DEVELOPMENT OF A NOVEL CONCEPT OF EXPLOSION-RESISTANT CARGO CONTAINER FOR NARROW-BODY AIRCRAFTS

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Abstract

The rise in worldwide terrorism has required measures be taken to harden aircrafts against catastrophic in-flight failure due to concealed explosives. The paper presents the development of a concept of flexible textile-based luggage container able to resist a small to medium explosion by controlled expansion and containment of the expansion and absorbing the shock waves whilst, at the same time, preventing hard luggage fragments from striking the main structure of the aircraft at high speed. A multi-layered "soft-sandwich" structure is required to absorb the large dynamic loads of the explosion and the large deformation related to the gas expansion. The concept under development is based on a multi-layered textile structures made of ballistic yarns as an internal high strength layer, coupled with an external "foldable" layer which is deforming in a controlled way during the explosion, in a kind similar to air-bags in cars. Composite elements and textile belts contribute with reinforcement and containment functions. A core layer is also considered to provide standoff distance between an explosive device and the aircraft skin panels to reduce shockholing and blast forces.

1 Introduction

Since the crashes of Air India Flight 182 (1985, 329 casualties) and Pan Am Flight 103 (1988, 270 casualties), both of which exploded due to bombs concealed within the passengers' baggage, much effort has been carried out by governments and international bodies to prevent such disasters; nevertheless, the risk that a small quantity of an explosive, below the threshold of the detection instruments, could get undetected is not negligible. The introduction of countermeasures to reduce the effects of on-board explosions has to be considered. Hardened luggage containers (HULD) have been developed for the latter scope [1], but their shortcomings, the biggest being their high weight and high cost, have prevented their wide utilisation and market acceptance; moreover, they are not available for most narrow-body aircrafts. The issue of containing explosions aboard narrow-body aircrafts has yet to be resolved.

A novel approach is based on the use of a combination of novel textile materials and composite materials to achieve a higher flexibility and reconfigurability for the luggage container, together with 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 customised for practically any application and configuration[2]. 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[3]. As explained in the following, a multi-layer structure has been developed to absorb the large dynamic loads of the explosion and the large deformation related to the gas expansion. 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 and containing the blast pressure (see Figure 1). The combination of different innovative textile materials shall allow achieving a great blast resistance while retaining an acceptably low weight.

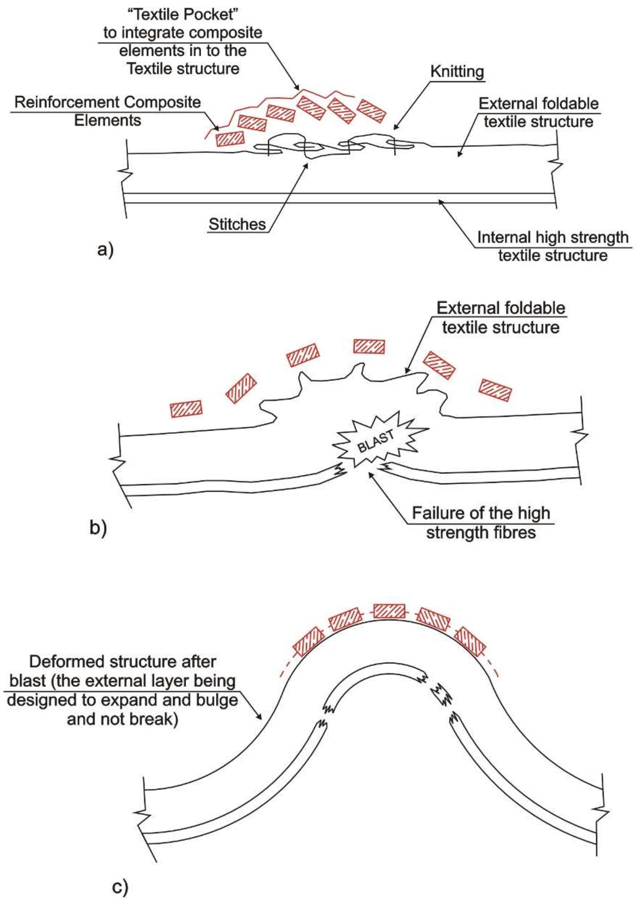


Fig. 1. Progressive Failure and energy absorption mechanisms of the textile ULD structure

2 Textile Technologies

A number of various textile materials and textile architectures are being considered for the different layers of the structure. Hybrid textile materials such as the ones shown in Figure 2 are the candidate material solutions, being made from different materials and, in principle, capable of addressing the contrasting requirements for high strength to resist the blast pressure and high deformability generated by the gas expansion.

