Abstract Transactions, SMiRT-22
San Francisco, California, August 18-23, 2013

PRELIMINARY EVALUATION OF THE SAFETY MARGIN OF A GEN II REACTOR SUBJECTED TO AN AIRCRAFT IMPACT

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ABSTRACT

The aircraft impact accident has become very significant in the design of a NPP particularly after the tragic September 2001 event, that raised the public concern about the potential damaging effects that the impact of a large civilian airplane could bring in safety relevant structures.

The aim of this study is therefore to evaluate preliminary the "global response" of a Gen II reactor building (RB) against military and/or civilian aircraft crash (actually classified as a beyond design basis event), the effects of which, mainly in terms of structural integrity, were not considered for the existing NPPs in their design phase.

The preliminary assessment of the safety margin of an existing nuclear facility, entails, of course, the evaluation of the RB minimum wall thickness necessary to ensure the overall plant safety.

In doing that, the dynamic response of the RB was properly studied adopting a suitable non linear finite element code and setting up further refined models of the reactor building and airplane. The location of the strike was considered near the junction of the dome and cylindrical body while the angle of incidence of the impact was assumed to be normal and/or inclined to the buildinf outer surface.

The results obtained highlighted that: the RB walls may undergo local damages in the area where the impact is localized; the penetration depth is related to the type of aircraft considered; away from the impact area the overall stability of the RB structure seemed to be ensured.

INTRODUCTION

The safety assessment of important structures, like the nuclear plants or facilities, against a deliberate or accidental aircraft impact has received significant attention throughout the world due to the raised public concern for the potential dangerous effects that an aircraft crashing could determine in safety relevant structures.

The outer reactor building, which is the last "defence in depth" barrier, is characterized by thicker and heavy reinforced concrete walls intended to provide to mitigate the consequences of the unforeseen event, like a large commercial aircraft impact.

The impact of a military or civilian aircraft would not be expected to penetrate the reactor building, for instance, of large Gen. III or III+ LWRs characterized by a double containment structure made of heavily steel reinforced concrete with thickness larger than one metre at least, such as the Areva's EPR and the Russian VVER-1200 containment walls.

The aim of this study was the understanding of the global response and evaluation of the vulnerability of the main safety relevant systems, structures and components (SSCs) in the postulated event. Especially it was evaluated if the wall thickness of the reactor building is adequate to ensure the overall plant safety (of meaningful importance because the damages caused to the outer containment structure could jeopardize the plant safety) (Crutzen and Reyneu, 1983; Abbas et al., 1996; Lo Frano and Forasassi, 2011).

The main structural effects and the failure mechanisms induced by a fast moving aircraft on the reactor building outer walls during the crushing interaction (to which both two these structures are dynamically undergoing and interactive contact) were analyzed.

In order to provide a realistic prediction of the crashing phenomenon, accurate dynamic simulations of the interaction were carried out. To simulate the interaction between the airplane and the building an adequate contact algorithm, that allows to automatically associate the structures deformation to the interface boundary conditions, was adopted.

AIRCRAFT IMPACT ASSESSMENT

The first requirements concerning the aircraft crash were introduced for nuclear reactors and fuel facilities (reprocessing plants, etc.) in 1979/80 by UK, France and USA. Even if formerly the considered reference aircraft was a military one, at present, accordingly to the 10 CFR 50.150 (US NRC, 2011), the impact of a large commercial aircraft must be considered to adequately evaluate the aircraft impact effects on a nuclear plant containment (both in supporting the NPP licensing process and the so-called stress tests assessments).

In fact International regulations require that to evaluate the aircraft impact assessment "*each applicant use realistic analyses to identify and incorporate design features and functional capabilities to show, with reduce use of operator actions, that either the reactor core remains cooled or the containment remains intact, and either spent fuel cooling or spent fuel integrity is maintained*" (US NRC, 2009).

Studies on aircraft impact of nuclear facilities predates the event of September 11, 2001. Some of the researches focused on the analysis of the impacted structure response were performed adopting the load function approach (Riera, 1968; Crutzen and Reyneu, 1983; Abbas et al., 1996; etc.); while others addressed non-malevolent aircraft impact using probabilistic approaches.

