Advances in Aircraft and Spacecraft Science, *Vol. 5, No. 3 (2018) 319-334*
DOI: https://doi.org/10.12989/aas.2018.5.3.319

Design validation of a composite crash absorber energy to an emergency landing

Michele Guida*[1], Francesco Marulo[1], Massimiliano Bruno[2], Bruno Montesarchio[2] and Salvatore Orlando[2]

[1]*Department of Industrial Engineering, Aeronautical Section, University of Naples "Federico II", Italy*
[2]*Magnaghi Aeronautica, Aeronautical Industry, Italy*

(Received September 5, 2017, Revised September 28, 2017, Accepted October 9, 2017)

Abstract. In this study, the failure mode and energy absorption capabilities of a composite shock absorber device, during an emergency landing are evaluated. The prototype has been installed and tested in laboratory simulating an emergency landing test condition. The crash absorber presents an innovative configuration able to reduce the loads transmitted to a helicopter fuselage during an emergency landing. It consists of a composite tailored tube installed on the landing gear strut. During an emergency landing this crash absorber system should be able to absorb energy through a pre-designed deformation. This solution, compared to an oleo-pneumatic shock absorber, avoids sealing checks, very high values of the shock absorber pressure, and results to be lighter, easy in maintenance, inspect and use. The activities reported in this paper have become an attractive research field both from the scientific viewpoint and the prospect of industrial applications, because they offer benefits in terms of energy absorbing, weight savings, increasing the safety levels, and finally reducing the costs in a global sense.

Keywords: aircraft design; carbon fibre composite; composites; delamination; finite element analysis; numerical simulation

1. Introduction

The design of a crash absorber requires an understanding of the material behaviour to high impact loads, then a detailed understanding of the vehicle concept and architectures to account for this energy absorption. In order to increase the safety of the passengers during a survivable crash landing, energy absorbers have also been integrated in the support structures of the overhead baggage compartments preventing their detachment from the primary aircraft structure and ensuring their structural integrity. These conceptual energy absorbers were based on metallic bending deformation, composite cylinder crushing and composite bearing failure.

During an emergency landing, the aircraft structure must be able to absorb the kinetic energy and to limit the forces and decelerations that are transmitted to the occupants, through seat and restraint systems, to tolerable levels. The airframe should experience minimal collapse, to the extent that a livable volume is provided to the occupants during the crash sequence. The reason for

*Corresponding author, Ph.D., E-mail: michele.guida@unina.it

http://www.techno-press.org/?journal=aas&subpage=7 ISSN: 2287-528X (Print), 2287-5271 (Online)

a crashworthy landing gear is to contribute to the global aircraft design requirements in the event of a crash. These requirements are to prevent occupant fatalities and injuries, damage to the aircraft, and damage and injury to adjacent equipment or persons. For helicopters the landing gear is part of a crash energy attenuation system to limit loads to the occupants and to minimize aircraft damage. The most stringent requirements are for helicopters designed to MIL-STD-1290, which requires maintenance of the occupied area and transmittal of no injurious acceleration loadings to occupants for up to a combined high angle impact of a vertical velocity of 42 ft/s and a longitudinal velocity of 27ft/s onto a rigid surface at specified roll and/or pitch angle attitudes, ref. Dept. of Defense (1986).

The applications of the crashworthy landing gear take into different rules design to define the failure sequence and how to counter for the contributions of the vertical, drag and side loads and their combinations during an emergency landing, ref. Currey (1988).

Composite materials are now widely used in the aerospace industry and are considered viable candidates for developing light weight energy absorbing devices due to their high strength-to-weight ratio and their high specific energy absorption (SEA) characteristics.

Many studies are focused on the correlation between SEA and material properties. Farley (1983, 1991), showed that the energy absorption capability of graphite/epoxy tubes is inversely proportional to fiber stiffness; the high ultimate failure strain of graphite composites with a toughened matrix is less than the energy absorption capability of a lower failure strain system.

Mamalis *et al*. (1996 and 1998) quantitatively evaluated the contribution of energy absorption sources such as friction, frond bending, interlaminar crack propagation, and axial splitting. Recently, the effects of interlaminar fracture toughness (GI and GII) have been studied by several authors, as for example (Ghasemnejad *et al*. 2009). They concluded that modes I and II fracture toughness show a strong correlation with the SEA of composite tubes made of carbon fiber reinforced plastics (CFRP) and glass fiber reinforced plastics (GFRP).

Formula 1 vehicles employ, the carbon fiber reinforced plastic (CFRP) and the use of advanced composite is largely diffused from the 1980’s. In aeronautics the first airplane with more than half of the primary structure in nonmetallic material made its first appearance only recently.

This work is concerned with the drivers for an alternative crash absorber design in case of high energy crash events, in order to change a high-pressure chamber devoted to absorb the loads transmitted during the landing of a military helicopter with a crash absorber can be easily repleaced. The geometry and the material characteristcs are two elements to investigate in order to define the best solution.

The most common composite materials investigated for energy absorption purposes have been graphite/epoxy (Gr/Ep), (Hadavinia *et al*. 2009), glass/epoxy (Gl/Ep) Thornton (1979) and Kevlar/epoxy (K/Ep) (Lavoie *et al*. 1996). The laminate stacking sequence has also been shown to have a great influence on the SEA and a limited number of studies have been performed to determine the optimal lay-up for the laminates as reported by Thuis and Metz (1994).