Two key issues to be addressed in the event of a blast in the cargo area are:

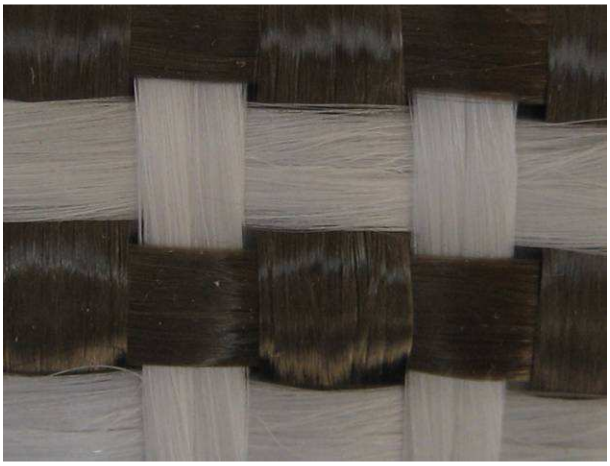
- resisting localised deformations of the luggage container walls caused by blast loads or fragment impact close to the walls of the container, and
- absorbing the energy input into the bag structure by the overall blast impulse. This will give a very high kinetic energy to the walls of the bag (each wall gaining a large outward velocity) and there is therefore a need to have a material for the walls that is sufficiently flexible and ductile to expand and dissipate this energy through plastic deformation, ideally without rupture.

Clearly, high strength textiles can be very useful in both these scenarios.

Many materials, specific textile constructions and combinations of them are on the market and under development worldwide. The candidate fibre material for the intended application is aramid, because of its ballistic properties. However the relatively high cost of such fibre material makes unfeasible a solution entirely made of such fibres and forces to find structural design solutions where also other fibre materials could be used and would make a significant contribution. Such structural configurations would be capable of restraining the deformations in some directions and allowing the structure to deform towards less critical areas. Load-taking threads integrated into fabrics to make hybrid textiles are therefore elements which have been considered for the construction of the multilayered anti-blasting structure of the textile luggage container.

A dense textile fabric structure is the target solution for the containment of the explosion and for the mitigation of the energy generated by the explosion and transferred to the airframe structure. As depicted in Figure 1, the desired absorption of the energy generated by the blast is through strain deformation up to failure of the high resistance threads and expansion of the textile layers *along specific directions*. In order to provide an extra resistance to the containment of the deformation towards the aircraft fuselage, additional elements are used in the construction, including special seams, which connect together the textile layers at specific locations and are designed to fail in a predictable way, as an additional energy dissipation mechanism, and belts which are added circumferentially around the external surface of the textile container.

The challenge of the study is to design the walls/joints/openings of the textile bag to deform but not fail under the pressure generated by the blast.



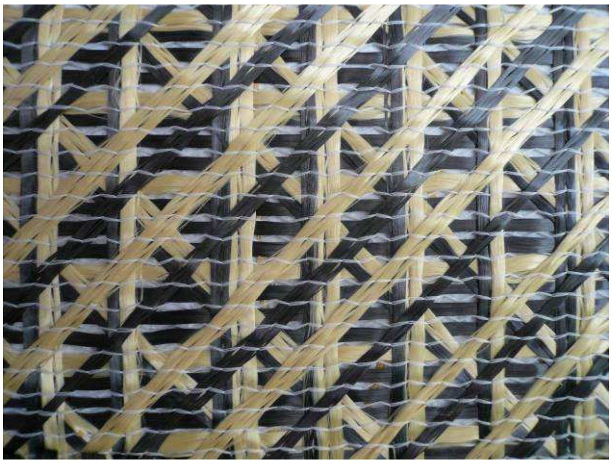


Fig.2. Blastworthy hybrid textile structures: plain wave hybrid structure made of carbon and dyneema fibres (above) and multiaxial structures from carbon and aramid fibres (below)

The variability of the loading conditions and the complex stress state generated by the blast require the use of isotropic textiles, characterised by mechanical properties balanced in the plane of the fabric. This can be achieved by a combination of traditional biaxial fabrics (such as the one shown in the upper part of Figure 2) oriented along different directions in the layered structure or using a multiaxial structure, where different layers of uniaxial fibres with different orientation are combined together. An example of multiaxial warp knitting having 4 different thread systems (0°- and 90°- direction as well as +/-45°-direction) is shown in the lower part of Figure 2 and the schematic is shown in Figure 3. This structure is able to absorb impact forces from all directions.

Other issues which the textile construction has to face are the high temperature and the fire which can be generated by the blast. To address these issues, textile materials with a low thermal conductivity are needed in combination with special thermal shielding layers.

Generally the textile materials for the application under study need to be characterised for quite a high temperature tolerance to comply with the high temperatures generated by the blast and the low temperatures which can be experienced during the normal service. Other requirements include the need that in case of fire, toxic emissions would not be generated.

To comply with service requirements on a life-cycle contest, the selected materials have to be resistant against weathering and UV-radiation and recycling strategies should be provided.

