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CONTAINMENT ULTIMATE PRESSURE CAPACITY WITH CONSIDERATION OF AIRCRAFT IMPACT

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ABSTRACT

The paper presents the procedure and the results from the assessment of the vulnerability of a generic pre-stressed concrete containment vessel subjected to the sequent occurrence of aircraft crash impact and elevated internal pressure, assuming hypothetical internal accident induced by the aircraft crash. The containment response under aircraft impact load is assessed for two large passenger aircrafts, respectively Boeing 767 and Boeing 747. The aircraft impact capacity is assessed by series of nonlinear dynamic analyses with increasing intensity of the loading. The ultimate pressure capacity is assessed by nonlinear static analyses restarted from the post crash initial conditions. The effect of the post crash damages on the containment ultimate capacity is assessed via comparison with the "pure" pressure capacity obtained without consideration of aircraft impact.

INTRODUCTION

The impact of a large commercial aircraft is multi-hazard loading: except direct mechanical loading on the impacted structures the aircraft impact also induces significant vibratory loading on the target building and extensive post-crash fires. The second two phenomena could lead to internal accident and elevated pressure and temperature loads in the hermetic volume. Therefore, the most widely adopted current approach for handling the aircraft impact load is by implementing the so called "double shell" concept, where an external shield structure provide protection from external hazards while an internal containment structure serves as ultimate barrier for radiological release in case of internal accidents.

Currently, almost all regulators have determined that the impact of a large commercial aircraft is beyond-design-basis event, which reflects on the acceptance criteria adopted. Heavy damages on the structures are accepted as long as do not lead to uncontrolled release of radioactive substances to the atmosphere. The second part of the first sufficiency criterion 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. The requirement that an intentional impact of commercial airplane shall not lead to severe accident conditions lead to the following sufficiency criteria:

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

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 containment remains intact if structural analyses performed show that perforation of a steel containment or concrete containment with steel liner does not occur on impact and that the containment ultimate pressure capability, given a core damage event, would not be exceeded before effective mitigation strategies can be implemented. Effective mitigation strategies are those that, for an indefinite period of time, provide sufficient cooling to the damaged core or containment to limit temperature and pressure challenges below the ultimate pressure capability of the containment. The containment ultimate pressure capability is appropriate for use provided there is no structural damage to the containment structure. If structural damage has occurred to the containment structure, a revised ultimate pressure capability considering the damaged condition must be determined NEI (2011).

SCOPE OF THE PROBLEM

Several designs for new built as well many existing nuclear power plants rely on the single containment concept. In such cases the assessment of the "intact containment" function is more complicated. Besides preventing local or global failure due to the aircraft impact, the containment shall be also capable to resist to the elevated pressure in case of impact induced internal accident. It is logical to expect that the ultimate pressure capacity of the containment structure in this case will be reduced by the initial damages due to the aircraft impact.

However, various existing studies, both experimental and analytical, on the response of pre-stressed concrete containments to high internal pressure showed ultimate pressure capacity about twice above the design basis accident pressure Therefore it could be expected that a typical pre-stressed concrete containment structure should be able to provide leaktightness under high pressure loading even with significant initial impact induced damages.

The current paper describes the results of the assessment of the ultimate structural capacity of a generic pre-stressed concrete containment structure subjected to sequent application of aircraft impact and internal pressure load, assuming that the aircraft impact has initiated internal accident. Furthermore, a procedure for integral containment capacity assessment taking into account both, the aircraft impact and internal pressure intensities is proposed and applied in the presented study. The capacity is presented as capacity envelope in "Pressure-Impact Force" coordinate system. Any combination of impact load and subsequent internal pressure within the capacity envelope means safe condition, i.e. containment intact. On the other side, any combination of impact load and internal pressure values outside the capacity envelope will refer to failure of the containment impact function. Thus the containment capacity can be assessed under any possible sequence of aircraft impact and internal accident conditions. For example to verify what could be the containment pressure capacity after the impact of certain aircraft under certain initial conditions (mass and velocity) or vice versa to verify what could be the maximum impact force which the containment could resist without losing its ability to provide leaktightness under the internal pressure from certain design or beyond design basis accident.

