EXPERIMENTAL TESTING AND NUMERICAL SIMULATION TO DESIGN AN INNOVATIVE BLAST RESISTANT TEXTILE LUGGAGE CONTAINER

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Abstract

This paper deals with the activities of virtual simulation and experimental testing and validation for the development of a textile container for the blast protection of cargo holds.

About 75% of the aircrafts in service are narrow-body aircrafts, and more than 70% of bombing attempts have been against narrow-body aircrafts. The risk that a small quantity of an explosive, below the threshold of the detection instruments, could get undetected cannot be discarded, and the introduction of countermeasures to reduce the effects of on-board explosions should be considered, especially for narrow-body aircrafts. Existing hardened unit load devices (HULD) have been developed to reduce the effects of on-board explosions, but they have some disadvantages which prevent their wider utilization: they are heavier and much more expensive than standard luggage containers and, notably, applicable only to wide-body aircrafts. The research and development of hardened containers for narrow-body aircraft are lagging behind the work on containers for wide-body aircraft. Limited research has been done on container role as part of a total architecture for aviation security; coordination with the airlines, airports, and aircraft manufacturers has been focused mainly on specific designs and utility requirements rather than on the security measures. HULD have largely been developed and designed as single stand-alone entities, alternative designs may be more practical than existing especially in the top-level total architecture of aviation security context.

The issue of containing explosions aboard narrow-body aircraft may be resolved with an innovative combination of energy absorption materials and a novel lightweight structural concept based on textile technologies.

Explosion-containment strategies for narrow-body aircraft, including the development of a concept for ULD for narrow-body aircrafts is the aim of the study presented. In particular, the paper presents the results of the blast tests carried out for the characterization of textile materials and composite elements used for the innovative blastworthy luggage container. The different textile materials considered vary for the fibre materials and the textile pattern. The tests have also considered sandwich elements characterized by asymmetric construction and variable core design. The materials have to survive the dynamic loads generated after the explosion characterized by an increase in pressure at the shock front which immediately begins to decrease as the blast wave moves outward from the explosion. Random parameters such as the luggage filling ratio and the position of the explosive inside the container have a relevant influence on the effect of the explosion and its mitigation (see Figure 1).

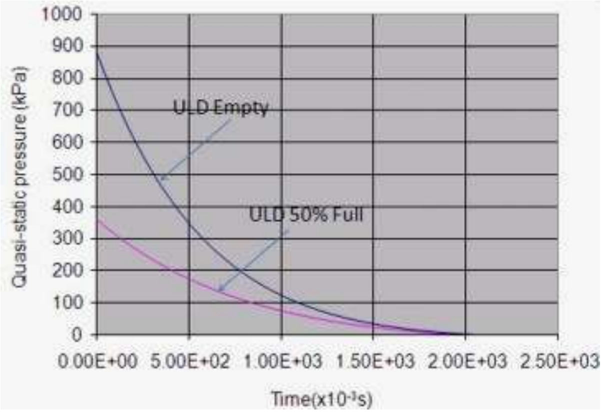

Fig. 1. Effect of luggage filling ration in ULD on quasi static pressure dissipation vs. time.

As the phenomena associated with explosions are of a highly nonlinear and time-dependent nature, wave propagation codes, like hydrocodes, are used to simulate the explosive events and to predict the material performance. Numerical simulations are carried out to perform sensitivity studies and as a tool to address the variability in test parameters, such as bomb placement, effect of the luggage inside the container structure and explosive charge performance (see Figure 2).