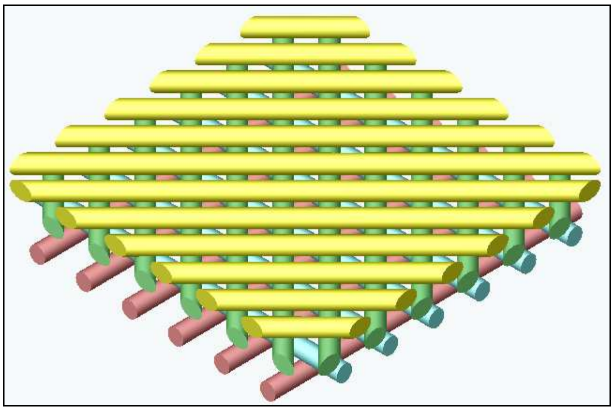


Fig. 3. Concept of a multiaxial structure, where different threads oriented at different directions are superimposed and connected together by stitching to form a self standing structure

Considering the above requirements, the different functions that the textile multilayer fabric has to provide include:

- foldable, drapeable (textile) structure → use of flexible, lightweight materials;
- resistance to the shock waves, protection against "shock holing" (pressure peak) → a high strength material is needed;
- withstanding the huge gas expansion, possibility of defined expansion →

ductility of material and/or structure, deformation zones have to be integrated;

- containment of the quasi-static pressure generated by gas expansion→ a certain degree of gas tightness is required with only slow venting of pressure into the cargo hold;
- slowing down and trapping of accelerated cargo good → energy absorption by inner friction and deformation;
- flame barrier, heat insulation → use of heat resistant and flame retardant ("afterburn") materials.

Therefore a multifunctional structure has to be considered where three main categories of materials are used:

1. high strength materials
2. ductile/deformable materials
3. insulation/flame resistant materials

which have to be integrated in the multilayer structure of the textile container walls. Several materials have been indicated to be suitable for the application in a multilayer design. These materials are being integrated within different textile architectures with the addition of functional coatings.

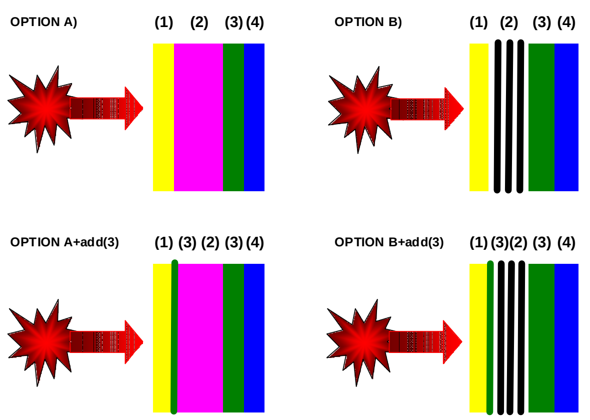


Fig.4. Different multifunctional structures obtained by combination of four functional layers: (1) gas/heat resistant and flame retardant, (2) inner deformation and energy absorbing layer, (3) reinforcing and splinter protection layer, and (4) outer deformation layer

Regarding the **multilayer** design, **four functional layers** [(1), (2), (3) and (4)] are being integrated in the blast resistant containment (see Figure 4, where the different functional layers are evidenced with different colours). The whole design has an inner (directly exposed to the blast) and an outer container side (facing the internal walls of the cargo area of the aircraft) as well as an asymmetrical sequence of layers. The following items provides a description of the material behaviour and his function for the corresponding functional layer:

(1) **Gas/heat resistant** and **flame retardant** barrier: Relatively gastight felts and nonwovens made of novoloid fibres (KYNOL®) or aramid fibres or a fire proof membrane. Functionality description: flexible layers are required able to withstand high temperatures (up to 500…1000°C) for a short time (seconds). Furthermore, these materials are characterised by a low thermal conductivity (in the range of 0,03…0,05 W/(mK)).

(2) Inner **deformation** and **energy absorbing** layer: Aramid or Innegra ® woven, KEMAFIL® multiaxial warp knits are considered. It is a relatively voluminous layer, which is flexible and allows an inner deformation of the layer itself. This inner deformation makes a distinctive contribution to the energy absorption by material compression and inner friction of the fibre/yarn macrostructure. This zone is preferably made of high strength and highly ductile material with specific macroscopic structures such as fabrics made of KEMAFIL®. However, it is believed that the use of high strength, horizontally extending yarns in conjunction with lower strength, higher elongation, vertically extending yarns increases the ductility and strength of the overall textile structure. Warp and fill yarns of the preferred fabric are foreseen to extend substantially in the plane of the fabric.