RESEARCH APPROACH

The structural capacity under the aircraft impact is assessed through a series of nonlinear dynamic analyses with increasing impact intensity. Several impact scenarios (aircraft type and impact locations) are considered, each one associated with a separate capacity envelope. The analyses are performed as decoupled, i.e. force-time history method. The internal pressure is then applied on the structure considering in this way the residual deformations and damages and thus the reduced stiffness of the structure.

Description of the analyzed containment building

The analyzed herein containment structure is a generic pre-stressed concrete containment vessel (PCCV) with parameters selected to approximate the main characteristics of the current 2nd generation reactor buildings utilizing the single shell concept. The generic containment is based on geometrical parameters typically found in such type of structures: cylindrical with radius in the range of 20-25m, shell thickness in the range of 1,0-1,5m and 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 pre-stressed to approximately 6-8 MPa 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.

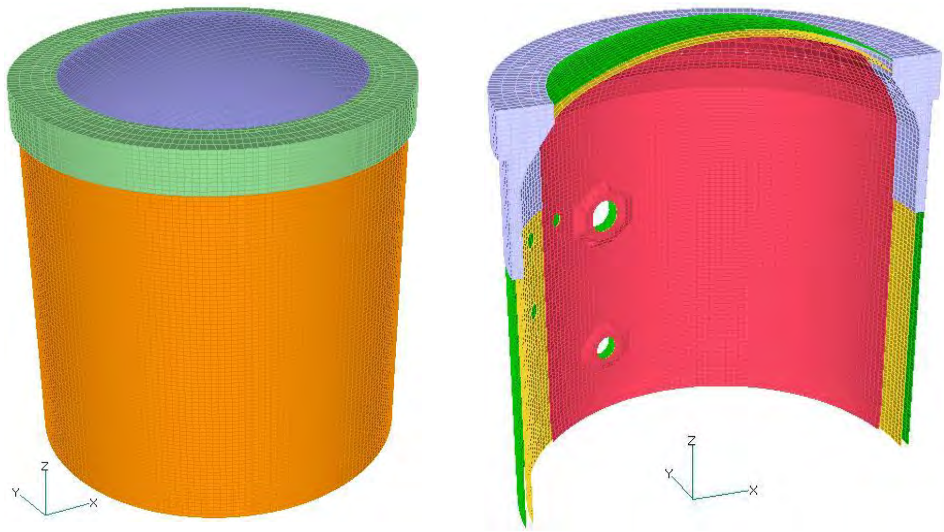


Figure 1. Three dimensional view of the studied containment structure.

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 pre-stressing tendons are also modeled in detail. Nonlinear material models have been used for modeling of the concrete and the steel elements considering also strain rate effects. 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.

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 by 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 area and load intensity range. 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 within the range of 100-450MN, while the peak force of the used functions for Boeing 747 is in the range of 200-650MN.

The selection of suitable impact locations over the target building is another important issue. Generally, the possible impact locations depend on the aerodynamic properties of the airplane on the one side and the NPP site layout on the other. 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 basis of the geometrical and structural properties of the target building, covering impacts at different height. Two impact scenarios have been considered with impacts in both cases in the middle of the cylinder: impact of Boeing 767 and impact of Boeing 747. The impact areas for Boeing 747 and Boeing 767, as used in these analyses, are shown on Fig.2. The internal pressure is applied on the internal face of the steel liner.