An alternative approach is based on mathematically simplified attempt to uncouple the problem of rigid vs. deformable body mechanics, with respect to the airplane impact, and then superpose their solutions analytically.

As for experimental tests concerned, the first true "crash tests" of aircraft were conducted by Jerry Lederer at McCook Field, Ohio in 1924. concerned with safety evaluation of the Three- Mile Island Nuclear Power Plant. Full-scale crash tests were conducted including the F-4D Phantom fighter (Sugano et al., 1993) and DC-8 carrier (Johnson et al., 1978). Several research groups continued this line of research until recently (Abbas, et al., 1995; Chadmail et al., 1985).

Finally it is possible to stress that a detailed reliability analysis for an aircraft crash is not common in the past literature.

Protection of a NPP against aircraft impacts relies upon strengthened reactor containment building and other safety buildings, together with wide application of the physical separation of the safety systems and enclosing building structures.

With reference to the these considerations, the problem of the reliability of a NPP is mainly related to the evaluation of the minimum wall thickness that is necessary to withstand against an aircraft impact and, in the same time, to prevent the local perforation, particularly in the case of a large aircraft crash. Therefore, to demonstrate the integrity of the reactor containment building a realistic impact analysis (deterministic approach) might be carried out as required by the international agencies and regulatory bodies, like the IAEA or the USNRC.

The dynamic behaviour of a RB may be carried out in terms of global or local response.

The first one allows to describe the dynamic behaviour of the structure subjected to excessive structural deformations or displacements, collapse, overturning ('overall missile effects') etc.. Moreover, the global response depends on the extent of the induced and propagated dynamic loads and on the main characteristics of the impacted "target". The latter allows to describe the structural damages, such as the penetration, perforation, scabbing etc., that could occur, characterize and locally lead to the failure of the impacted structure, as a result of the combined effects of the primary (noise and fuselage) and secondary (engines) missiles impact.

Before a structural analysis can be made, initial conditions of the aircraft impact might be defined. These include important parameters, that could influence the evolution of the accident scenario and its consequences on the target structure, like: aircraft velocity, plane trajectory, roll angle and orientation with respect to the floors, angle of impact, point of impact, mass and stiffness of the structures. In addition it is worth to note that these initial condition are dependent on the type of the crashing aircraft (military or commercial).

For the purpose of this study, a Gen II reactor containment building, like the one shown in Fig.1, was considered (Jeffrey et al., 1998). It is worthy to note that for the existing plants, the evaluation of their reliability shall refer to the plant as it has been built and operated, while for those under construction, the reassessment of the load bearing capability shall refer to the licensed design.

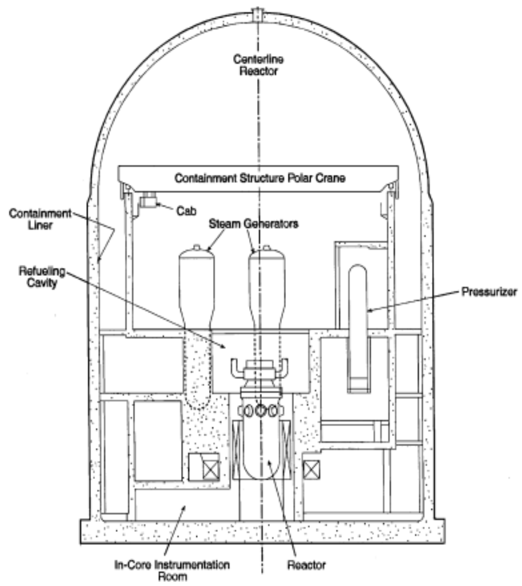


Figure 1. Overview of a typical PWR containment.

The RB structure is characterized by heavy and thick reinforced concrete walls designed to not exceed the allowable stresses, in agreement with ACI Standard 349 (ACI, 2001).