(3) **Reinforcing** and **splinter protection** layer/zone: Made of high strength material in a relatively dense textile structure (warp knitted or woven) i.e. aramid or carbon fibre, additionally coated with rheopectic substances (shear thickening nanoparticles). This layer has to trap and slow down accelerated cargo goods and explosion generated splinters. It is

preferably made from high strength woven or warp knitted fabric.

(4) **Defined outer deformation** layer: A flexible net or strap structure (with the addition of belts) made of high strength polymers (i.e. Dyneema®, Vectran® or Spectra®) which envelopes the whole container. High strength polymer fibres have some very interesting properties that make it potentially very useful for our application. They have extremely high tensile strength and relatively limited tensile strain at fracture. This means that (if a structure is well designed) it should be possible to dissipate very large amounts of energy through plastic deformation of the fibre material in direct tension (e.g. when the side walls of a container stretch into membrane tension as the container is pressurised from inside), without having enormous lateral deflections. This open net or strap construction is the outer layer of the container and is designed to deform in a preferred and predictable manner after the blast, in a way to avoid that the main shock generated by the blast would be directed towards the surrounding fuselage structures.

Furthermore, the interaction between all selected layers has to be considered. Friction between those layers and integrated predetermined breaking points can be also used for energy absorption.

3 The Structural Concept

As anticipated, the blast event is complex since is characterized by many uncertainties, including the quantity of the detonating substance, its position inside the ULD, its type, the quantity of luggage in the container and between the explosive charge and the container wall.

In a blast phenomenon, there are two major blast issues. One is the Quasi-Static Pressure (QSP) from the release of the gas products in a detonation, and the other is the direct shock from the blast waves. The first mechanism will be lasting some seconds and causing extended damage to the whole bag surface, with a constant pressure over the whole volume of the order of 100-400 kPa. The second is much more intense and short-duration than the first, with a magnitude likely to be in MPa and duration a few milliseconds.

The quasi static pressure could represent a great danger to the airframe if it is let venting through too quickly, in reason of the limited space available in the cargo hold of narrow body aircrafts (compared to the room available in wide body aircraft, significantly higher); the bag is required to have some gas-tightness, to let the pressure vent through in a controlled way.

If this volume of pressurised gas was instantaneously leaked into the cargo hold, it would almost certainly rupture the fuselage. On the other hand, if the pressure was vented over many tens of seconds, it would be able to leak out of the hold via the normal ventilation processes.

In previous paragraph various "bag" materials and structural concepts have been presented which are intended to contain the QSP effect: essentially we need a bag that is almost impermeable, and that is sufficiently strong to withstand the stresses when the internal pressure increases dramatically. The bag must be sufficiently impermeable to retain the pressure build-up from the explosion for a "reasonable" length of time. The pressure must be vented out over many seconds (probably >10s). If the pressure is released more rapidly, it is likely that structural damage would occur to the airframe before the pressure release valves in the airframe had time to operate.

The second blast issue is the intense shock which is generated by the explosion. The most intense shock effect will be on the wall closest to the placement of the explosive. On that respect the most critical position of the detonation charge would be close to the angled bottom corner of the ULD. This is considered to be the most vulnerable location because the air frame is closest to the ULD at this point. To address this issue, a stiffening composite panel along the base of the ULD and up along the angled bottom corner has been included in the design.

Fundamentally, the fabric bag is providing the overall structural strength of the luggage containment bag, and the composite panel is a sacrificial sheet that acts as a means to distribute the localised high blast pressure over a larger area of fabric bag. In the final scheme, the composite panels are only being supported by the bag itself. We decided not to have a structural skeleton inside the bag, due to the low chance that it would be able to resist the loads that the side walls would place onto it when an internal detonation occurred. The resistance of the bag relies on the circumferential tension as the bag expands. The internal composite panel is essentially there to protect the key vulnerable section of the bag, and will bear against the fabric bag as the detonation occurs and imposes a shock load onto the composite panel.

The likely timescales and load magnitudes involved are difficult to asses precisely. It is estimated that the initial shock will impose a specific impulse of the order of 2-500Ns/m^2 on the composite panel. The precise figure depends crucially on the exact charge size and distance, and the softening effect of the luggage. The impulse also decays rapidly with radial distance from the epicentre, so a 2m^2 panel would not experience twice the total impulse that a 1m^2 panel would do – clearly therefore, a larger panel would pick up less overall velocity. This impulse will be applied pretty much instantaneously (over perhaps 1-2 milliseconds after detonation). There will actually be a very non-uniform spatial variation of impulse across the panel, with the epicentral impulse being very much greater (maybe 10 times greater) than the impulse at the periphery of the panel. It is this non-uniform impulse that tends to cause shock holing. The material directly closest to the detonation receives a higher impulse and therefore picks up a higher kinetic energy than the peripheral material and this intense and suddenly applied variation tends to cause very high local shear stresses. The job of the panel is to withstand this effect and to distribute the impulse more uniformly across the bag wall. If the panel does survive, it will push against the bag wall with a velocity which would be likely of several 10s m/s. As it does so, the entire bag will be filling with gas from the detonation products, and (in the absence of a stiff skeleton) trying to become more spherical, thus generating circumferential tensile stresses. This will be occurring over a slightly slower timescale – several 10s of milliseconds – and will eventually cause the whole bag to become stiffer. The fabric bag is designed to retain the composite plate without a) tearing and b) deflecting so far that it impacts the airframe and damages it. Tearing can be minimised by having sufficient strength in the fabric bag, by not having sharp corners bearing against the fabric and by having a sufficiently large composite panel so that a sufficiently large area of fabric is mobilised to decelerate it. Deflection can be minimised by either having a heavy composite panel, or by mobilising significant mass and/or stiffness in the fabric to decelerate the panel.