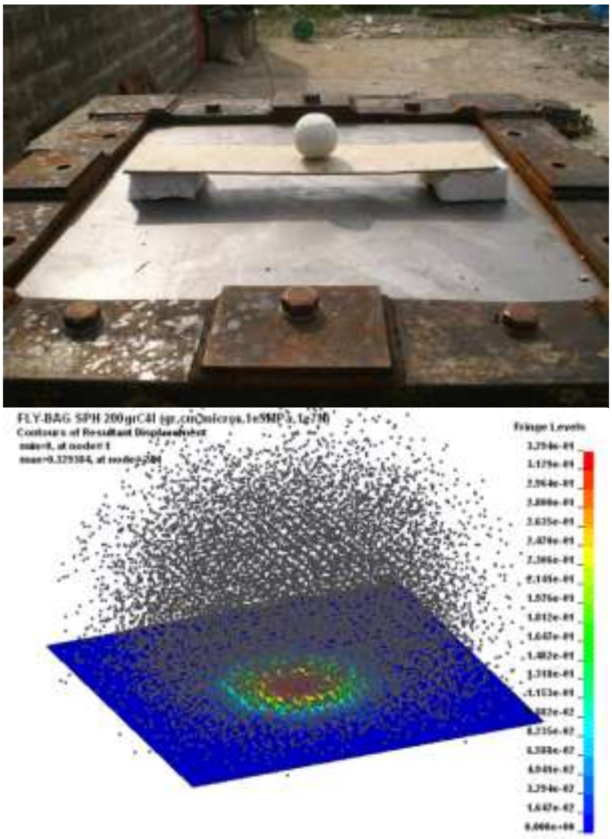

Fig. 2. Test set up for blast test (top) and numerical simulation (bottom)

Full scale blast tests are then performed for the validation of the numerical simulations and for the demonstration of the concept.

Although experimental testing is always necessary, there are considerable motivations for an extended use and support of numerical simulation. For example, the response of blast load on structure is correlated with many parameters, and an understanding of these dependencies by numerical simulations validated through experimental testing can provide a better understanding of the complex phenomenon and a better interpretation of the test, resulting into a synergistic approach to be used in the field of aviation security.

1 General Introduction

This paper presents the results of the blast tests carried out for the characterization of textile materials used for an innovative blast resistant luggage container. Numerical simulations have been also carried out to perform sensitivity studies and as a tool to address the variability in test parameters, such as bomb placement and explosive charge performance.

The activities described in the present paper have been developed within the framework of FLY-BAG [1] Research Project, funded by the European Commission (Grant Agreement No. 213577), whose final goal is to protect aircrafts from explosions caused by bombs concealed inside the checked luggage.

The combination of textile fibres and composite materials, allows the container to achieve a high flexibility and reconfigurability, a low weight and a high resistance to blasting events; moreover, this concept applies to both wide- and narrow-body aircrafts and can be further customized for practically any application and configuration.

Textile structures are flexible, light and can be designed to resist explosions by controlled expansion and mitigation of the shock waves, while at the same time retaining hard luggage fragment projectiles and preventing them from hitting the aircraft fuselage at high speed. A multi-layered structure is being developed to absorb the large dynamic loads of the explosion and the large deformation related to the gas expansion (see Figure 3). The idea is to use a textile structure made of ballistic yarns as an internal high strength layer to stop the ejected debris, coupled with an external layer which could deform in a controlled way during the explosion, in a way similar to car airbags, mitigating the blast pressure.

Fig. 3. A sample of textile structure and material investigated in FLY-BAG Project

Composite elements, like thin strips or thin sheets, for reinforcing specific regions of the textile-based container, contribute with reinforcement and containment functions. A core layer has been considered as well to provide a standoff distance between an explosive device and the aircraft skin panels, in order to reduce shock-holing and blast forces. The combination of different innovative textile materials shall allow achieving a great blast resistance while retaining an acceptably low weight.

2 Textile Materials Characterization

Material testing has been performed on specimens of representative scale as to determine material response and ascertain the material constitutive model and obtain material parameters required for the modelling of the phenomena.

Currently, precise data on official blast tests (for instance the ones by the Federal Aviation Administration in the USA) are confidential. The first step has been to define a suitable experimental protocol, trying using our own expertise to ”reverse engineer” the likely loading considerations from data which has been released into the public domain. Within the framework of the Project, a testing protocol has been set up for the textile characterization tests.

The most important finding from this work has been to identify the need for the ULD to be able to both withstand intense localized shock loading (MPa range for very short duration) from the initial detonation of a device, and contain the subsequent quasi-static pressure (QSP) caused by the release of gas from the chemical decomposition of the explosive. Failure under either of these types of load is likely to lead to severe damage to an aircraft fuselage, from either localized air-shock and fragment damage, or general over-pressurization of the cargo hold.

Previous work has been conducted in the USA on quantifying the reduction in both shock and QSP loading when a ULD is partially or completely filled with luggage e.g. [2]. Consequently, a test protocol has been designed in which materials are assessed in terms of their ability to withstand both shock blast pressure and QSP generated by the detonation of an explosive charge inside an item of luggage in a partially filled ULD. Figure 4 shows the effect of such loading on a standard ULD.

