Non-structural Mass Modeling in Aircraft Impact Analysis Using Smooth Particle Hydrodynamics

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1 Introduction

The term “non-structural” mass is used for the mass of all elements and equipment in the aircraft which are not part of its structure. This includes the mass of the electrical equipment, avionics, seats, equipment used by the flight attendants, etc. The non-structural mass also includes the mass of the cargo, passengers with their luggage and fuel. The non-structural mass contributes to the kinetic energy of the impacting aircraft but it breaks or disperses at impact.

Different approaches exist for modeling of the non-structural mass using the software tool LS-Dyna. The most straightforward of them is to include this mass as additional mass density of the corresponding structural elements. The mass of the fuel, for instance, can be included as additional mass 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 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.

Alternative approach available for modeling of the non-structural mass in LS-Dyna is the Smooth Particle Hydrodynamics (SPH) method. The SPH is a method which requires no mesh (mesh-free). The SPH particles are not connected to each other and therefore, the SPH configuration may undergo large deformations and retain stability. An object made of SPH 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 in the literature resources [1],[2],[4] and [6].

In the current paper we compare the damage effects on a reinforced concrete containment structure due to impact of a large commercial airplane. Two cases are considered – in the first case the non-structural mass of the aircraft is included as additional mass 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 model using SPH. The aircraft chosen for the analyses is B777 as this is one of the most widely used airliners worldwide. The damage effects which are 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.

2 Analyses set-up

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 modelled as a generic type. Non-linear material models are used for the concrete and the reinforcement steel. The concrete is modeled with **`*MAT_CSCM`** and the **`*MAT_PIECEWISE_LINEAR_PLASTICITY`** is used for the reinforcement. The aluminum in the aircarft is modeled with **`*MAT_JOHNSON_COOK.`** The corresponding material model parameters are fitted by prelimianry analyses. 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 the most unfavorable scenario from structural point of view. The aircraft selected for the analyses is B777. 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 in [3]. The scheme of the impact configuration and the Finite Element (FE) model of the airplane are shown in Figure 1. The characteristics of the model of the airplane are given in Table 1. The aircraft model where the non-structural mass is modeled by SPH contains totally 1 310 465 particles (181 046 SPH fuel particles, 295 073 SPH cargo particles and 834 346 SPH particles corresponding to passengers and luggage).

Fig.1: Impact configuration (left) and FE model of the aircraft (right)