AIRCRAFT IMPACT SIMULATION

To determine the global response of the RB structure considered and evaluate if its outer walls are sufficiently robust to bear the aircraft impact load, a deterministic method (through realistic analyses, as required to the applicants, to verify "the acceptance criteria" are respected) has been adopted.

Therefore non linear dynamic analyses were carried out, adopting refined FEM models, set up by means of MSC©codes, implementing a suitable contact algorithm and assuming reasonable hypotheses for the materials behaviour (e.g. concrete and steel), the geometrical dimensions, velocity and impact direction (Lo Frano and Forasassi, 2011).

In the structural analyses, the point of the aircraft impact was assumed to be located in correspondence of the connection between the hemispherical roof and the cylindrical body of the RB. Moreover it was assumed a horizontal impact to simulate the worst accident scenario.

The aircraft impact phenomenon is considered to cause stresses in the RB beyond the elastic limits in an extremely short period; of course large deformations are possible depending on the containment building structural characteristics.

The impact process was simulated as an interactive process between a very large and stationary building and a small but fast moving airplane, both of which may undergo considerable deformation.

The interaction between the impacting and impacted components is considered by monitoring the contact force and comparing the magnitudes of the forces required to instantaneously deform one or the other.

The kinetic energy transmitted during the impact might be partially dissipated by plastic deformation and fracture of the RB walls (“strain energy”) and in part by the crushing and breakup of the plane.

Description of structure

The reactor containment building considered is about 60 m tall and about 45 m in diameter (Fig. 2), with thicker walls (Fig. 2) of about 1 m (ASCE, 1980).

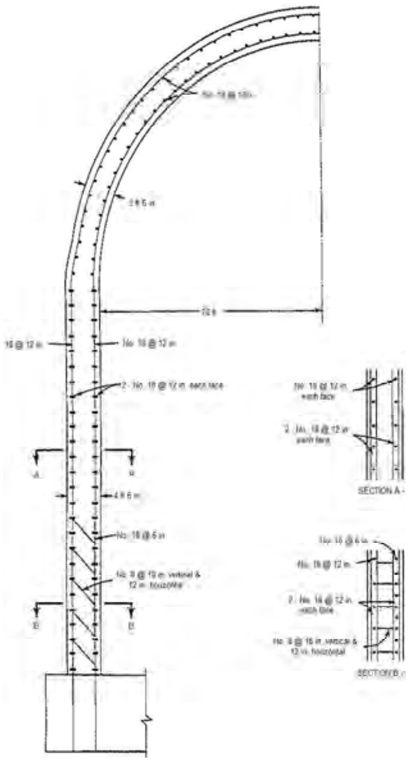


Figure 2. RB main dimensions (ASCE, 1980).

Moreover according to the IAEA rules, if the only function of the reactor building is to stop the aircraft and ensure the global stability, the building may be hence designed with:

- plastic excursions of reinforced bars reaching ε = 2% deformation;
- impact characteristics representative of the worst scenario (for the evaluation of local effects);
- wall thickness in the range between 0.9 to 1.6 m in order to avoid the scabbing and prevent or limit the perforation;
- Shear reinforcement (stirrups) to prevent shear punching failures.

Based on the above mentioned characteristics, a quite detailed FEM model of the reactor building was set up and implemented, assuming its foundations based on a rock soil.

Aircraft impact modelling

Non-linear dynamic FEM codes, based on an explicit method, were used to adequately simulate the interactive process through suitable contact conditions. Moreover an external coupling procedure

involving suitable structural (MSC©Marc, 2010) and dynamic (MSC©Dytran, 2010) FEM codes was implemented. Quite refined finite element models for both RB and airplane structures were set up. To simulate the interaction (approximate) between structural parts undergoing dynamic deformation following the postulated aircraft impact a suitable contact algorithm was implemented assuming explicit large deformation.
The modelling of contact interfaces between two interacting bodies, during crashing, is fundamental to investigate the adaptive contact in dynamic simulations. The contact algorithm was used in addition to the classical initial, kinematic and dynamic constraints (boundary conditions of continuum mechanics) that govern the motion of the interfaces: the contact force is calculated at each time step (dynamic transient problem) according to the conservation of the impulse.