Because of the wide range of candidate materials, it is not feasible in the timescale of the project to determine dynamic material properties at a wide range of loading rates. Instead, performance-based test series have been conducted on candidate materials. The requirements are that the fabric material be able to withstand the internal QSP which is essentially uniform throughout the container and independent of location of the explosive charge, whilst the composite strengthening panels should provide resistance against the local shock-holing effect if the detonation occurs close to a side wall or base of the container. Two separate test series have therefore been undertaken.

(a)

(b)

Fig. 4. Un-Strengthened ULD Blast test (a) Pre-Test (b) Post Test

Series 1 is intended to identify relative performance of the fabric materials to QSP. In these tests, a small explosive charge is detonated in the base of a 1 m^3 five-sided strong steel box, with the open face of the box covered by a sheet of fabric material, clamped around the edges.

Series 2 is intended to identify the relative performance of composite strengthening panels to the near-field shock-holing. In this series, 400 mm square samples of composite panel material have been subjected to damped blast loading, by placing an explosive charge on packs of towelling material of different thickness (Figure 5). The purpose of these tests is to identify the resistance of the panels to shock-holing as the thickness of the towelling pack (and therefore the proximity of the explosive charge) is reduced. High speed digital video is used to view the rear face of the composite panel through an angled mirror, and hence identify the time and mode of any damage that occurs. Figure 6 shows examples of shock-holing failure and no-failure for an identical panel as the depth of pack was increased.

Fig. 5. Arrangement for shock-holing tests on composite panels

(a) (b)

Fig. 6. Shock-holing tests (a) shock-hole failure and de-lamination at with thin towelling pack (b) no failure with thicker towelling pack

3 Numerical Simulations

A suitable methodology for the simulation of the blast phenomenon has been assessed, taking into account both the gas dynamics and the blast wave propagation to the aircraft structures.

The *Smoothed Particle Hydrodynamics* (SPH) method has been used to simulate the blast detonation inside the innovative textile container and to predict its structural response.

SPH is a meshless method for solving physical problems governed by partial differential equations. It is implemented in the LS-DYNA code, a non-linear explicit dynamic finite element analysis software. There are no connections among the nodes of an SPH mesh, therefore the method handles extremely large deformations and has the advantage to be a continuum-based method. Fluid dynamic of the gas expansion is traced by SPH nodes and it is represented by spatial distribution of SPH elements [3], [4]. The combined meshless-Lagrange characteristic of SPH method makes it suitable for simulating deployment due to shock wave propagation.

The starting point of the work was to evaluate the behaviour of a standard aluminium Unit Load Device (ULD) under a blast load event. The comparison of the experimental results with the numerical simulations was fundamental for setting the parameters of the numerical model. As previously described, the experimental tests were performed on a standard Unit Load Device. The full size container was placed in open air and filled with 50% of luggage, with the charge inside a suitcase. The testing procedure required that the explosive charge was placed on the sloping edge of the container, which is the most critical part.

The numerical simulation with the SPH approach required that the spherical charge was modeled with discrete elements, while the surrounding air was not considered in the analysis. The container was discretized using the shell elements: its main components (beams, sheets and gussets), made of aluminium alloys, were modeled in LS-DYNA, implementing the elasto-plastic behaviour.

The explosive effect was modeled using the classical equation of state of Jones-Wilkins-Lee (JWL) equation, which defines the pressure in the elements as a function of the relative volume and of the internal energy [5], [6], [7].

The comparison of the simulations with the experimental data (see Figure 7 and Figure 8), confirms the need to improve security and give an idea about the capability to numerically predict the blast load effect inside a structure.

