

NON-STRUCTURAL MASS MODELING IN AIRCRAFT IMPACT ANALYSIS

Marin Kostov¹, Milko Miloshev², Zhivko Nikolov³ and Ivaylo Klecherov⁴

¹ PhD, Director, Risk Engineering Ltd, Sofia, Bulgaria

² MSc, Chief Expert, Risk Engineering Ltd, Sofia, Bulgaria

³ MEng, Specialist, Risk Engineering Ltd, Sofia, Bulgaria

⁴ MEng, Specialist, Risk Engineering Ltd, Sofia, Bulgaria

ABSTRACT

The current paper presents an investigation of the effects on a generic reinforced concrete containment structure subjected to impact by a large commercial aircraft, whereas different modelling approaches for the non-structural mass are applied. The straightforward approach for modelling of the non-structural mass of the aircraft (e.g. fuel and payload) is to include it as additional density to the corresponding structural elements. This approach, which is referred to as “rigid mass modelling” would lead to conservative results in case of impact analysis as the non-structural mass remains attached to the aircraft for the entire duration of the calculation, resulting in an overestimation of the impact effects. An alternative approach for modelling of the non-structural mass is the application of the Smooth Particle Hydrodynamics (SPH) method. For the purposes of the current study, two models of the aircraft B777-300ER are created – one with the non-structural mass considered as additional mass density and another one, with the non-structural mass modelled with SPH particles. The crushing pattern of the plane corresponding to the two models is compared by impact simulation into a rigid wall. Additionally, the influence of the non-structural mass model on the structural capacity of a generic reinforced concrete containment is investigated. The damage effects, in terms of perforation area and displacement at the impact location, are compared; fragilities for perforation scenarios are presented, too. As a conclusion, it is shown that the “rigid mass modelling” seems more conservative than the realistic SPH model of non-structural mass although the latter may require significant computational effort.

INTRODUCTION

The non-structural mass in an aircraft includes the mass of the cargo, passengers with their luggage, fuel, as well as the mass of the equipment, avionics, seats, etc. The most straightforward approach for considering the non-structural mass is to include it as additional density of the corresponding structural elements. The mass of the fuel, for instance, can be included as additional density of the wing ribs in the fuel tanks. In the current paper, this approach is referred to as “rigid mass” model. The drawback of this approach is the fact that the non-structural mass remains rigidly attached to the structure at impact, leading in this way to an exaggerated inertial force. Furthermore, the “rigid” model of the non-structural mass does not allow debris cloud calculations to be made, i.e. it is not possible to estimate the amount of the debris and fuel, which interact (or penetrate) with the target structure and the aircraft.

An alternative approach for modelling of the non-structural mass is the Smooth Particle Hydrodynamics (SPH) method. An object made of SPH elements imparts its kinetic energy on the target but it disperses at impact, allowing, in this way, estimation of the debris and fuel cloud. Analyses of aircraft impact with fuel modeled by SPH particles are presented by Bocchieri et al. (2012), Kirkpatrick et al. (2006), Lee et al. (2014), and Wilt et al. (2011), and others.

In the current paper, we compare the damage effects on a reinforced concrete containment structure due to impact of a large commercial airplane. Two basic cases are considered – in the first case the non-

structural mass of the aircraft is included as additional density of the structural elements (i.e. “rigid mass”) and in the second case the non-structural mass including mass of fuel, cargo, passengers and luggage is modeled using SPH. The aircraft used for the analyses is primarily the B777-300ER, as this is one of the most widely used airliners worldwide. The damage effects compared are the displacement at the impact location and the area of the perforation of the target structure. The former is related to the possibility for assessment of secondary effects, i.e. impact on internal structures and safety related installations and the latter is related to the amount of debris and fuel that can penetrate into the containment.

Furthermore, fragility curves showing the probability for exceeding perforation areas of 1 m², 5 m², 15 m² and 50 m² are derived. The fragility curves are based on more than 50 impact analyses with different large commercial airplanes - B777-300ER, B767-200 and Airbus A340-400. These analyses are performed with different impact velocities, different mass of the aircraft at impact and different impact angles. For the fragility analyses the non-structural mass of the airplanes is modeled via three different approaches: fuel and payload modeled as “rigid mass”, fuel with SPH and payload as “rigid mass”, fuel and payload with SPH.