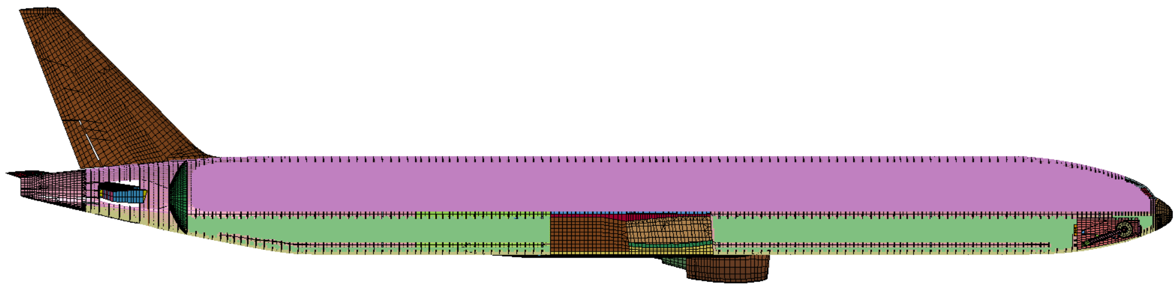

Fig.2: Position of the SPH corresponding to passengers, luggage and cargo

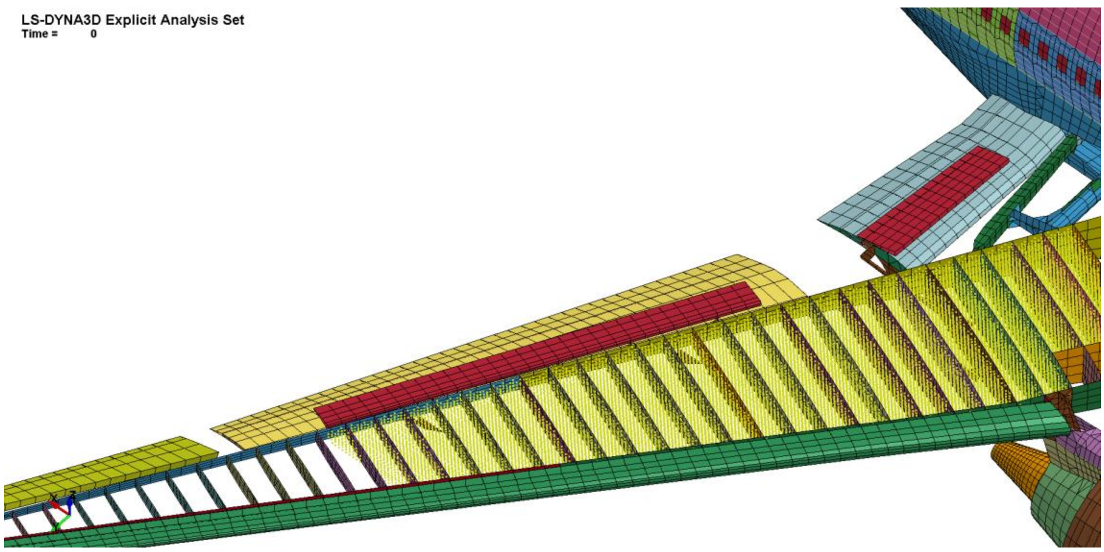

Fig.3: SPH fuel particles

Figure 2 shows the position of the SPH corresponding to payload in the aircraft. The position of the SPH fuel particles in the wing of the aircraft is shown in Figure 3.

For the impact analysis with "rigid model" of the non-structural mass ***CONTACT_AUTOMATIC_GENERAL** is used. For the analysis with SPH model for the non-structural mass different contacts are applied for the different interactions. For instance ***CONTACT_AUTOMATIC_SURFACE_TO_SURFACE** is used for the interaction of the airplane with the containment. ***CONTACT_AUTOMATIC_NODES_TO_SURFACE** is used for the interaction of the SPH with the airplane and the containment structure.

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

Table 1: Characteristics of the model of B777

The friction for the corresponding interactions is considered through the contact definitions. For the case of "rigid mass" model, one friction coefficient of 0.5 is applied in the definition of the ***CONTACT_AUTOMATIC_GENERAL.** Fort the case of SPH fuel model of the non-structural mass, different friction coefficients are used in the different contact definitions. Friction coefficient 1.3 is used for the interaction aluminum-aluminum, friction coefficient 0.5 is used for the contact aluminum-concrete. Friction coefficient of 0.1 is also considered for the contact of the SPH particles with the airplane and the concrete structure.

Equation of state ***EOS_GRUNEISEN** and ***MAT_NULL** are used for the SPH corresponding to fuel and payload.

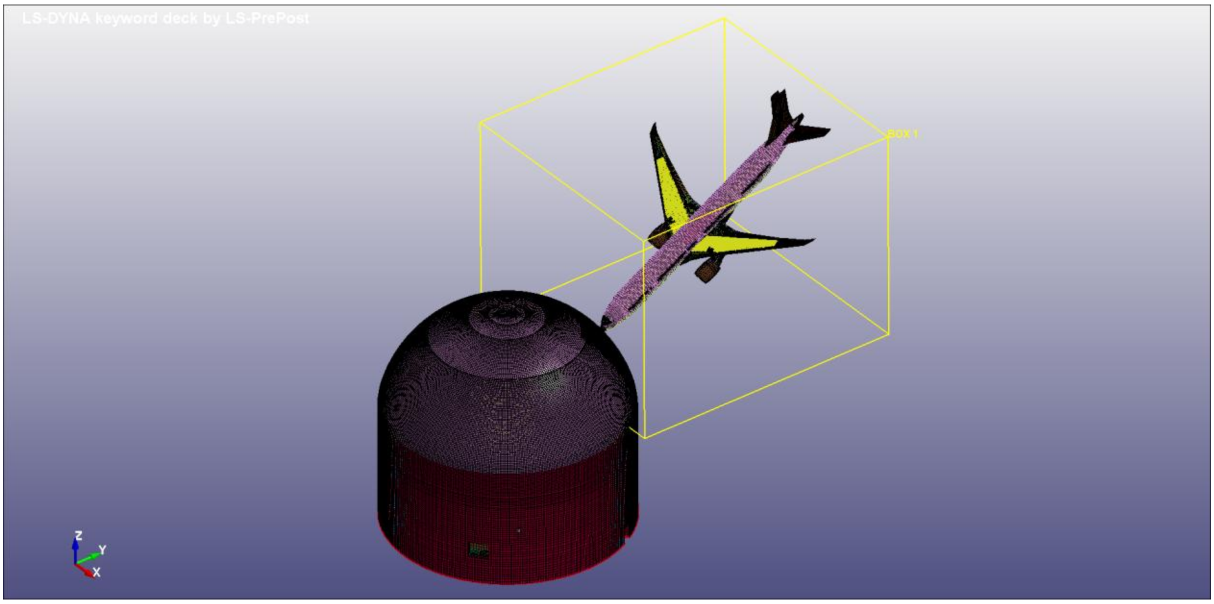

Fig.4: Box for the SPH approximation

Figure 4 shows box which is defined for the SPH calculations. The particles which have gone out of the box are deactivated. This reduces significantly the computation time by eliminating particles which no more interact with the structure.