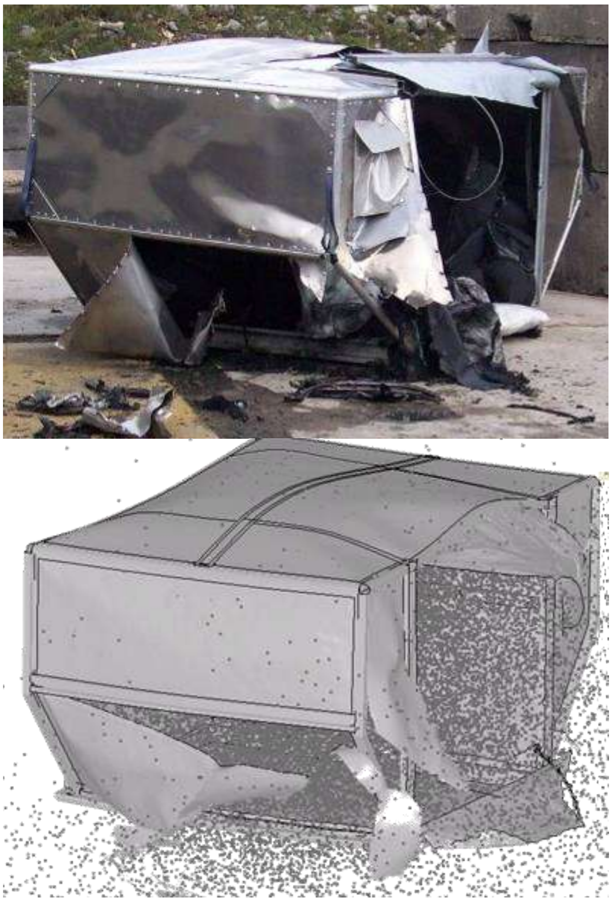

Fig. 7. Comparison of experimental test with numerical simulation, lateral view of the container

Fig. 8. Comparison of experimental test with numerical simulation, back view of the container.

Simulation activities were then directed to support the design of the textile-based container, through the evaluation of forces, displacements and stress during the blast event. The belts enveloping the bag were further considered in the numerical activities.

The comparison of different configurations was made in terms of variation of the forces on the beams and of the bag displacements. Same boundary conditions in all the analyses were considered: the only difference was related to the position and the number of belts.

The reference model is reported in Figure 9, where the frame is schematized by 12 cylinders. The container is constrained in the fixing points placed in the upper side (see Figure 10).

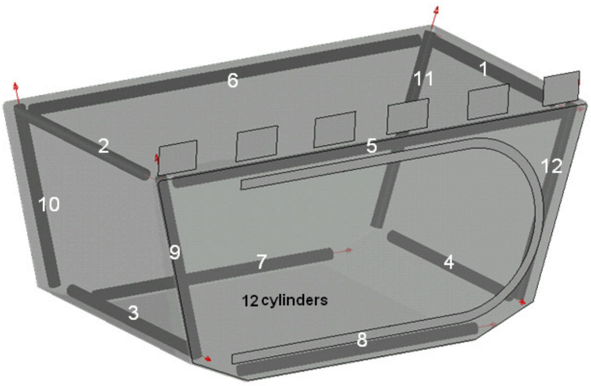

Fig. 9. External textile-based container and frame represented by 12 cylinders, in order to evaluate the force

In this configuration, the trial material used for simulating the textile was an aramid fabric, with 2800 [MPa] as tensile strength and 80000 [MPa] as tensile modulus. It was calculated a maximum bag displacement of 175 [mm] (see Figure 10).

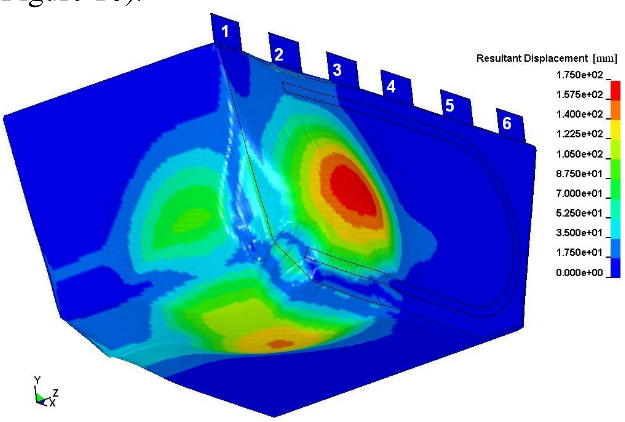

Fig. 10 Textile-based container (no belts) - Resultant displacement [mm]

Further numerical analyses were performed considering a configuration with 2 belts and 4 belts respectively. All belts were fully constrained in the corners.