ANALYSIS SETUP

The analyses are performed by the missile-target interaction method. The target structure is a reinforced concrete containment which consists of a cylinder and half-spherical dome. The containment structure is modeled as a generic type. Non-linear material models are used for the concrete and the reinforcement steel. The chosen impact location is at the dome. The approach angle is selected so that normal impact at the dome occurs. This is considered to be an unfavorable scenario from structural point of view. The aircraft used primarily for the analyses and used for graphic illustration further on is B777-300ER. Its impact mass corresponds to the Maximum Takeoff Weight. This is a conservative assumption because the probability for takeoff with such mass is very low as it is shown by Kostov et al. (2013). A scheme of the impact configuration and Finite Element (FE) model of the aircraft are shown in Figure 1. The position in the fuselage of the SPH particles corresponding to passengers, luggage and cargo is shown in Figure 2. The position in the wing of the SPH particles corresponding to fuel is shown in Figure 3.



Figure 1. Impact configuration and FE model of the airplane

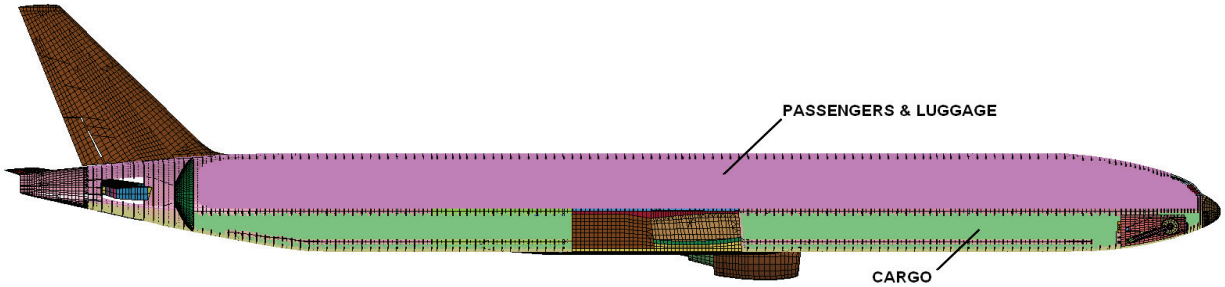


Figure 2. Position of the SPH particles corresponding to payload

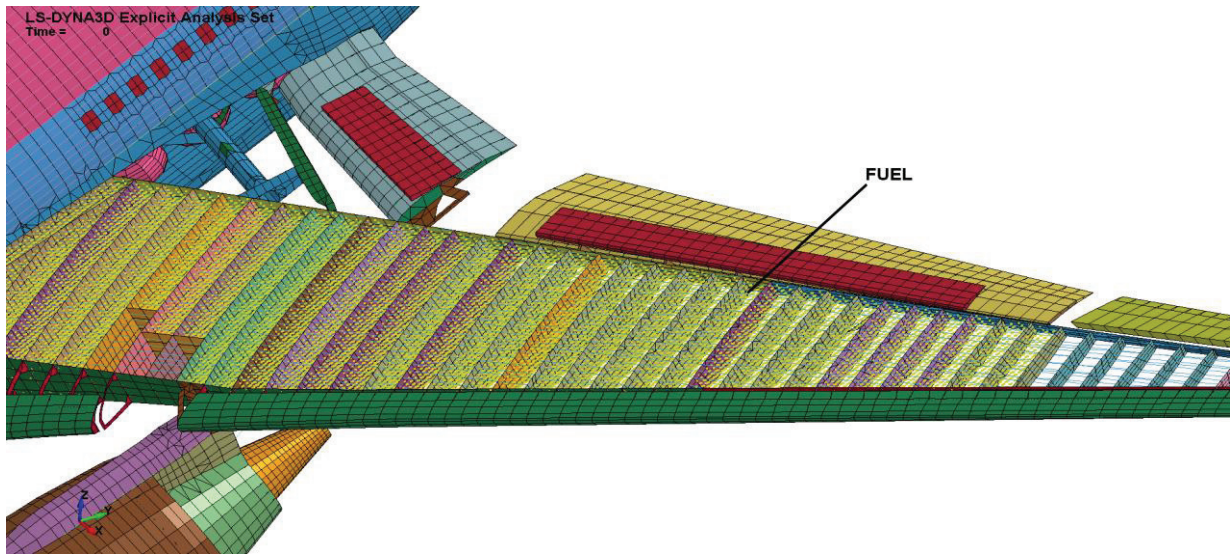


Figure 3. Position of the SPH particles corresponding to fuel

IMPACT INTO RIGID WALL AND CONCRETE CONTAINMENT