3 Impact into Concrete Containment

The impact of the aircraft with "rigid mass" model and SPH model of the non-structural mass are shown in Figure 5 and Figure 6, correspondingly. The energy ratios of the two analyses are shown in Figure 7. The energy ratio of the analysis with "rigid mass" is equal to 1 and the energy ratio of the SPH model oscillates but still it remains in the prescribed boundaries 0.9 to 1 as discussed in [5]. The energy ratios imply preservation of the energy balance in the course of the analysis.

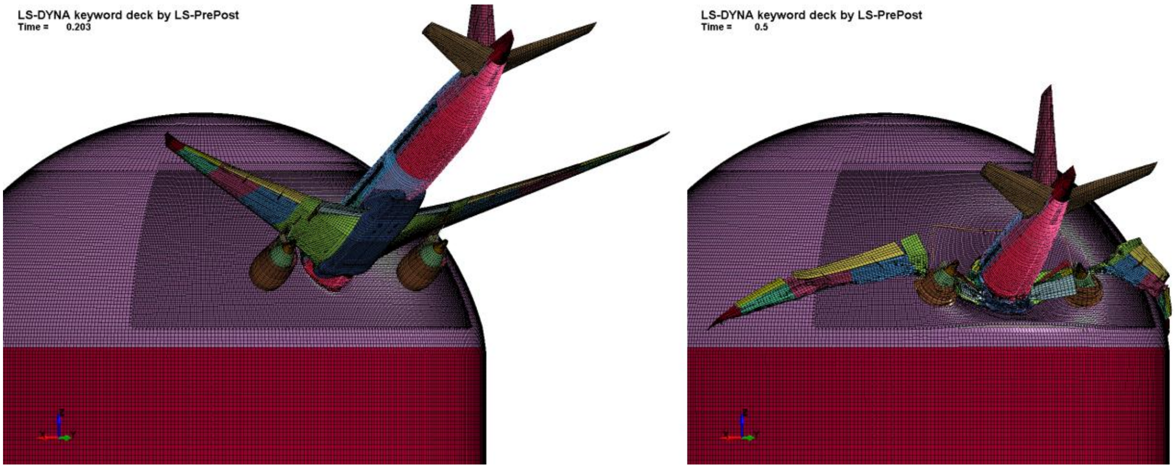

Fig.5: Impact at the containment with "rigid mass" model

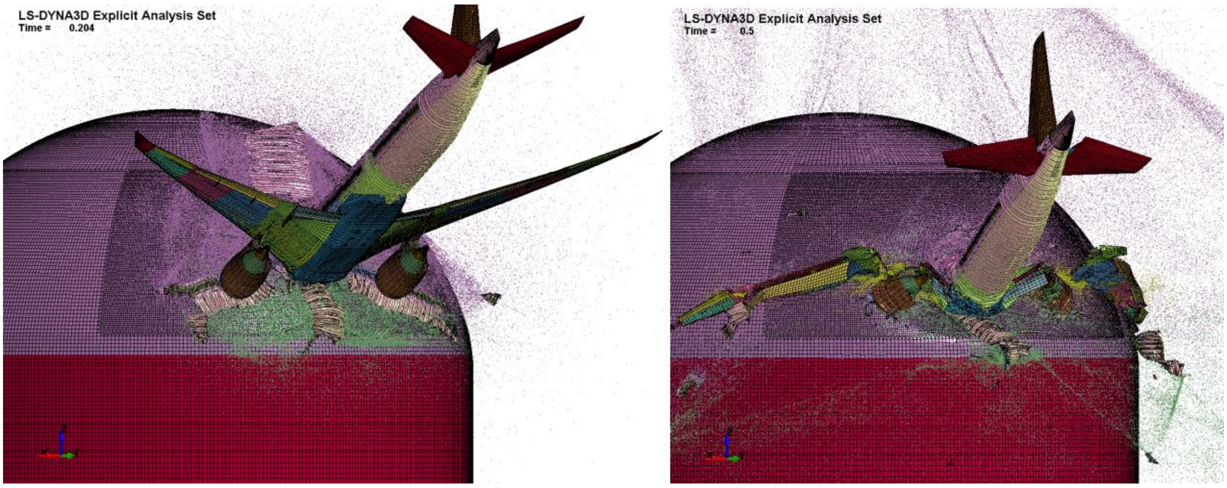

Fig.6: Impact at the concrete containment with SPH model

The normalized resultant contact force of the interaction airplane-dome from the analysis with SPH mass model is shown in Figure 8. The total force is the sum of the contact forces of the different parts – airplane, payload and fuel (modeled with SPH). Comparison of the resultant contact forces form the analysis with "rigid mass" and SPH model is shown in Figure 9. The force of the SPH model is about 20% higher than the one with "rigid mass" model. This is attributed to the friction 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 10 shows comparison of the impact momentum and the impulse of the contact force resulting from the two analysis cases under consideration. The graphs are normalized to the initial impact momentum. The figure shows that change of the momenta (initial minus final) of the two analyses is equal to the corresponding impulses of the contact force.