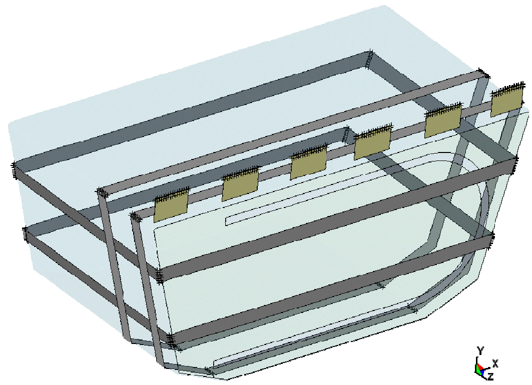

Fig. 11. Textile-based container with 6 fixing points and 4 belts

The results of the numerical simulations carried out on the configuration with 2 belts, is shown in Figure 12: the explosion inside bag now produces a maximum displacement of 140 [mm] (the previous was of 175 [mm]). The corresponding peak of force was found on the fixing point n° 2 (see Figure 10), equal to 23 [kN], lower than that calculated previously (52 [kN]).

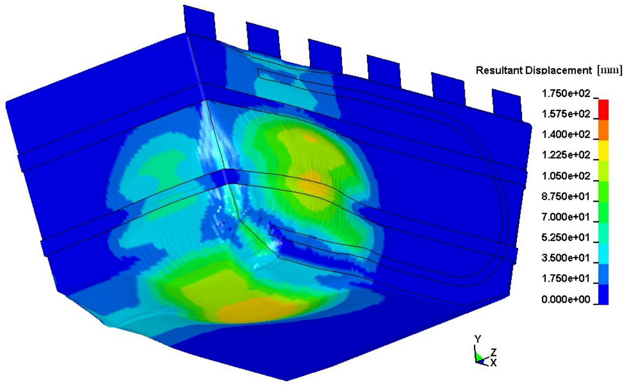

Fig. 12. Textile-based container (2 belts) - Resultant displacement [mm]

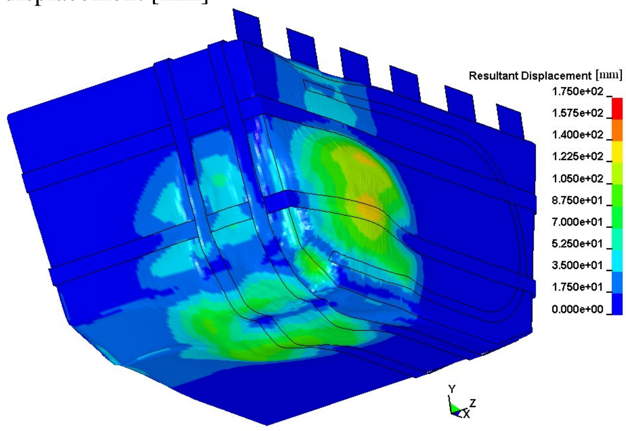

Fig. 13. Textile-based container (4 belts) - Resultant displacement [mm]

The simulation carried out on the configuration with 4 belts, has a maximum resultant displacement of 122.5 [mm], calculated on the left side of the container (see Figure 13). In order to summarize the results of the simulations, a comparison in terms of force and number of belts is reported in Figure 14 and in Table 1, where displacements and forces are shown.

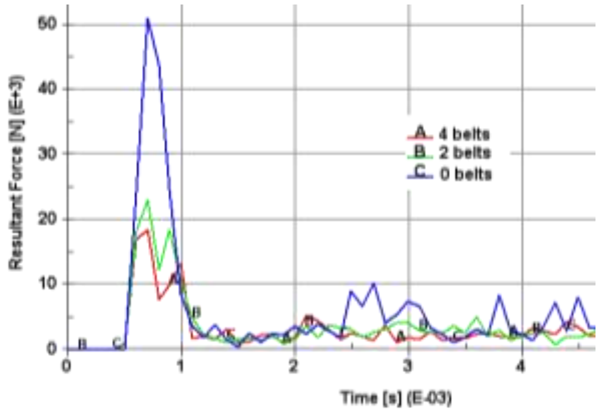

Fig. 14. Comparison of resultant force increasing the number of belts

	Bag Displacement	Force on fixing point 2	Force on cylinder n°9
0 belts	175[mm]	52[KN]	200[KN]
2 belts	140[mm]	23[KN]	122[KN]
4 belts	122,5[mm]	18[KN]	86[KN]

Table 1. Bag displacements, force on fixing point n° 2 and cylinder n° 9

All the results coming from the numerical simulations and the experimental tests are focused on the design of a textile-based luggage container.

The next operative steps of the on-going project [1] are leading in this direction.

