, aircraft type and mass (fuel and payload).

A load intensity parameter, which includes the main aircraft impact characteristics- stiffness, mass and velocity, is the peak impact force (PIF) calculated by using the Riera’s method, Riera (1968), or through finite element analysis. The peak impact force is one of the impact intensity parameters used in this research study. Since the same PIF can be obtained by a different combination of aircraft mass and velocity, the calculated aircraft impact capacity/margin referred to PIF could be related to several crash scenarios with different initial conditions (mass and velocity). However, the parameter PIF does not take into account the impact area, i.e. the aircraft type. Therefore if fragility curves based on PIF are used, they shall be also calculated per impact scenario, which includes aircraft type and impact location. It is logical to expect that the maximum load per unit surface shall provide better indication about the load intensity and the potential for initiation of failure of the investigated structure. Therefore, the applicability of the peak impact pressure (PIP) as reference parameter for fragility curves is also investigated. The PIP is obtained by simply dividing the PIF to the total impact area (the maximum value through the entire load time history). The advantage of using PIP is that the impact area, i.e. the aircraft type, is included within the reference parameter. Therefore the fragility curves can be calculated only per impact location i.e. will be function solely of the structure. The current research paper proposes and assesses the applicability of a third parameter for expressing the aircraft impact intensity, which is momentum over area (MoA). The momentum, which is simply the product of the mass and the velocity: $I=m*V$, is commonly used as measure of the impact intensity. The momentum can be converted very simply to any arbitrary combination of aircraft mass and velocity. If the momentum is divided to the impact area, this intensity measure can be easily related to any arbitrary combination of aircraft type, mass and velocity. Therefore the fragility curves can be calculated only per impact location.

Results and further discussion on PIF, PIP and MoA based fragilities are given in the further sections of this paper.

RESEARCH APPROACH

The commonly accepted current understanding is that the deliberate impact of large commercial airplane shall be considered as Beyond Design Base Accident (BDBA) / Design Extended Conditions (DEC), NEI (2011) and IAEA (2013). The requirement that an intentional impact of commercial airplane shall not lead to severe accident conditions leads to the following sufficiency criteria, NEI (2011):

- Reactor core remain cooled or the containment remains intact, and
- Spent fuel pool remains cooled and spent fuel poll integrity is maintained.

The current paper deals with the second part of the first sufficiency criterion which is related to the two main functions of the containment structure: to protect the safety related nuclear equipment from external impacts and to protect the environment from the radiological substances inside the containment volume, i.e. to provide confinement. According to the requirements in NEI (2011) the containment structure is considered to be acceptable if the containment is maintained intact from both the local and global impact analyses.

The current paper is focused only on the assessment of the containment safety function to protect the safety related nuclear equipment from external impacts, i.e. assessment of the structural resistance against aircraft impact loading. The structural resistance against aircraft impact within this study is assessed in terms of resistance against global failure due to the overstressing of wide zones of the containment wall. The assessment for local failure and for the other two significant phenomena associated with the aircraft impact, the induced vibrations on the internal structures and the fire load, are not discussed herein.

Description of the studied containment building

The studied herein containment structure is a generic pre-stressed concrete containment vessel (PCCV) with parameters selected in a way to be close with the main characteristics of many current 2nd generation reactor buildings using large dry post-tensioned concrete containment with steel liner as a single shell providing confinement of radioactive materials and protection of the internals from any external hazards. The generic containment is based on the geometrical parameters typically found for such type of structures: radius of the cylindrical part in the range of 20-25m; shell thickness in the range of 1,0-1,5m; height of the cylindrical part in the range of 40-50m;

The cylindrical part is closed by a dome structure at its top. The entire internal surface is lined with steel liner for providing of a leaktightness. Two reinforcement grids with standard for these types of structures bar diameters and spacing are located approximately 10cm inside from both surfaces. The cylindrical and dome parts of the containment are post-tensioned to approximately 6-8MPa hoop and meridian compressive stresses within the concrete section. The containment is restrained in a thick plate which is part of a spatial fundament block.