Different composite sandwich core designs are being considered for making the rigid parts of the container in contact with the aircraft cargo floor, aiming at obtaining the highest blast protection within the minimum panel thickness. Details of the panel design and panel testing will be provided in an accompanying paper[4].

4 Material Testing

The material structural concepts are validated through an extensive programme of flame and blast testing at different scale up to the full scale validation of the prototype.

Flame tests are carried out on single fabric and laminates based on the test conditions of FAR 25 (Federal Aviation Regulations – airworthiness standards), category fire protection. Flame tests are carried out in order to investigate the behaviour of the materials with respect to the fire, with the evaluation of the rate of burning and/or extent and time of burning, and the surface flammability of the materials. Figure 5 shows the flame test apparatus available at STFI, Germany, used for the tests.

The test gives information on the fire spread and its speed (burn-length and after-flame time). Burning or hot drippings can cause new fire sources and must therefore be avoided.

The after-glow time is an indicator for the thermal insulation of the layer, e.g. how the heat is transmitted to a nearby layer. Pictures of the flame test allow showing how the flame spreads through the fabric/laminate and how gases from the fabric are inflamed and for how long. Pictures of the samples after test also show whether the material is carbonized and if the height of carbonized area. Notably, the selected aramid, novoloid and polyimide fibre made fabrics all passed the flame tests.

Fig.5. Flame test rig for fire testing of textiles available at STFI

In addition to flame tests, also blast tests have been carried out to measure the effectiveness of the selected textiles at resisting the raise of Quasi Static Pressure generated by the blast.

QSP tests are conducted by clamping a panel/sheet of material on the open face of a stiff steel box where an explosive charge is placed at a certain distance from the material to be tested. The test metrics of interest comprise a measure of how well the panel/sheet of material retains the pressure and the level of damage experienced.

The QSP tests have concentrated on 1m x 1m samples on the front face of a 1m cube steel box, with a small high explosive charge detonated inside the box. The placement of this charge can be varied to test either QSP or direct shock plus QSP effects on the bag material. Clearly, when the explosive charge is brought close to the fabric bag sample, the fabric is torn due to the direct shock loading. This gives a baseline for the strength of the bare fabric bag so that to then study the improvement when a composite strengthening panel is placed over the fabric.

Using 1m x1m composite panels, covering the entire face of the test fabric specimens, the lowest possible impulsive velocity is imparted to the composite panel, and the largest area of fabric is mobilised to decelerate it.

Fig. 6. Test box for the evaluation of the performance of textile layers against the Quasi Static Pressure generated by an explosive charge placed inside the box

Figure 7 shows the result of a preliminary test of a sample of fabric resulting into the failure of the textile material which experienced a large tearing in correspondence of the clamping area.

Fig. 7. Result of preliminary test of fabric layer showing tearing of the material

Figure 8 shows the sequence of the QSP testing of the textile layer. Few milliseconds after the detonation, a fireball is generated by the afterburn contributing to the increasing of the QSP. The fabric is subjected to extremely large deformation as it bulges from the box and large tension stresses which results in failure of the fabric in correspondence of the clamping section.