The final simulation activities described in this paper were carried out for the evaluation of the performances of the novel textile-based container during a blast event on board, inside the cargo area.

For this activity a detailed model of the fuselage and of the corresponding cargo area compartment was developed. The model has the following dimensions: length 3.34 [m], diameter 3.95 [m] (see the position of the section FR24 - FR35 on the aircraft in Figure 15).

In Figure 16 is possible to notice the internal structure of the aircraft with ribs, stringers and the floor that separates the cargo area from the passengers area.

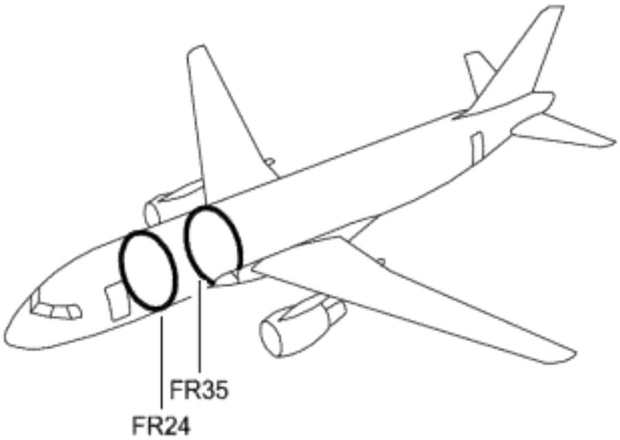

Fig. 15. Aircraft forward fuselage FR24 - FR35

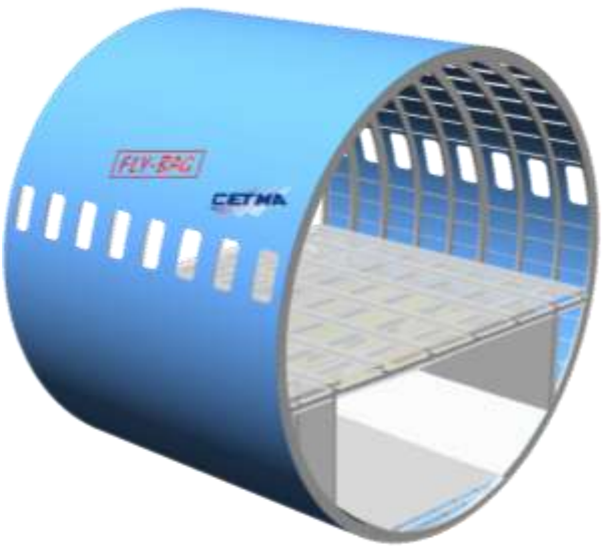

Fig. 16. FR24 - FR35 forward fuselage section 13-14

The 3-D full scale model of the fuselage with 1.7 millions of shell elements allowed evaluating the effects of the detonation on the aircraft structure. Each part of the structure was modeled with the suitable aluminium alloy. Preliminary evaluation was carried out considering the effect of a blast load inside an empty cargo area with the same approach and loading conditions used for the unit load device. Figure 17 shows the initial propagation of the blast wave.

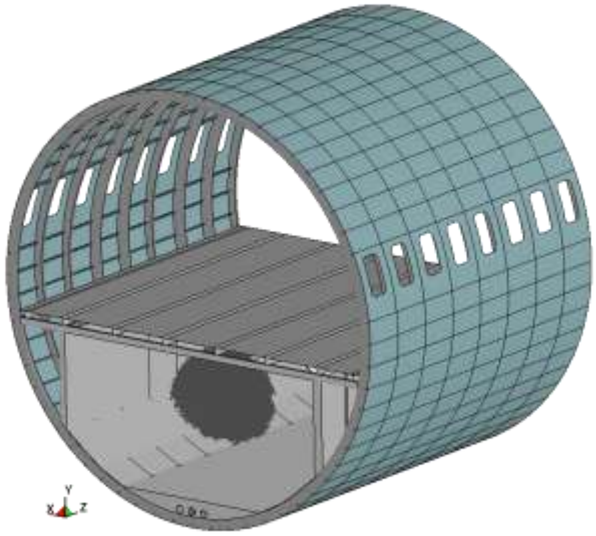

Fig. 17. Blast wave propagation inside the empty cargo area with the SPH approach

The foreseen damage caused by the explosive is shown in Figure 18, where it is possible to notice the rip in the fuselage near the detonation area. The stringers and the skin panels are completely removed while the floor is subjected to local bulges between the beams.

