

PARAMETRIC STUDY OF THE STRUCTURAL CAPACITY OF REINFORCED CONCRETE CONTAINMENT SUBJECTED TO LARGE COMMERCIAL AIRCRAFT IMPACT

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ABSTRACT

The current paper presents a sensitivity analysis of the effects on a reinforced concrete containment subjected to impact by a large commercial aircraft. The containment structure consists of a vertical cylinder and half-spherical dome. The sensitivity analysis is performed under variation of the horizontal and vertical impact angle. The reference impact configuration is normal impact at the dome which corresponds to 30deg vertical angle and 0deg horizontal angle. Three horizontal (15deg, 30deg and 45deg) and two vertical (3deg and 15deg) impact angles are considered. Additionally, analysis with bank angle of 30deg is also performed. The aircraft used for the study is a Boeing B777. The Finite Element Model of the aircraft is validated by impact analysis into rigid wall and the obtained load-time function is compared to the one calculated by the Riera method. The area of perforation of the containment structure and the displacement at the impact location are chosen as quantitative parameters for the damage effects. The former is related to the amount of debris and fuel that can penetrate into the containment and the latter is related to the possibility for assessment of secondary effects, i.e. impact on internal structures and safety related installations. The damage effects in terms of the abovementioned parameters are compared and conclusions are drawn. The main result of the investigation is that the deviation from the reference impact configuration leads to decrease of the damage effects and hence less debris and fuel may penetrate through the containment structure.

INTRODUCTION

In the design of nuclear facilities, aircraft impact is usually considered under the assumption of accidental crash of a small military or a small commercial airplane (general aviation). However, the 9/11 events and the most recent case of Germanwings Flight 9525 have shown that the possibility for a deliberate crash of a large commercial aircraft should not be excluded. A safety assessment for malevolent crash as a beyond design basis event is often required by the nuclear regulators. Although there is a small probability of realization, the structural damage to a nuclear power plant (NPP) caused by an aircraft impact may have dire consequences.

The damage to a NPP due to aircraft impact depends very much on the impact scenario, i.e. extensive damage will be caused if the reactor building is hit at a critical location. In the case of an accidental or even deliberate aircraft crash, there exists a great deal of uncertainty whether the plane can approach the structure so that the impact occurs at the most vulnerable location. The uncertainty is attributed to factors such as the topology of the relief where the facility is located, the presence of artificial hurdles (chimneys, cooling towers), the ability of the pilot to control the plane at high approach velocity (in case of deliberate attack), etc.

There is a common requirement for an impact analysis – realistic assessment of the impact scenario. The current study is intended to investigate the damage effects caused on a reinforced concrete containment due to an oblique aircraft impact, i.e. at horizontal and vertical angles of approach that differ from normal. The problem is not new, Riera (1980) suggested a quite efficient and simple formulation for the case of oblique impact.

We intend to study the problem with the contemporary analytical set available, Henkel and Kostov (2014). The aircraft chosen for the purpose of the investigation is a Boeing B777, which is one of the most widely used airliners worldwide. The main goal of the study is to contribute to a realistic assessment of that severe load case.

GENERAL CONSIDERATIONS AND ANALYSIS SETUP

The study is performed by the missile-target interaction analysis. As mentioned above, the selected airplane is a B777 and its mass corresponds to the Maximum Takeoff Weight (MTOW). This is a conservative assumption because of the small probability for takeoff with such mass as shown by Kostov et al. (2013). A Finite Element model of the airplane is shown in Figure 1. The main characteristics of the model are presented in Table 1.

Table 1: Characteristics of the FE model of B777

Model mass	331,524 kg
Number of nodes	159,187
Number of shells	146,965
Number of shell parts	108
Number of beams	46,641
Number of beam parts	9
Total number of elements	193,606
Total number of parts	117



Figure 1. Finite Element model of B777

The target structure is a reinforced concrete containment which consists of vertical cylinder and half-spherical dome. The selected impact location is at the dome of the containment. The calculations are

performed with the software package for explicit dynamics LS-DYNA. Nonlinear material models are used for the concrete and the reinforcement of the containment as well as for the materials used in the airplane model.