The studied containment structure does not refer to any existing or planned design. However, containment structures with similar characteristics are used for various PWR, PHWR and WWER reactor designs constructed worldwide.

The containment is modeled with six layers of solid elements and takes into account all main changes in the wall thickness – penetrations and thickened sections. The reinforcement, the liner and the post-tensioning tendons are also modeled in detail. Nonlinear material models have been used for modeling of the concrete and the steel elements. The concrete material model corresponds basically to the Ottosen model. The material properties (elastic modulus, cracking and crashing stresses and strains) have been selected as for concrete C40. Bi-linear elastic-plastic materials are used for modeling the reinforcement and the liner. The software code SOLVIA, has been used for performing the numerical analyses.

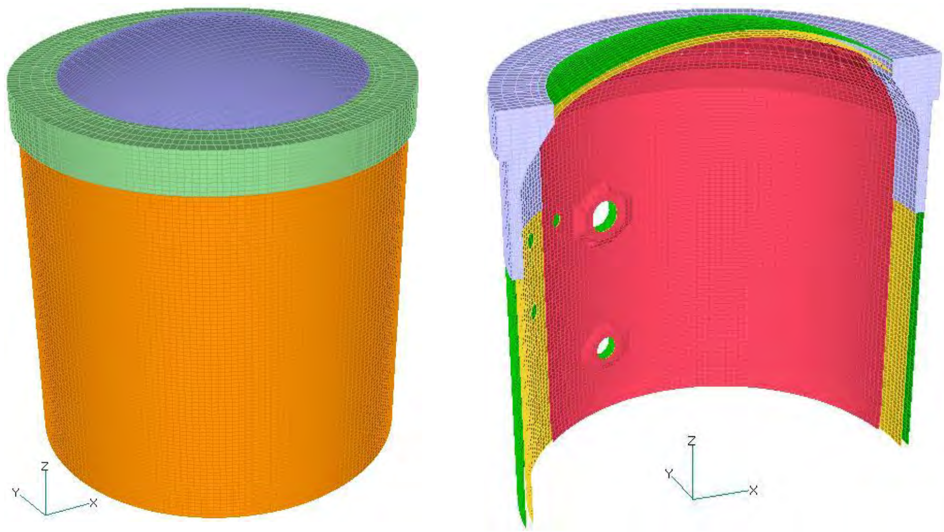

Figure 1. Three dimensional view of the studied containment structure (left) and section view showing also the steel liner (red), the internal reinforcement (yellow) and the external reinforcement (green).

Loading and impact scenarios

The problem was solved using the decoupled formulation, i.e. applying a load time function on a specific stamp on the structure. The presented herein analyses are based on load time functions calculated using the Riera approach, Riera (1968). However, the method for loading definition does not provide any influence on the current impact margin assessment and load function derived via FEA or direct loading application via coupled analysis can be equally used. Two airplane types have been considered: Boeing 767 and Boeing 747, with their specific load areas. For each aircraft type, different impact intensities have been considered by scaling the load time functions and thus taking into account any mass and velocity variation of the impacted aircraft. The peak force of load time functions of Boeing 767 used is in the range of 100-450MN, while the peak force of the used functions for Boeing 747 is in the range of 200-650MN.