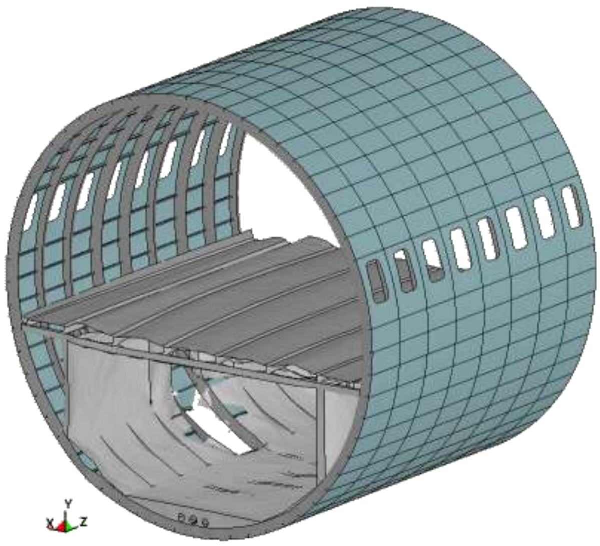

Fig. 18. Blast wave effect inside the empty cargo area

The numerical simulation, with this level of detail, is of fundamental importance for evaluating different configurations before carrying out the final experimental tests on the textile-based container.

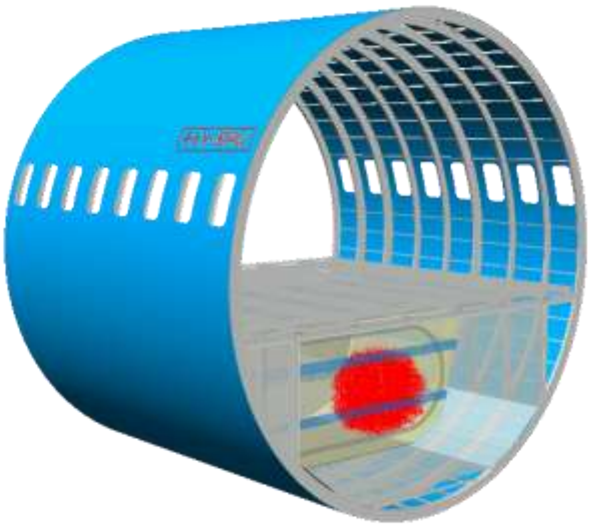

Fig. 19. Blast wave propagation inside the textile-based container with SPH approach

The Figure 19 shows a textile based container made of aramid textile, in which 4 belts have been used. The current operative step is to find the most suitable blast resistant design, in terms of selection of textile materials and lay-up of layers.

4 Conclusions

A combined experimental and numerical approach has been considered for supporting the development of an innovative blast resistant textile luggage container, designed to protect the aircrafts from explosions caused by bombs concealed inside the checked luggage.

The most important finding from the experimental work was to identify the need for the container to be able to both withstand intense localised shock loading from the initial detonation of a device, and contain the subsequent quasi-static pressure (QSP) caused by the release of gas from the chemical decomposition of the explosive.

Two different test series were carried out: the first was intended to identify the relative performance of the fabric materials to QSP, the second to identify the relative performance of composite strengthening panels to the near-field shock-holing.

Although experimental testing is always necessary, there are considerable motivations for an extended use and support of numerical simulations, as a tool to address the variability in test parameters, such as bomb placement, effect of the luggage inside the container, structure and explosive charge performance.

The *Smoothed Particle Hydrodynamics* (SPH) method has been used to simulate the blast detonation phenomenon inside the textile container and to predict its structural response.

The blast test carried out on a standard aluminium ULD was modeled by using the LS-DYNA code, with the aim to set the parameters of the numerical model. Further analyses were performed on a textile container made of aramid: several configurations were numerically tested for evaluating the influence of the belts around the container, in terms of displacements and stresses calculated on the textile.

The last numerical analysis was carried out for predicting the effects of a blast wave propagation inside the empty cargo area of the forward fuselage of a narrow body aircraft, without luggage container. The analysis was performed considering the same explosive charge considered in the previous simulations. In this case, the damage of the fuselage is relevant: the stringers and the skin panels are completely removed while the floor is subjected to local bulges between the beams.

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