Preliminary impact analyses of the airplanes with the two models of the non-structural mass are performed into a rigid wall. Figure 4 shows comparison of the impact at time $t=0.3$ s. The difference in the crushing pattern of the aircraft in the case of “rigid mass” and SPH mass model can be clearly seen. The fuselage of the aircraft with SPH mass model is destroyed by the pressure of the SPH particles in the course of the impact. This leads to decrease of the stiffness of the fuselage, which in turn leads to decrease of its impinging force. Visual comparison with photographs of real aircraft crashes leads to the conclusion that such crushing pattern of the aircraft can be considered realistic.

The impact of the aircraft with “rigid mass” model and SPH for the non-structural mass into the containment structure is shown in Figure 5. Table 1 and Figure 6 show comparison of the change of momentum (initial minus final) and the impulse of the contact force resulting from the two analyses under consideration. The values in Table 1 are normalized to the corresponding momentum changes. The graphs in Figure 6 are normalized to the initial impact momentum. The figure shows that change of the momentums of the two analyses is equal (within 1%) to the corresponding impulses of the contact force. Comparison of the resultant contact forces from the analysis with “rigid mass” and SPH model is shown in Figure 7. The force from the analysis with the SPH model is about 20% higher than the one from the

analysis with “rigid mass” model. This is attributed to the interaction of the SPH with the surface of the dome, i.e. the contribution of each SPH particle to the friction forces leads to total increase of the resultant contact force.

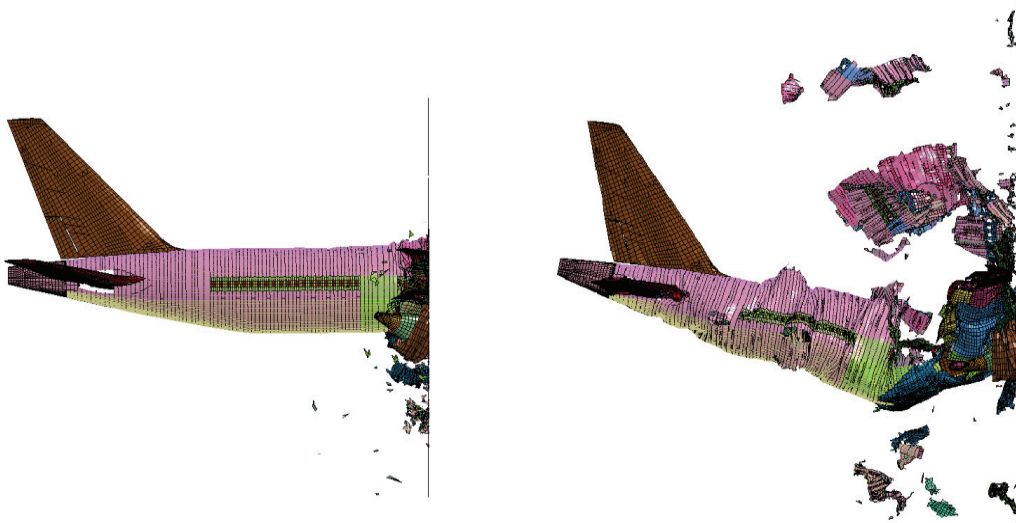


Figure 4. Impact into rigid wall at time $t=0.3$ s of the aircraft with “rigid mass” (left) and SPH (right, the SPH particles are not shown)