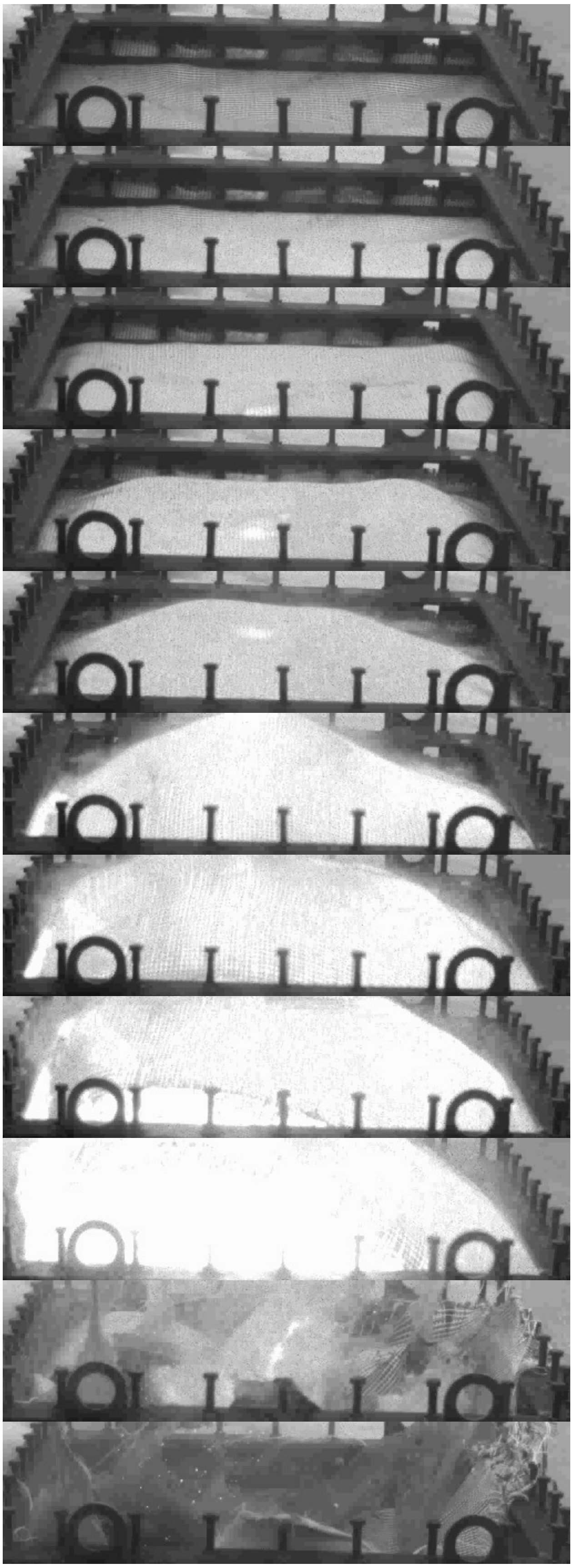


Fig. 8. Sequence of burst testing of fabric showing large deformation of the textile structure followed by breakage at the test rig border and final structural failure

5 Prototyping and Virtual Validation

The findings of the tests discussed in previous paragraph have been fundamental for the selection of the materials to be used for the manufacturing of the anti-blasting luggage bag. The approach to the manufacturing of prototypes has followed the sequence of steps shown in Figure 9. After integration of the 3-dimensional drawing model in a CAD tool, simulation of the unfolding of the fabric construction was carried out using a spreadsheet to get the 2-dimensional sewing patterns from the 3- dimensional model.

Various small scale models have been assembled (from 1:20 up to 1:2 scale) using a thick nonwoven material in order to verify the feasibility of different solutions, in particular concerning the position of the seams (“hood” bag and “side-seam” bag). The main parameters which were investigated whose variations had an effect on the prototype feasibility comprised:

- Type of nonwoven fabrics (e.g. Optiknit®, a rather stiff material) to effectively simulate the real construction and the assembly and unfolding operations;
- Common and flame-retardant lamination adhesives which are commercially available;
- Position of openings and type;
- Location of seals and their design.

Virtual validation of the full bag is described in an accompanying paper [4]. Here the simulation of the QSP tests described in previous paragraph is reported. Such simulations have been carried out with the intent of reducing the number of experimental tests and as a tool for the optimisation of the textile multilayer structure. Figure 10 shows the simulation of the QSP test, carried out using the LS-Dyna explicit code, which is particularly suitable for the analysis of rapid phenomena[5]. The upper figure shows the numerical model of the blast testing box, with the textile layer clamped to the upper face of the box and the explosive charge in central position at a certain height in the box. The following pictures show the results of a simulation where the multilayer textiles which was considered did not pass the tests and failed catastrophically, similarly to the real sequence shown in Figure 8.

Figure 11 on the contrary shows the results of the simulation where the final multilayer structure was modelled. In this case the textile structure survived the blast test and the figure shows the evolution of the deformed structure and the distribution of the stress (expressed in Pa) in the x direction of the model in correspondence of different calculation times.