The 3-D model of the RB structure, which were set up accordingly to the ASCE and ACI standards requirements, is shown in Fig. 3, while the aircraft models, representative of the Phantom F4 and Boeing 747 airplanes are shown respectively in Fig. 4 (a) and (b). The finite element models of both building and airplane structures were set up by means of CQUAD4 shell elements, which was assumed to behave as an elastic-plastic material (DMATEP with a maximum plastic strain limit).

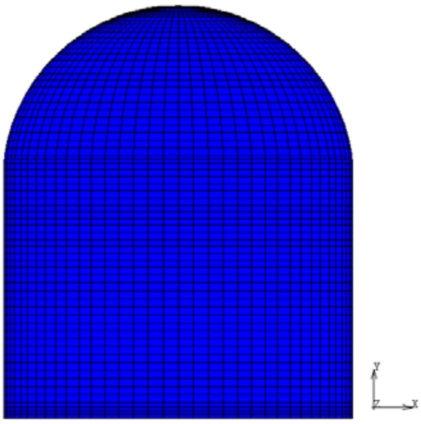
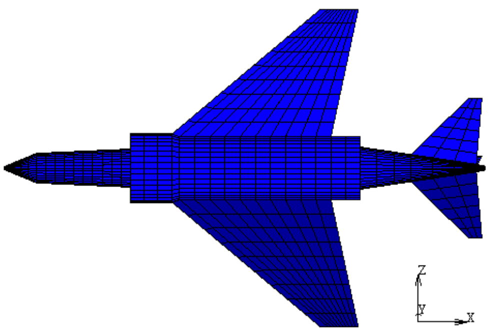
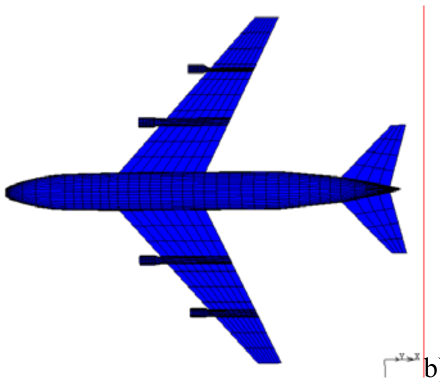


Figure 3. RB model.



a)

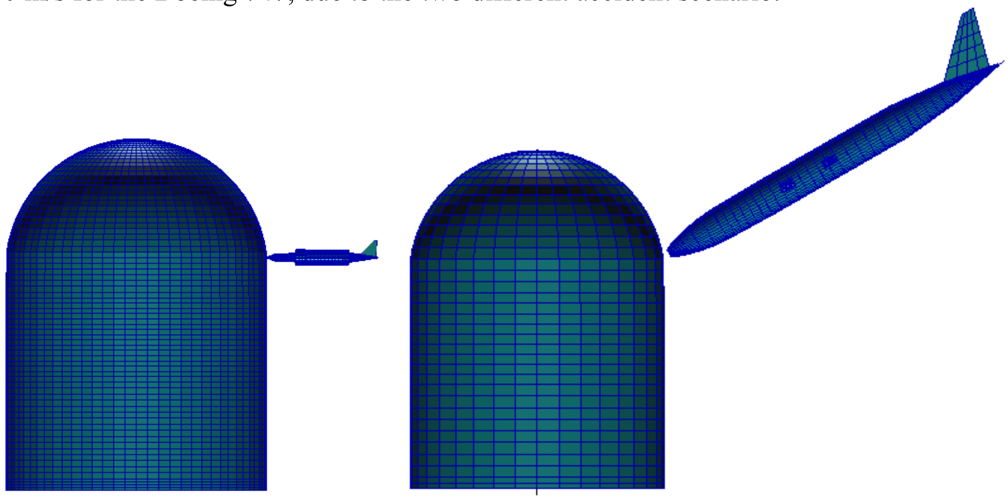


b)

Figures 4. Phantom F4 (a) and Boeing 747 (b) models.