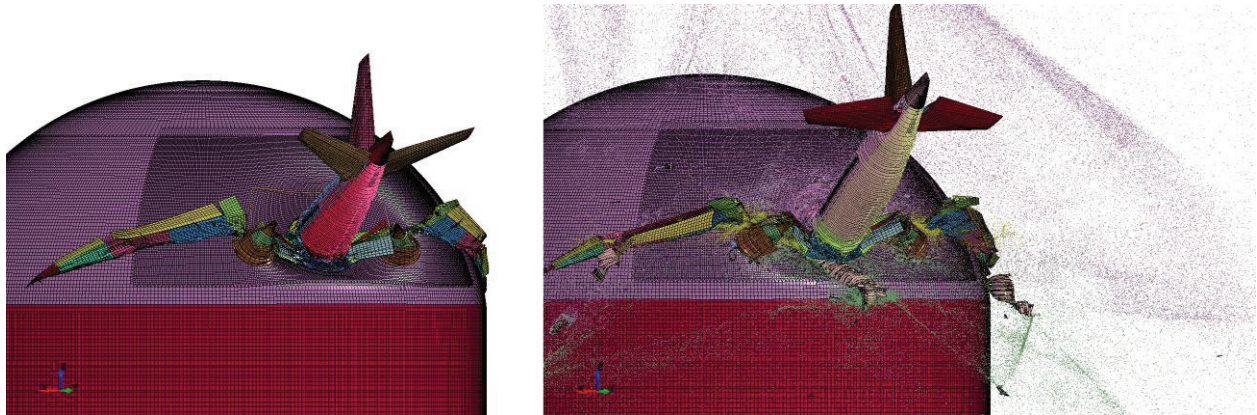


Figure 5. Impact into the containment of the aircraft with “rigid mass” (left) and SPH (right)

Table 1. Normalized change of momentums and impulses

	Norm. momentum change	Norm. impulse
“Rigid mass” model	1	0.990
SPH model	1	0.998

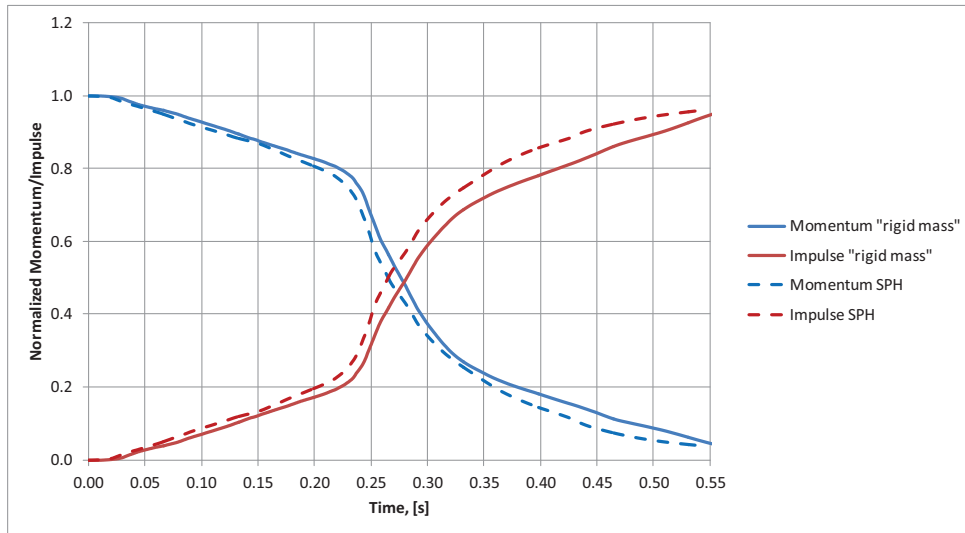


Figure 6. Normalized momentum and impulse of the contact forces from the considered analysis