Figure 11 demonstrates comparison of the aircraft impact into the structure at different instances in time. 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. Comparison with photographs of real aircraft crashes leads to the conclusion that such crushing pattern of the aircraft can be considered realistic.

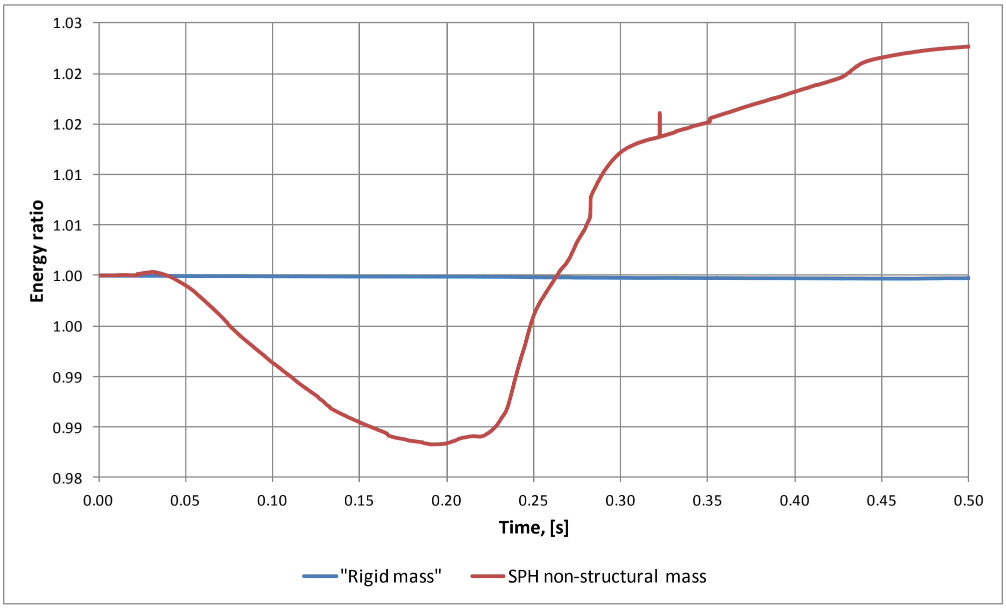

Fig.7: Energy ratios of the analyses with "rigid mass" and SPH model of the non-structural mass

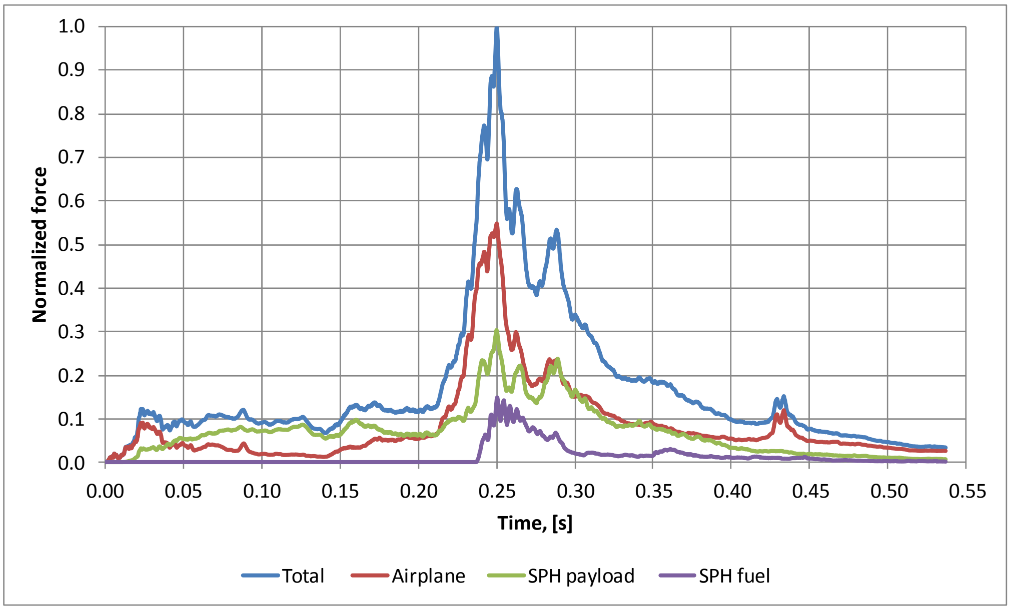

Fig.8: Resultant contact force form the analysis with SPH model of the non-structural mass