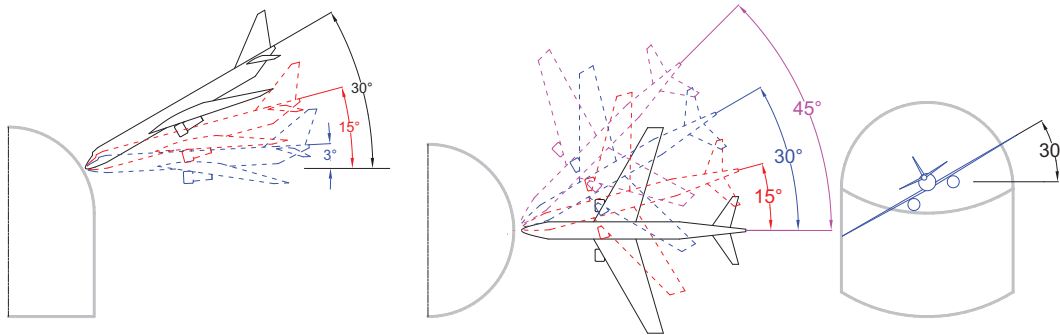


Figure 2. Impact scenarios: vertical impact angles (left), horizontal impact angles (middle) and bank angle (right)

The analysis setup is shown in Figure 2. The variation of the vertical angle includes impacts at 3deg, 15deg and 30deg. The impact direction at 30deg corresponds to normal impact. The variation of the horizontal angle includes impacts at 15deg, 30deg and 45deg, at the same time the vertical angle is kept 30deg. As shown in Figure 2, the vertical angle is measured with respect to the horizontal and the horizontal angle is measured with respect to the normal. In addition, an analysis with bank angle of 30deg is performed whereas the vertical angle is also 30deg.

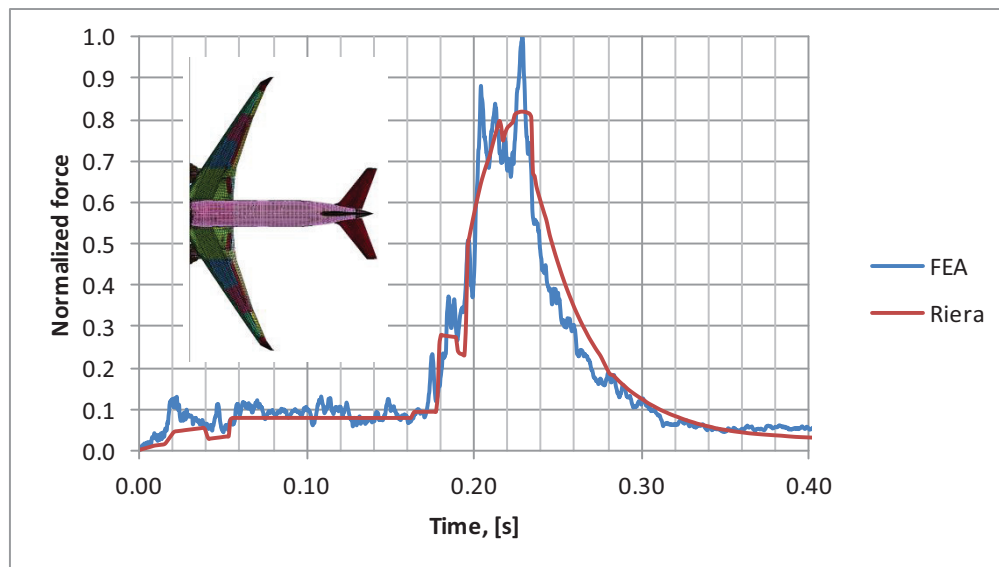


Figure 3. Comparison of FEA and Riera load-time functions for normal impact into rigid wall