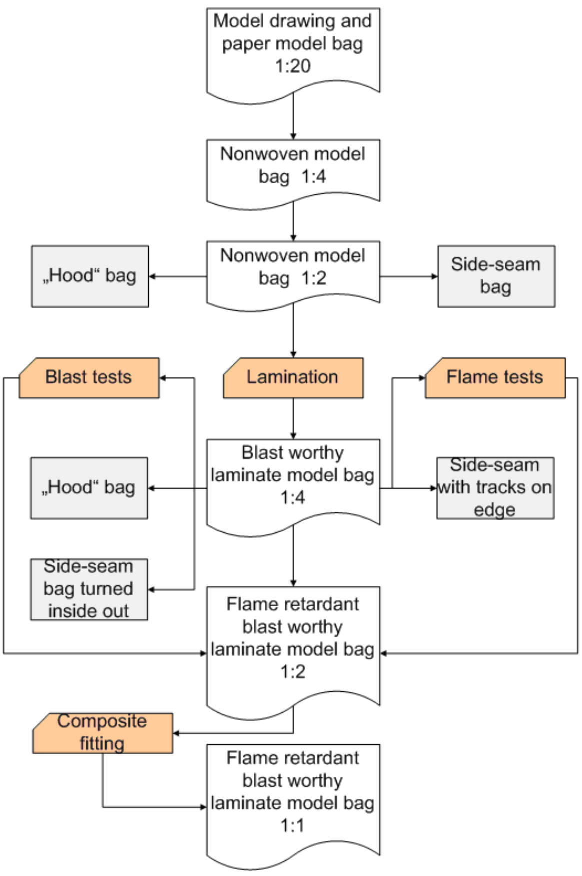


Fig. 9. Procedure adopted for the manufacturing of full scale prototype

6 Conclusions

Textile structures are flexible, relatively light weight, reconfigurable and adaptable, and can be designed to resist explosions by controlled expansion and the choice of specific fibres architectures and materials. The specific characteristics of textiles make them an interesting alternative to rigid materials for application in airplanes, where there is a need for protection against on-board explosions of bombs concealed among the luggage in the cargo holds of airplanes.

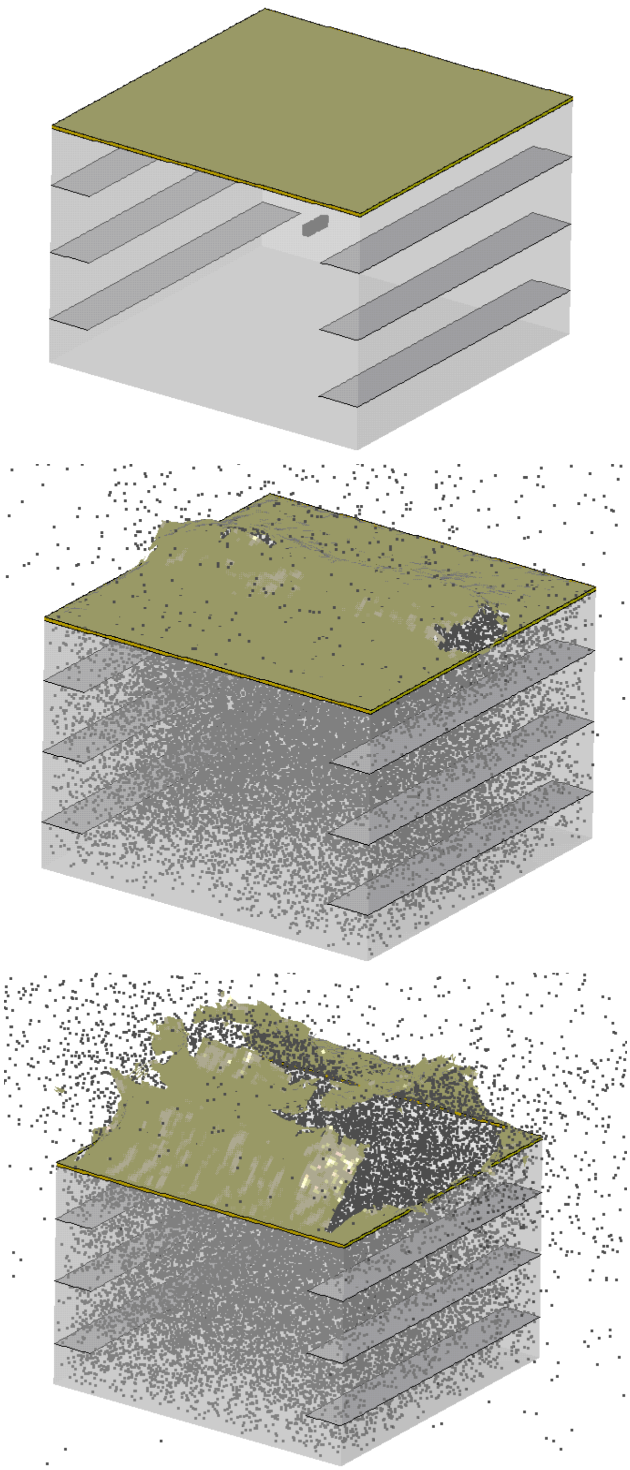


Fig. 10. Simulation of burst test of fabric, in this case showing structural failure