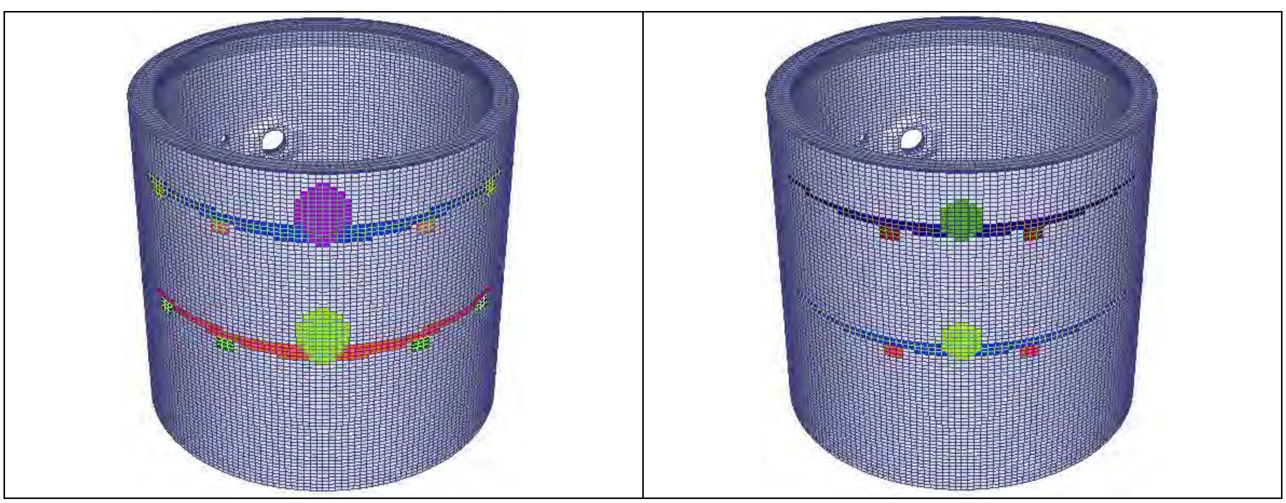

Figure 2. Impact stamps and locations: Boeing 747 (left) and Boeing 767 (right).

The possible impact locations generally depend on the aerodynamic properties of the airplane from one side and the NPP site layout from the other side. The focus of this paper is the structural resistance assessment of a generic/typical reactor containment, not associated with any particular power plant. Therefore, the impact locations are selected solely on the geometrical and structural properties of the target building, covering impacts at a different height. Two impact locations have been considered: impact on the uppermost part of the cylinder and impact at the middle height zone. The two impact locations together with the impact areas for Boeing 747 and Boeing 767 are shown on Fig.2.

The following impact scenarios are defined: Impact Scenario I – impact of Boeing 747 on the upper part of the cylinder; Impact Scenario II – impact of Boeing 747 on the middle part of the cylinder; Impact Scenario III – impact of Boeing 767 on the upper part of the cylinder; Impact Scenario IV – impact of Boeing 767 on the middle part of the cylinder.

Failure Criteria

The failure criteria are derived by taking into account the specific characteristics of the studied containment structure and the main failure modes of RC structure subjected to soft impact: global flexural and shear failure of the impacted wall. Failure of the impacted wall is considered to occur, when at least one of the following response parameters have been reached:

- Shear strain in the concrete above 0,5%;
- Compressive strain in the concrete above 0,2%;
- Tensile strains in the flexural reinforcement and the liner above 1%;

Definition of fragility curves

The fragility curves are defined by using the simulation method. For the purpose several deterministic analyses with increasing load are conducted for each impact location and aircraft type. The capacity of the structure at each loading level is derived based on the ratio between the failure strain (resistance) and the strain obtained from the analysis (load) for each loading level. Due to the ongoing status of the presented research, sensitivity analyses have not been conducted yet. Standard deviation of 10% is assumed for the “resistance” and 30% for the “load”. Then the uncertainties associated with the structural capacity are estimated and discrete values of the fragility curve related to the controlled response parameter (strain) are determined. In the end the fragility curve is transferred to the external loading parameters used.

The final result is the conditional failure probability relative to a defined parameter used for the generation of the fragility curves. This failure probability is commonly expressed as a group of fragility curves with median curve and upper and lower confidence limits. As margin value for evaluation of the investigated phenomena (component failure or loss of the safety function), the level of the evaluated excitation can be defined, at which a High Confidence of Low Probability of Failure (HCLPF) should be declared. Typically this HCLPF is defined as 95% confidence of less than 5% probability of failure.