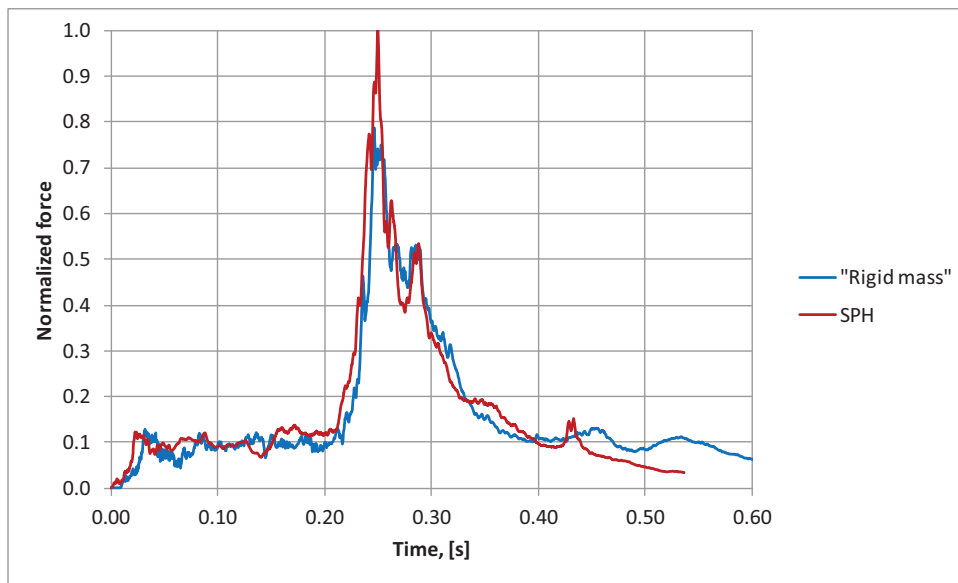


Figure 7. Comparison of the resultant contact forces

As mentioned above, the damage effects under consideration are the area of the perforation of the outer shell and the displacement at the impact location. For analyses with “rigid mass” model, the amount of debris and fuel which penetrate through the shell can be indirectly defined. On the other hand, the application of SPH allows the amount of penetrating debris and fuel to be directly defined by measuring the SPH as shown in Figure 11. The corresponding perforations are shown in Figure 8 and Figure 9, respectively. Normalized values of the perforation areas and displacements are given in Table 2. The perforation area in the case with SPH mass model is more than 50% smaller than in the case with “rigid mass” and the displacement is 13% smaller. Figure 8 shows that contour of eroded elements is formed around the impact area and the outer tension reinforcement is ruptured. The reason for such damage pattern is the fact that in the case of “rigid mass” model, the impact force is concentrated over smaller

area. On the other hand in the case of SPH model, the impact force is spread over larger area due to dispersion of the SPH particles.