The FE model of the aircraft, shown in Figure 1, is verified by impact into rigid planar target (rigid wall) with velocity 150 m/s. The load-time function obtained by the Finite Element Analysis (FEA) is compared with load-time function derived by the Riera formulation, i.e. one-dimensional perfectly-rigid perfectly-plastic stick model, see Riera (1968). The mass distribution function and crushing strength distribution function along the aircraft axis which are required for calculation of the Riera load-time

function are developed based on analytical calculations. Comparison of the normalized load-time functions obtained by FEA and by the Riera method is shown in Figure 3. The figure shows similar overall shape of the two load-time functions. The differences are due to different analytical and modelling assumptions (e.g. the Riera load-time function is based on stick model and does not account for failure and disconnection of elements at impact). Table 2 shows comparison of the momentum change with the impulses of the Riera and FEA load-time functions (normalized values). The differences between the momentum change and the corresponding impulse is within 5.5%.

Table 2. Comparison of the momentum change with the impulses of the load-time functions

Normalized change of momentum	Normalized impulse of the FEA load-time function	Normalized Impulse of the Riera load-time function
1	1.051	1.053

INFLUENCE OF THE IMPACT ANGLE AND THE TARGET GEOMETRY ON THE IMPACT FORCE, RIGID BARRIER

The influence of the angle variation on the impact force is demonstrated by performing analyses into a rigid wall under different horizontal angles – 0deg (normal impact), 15deg, 30deg and 45deg. Three different cases are considered for the contact between airplane and rigid wall: no sliding contact, friction with coefficient $\mu=0.5$ and frictionless sliding.

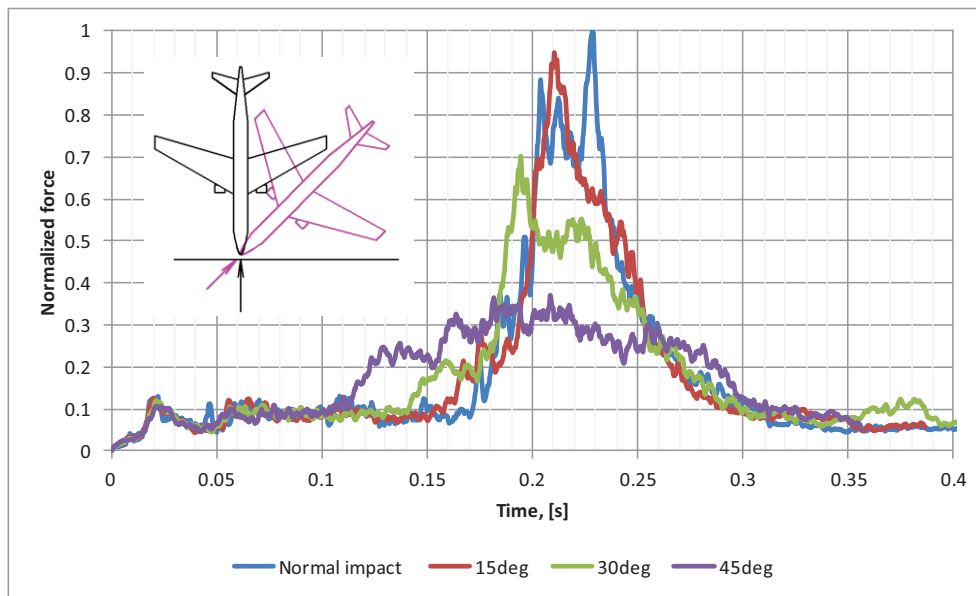


Figure 4. Comparison of the resulting impact forces – no sliding contact

The resulting impact force is obtained by summation of the normal and tangential rigid wall forces, i.e. it is the resultant reaction of the rigid wall, see LSTC (2007). Comparison of the calculated impact forces for the case of no sliding is shown in Figure 4. The graphs are normalized to the peak force value obtained from the normal impact. For the case of friction coefficient $\mu=0.5$ the tangential component of the impact forces will be limited to the corresponding friction force. For the case of frictionless sliding no tangential component will be present at all and the impact force will correspond only to the normal rigid wall force. Depending on the contact condition, the angle of the impact force will vary starting from the impact angle (in case of no sliding) to 90deg (in case of frictionless sliding). Figure 5 shows plot of the

normalized peak impact force as function of the cosine of the impact angle for the three contact cases under consideration.