As for the carried out dynamic analyses concerned, the aircraft impact assessment should be considered conservative because the RB walls were not lined with steel anchored into the concrete by shear studs.

The aircraft impact simulation in this study (Figs. 5) were carried out assuming a horizontal (corresponding to the most unfavorable impact condition in agreement also with the Riera formulation) and/or an inclined impact: the angle of impact with respect to the impact direction was considered equal to 30°. Moreover the impact velocity was assumed equal to about 115 m/s in the case of the Phantom F4 and about 250 m/s for the Boeing 747, due to the two different accident scenario.



Figures 5. Aircraft impact simulation cases.

RESULTS DISCUSSION

The local deformation of the outer RB walls starts immediately with the crashing of the fuselage and wings determining the walls penetration; this deformation may continue, depending on the energy released on the reactor building during the impact by the airplane. The penetration may continue until the phenomenon of perforation may occur.

In the light of assumed hypotheses, the military/civilian aircraft impact determines, during the initial phase of crashing of the "nose" of the airplane, in the area where the impact is localized, an extensive penetration (about 0.8 m for the Boeing 747 and about 0.3 m for the Phantom F4, as shown in Fig. 6) of the reinforced concrete outer walls followed by the eventual spalling of the inner walls surface phenomena.

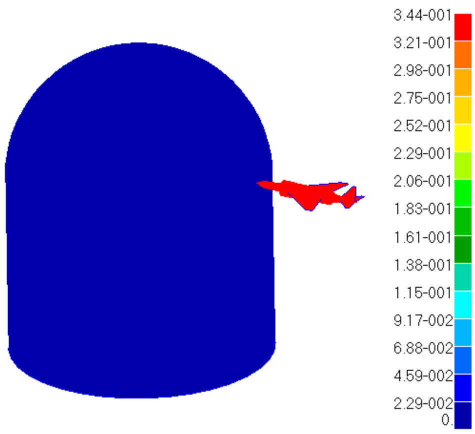


Figure 6. RB penetration depth for Phantom F4 horizontal impact.

The horizontal impact of both Phantom F4 (Fig. 6) and Boeing 747 aircrafts was observed to be more damaging than the inclined impact ones, because of the energy transmitted during the crushing that resulted in an increase of the stress level in the RB wall.
Moreover it was noted that in the area, where the impact is localized, the RB is characterized by a local penetration (as for example for Phantom F4 horizontal impact represented in Fig. 9), while the response away from the impact seems to ensure the stability and integrity of the structure itself. The penetration depth was obviously observed to be dependent on the type of aircraft considered.

The penetration of the reinforced concrete outer walls and eventually the spalling of the inner walls surface phenomena, determined an increase of stress level up to its limit value in the impact area, while away from this one the stability and integrity of the RB/CB structure may be ensured (Fig. 7).

The Von Mises stresses (Figs. 7), induced on the structure during the crashing, were greater in correspondence of the impact point than other locations far from that point. These results were compared to those obtained applying the Riera approach (Lo Frano and Forasassi, 2009; Lo Frano and Forasassi, 2011) based on load functions (based on the airplanes properties and characteristics) applied directly on the reactor building walls. The comparison of the results were found in quite good agreement.