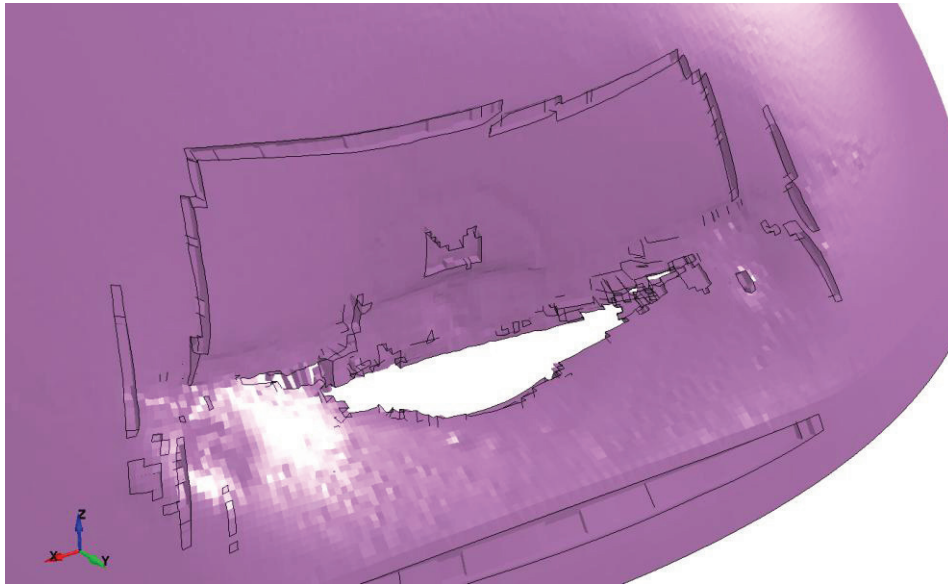


Figure 8. Perforation of the dome from the analysis with “rigid mass” model

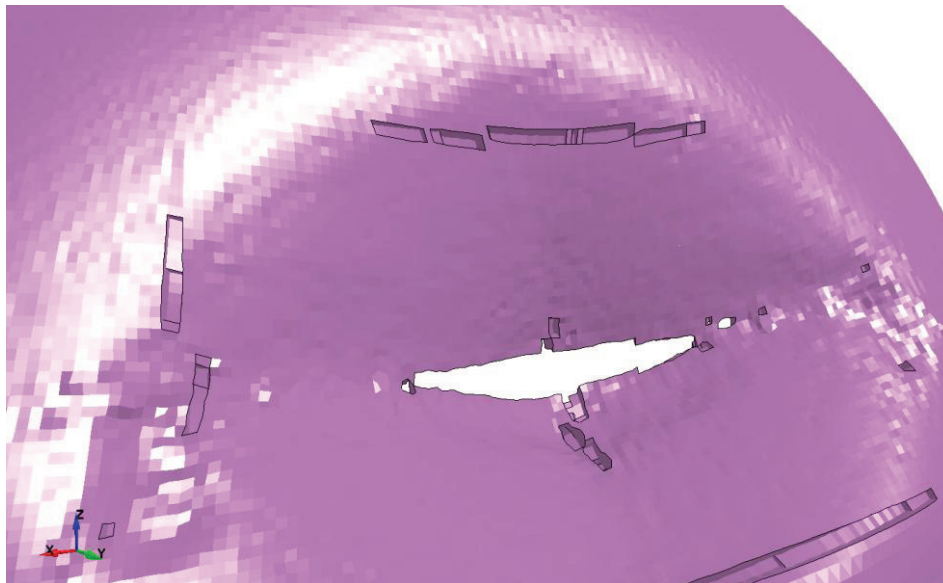


Figure 9. Perforation of the dome from the analysis with SPH model

Table 2. Normalized damage effects

Non-structural mass model	Normalized area of the perforation	Normalized displacement
“Rigid mass”	1	1
SPH	0.43	0.87

The dispersion of the SPH particles is shown in Figure 10. The SPH particles corresponding to fuel and payload which penetrate through the perforation of the shell can be seen in Figure 11. For this particular analysis scenario (mass, velocity, impact angle), a small amount of SPH particles penetrates the structure due to the relatively small perforation which is formed. The greater part of the SPH particles disperse outside the structure at impact.