Numerical analyses

The impact analyses have been performed as decoupled using load time functions derived via the Riera method. An implicit dynamic analysis is used to solve the impact response, with impact load applied on the initial stress conditions due to gravity and pre-stressing loading through restart from static analysis.

RESULTS

The results from the performed structural analyses for the four investigated scenarios and different impact intensities are presented below. Due to the limiting space to present the obtained results, the results are synthesized to the most representative and illustrative ones for the containment response under impact loads.

Structural response

After the analysis of the obtained results, it was found that the shell responds to the impact almost essentially in compression, with hoop compressive strains as a dominant parameter. The only exceptions are the meridian tensile strains on the internal face of the wall beneath the impact stamp and on the external surface in the zones surrounding the impact stamp. Respectively, tensile strains in the reinforcement and the liner can be found only at these locations and in meridian direction.

Explanation of the results can be found in the "static schemes" in the two main directions: double fixed arc with linear load in the central part in hoop direction and double fixed beam with point load in meridian direction. It should be pointed out here that this particular structural behavior in the present case study is attributed to the assumed characteristics of the containment (radius, thickness, pre-stressing) of the containment and the loading shape/area.

The containment failure is controlled by excessive compressive and shear strains. The failure mode is associated by compression overstressing of the external half of the cross section, reduction of the load bearing capacity of the impacted shell and subsequent rapid increase of the shear strains. As can be seen from the results in the current research study, compressive or shear failure may be dominant depending on the shape/area of the impact stamp. Generally, the failure mode will depend on the geometry (radius, thickness) of the target, the shape/area of the impact stamp and the combination of both.

The propagation of the compressive and the shear strains as function of the peak impact force for the considered impact scenarios are presented on Fig. 3. The results are used to derive the ratio "Resistance/Load" for each load level, used afterwards for fragility curves generation.

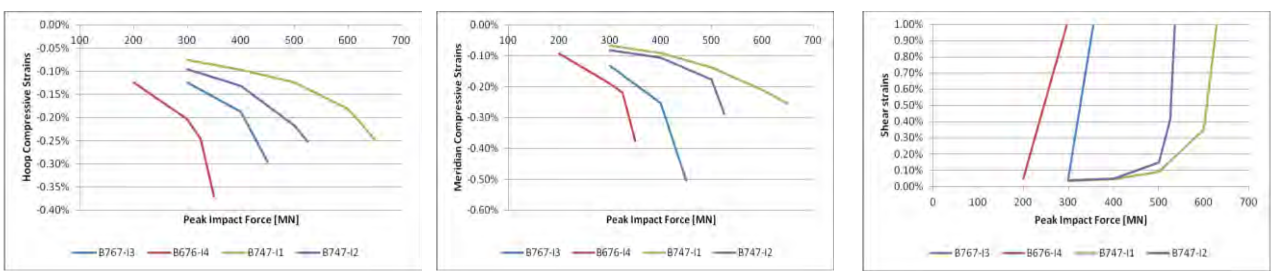

Figure 3. Concrete hoop (left) and meridian (center) compressive strains, and shear strains (right) depending on the impact intensity (peak impact force) and the impact scenario.

The impact resistance of the containment for impacts at the upper part of the cylinder is about 25-30% higher than impacts at the middle part. It can be seen also that the impact of the smaller aircraft produces higher strains even at lower impact force. This is due to the almost twice lower loading area of the B767 plane compared to B747.

Fragility curves

The fragility curves are generated using the results presented on Fig.3. For each impact scenario (aircraft type and impact location) three fragility curves are generated for each of the controlled failure modes (Fig.4): excessive hoop compressive strains (blue lines), meridian compressive strains (red lines) and shear strains (black lines). The fragility curve giving 0,5 probability of failure at the lowest load level is selected as representative of the particular impact scenario.