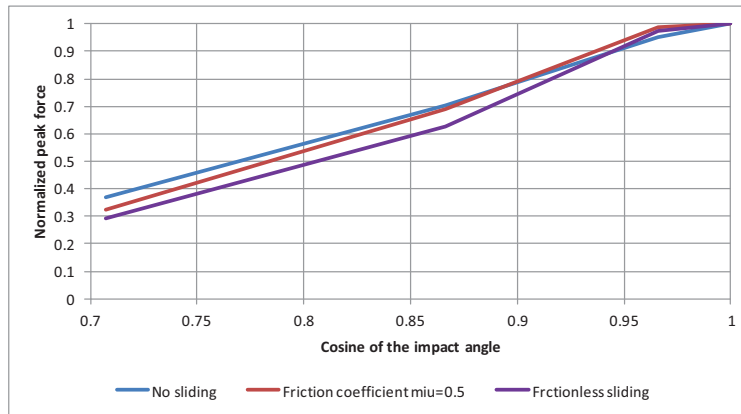


Figure 5. Normalized peak force as function of the cosine of the impact angle

Figure 4 and Figure 5 show that the reduction of the impact force is larger than the corresponding cosine of the impact angle. This implies that the impact force at oblique angle cannot be regarded as a projection of the impact force at normal impact. The reason for the reduction of the impact force at oblique angle is the change of the sequence with which different parts of the aircraft (wings, engines, landing gear, etc.) hit the target, compared to the case of normal impact. In the context of the Riera formulation this would mean change of the equivalent impinging force and mass distribution along the axis of the airplane.

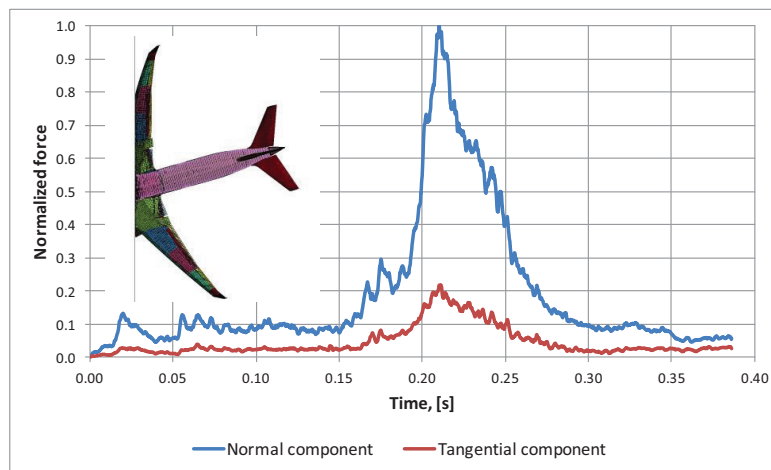


Figure 6. Normal and tangential component of the impact force, impact at 15deg, no sliding

Figure 6 to Figure 8 show plots of the normal and tangential components of the impact force obtained from the angle variation analyses into a rigid wall for the no-sliding case. The normal and the tangential forces are normalized to the peak value of the normal force at 15deg. Figure 8 shows difference between the normal and tangential component of the impact force for the impact at 45deg. This effect is attributed to buckling of the fuselage of the aircraft in the course of the impact, which in turn leads to a deviation of the impact force from the initial impact angle of 45deg.

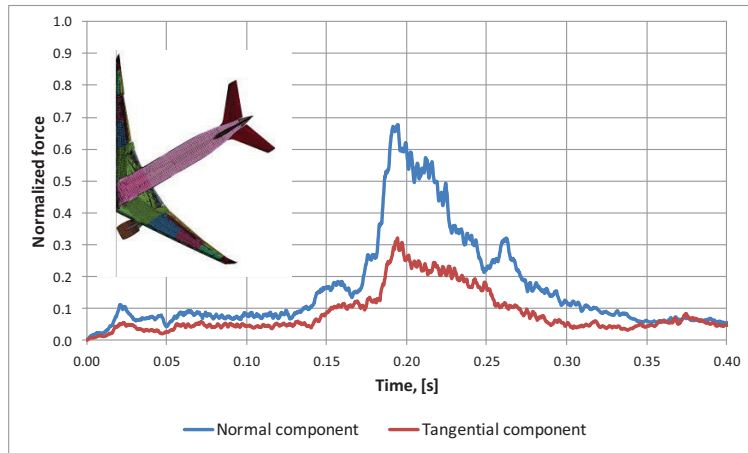


Figure 7. Normal and tangential component of the impact force, impact at 30deg, no sliding