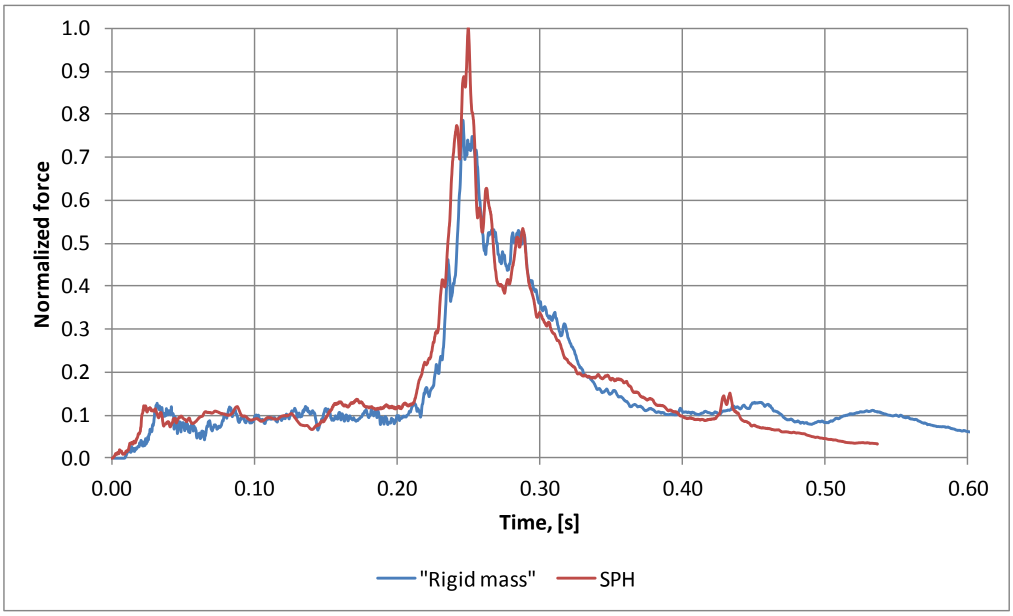

Fig.9: Comparison of the resultant contact forces

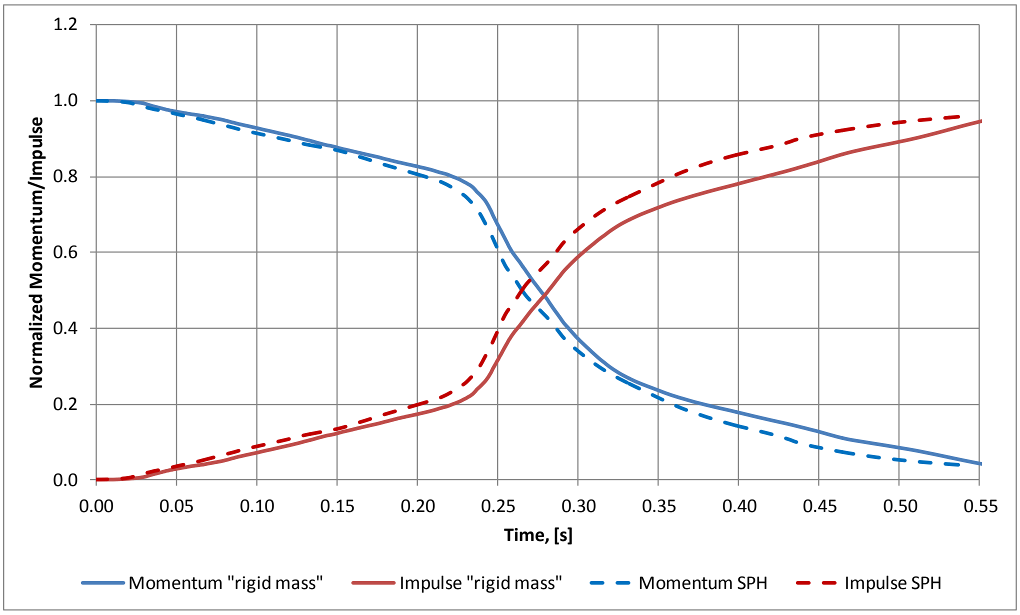

Fig.10: Normalized momentum and impulse of the contact force of the considered analyses