Several observations can be drawn on the basis of the obtained curves. The fragility curves for shear failure have much steeper slope, i.e. lower uncertainty. The reason for this is in the highly brittle nature of the shear failure leading to a very sharp increase of the shear strains after sudden critical moment of overloading, see Fig.3.

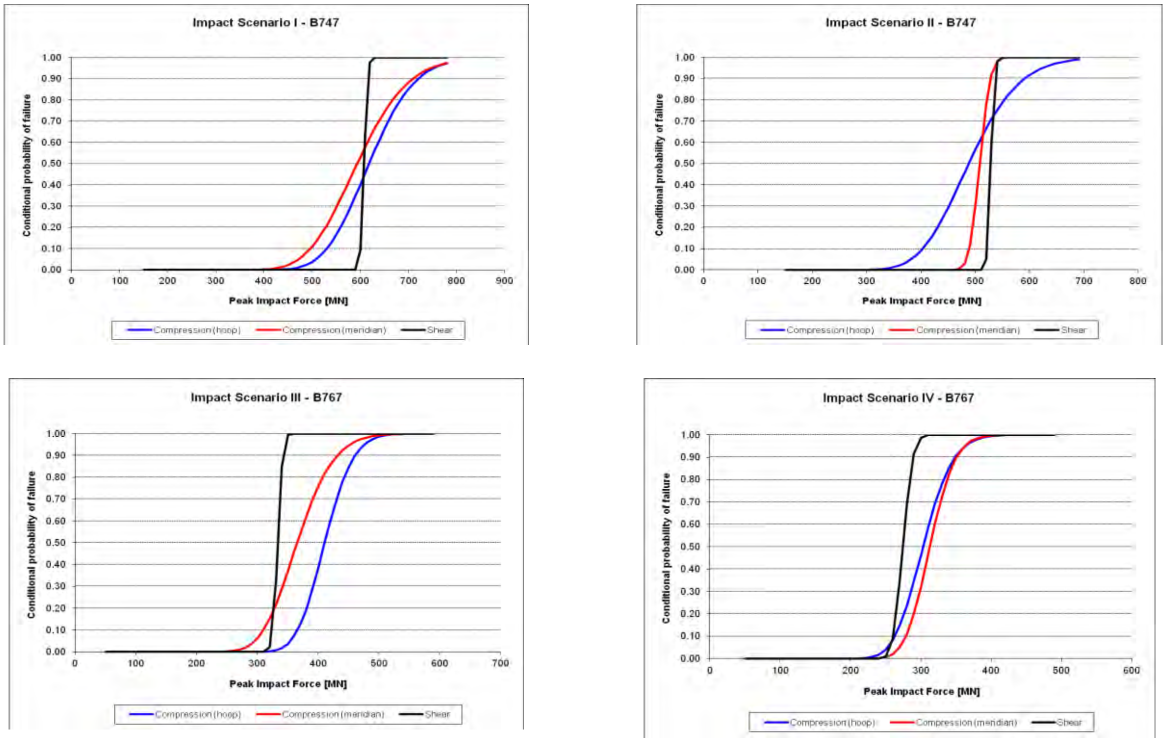

Figure 4. Fragility curves for each failure mode and impact scenario: Impact Scenario I (upper left corner), Impact Scenario II (upper right corner), Impact Scenario IV (lower left corner) and Impact Scenario IV (lower right corner).

Another interesting result is that the failure mode from the impact of B767 is dominated by shear, while the failure mode associated with the impact of B747 is dominated by a compressive overstressing. The reason may be searched in the smaller and more compact impact stamp of Boeing 767. However, it should be pointed out that for containment structures with different characteristics: geometry, pre-stressing and reinforcement quantity, this observation may not be valid.

The fragility curves based on the PIF and PIP for the four considered impact scenarios are shown on Fig.5.