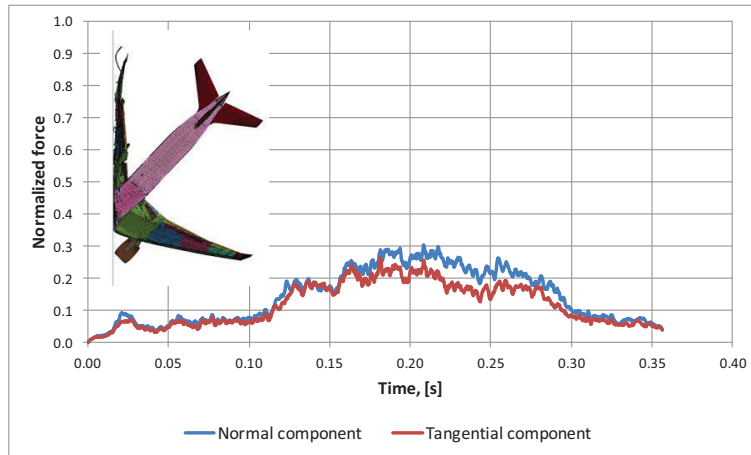


Figure 8. Normal and tangential component of the impact force, impact at 45deg, no sliding

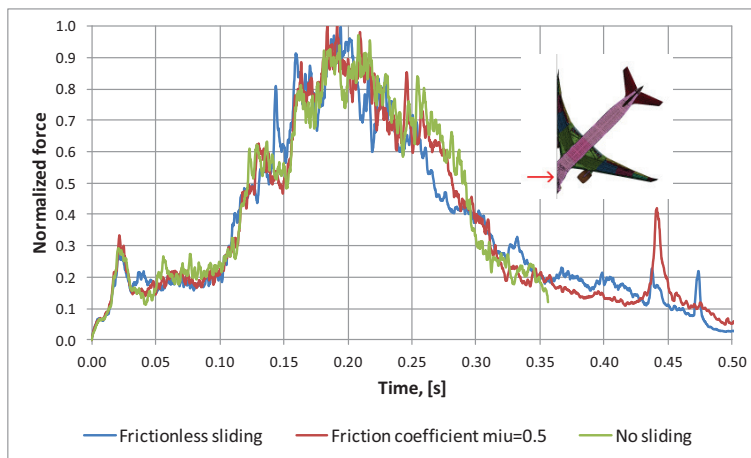


Figure 9. Comparison of the normal components of the impact force, impact at 45deg

Figure 9 shows a comparison of the normal components of the impact force obtained from the impact at 45deg. The figure shows no significant differences between the normal forces for the considered contact cases. The same tendency is observed also for the impact at 15deg and 30deg. A conclusion can be drawn that the normal component of the impact force does not depend on the contact condition.

The influence of the target geometry on the impact force is studied by performing analyses into rigid cylinders with diameter 100 m and 70 m and velocity $v=150$ m/s. The resulting impact forces are compared with the one obtained from impact into rigid wall. The comparison is shown in Figure 10. The impact into a cylindrical target with diameter 100 m leads to small decrease of the peak impact force in comparison to impact into planar target. This is due to the large diameter of the target. The change of the diameter of the rigid cylinder from 100 m to 70 m, however, leads to approximately 10% decrease of the peak impact force. The comparison shows that for this particular aircraft the variation of the impact angle has more pronounced influence on the impact force rather than the target geometry (if cylindrical target is considered).