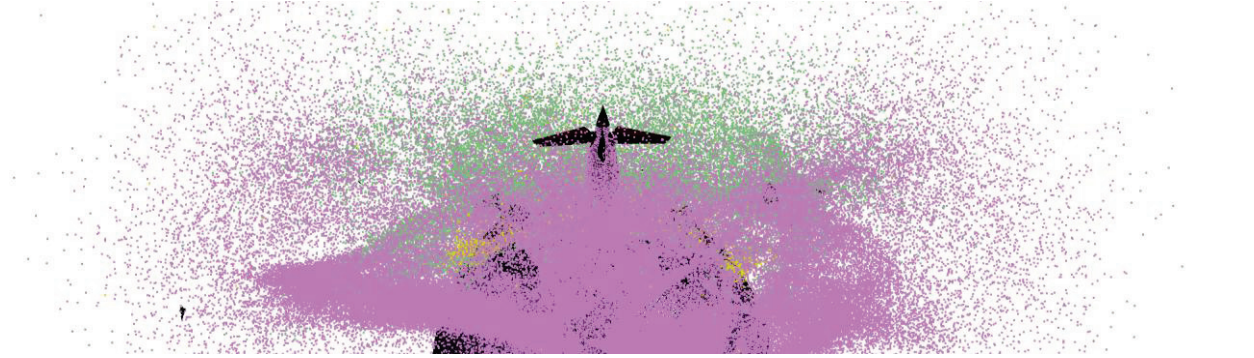


Figure 10. Debris cloud from the impact of the airplane with SPH

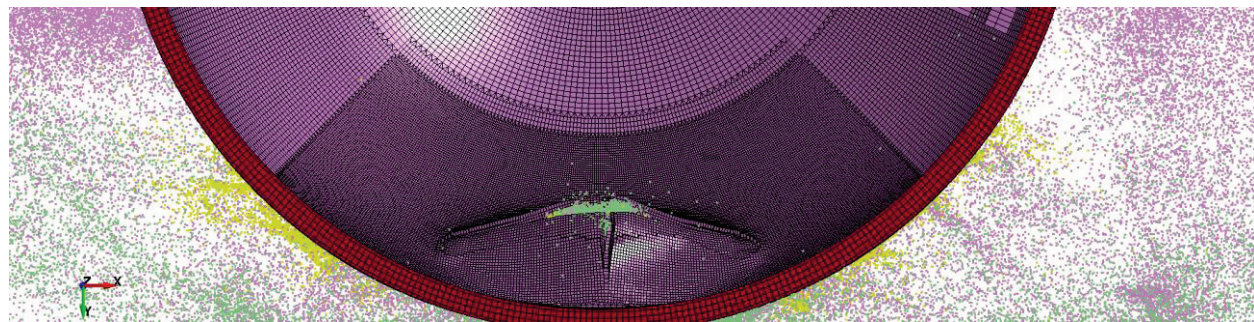


Figure 11. Penetrating SPH particles, bottom-up view

FRAGILITY CURVES BASED ON ANALYSES WITH “RIGID MASS” AND SPH

More than 50 analyses with 3 large commercial aircraft (B777-300ER, A340-600 and B767-200) are performed. Several velocity scenarios in the range of minimum to maximum impact velocity (different for each aircraft) with different impact angles are considered, together with variation of the mass at impact. The non-structural mass of fuel and payload is modeled via three different approaches:

- Fuel and payload as “rigid mass”.
- Fuel as SPH particles and payload as “rigid mass”.
- Fuel as SPH particles and payload as SPH particles.

The best fit to the data is provided by fragilities in terms of the kinetic energy over impact area of the missile. For simplicity the results hereafter are presented for normalized kinetic energy over impact area. In previous analyses we have used also fragilities in terms of impact velocities, maximum impact force, impact pressure, momentum and momentum over impact area, see Henkel and Kostov (2014). The best correlation of effects in terms of perforation area is achieved for kinetic energy over impact area.

We have considered many effects due to impact, however, only perforation scenarios are presented hereafter. We may group the perforation effects in groups, e.g. very small perforation up to 5 m² (i.e.

intrusion of debris and fuel is limited), moderate – up to 15-20 m² and large perforations – more than 50 m². In Figure 12 an example is given for a best estimate fragility curve for a scenario “perforation larger than 50 m²”. The data obtained is plotted on a XY-Scatter graph with the normalized kinetic energy over impact area on the abscissa and the conditional probability of exceeding as ordinates. The conditional probability of failure is calculated assuming log-normal distribution of both load and resistance and 0,4 variation of load and 0,2 for resistance, respectively. Data points are processed to suit up a regression analysis. Gaussian least squares approach is performed, in order a fit of the log-normal cumulative density function to be obtained.

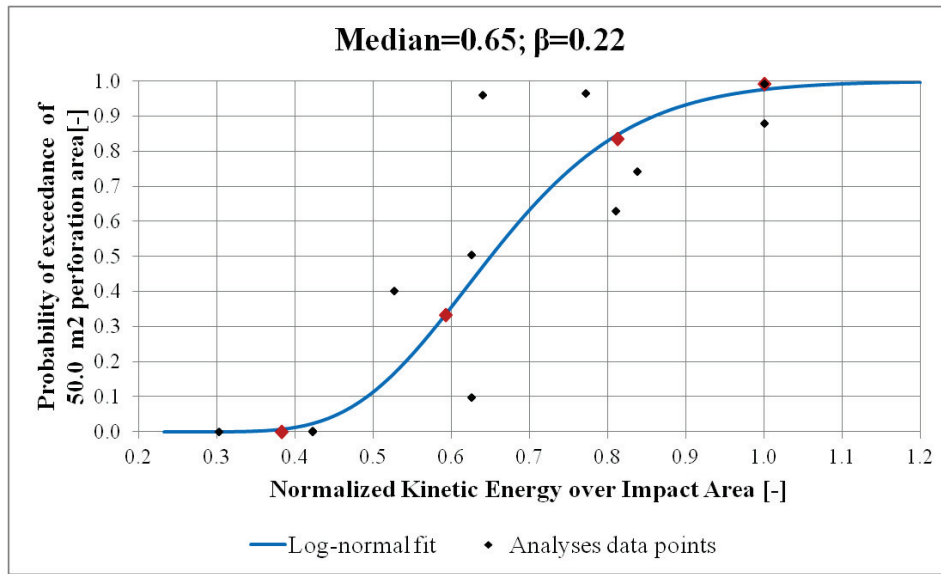


Figure 12. Best estimate fragility for scenario “perforation larger than 50 m²”