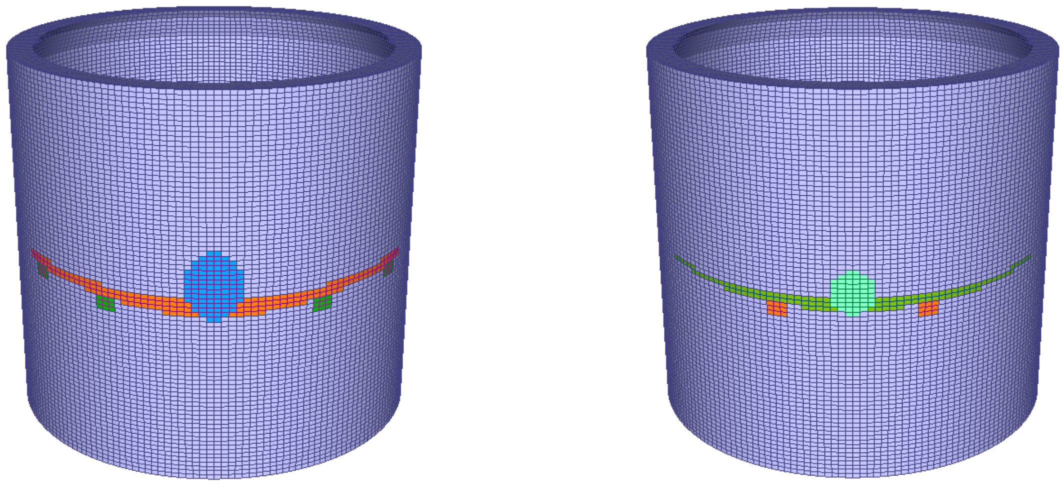


Figure 2. Impact stamps and locations: Boeing 747 (left) and Boeing 767 (right).

Failure Criteria

The failure criteria are derived by taking into account the specific characteristics of the studied containment structure and specifics of the applied loads. Two sets of failure criteria are considered, respectively for the impact analysis and for the assessment of the ultimate pressure capacity.

Failure of the impacted wall is assumed 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%;

Failure of the containment under pressure loading is considered to occur, when at least one of the following response parameters have been reached:

- Free field tensile strains in the flexural reinforcement and the liner above 0,4%;
- Free field tensile strains in the tendons above 0,4% (excluding the initial strains due to the pre-stressing);

Numerical analyses

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. All analyses are performed using nonlinear material models. The pressure loading is applied on the internal surface of the steel liner as monotonically increasing up to the moment of failure loading. The pressure is applied on the structure through a restart analysis using the initial conditions/damages in the structure due to the aircraft impact. Sufficient solution time is provided in the impact dynamic analyses in case to allow the structure to damp out any vibrations, so the pressure loading is applied on a static condition.

RESULTS

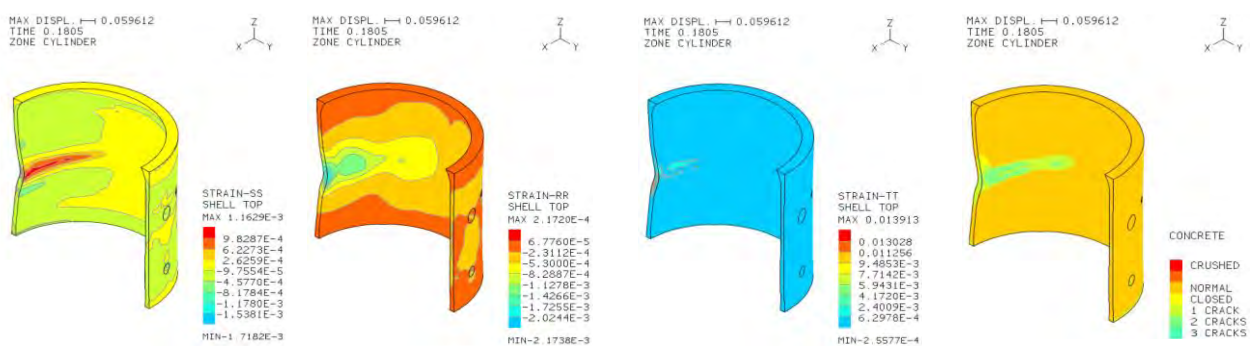
The results from the performed structural analyses for the investigated scenarios and different impact intensities are presented below. The results are synthesized to the most representative and illustrative for the containment response under impact loads.