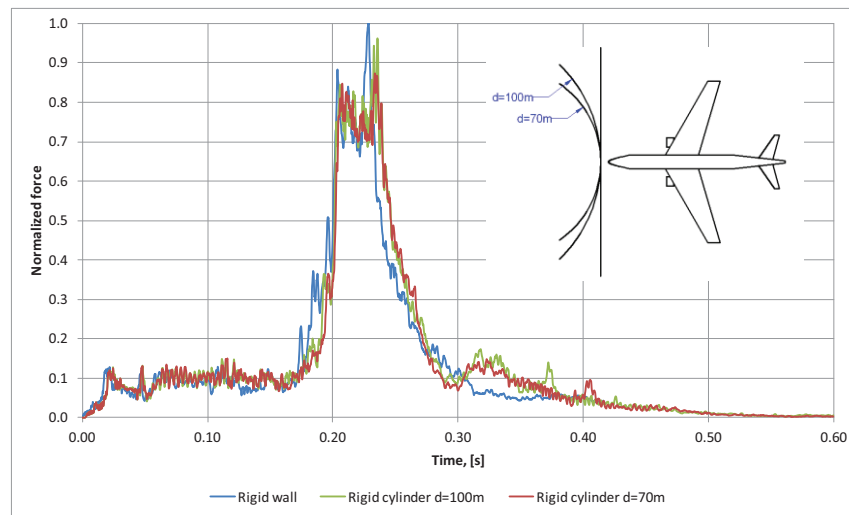


Figure 10. Impact force from impact into rigid wall and rigid cylinder

OBLIQUE IMPACT INTO REINFORCED CONCRETE CONTAINMENT

Missile-target interaction analysis into reinforced concrete containment is performed considering variation of the horizontal and vertical impact angle. The containment structure is modelled as a generic type with typical dimensions and reinforcement ratios. The purpose of using real concrete characteristics is to study the damage effects on a deformable target such as displacement at the impact location and area of the perforation. The former is related to the assessment of possible effects on the internal structure and safety-related installations and the latter is related to the amount of fuel and debris which could penetrate into the containment. A friction coefficient $\mu=0.5$ is considered for the interaction between airplane and containment.

Variation of the Horizontal Impact Angle

The horizontal angles considered for the analyses are shown in Figure 2. The horizontal angle variation analyses are performed for the same velocity. Pictures of the impact into the containment structure can be seen in Figure 11. The resultant contact forces extracted from the analyses are shown in Figure 12. The contact forces are normalized to the peak force corresponding to normal impact. Table 3 contains the

normalized perforation areas of the dome of the containment and the normalized displacements at the impact locations.