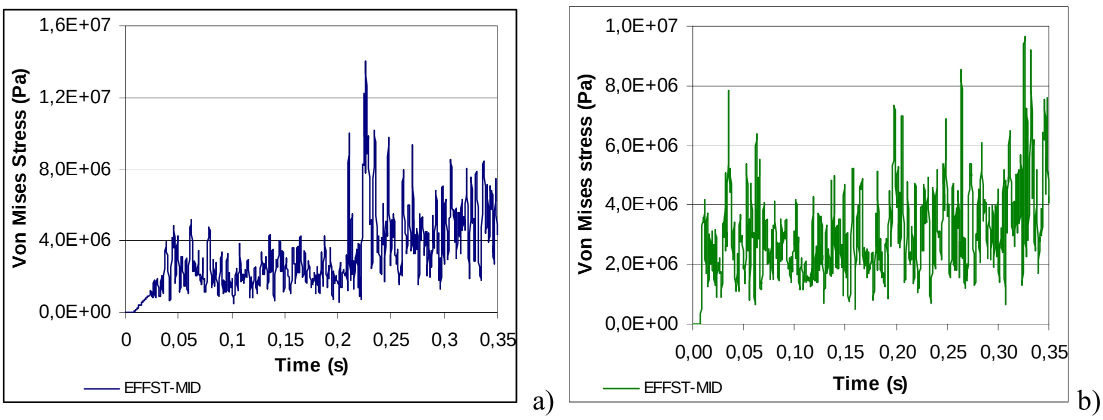


Figure 7. Stress behaviour in the wall close (a) and far away (b) the area of impact.

Furthermore Figs. 8 and 9 show the Von Mises stresses vs. time at the beginning of the impact phenomenon, when the kinetic energy is instantaneously transferred to the building walls, and at the instant of missile impact (Fig. 8 b), for both the horizontal and inclined impacts of the Boeing 747.

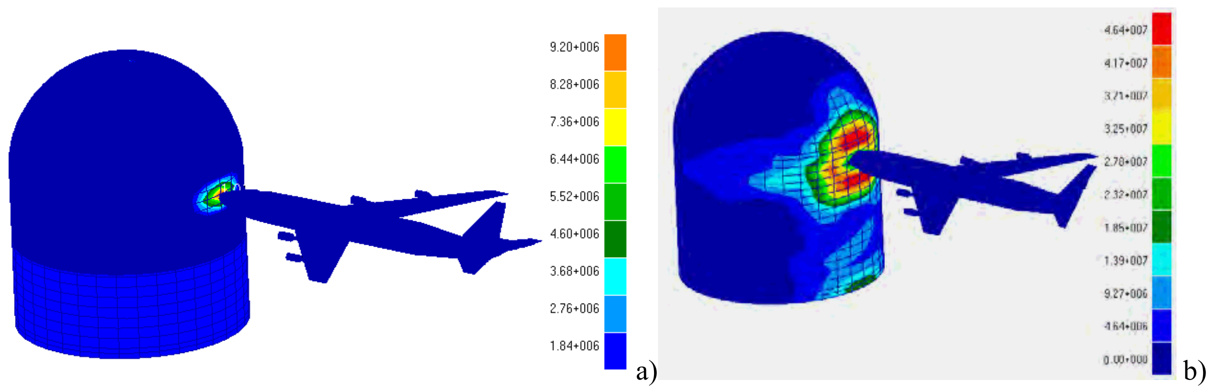
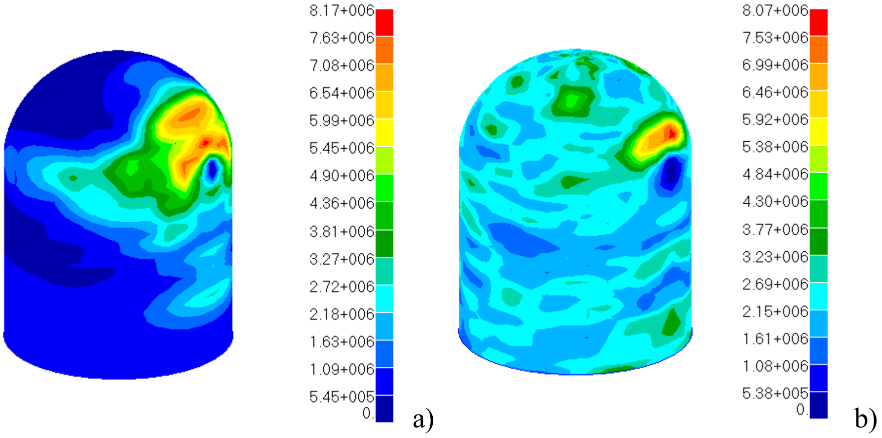
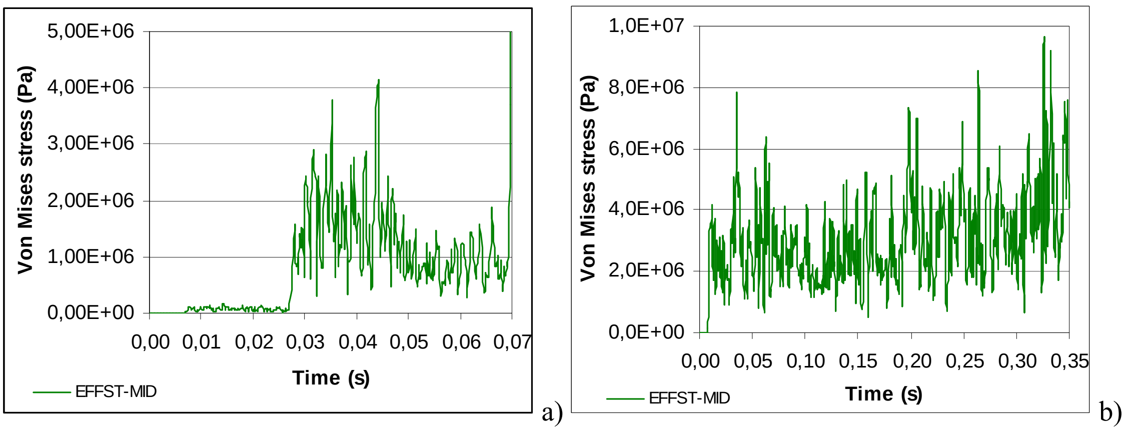