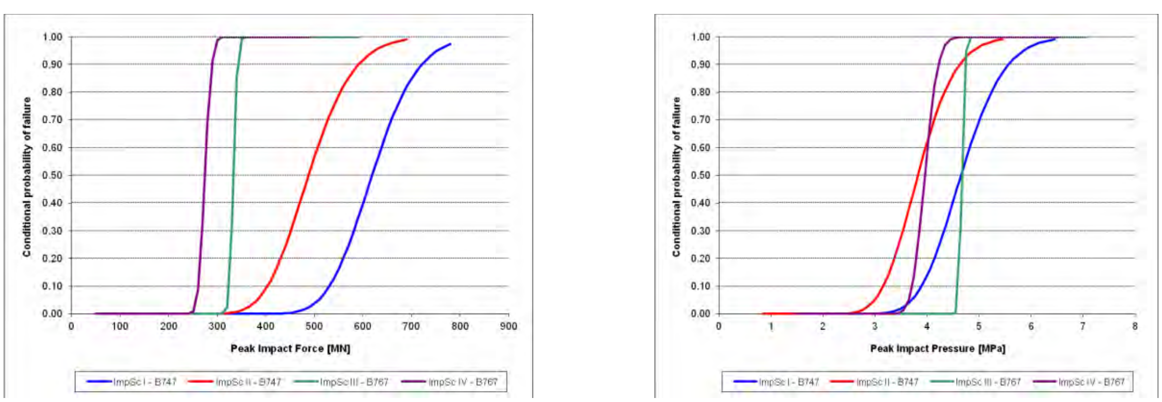

Figure 5. Fragility curves based on peak impact force [MN] (left) and peak impact pressure [MPa] developed per impact scenario.

The peak impact force provides good physical "feeling" about load, but does not represent well the "loading intensity" since it neglects other important loading parameters which affect the response as the impact area. Therefore the fragility curves based on peak impact force (Fig. 5, left.) shall be always developed per impact scenario which includes the aircraft type/load area. Additionally, it is not so straightforward to relate the peak impact force to the physical properties of the loading (aircraft type, mass and speed).

The use of peak impact pressure provides a much better description of the load intensity in terms of structural damage potential, since the aircraft type is indirectly considered by the load area. The 50% probability of failure for each impact location obtained for different aircraft types are very close. The main difference in the two fragility curves for each impact location is the slope, i.e. the uncertainty in the obtained capacity. The reason is in the different physics of the two failure modes as explained above. Therefore, it should be reasonable to combine the two fragility curves for each impact location (Fig.5, right) and thus to develop the fragility curves per impact location. However, the peak impact pressure also fails in providing clear and straightforward "physical" description of the impact load. The impact pressure can not be directly related to aircraft type, mass and velocity.

The third alternative parameter used for the description of the impact intensity in this paper, the momentum, which is simply the product of the mass and the velocity - I=m*V, is commonly used as a measure of the energy potential of an impact load. The loading applied in the structural analysis can be also directly converted to the momentum scale using the principle of conservation of momentum, i.e. calculating the impulse which is basically the area under the load time function. If the momentum is divided to the impact area, this intensity measure MoA (I/A, or m*V/A) expressed in MPa*s can be easily and directly related to any arbitrary combination of aircraft type, mass and speed. The fragility curves based on this impact intensity parameter are shown on Fig.6.