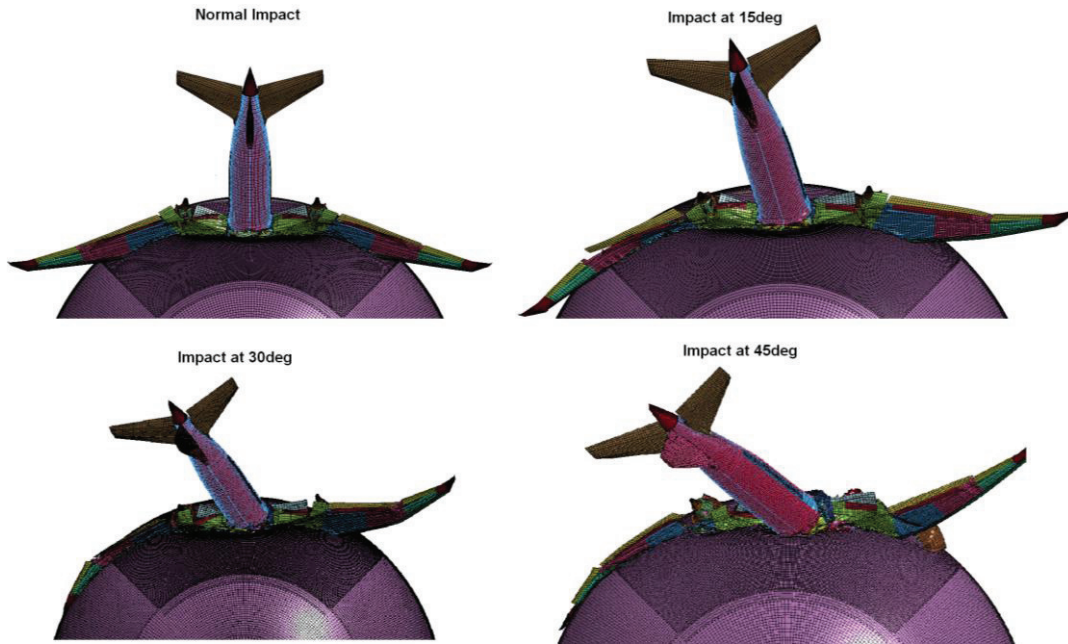


Figure 11. Impact into the concrete containment under varied horizontal approach angles

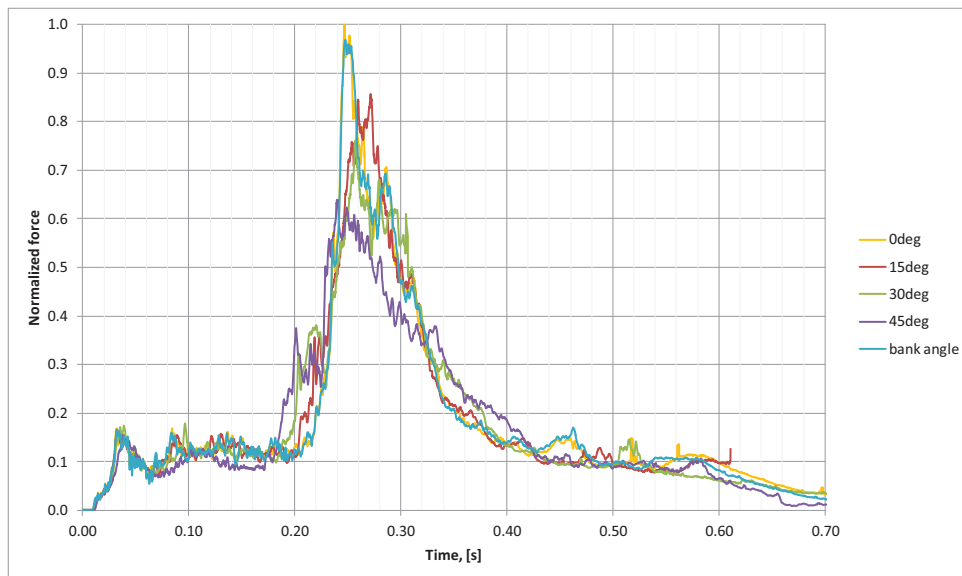


Figure 12. Normalized resultant contact force histories extracted from the analyses

The results in Table 3 demonstrate almost the same perforation and displacement for normal impact and impact at 15deg. Although the peak contact force from the analysis with bank angle has the same magnitude as the one from the normal impact, the corresponding perforation area is about 50% smaller. This is due to the fact that the two engines strike the containment at different levels – the lower one hits the junction between cylinder and dome and thus causes less damage on the dome. Figure 13 shows plot of the normalized peak resultant contact force as function of the cosine of the horizontal impact angle.

Table 3: Normalized perforation areas and displacements due to horizontal angle variation

Analysis	Perforation area	Displacement
Normal impact	1	1
15deg	1.017	0.981
30deg	0.358	0.830
45deg	0	0.436
Bank angle	0.521	1.02