Structural response due to aircraft impact

The strain and damage distribution over the containment for the case of impact of Boeing 747 are presented on Fig.3 and Fig.4. The results on Fig.3 present the response at maximal response, while the results on Fig.4 show the residual values observed at the end of the dynamic response of the containment.

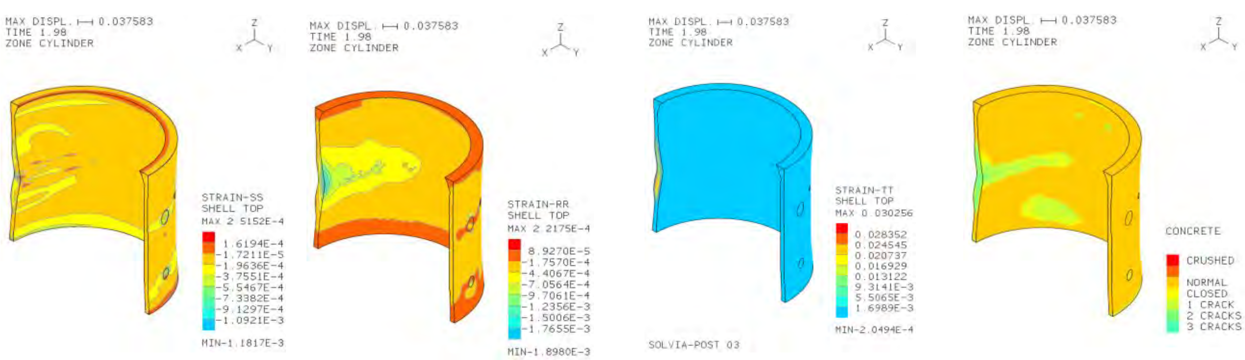
After the analysis of the obtained results was found that the shell responds to the impact almost essentially in compression, with hoop compressive strains as dominant parameter. The only exceptions are the meridian tensile strains on the internal face of the wall beneath the impact stamp and on the external surface in the zones surrounding the impact stamp. Respectively, tensile strains in the reinforcement and the liner can be found only at those 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 the hoop direction and double fixed beam with a point load in the meridian direction. It should be pointed out here that this particular structural behavior in the present case study is attributed to the assumed radius of the containment and the loading shape/area.



Meridian strains Hoop strains Shear strains Damage state

Figure 3. Strain and damage distribution in the containment depending on the containment due to the impact of Boeing 747 - results at the time of maximal response.



Meridian strains Hoop strains Shear strains Damage state

Figure 4. Strain and damage distribution in the containment depending on the containment due to the impact of Boeing 747 – residual values.

The containment failure is controlled 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. Also, the most significant residual deformations observed at the end of the dynamic analyses are the hoop compressive strains concentrated beneath the impact stamp and the shear strains concentrated around the impact stamp.

The ultimate “aircraft impact” capacity of the analysed containment structure is assessed by the use of fragility curves. The fragility curves are generated by using the results from the performed numerical analyses through the simulation method. For each impact scenario (aircraft type and impact location) three fragility curves are generated for each of the controlled failure modes: excessive hoop compressive strains, meridian compressive strains and shear strains. The fragility curve giving 0,5 probability of failure at the lowest load level is selected as representative of the particular impact scenario. The obtained impact capacities for the impact of B767 and B747 are respectively 275MN and 493MN. More information and results about the assessment of the ultimate “aircraft impact” capacity of the analyzed containment structure, as well discussion on this topic, can be found in the accompanying paper, Andonov et al. (2013), within these proceedings.

Structural response due to internal pressure

As discussed in the text above the internal pressure is applied on the structure by restart analysis taking into account the residual deformations obtained at the end of the dynamic analysis of the aircraft impact. The results from the ultimate pressure capacity using the initial conditions of the impact analysis with impact force closest to the estimated impact capacity are used in this paper. The results for the obtained ultimate pressure capability are compared with the response and the capacity of a reference case without considering the initial aircraft impact damages.