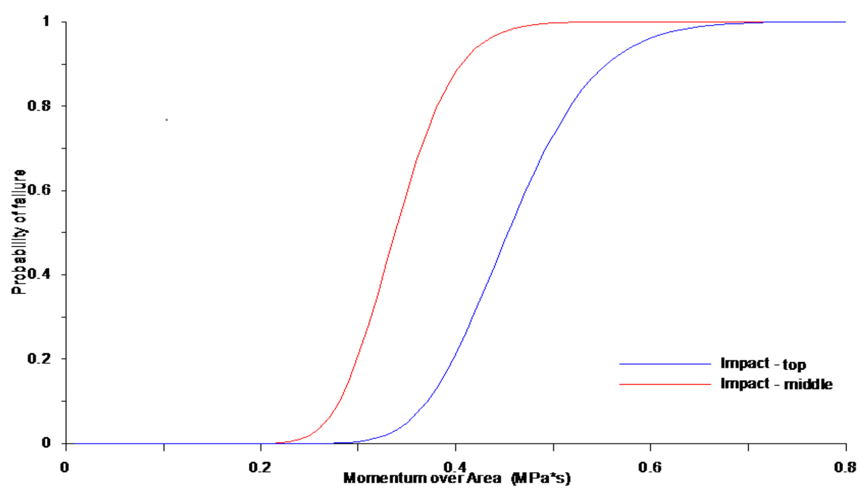

Figure 6. Fragility curves based on "Momentum over Area" [MPa*s] developed per impact location.

The fragility curves are derived per impact location since the aircraft type (impact area) is taken into account by the impact intensity measure. The two curves (from the different aircrafts) derived for each impact location are combined using the average of the mean capacities and the square root of the squares of the two uncertainties. The most proper combination of the fragility curves derived for each location is still an open issue and subject of further research.

The main advantage of using the MoA as intensity measure is that it can be directly and very simply converted into any arbitrary combination of aircraft type (impact area), mass and velocity. Such Impact intensity scale is presented in Table 1. For each value of the parameter MoA a set of arbitrary combinations of aircraft type, mass and velocity is provided. The table can be easily extended to take into account a wider range of airplanes with the corresponding boundary conditions in terms of mass (maximum takeoff and empty mass) and velocity.

Table 1: Impact intensity associated to arbitrary combinations of aircraft type, mass and velocity.

	Momentum over Area [MPa*s]			
Aircraft type, mass and velocity	0,2	0,4	0,6	0,8
	B747- 328t x 80m/s	B747- 374t x 140m/s	A380-536t x150m/s	A380-536t x200m/s
	B747- 218t x 120m/s	B747- 262t x 200m/s	A380-447t x180m/s	
	B767- 110t x120m/s	B767- 132t x200m/s	B747-393t x200m/s	
	B767- 166t x80m/s	B767- 190t x140m/s	B767-198t x200m/s	

DISCUSSION

An essential element of the presented research study is the development of adequate fragility curves. Two are the most crucial issues – selection of appropriate response parameter representing the failure and selection of appropriate reference parameter representing the load intensity. Both are not studied well yet and limiting information is available in the technical literature.

The current study is based on shear and compressive strains as failure reference parameters, which was found to be illustrative for the failure mode of the studied structure. However, it should be pointed out that these parameters may not be valid for other type of structures including containment structures with significantly different characteristics from the selected case study.

The selection of reference parameter describing the aircraft impact intensity is maybe more controversial. Despite, that both mass and speed provides good physical "feeling" about impact intensity and can be directly related to any impact scenario, they are not suitable for reference parameter in the definition of aircraft impact fragility curves. The same impact intensity could be obtained by different combinations of aircraft mass and speed, thus one of the parameter shall be "fixed" while varying the other. This will lead to "case specific" fragility curves which are valid only under these initial conditions. On the other side, any arbitrary combination of mass and velocity is implicitly considered within all of the three parameters used in this paper. The following remarks can be pointed out:

- Aircraft impact fragility curves based on peak impact force can be used but should be defined per impact scenario, i.e. for each aircraft type considered in the assessment. Some experience is necessary to relate the peak impact force to any arbitrary combination of mass and velocity.
- Aircraft impact fragility curves based on peak impact pressure can be calculated per impact location, since the aircraft type (impact area) is already taken into account implicitly. The disadvantage is that PIP can not be directly related to the initial aircraft parameters.
- Aircraft impact fragility curves based on MoA combines the advantages and eliminates the weak points of the two impact intensity measures considered above. The aircraft type is taken into account by the impact area. Therefore the fragility curves can be defined per impact location even when more than one aircraft type is considered. Furthermore, which is actually the biggest advantage of the proposed reference parameter, the MoA can be very simply and directly related to any arbitrary combination of aircraft type (impact area), mass and speed practically without the use of any complex calculations. Therefore the obtained fragility curves and the corresponding median or HCLPF capacity/margin can be directly converted to resistance against failure under any arbitrary combination of aircraft type, mass and speed.

CONCLUSION

The current paper describes the procedure and the results from the assessment of the vulnerability of a generic pre-stressed containment structure subjected to a large commercial aircraft impact. The studied containment structure does not refer to any existing or planned design. However, the selected geometrical and material characteristics are in the range of the commonly used values for such type of structures. The containment vulnerability is expressed by fragility curves developed for each impact scenario. The fragility curves are based on the results from a number on nonlinear dynamic analysis.

Three reference parameters have been considered as impact intensity measures in the fragility curve definition: peak impact force, peak impact pressure and momentum over area. The current paper recommends the use of the last one as most suitable and directly related to the physical parameters of the aircraft impact load.

Several important observations can be drawn for the analyzed containment structure based on the results from the current study:

- The studied containment expressed adequate capacity to resist impact loads in the upper range of the studied diapason. Recently published parametric study on impact load time functions for large commercial airplane, Kostov et al. (2013), has shown for example that the peak impact force with 95% confidence level for non-exceedance for Boeing 747 is about 600MN.
- The mean capacity of the containment measured in MoA is in the range of 0,3-0,45 MPa*s which corresponds to impact of practically fully loaded Boeing 747 or Boeing 767 with impact speed of minimum 140m/s.
- The failure mode of the cylindrical shell is controlled primarily by excessive compressive and shear strains, with increasing role of the compressive strains with the increase of the impact area and vice versa.
- The aircraft impact capacity of the containment for impact in the upper part of the cylindrical shell is about 25-30% higher than the capacity for impact in the middle part of the cylindrical shell.

The obtained fragility curves reefed to MoA can be then used for various additional calculations in the safety assessment of nuclear facilities under aircraft impact. At least the following can be pointed out:

- Estimation of the risk for containment failure under accidental aircraft crash with known probability of occurrence.
- Assessment of the containment safety using different acceptance criteria, i.e. different probability of failure, for aircraft crash scenarios with different probability of occurrence or load intensity.
- Better assessment of the benefits of any design modifications (for new built) and strengthening measures (for existing facilities).

ACKNOWLEDGMENTS

These analyses are partially supported by a research grant of the European Commission, research project RiskProtecCI, HOME/2010/CIPS/AG/045. The valuable comments of Mr. Georgi Varbanov and the kind technical support of Ms. Nikolina Koleva are deeply acknowledged.

REFERENCES

Riera, J. D. (1968). “On the stress analysis of structures subjected to aircraft impact forces”, Nuclear Engineering and Design, vol.8, 415-426.

NEI (2011). NEI 07-13. Rev.8P. “Methodology for Performing Aircraft Impact Assessments for New Plant Designs”, Nuclear Energy Institute.

IAEA (2012). Draft Safety report DD1086. Rev.:R1-1. “Safety Assessment of NPP Structures against Human Induced External Events”, IAEA Safety report Series. IAEA.

IAEA (2013). Draft Safety report DD1086. Rev.:R1. “Margin Assessment of NPP Against Human Induced External Events”, IAEA Safety report Series. IAEA.

Kostov, M., Iliev. A, Andonov, A. (2013). “Load Time Function definition for large commercial aircraft impact: Parametric Study”, Structural Mechanics in Reactor Technology (SMiRT22), San Francisco, USA.