Figure 8. Penetration analysis results: stress distribution for horizontal impact



Figures 9. Penetration analysis results: stress distribution for inclined impact

Furthermore it is worth stressing that the horizontal impact is most damaging than the inclined one, like the impact of a civilian aircraft in respect to the military one (Figs. 14).



Figures 10. Comparison between civilian and military aircraft impact stresses

As a result of the impact, a finite amount of kinetic energy, which depends upon the inertial and stiffness properties of missile and target structure, is transferred from the "striking" aircraft to the impacted walls: the reactor containment building will deform elastically and beyond up to the point of permanent yielding, while some components of the aircraft, sufficiently tough (assumed as rigid projectiles), will strike and eventually might begin to penetrate the building walls.

In general the stress values induced by the impact indicate that the structural failure of RB does not occur, even in presence of ongoing progressive failure, due to the robustness of RB capable to absorb the impact energy. Moreover it has been confirmed that the impact of large commercial airplanes (under the considered assumption of RB wall thickness larger than 1 m) did not determine a complete RB wall perforation.

Analysing the obtained results it was also observed that the propagation of dynamic loading inside the considered NPP did not determine relevant displacements that could trigger the internal structures, particularly the containment vessel.

Finally it is important to stress that a validation of the implemented models and approaches based on the Sandia experimental data is ongoing to be complete and will be quoted in a following study.

CONCLUSIONS

In this study the global response of a Gen II reactor subjected to a commercial aircraft impact has been preliminary analyzed adopting a deterministic approach. The structural response of the RB was analysed by means of a dynamic finite element codes (MSC.Marc © and MSC.Dytran©) that allowed to implement a Lagrangian contact algorithm and take into account the non-linear materials behaviour.
The obtained results highlight:

1) the RB walls may undergo local damages in the area where the impact is localized;
2) the penetration depth is related to the type of aircraft considered (e.g. about 1 m in the case of Boeing 747 impact for horizontal impact);
3) the penetration depth resulted lesser for the inclined impact (in agreement with Riera approach);
4) away from the impact area the overall stability of the RB structure seemed to be ensured for both military and commercial aircraft impacts considered.

Finally it is possible to state that the considered structures configuration showed a remarkable potential to withstand the impact of large civil aircrafts, even in presence of ongoing concrete progressive failure (some penetration and spalling of the concrete walls) of the impacted area.
The containment walls seemed nevertheless capable to ensure the overall plant integrity.

A validation of the proposed approaches based on the Sandia experimental data is ongoing to be completed and will be quoted in a future study.

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