According the requirements of the recent regulations, NRC (2010), the ultimate pressure capability capacity of cylindrical pre-stressed concrete containments is reached at internal pressure leading to the following strain limits: (1) a total tensile average strain in tendons away from discontinuities of 0,4% excluding the strains from the pre-stressing and (2) a global free-field strain for the other materials that contribute to resist the internal pressure (i.e., liner and rebars) of 0,4%.

The critical zone is the middle 1/3 of the cylindrical part of the containment. The failure mechanism is controlled by excessive increase of the hoop strains in the reinforcement, the liner and the tendons. The propagation of the tendon hoop strains in the critical zone in function of the applied internal pressure is given on Fig. 5 and Fig.6. The results on Fig.5 are for the middle of the critical zone which in this case middle height of the containment. The results on Fig.6 are for the lower border of the critical zone which corresponds to one third from the containment height. On the left side of each figure, the strain histories for the “pure” pressure analysis are given; the strain histories obtained by the analyses considering the impact of B767 with impact force of 300MN and the impact of B747 with impact force of 500MN are given respectively at the center and the right side of the two figures. At each graph, the strains at four locations, equally distributed at 90 degrees along the cylinder perimeter are given. The controlled locations closest to the two main openings of the containment are referred as SC22-1 and SC33-1 and are given with blue lines on the graphs. The controlled locations closest to the impact zone are referred as SC22-3 and SC33-3 and are given with green lines on the graphs. These two locations are situated on the opposite sides of the containment vessel (the aircraft impact is at the opposite side of the zone with main penetrations of the containment). The average hoop strains for each of the two levels/zones are illustrated with thick black lines at each graph.

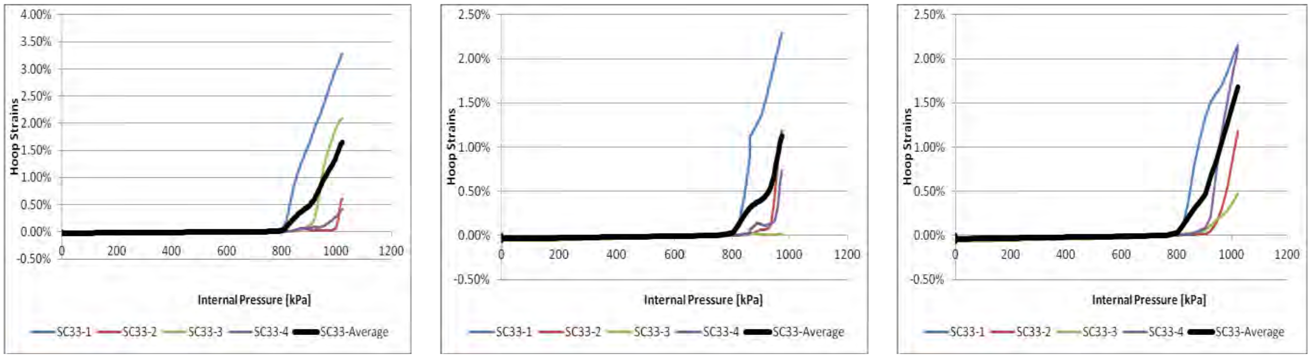


Figure 5. Hoop tendon strains in the middle height of the containment in function of the internal pressure: without consideration of aircraft impact (left), after the impact of Boeing 767 with peak impact force of 300MN (center) and after the impact of Boeing 747 with peak impact force of 500MN (right).