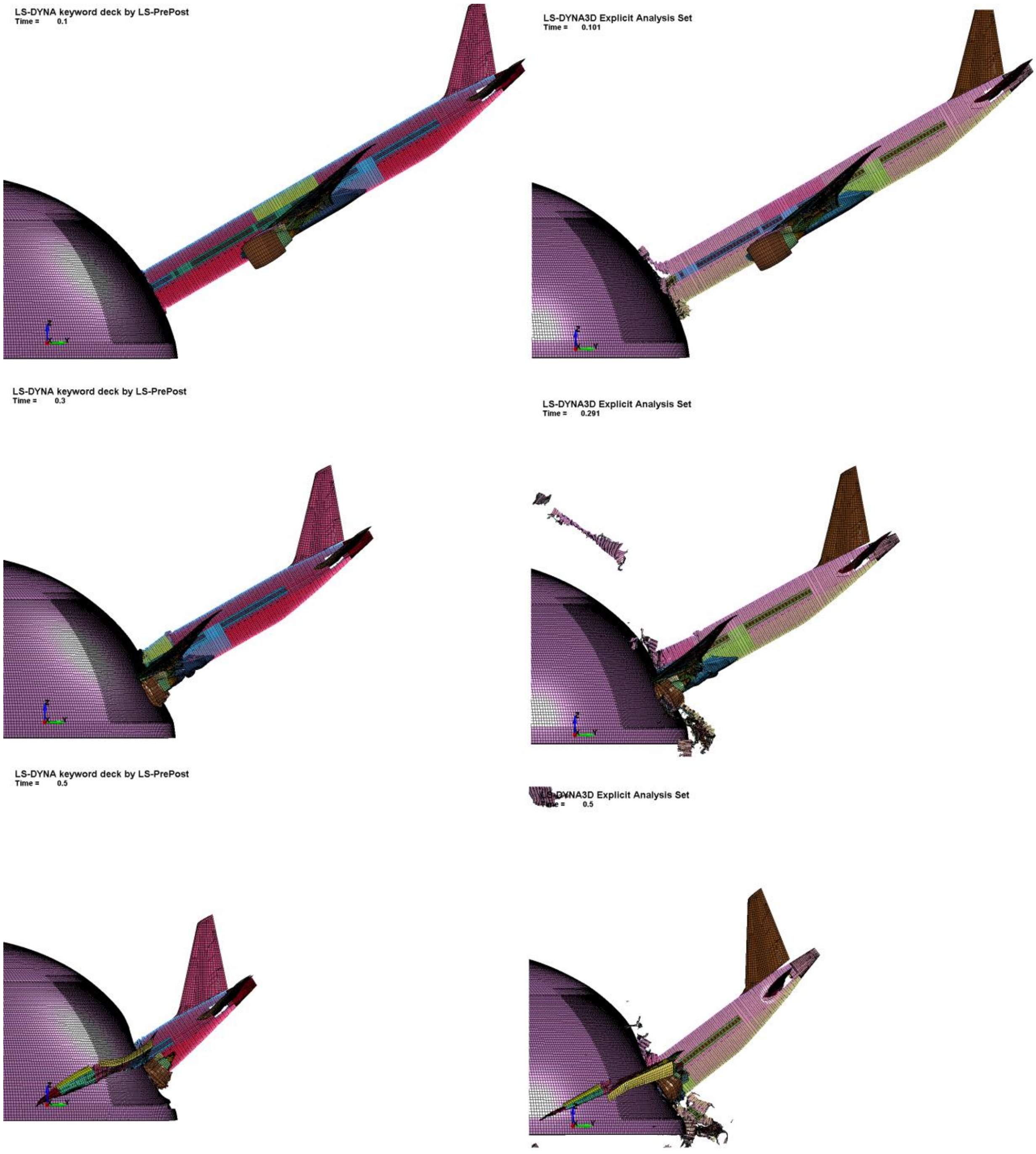

Fig.11: Impact of the aircraft with "rigid model" (left) and SPH model (right, SPH particles are not shown)

As previously discussed, 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 15. The corresponding perforation areas are shown in Figure 12 and Figure 13. Normalized values for 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 12 shows that contour of eroded elements is formed along 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 small 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.