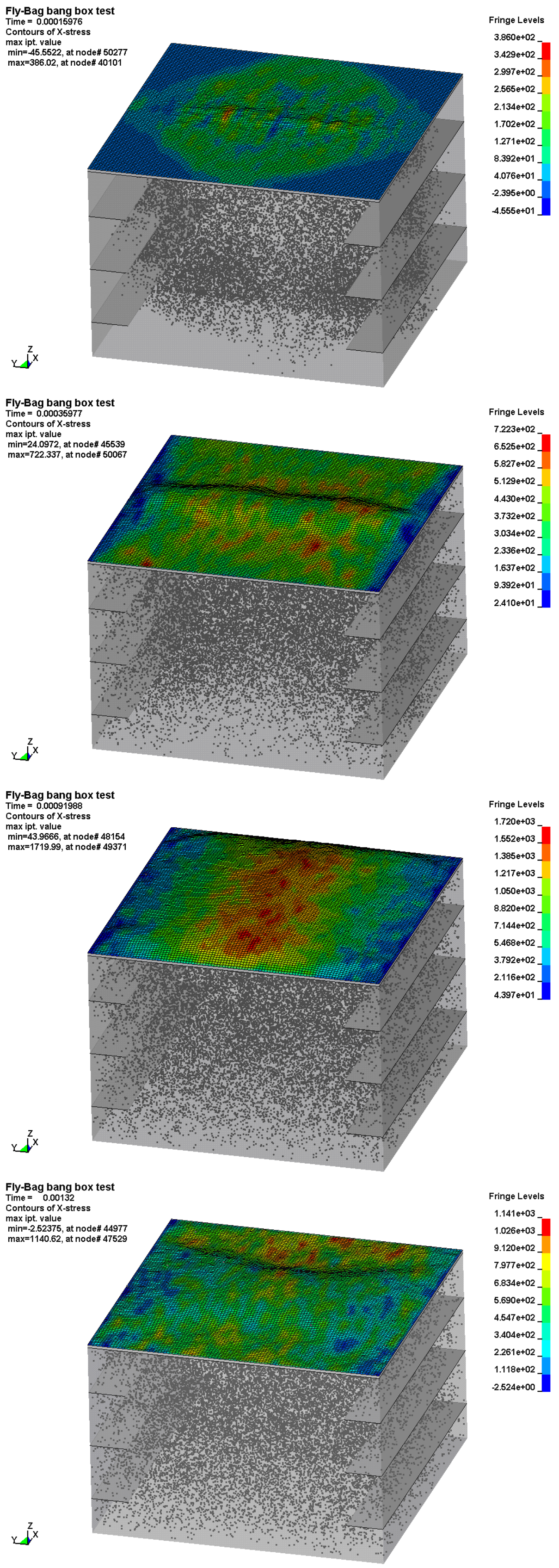


Fig. 11. Simulation of burst test of fabric where the structure passed the test without failure. The sequence show the distribution of the stress (Pa) along the x direction at different calculation times

A multi-layer multifunctional structure has been designed to absorb the large dynamic loads of the explosion and the large deformation induced by the gas expansion. The textile structure is made of different textile layers with specific features designed to perform the different functions requested by the application.

Flame and blast tests have been used to characterise the various fabrics and their combination. Numerical simulations have been successfully performed in order to reduce the number of tests and as a tool for the optimisation of the multilayer structure.

The results show that a multilayer textile fabric can be designed to survive the Quasi Static Pressure generated by the blast and to provide an effective protection to the airplane main structure, containing the deformation of the structure towards the fuselage and preventing the pieces of fragmented luggage from hitting the main airplane structures at high speed.

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References

[1] Gatto J A and Krznaric S, *Pressure loading on a luggage container due to an internal explosion*, Proceedings of the 1996 4th International Conference on Structures Under Shock and Impact, SUSI Udine, Italy, pp. 61-67, 1996

[2] Zangani D., *Textiles for blast protection from terrorist attacks in aeronautics*, Nanoitaltex 2009, Milano, 10-11 November, 2009

[3] Helbig F, Haag J, Rohr I and Pasch U., *Entwicklung von explosionsfesten textilen Transportbehältern für den Stückguttransport*. Report AiF 142ZBG, STFI e.V., 2006.

[4] Dotoli R, Bozzolo A, Fay S, Bardaro D, *Experimental testing and numerical simulation to design an innovative blast resistant textile luggage container*, presented at ICAS 2010

[5] LS-Dyna, *Theoretical Manual*, ed. by J.O. Hallquist, Livermore Software Technology Corporation, 2008

[6] *Blastworthy textile-based luggage containers for aviation safety*. Funding Scheme: Collaborative project (Small or medium-scale focused research) - Starting Date: 01/12/2008 – 7th Framework Program – Project Acronym: FLY-BAG – Grant Agreement: 213577.

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