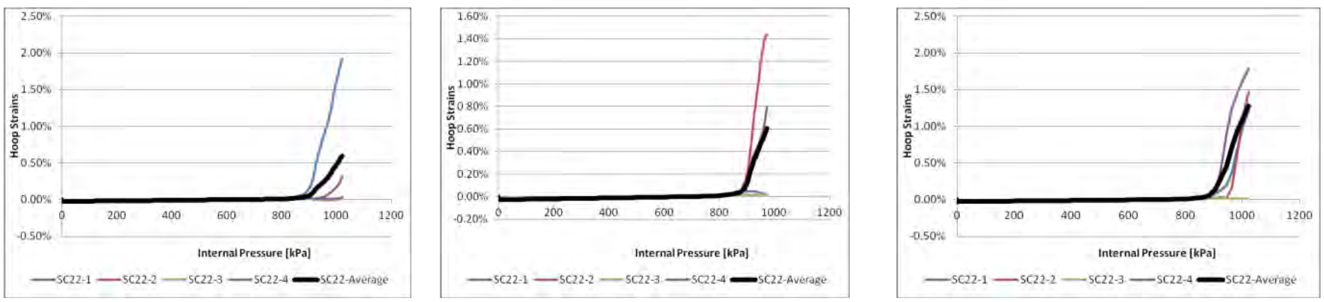


Figure 6. Concrete hoop (left) and meridian (center) compressive strains, and shear strains (right) depending on the impact intensity (peak impact force) and the impact scenario.

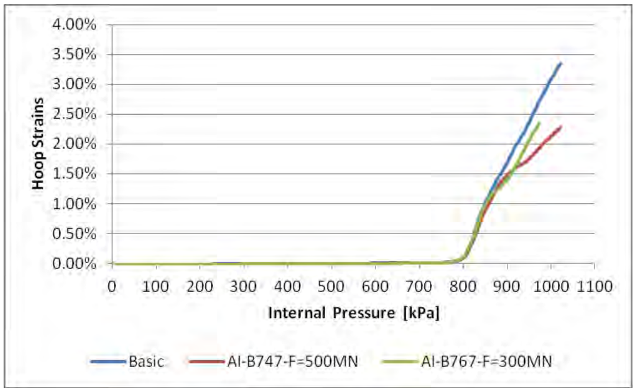
The following observations can be drawn based on the obtained results from the analysis of the "pure" ultimate pressure capacity:

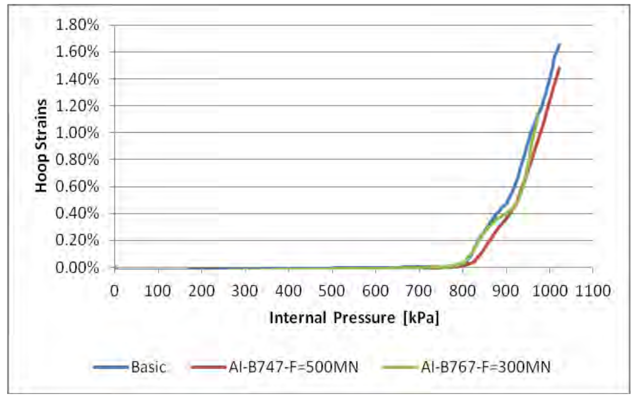
- The failure is initiated in the middle height of the containment, where the failure criterion is firstly reached. The zone with the highest strain concentration is observed in the vicinity of the two main penetrations/hatches. This is also the zone where the failure criterion is firstly reached.
- The strains observed in the other three locations are much lower and the failure criterion is later reached.

The assessment of the results from the other two analyses of the ultimate pressure capacity with consideration of the initial damages due to aircraft impact leads to the following conclusions:

- The aircraft impact (in the two considered scenarios) does not change the basic characteristics of the pressure failure mode. The critical zone remains the middle height of the containment and the critical section remains again this closest to the main penetrations/hatches.
- The strains observed in the other three locations are significantly higher than these in the analysis of the "pure" pressure capacity, which is actually the main difference in the pressure response of the containment for the cases considering aircraft impact.

The strain histories given on Fig.5 are synthesized on Fig.7. The strain history from the solution without consideration of aircraft impact is given with blue line, the one from the solution with consideration of the impact of B747 is given with red line and this one considering the initial damages from the impact of B767 is given with green line. The left side of Fig.7 presents graph of the strain histories in the critical section (SC33-1), while the right side of the figure presents the "average" strain histories for the four controlled locations in the middle zone.





Critical section Average

Figure 7. Strain histories in the critical zone.