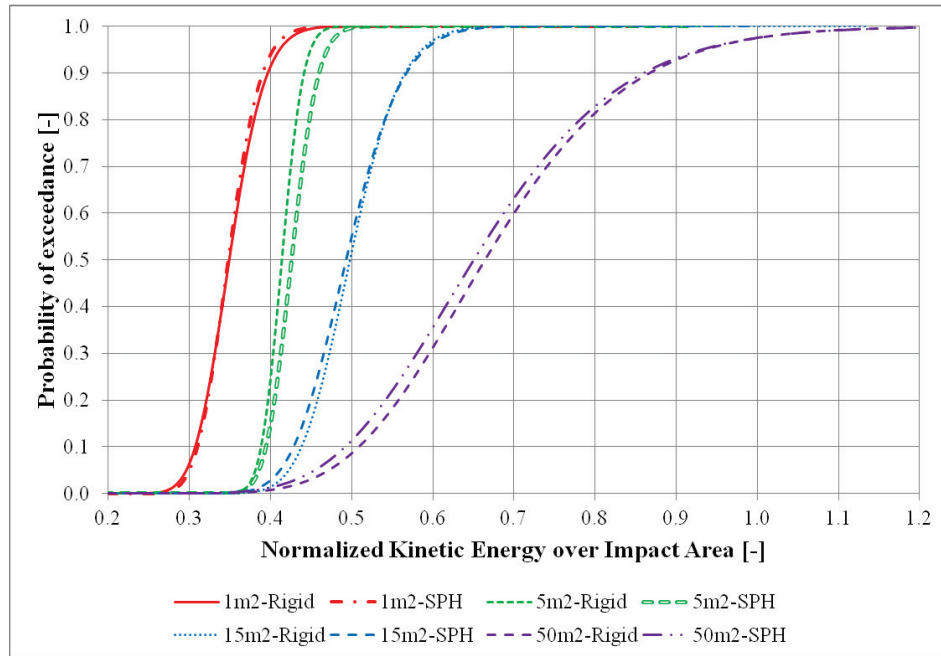


Figure 13. Fragilities for scenarios “perforation larger than 1, 5, 15 and 50 m²”

CONCLUSION

The current paper compares aircraft impact analyses with different models of the non-structural mass. The target is a reinforced concrete containment structure. The non-structural mass in an aircraft includes fuel, cargo, passengers, luggage and other items which are not related to the structure of the aircraft. In the first case, the non-structural mass is considered as additional density of the structural elements. This model is referred to as “rigid mass” model. In this way the non-structural mass remains attached to the crushing aircraft and does not disperse at impact. A possible approach to overcome this drawback is the application of SPH. In the second analysis case, the fuel and the payload are modeled with SPH. The damage effects on the structure, in terms of perforation area and displacement obtained from the analyses, are compared. For relatively low to moderate energy impact in the case of SPH mass model, the perforation area and displacement are smaller than in the case of “rigid mass”. Furthermore, in the latter case, a contour of eroded elements and ruptured outer tension reinforcement is formed around the impact area. The reason for the more extensive damage, obtained from the analysis with “rigid mass” is attributed to the fact that the impact force is distributed over a smaller area (only the cross section of the fuselage), while in the case of SPH mass model, the impact force is spread over larger area due to the dispersion of the particles. It is also shown that the airplanes with the different non-structural mass models demonstrate different crushing pattern in the course of impact. The airplane with SPH mass model is destroyed by the pressure of the particles and pieces of the fuselage are torn apart at the impact. The airplane with “rigid mass” model has a pronounced plastic crushing pattern and only small pieces of the fuselage are torn apart. One very important advantage of the use of SPH demonstrated here is the possibility to estimate the spreading of debris and fuel as well as the amount of debris and fuel which penetrate the target structure. The fragilities developed on the base of those analyses do not demonstrate large difference between “rigid mass” and SPH mass models. The difference seems to be even less for larger energy impacts, where the inertia part of the impact force is dominating.

Although the computational effort is significant for applying SPH models, we believe that the latter would more realistically predict both missile and target damage patterns, impact load will be more realistically applied, i.e. on a larger area, and debris cloud and especially fuel dispersion (intrusion) could realistically be assessed.

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