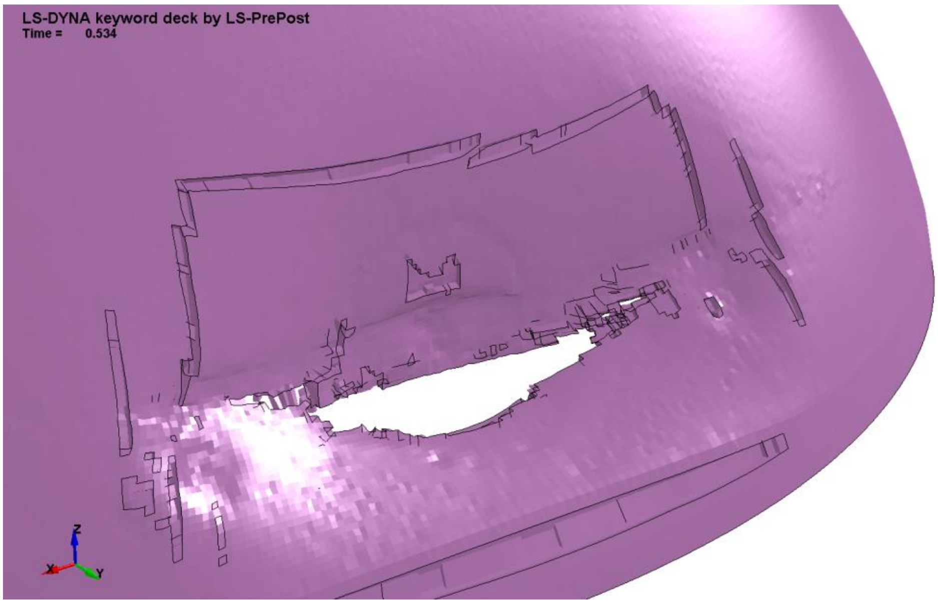

Fig.12: Perforation of the dome from the analysis with "rigid mass" model

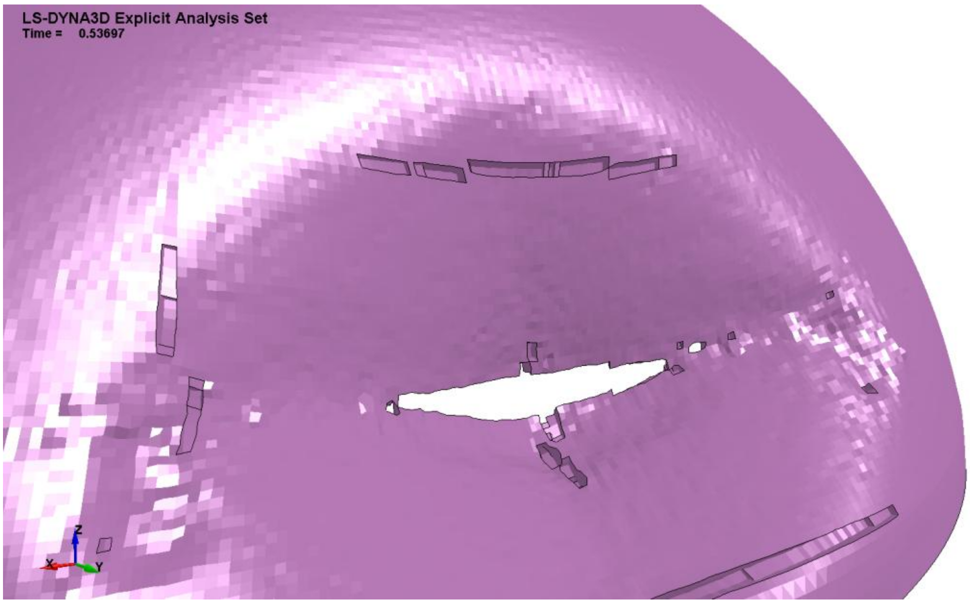

Fig.13: Perforation of the dome from the analysis with SPH model

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

Table 2: Normalized damage effects

The dispersion of the SPH particles at different time instances is shown in Figure 14. The SPH particles corresponding to fuel and payload which penetrate through the perforation of the shell can be seen in Figure 15. For this particular analysis set-up (mass, velocity, impact angle) small amount of SPH particles penetrate the structure due to the relatively small perforation which is formed. The greater part of the SPH particles disperse outside the structure at impact.