It can be seen that the results obtained are very close. The ultimate pressure capacity is practically not reduced by the aircraft impact (for the considered impact scenarios). The ultimate pressure capacity obtained based on the average strain curves is 880kPa (980kPa absolute pressure in the containment). More conservative assessment based on the strain curves in the critical section (SC33-1) gives an ultimate pressure capacity of 820kPa (920kPa absolute pressure in the containment).

Integral containment capacity

Except strong mechanical impact and structural damages, the accidental or malicious aircraft crash on nuclear reactor building will produce also strong (but short in duration) vibratory loading and post crash fire. The last two phenomena could provoke failure of the reactor internals and the safety systems, which in turn could be a reason for an internal accident with increasing the internal pressure. This is implemented in the sufficiency criterion, NEI (2011), that "the containment structure is considered acceptable if the containment is maintained intact from both local and global impact analyses. The containment remains intact if structural analyses…show that perforation of a steel containment or concrete containment with steel liner does not occur on impact and the containment ultimate pressure capability, given a core damage event, would not be exceeded…".

The containment ultimate capacity for sequent application of aircraft impact load and internal pressure due to impact induced internal accident can be presented by a capacity envelope, presenting the capacity in function of both parameters – impact force and internal pressure. The capacity envelopes of the studied containment structure for the two considered impact scenarios are presented on Fig.8.

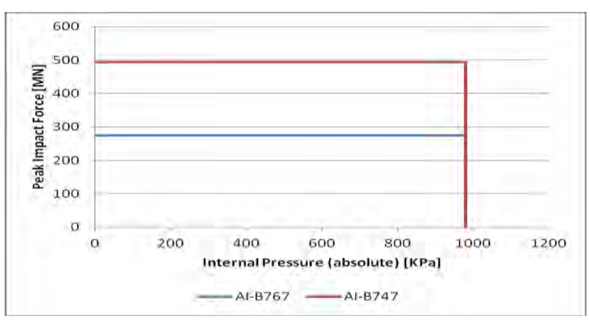


Figure 8. Capacity envelope of the studied PCCV.

For this particular case, this particular generic containment structure under these aircraft impact scenarios, the ultimate pressure capacity remains constant at any arbitrary aircraft impact load lower than the ultimate "aircraft impact" capacity. Therefore for this particular case the capacity envelopes on Fig.8

(considering the impact of Boeing 767 with blue and Boeing 747 with red) consist of crossed vertical and horizontal lines. However, for other types of containment structures and impact scenarios this trend may not be valid. For other cases, where the aircraft impact induced damages will have stronger influence on the pressure capacity reduction, the capacity envelope will be composed of a curve giving a reduced ultimate pressure capacity with increasing the aircraft impact load.

Any arbitrary combination of aircraft impact load with a certain peak impact force, followed by an internal accident with a certain peak pressure will give a single point result. If the point is within the capacity envelope the containment is considered intact for this load sequence and vice versa. For the assessed herein PCCV the design accident pressure is usually in the range of 0,4-0,5 MPa. At this particular case it could be concluded that the analysed generic containment vessel can resist any aircraft impact load below 275MN in case of impact of B767 and bellow 490 MN in case of B747, without losing its “nominal” ultimate pressure capacity, i.e. will still have a safety factor of two in case of design basis accident pressure. Further, if the values of maximum pressure from severe accident scenarios are available, the containment vessel can be assessed for the maximum impact load which can be resisted and yet provide adequate pressure capacity to resist the postulated severe accident.

DISCUSSION

The capacity envelopes presented on Fig.8 use the peak impact force as reference parameter describing the aircraft impact intensity. As can be seen the capacity prediction as peak impact force differs with more than 50% for the two airplanes. The main reason for this lies in the huge difference in the impact areas of the two airplanes, which also differs in approximately 50%. Thus the capacity envelope shall be developed for each aircraft type considered in the assessment.