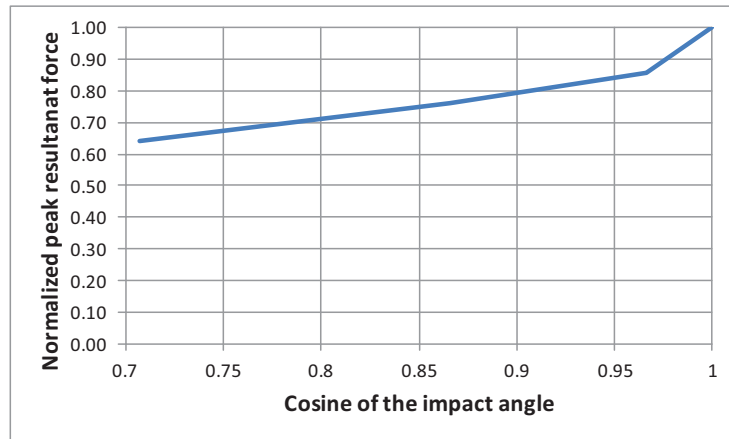


Figure 13. Normalized peak force as function of the cosine of the impact angle

Variation of the Vertical Impact Angle

The vertical angles under consideration for the analyses are shown in Figure 2. The resultant contact forces extracted from the analyses are shown in Figure 14. The normalized perforation areas and displacements are shown in Table 4. The analyses into the containment structure with vertical angle variation are performed with lower velocity than those with horizontal angle variation and the damage effects observed are smaller.

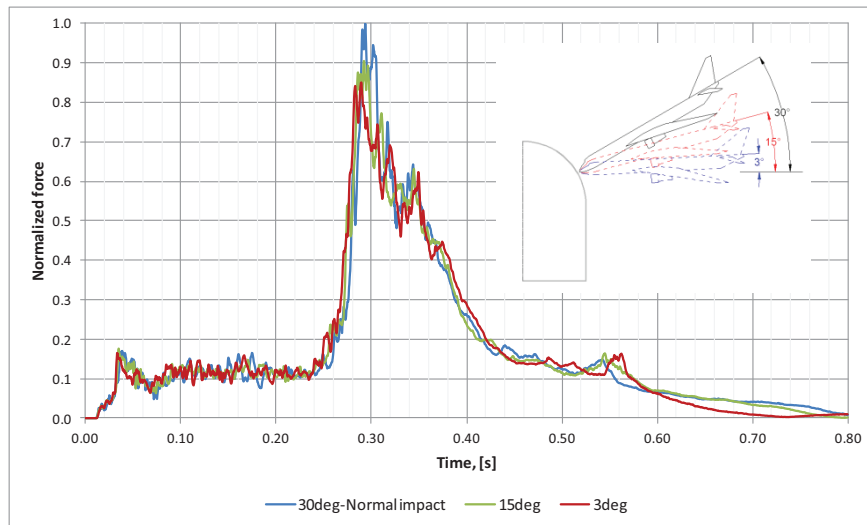


Figure 14. Normalized resultant contact force histories extracted from the analyses

Table 4: Normalized perforation areas and displacements due to vertical angle variation

Analysis	Perforation area	Displacement
Normal impact	1	1
15deg	0	0.894
3deg	0	0.619

CONCLUSION

The purpose of the current paper is to investigate the damage effects caused by an oblique aircraft impact. Both rigid barriers and a generic reinforced concrete containment structure are analyzed. The analyses considering horizontal angle variation show significant reduction of the impact force, i.e. reduction larger than the corresponding cosine of the impact angle. The oblique impact forces cannot be estimated as projections of the impact force obtained at normal impact. The reduction of the impact force at oblique angle is attributed to the different crushing sequence (mode) of the airplane in comparison to normal impact. This in terms of the Riera formulation means different effective mass and effective stiffness distribution along the axis of the airplane, compared to the normal impact. The analyses into a rigid wall show that the normal component of the impact force does not significantly depend on the friction contact condition. On the other hand, the tangential force depends on the friction contact condition. If friction is present, the maximal tangential force is limited to the friction force. The analyses into rigid cylinder demonstrate small change of the peak impact force as the cylinder diameter is decreased. For the selected analysis setup the impact angle has a more significant influence on the impact force than the diameter of the cylindrical target.

The impact analyses into the concrete containment considering variation of the horizontal impact and the vertical angle demonstrate significant reduction of the damage effects in terms of perforation area and displacement of the impact area. The smaller reduction of the impact force in comparison to the case of rigid wall is attributed to the more complex interaction between the deformable airplane and deformable reinforced concrete target.

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