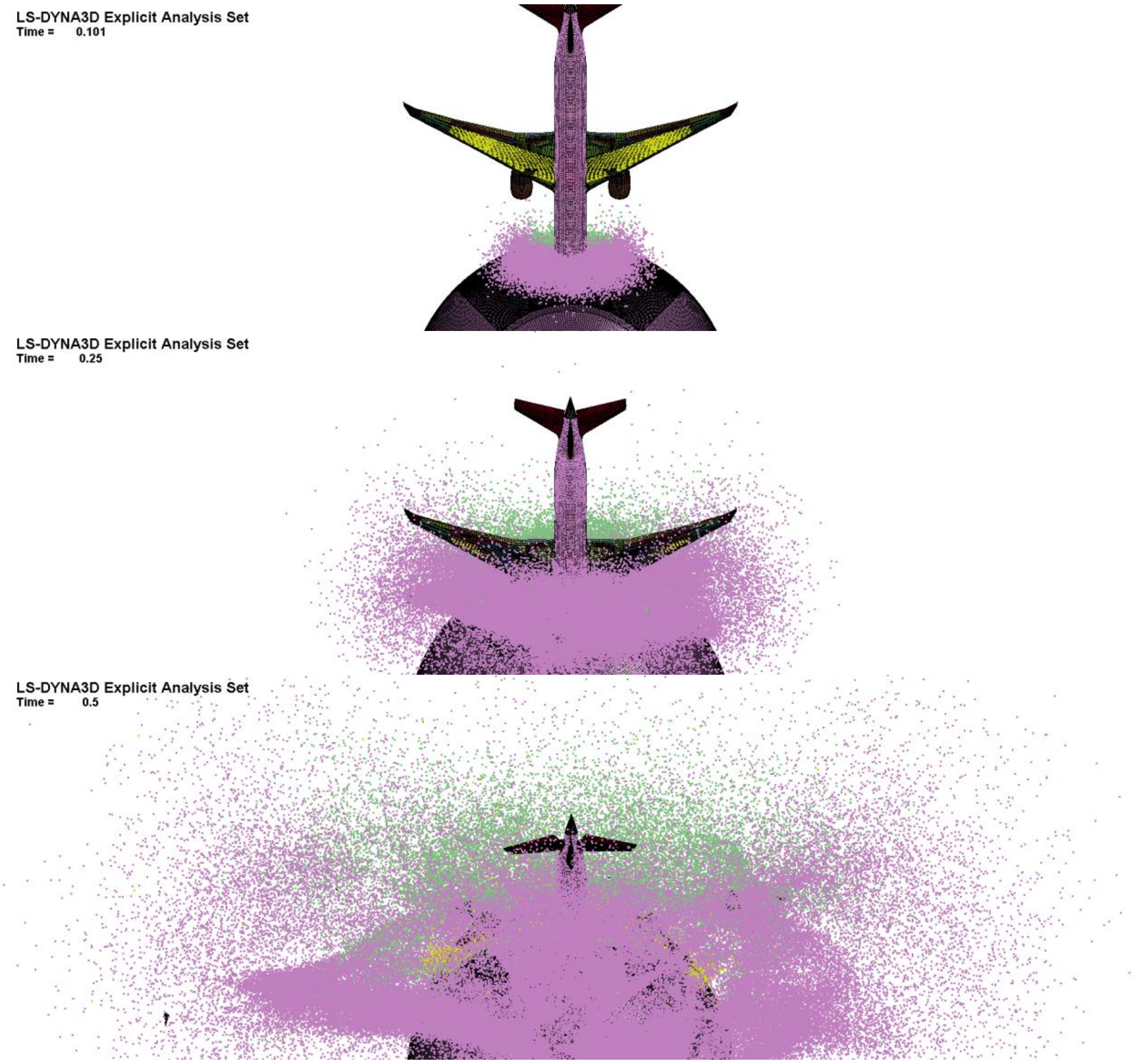

Fig.14: Debris cloud at different stages of the analysis with SPH mass model

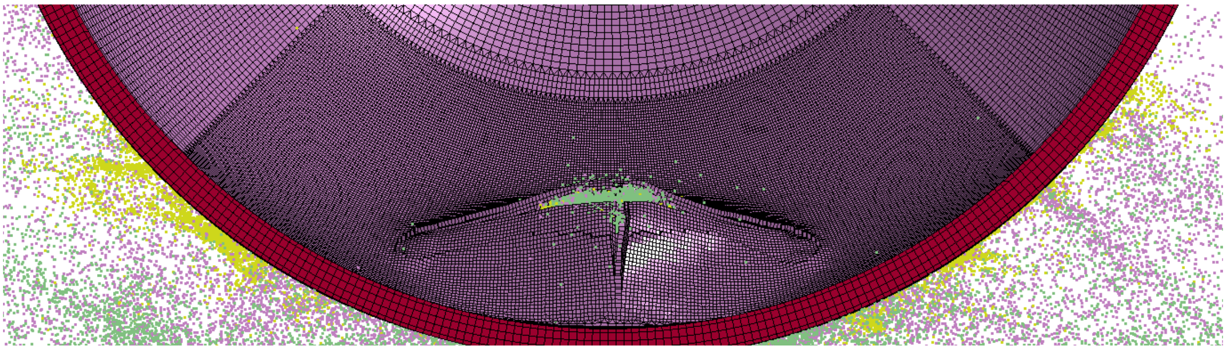

Fig.15: Penetrating SPH into the containment structure, bottom-up view

4 Summary

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 is modeled with SPH. The damage effects on the structure in terms of perforation area and displacement obtained from the analyses are compared. 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 smaller area (only the cross section of the fuselage) while in the case of SPH mass model, the impact force in 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 an accordion-like crushing pattern and no 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.

5 Literature

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