Recent research paper, Andonov et al. (2013), research the issue of aircraft impact capacity assessment, based on fragility curves. Three reference parameters have been considered: peak impact force, peak impact pressure and momentum over area, and based on the obtained results, the last one is recommended as most suitable one. The momentum, which is simply a product of the mass and the speed, can be easily obtained for any arbitrary combination of aircraft mass and impact velocity. If the momentum is divided to the impact area, the obtained parameter MoA (momentum over area) can be easily obtained for any arbitrary combination of aircraft type, mass and impact velocity. The momentum is related to the results from the numerical analyses through the impulse of the load time function used for the particular analysis (the area beneath the load time function). The results of the obtained capacity envelopes are given on Fig.9. As can be seen the two curves are very close, with difference in the predicted impact capacity of about 6 %, which is extremely small considering the significant uncertainties in such analyses. Therefore, if the MoA is used as a reference parameter for the aircraft impact intensity, it is reasonable to express the results from the two aircraft impact scenarios by one capacity envelope. The more conservative or a capacity envelope with average values may be used, depending on the required level of conservatism.

The advantage of using MoA is that the obtained aircraft impact containment capacity can be directly and very easily transferred to any arbitrary combination of aircraft type, mass and speed, which provides good “physical” feeling for the obtained result. For example, the obtained impact capacity for the assessed herein generic PCCV of MoA=0,33 MPa*s can be related to the following crash scenarios: impact of Boing 747 with mass at impact of 350 t and impact speed of 120 m/s; impact of Boing 747 with mass at impact of 260 t and impact speed of 160 m/s; impact of Boing 767 with mass at impact of 186 t and impact speed of 120 m/s; impact of Boing 767 with mass at impact of 140 t and impact speed of 160 m/s.

The capacity envelopes presented on Fig.8 and Fig. 9 present the “best estimate” capacity. However, capacity envelopes with different confidence levels can be easily derived, based on sensitivity analysis and estimation of the uncertainties in the capacity assessment, for both the aircraft impact and the pressure analyses.

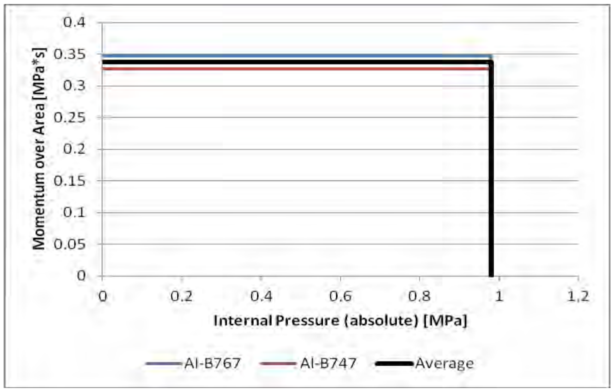


Figure 9. Capacity envelope of the studied PCCV in function of the "Momentum over Area" and the internal pressure.

CONCLUSION

The current paper presents the procedure and the results from the assessment of the vulnerability of a generic pre-stressed concrete containment vessel subjected to the sequent occurrence of aircraft crash impact and elevated internal pressure, assuming hypothetical internal accident induced by the aircraft crash. 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 types of structures. The containment response under aircraft impact load is assessed for two large passenger aircrafts, respectively Boeing 767 and Boeing 747, represented by their load time functions and loading areas.

The aircraft impact capacity is assessed by series of nonlinear dynamic analyses with increasing intensity of the loading. The ultimate pressure capacity is assessed by nonlinear static analyses restarted from the post crash initial conditions. The effect of the post crash damages on the containment ultimate capacity is assessed via comparison with the "pure" pressure capacity obtained without consideration of aircraft impact.

The following main conclusions can be drawn, based on the obtained results from this particular case study:

- The studied containment structure was found to be capable to resist high impact loads associated with the impact of large commercial airplanes. The obtained capacity corresponds to impact of practically fully loaded B747 or B767 with impact speed of minimum 140m/s.
- The containment ultimate pressure capacity is not affected negatively from the aircraft impact, providing that the aircraft impact load is below the failure load.

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