Then Daryadel (2015) investigated the pultruded hybrid composite specimens made of glass and graphite/epoxy with different combinations of fibers dynamically loaded using a modified compression SHPB, where the glass fiber/epoxy specimens exhibited higher ultimate compressive strength and specific energy absorption compared to pure graphite/epoxy samples, while graphite hybrid showed higher stiffness. Generally, is is possible to observe that the hybrids’ compressive stiffness, ultimate strength and specific energy absorption are highly dependent on the type and location of fibers.

Another important aspect to explore is the geometrical evaluation; Zahran (2017), investigated as adding external longitudinal stiffeners on the circular stepped tubes, where the results showed that addition of external longitudinal stiffeners on circular stepped tubes could imply greatest improvement for the energy absorption, specific energy absorption capability, and the crush force efficiency.

Recently, Mahdi and Sebaey (2014) have reported that radial reinforcements improve crashworthiness capabilities. Besides, some studies have investigated the absorption capabilities of natural fibers reinforced polymer composite tubes as studied by Alkbar (2014).

Finally, Priem *et al*. (2014) carried out an experimental program was carried out to investigate the crashworthiness performance braided thermoplastic composite tubes to evaluate the influence of tube length and braiding angle.

2. Industrial methodology

When the amount of energy to absorb is very large, as for a commercial airplane, different components are devoted to absorb the energy, so the landing gear is equipped with different solutions to reduce the load peaks of a crash landing. The rear spar wing attachments of the main landing gear of the Boeing 777 are controlled by a series of fuse pins, which connect the landing gear to the wing fittings, Oeberman (2010). These fuse pins are designed to fail under a prescribed load in case of a landing gear breakaway event, thus protecting the wing fuel tank structure.

The Boeing 737 main gear trunnion forward bearing bolt is designed to fail if the landing gear receives a severe impact, thus minimizing damage to the structure. A special shear bolt is used for the upper attachment of the drag brace to minimize damage to the structure should the landing gear receive a severe drag impact Brady (2014).

Similar application is installed into the Saab 340, where the main landing gear support fitting and trunnion fitting are attached to wing structure by fusible bolts, which are sized to fail before any gear element, ref Roskam (2007).

Contrarily the Sikorsky company adopted, for many helicopters, a honeycomb energy-absorption system, (Emerson *et al*. 1966), consisting of a strut filled with pre-crushed metal honeycomb in series with the oleo. This device is activated at high sink speeds, when hydraulic lockup of the shock strut is encountered. When the load reaches a predetermined value, specially calibrated pins are broken, nextly the strut compresses the honeycomb in a plastic manner, efficiently absorbing the kinetic energy of impact. The manufacturer judges this device as being successful in service.

The Sikorsky CH-54A Army Flying Crane is a twin engine heavy lift helicopter and it uses a pressure-relief valve for its energy-absorption system (Foye *et al*. 1981). It requires servicing after use. The main landing gear is designed so that the primary stage strokes before the secondary stage for any crash condition. During a crash, the tire first flattens then the wheel collapses and the primary stage of the shock strut bottoms. Pins then shear, allowing the secondary stage to begin to stroke and crush the honeycomb. As the honeycomb crushes, the gear swings up and outboard along an arc defined by the side brace. This sequence of events is desirable to prevent the buildup of large bearing friction forces in the primary stage caused by the secondary stage stroking first and swinging the gear outward.

Furthermore, there are several types of energy absorption devices which may be considered.

• Air-Oil Strut: Required for meeting normal landing requirements. It is repeatable and can be compressed for retraction and air transportability. It can be designed for high efficiency for normal operation, but it is not as efficient when used for crash conditions. This device is velocity sensitive and requires modifications to prevent "hydraulic lock". Because oil damping force is a function of closure velocity squared, at high stroking rate the hydraulic loads rapidly reach strut failure or mount failure. Possible modifications are considering a hydraulic relief valve that would reduce load so the strut can stroke without failure or an energy absorber in series with the shock strut to reduce closure velocity so the strut can stroke at a load below the failing load.

• Honeycomb Structure: Although not the lightest non-replaceable structure, it is easy to install and requires a minimum of testing to develop a high efficiency. It is considered repeatable and highly reliable. In addition to the various crush load magnitudes which may be obtained by selection of material, foil thickness and cell size, pre- crushing can be applied to eliminate the peak load and provide a controlled load over the entire stroke.

• Tube Cutter Device: This device consists of a metal tube with a cutting die located at one end. Energy is dissipated when the die is forced into the metal tube, cutting it lengthwise.

• Invertube: Absorption of energy by the invertube process involves the controlled inversion of a soft metal tube during application of an axial load. One end of the tube is clamped to a plunger which inverts the tube causing energy to be absorbed by plastic bending, compression, and shearing plus friction. It is difficult to obtain consistent load during stroking.

• Buckling of Metal Shells: This energy absorption method utilizes a metal shell of cylindrical, spherical, or conical shape. Impacting at one end initiates a local buckling condition which progresses in regular stages during which the folds form a geometrical pattern from one end to the other until a completely collapsed condition is obtained. Stroke lengths reaching 90% of initial length are not uncommon for thin shells. Rebound force is usually negligible since a buckled shell has substantial resistance to being expanded axially.

• Energy Strap: This method utilizes a metal tension strap deforming in the plastic range as a means for absorbing landing impact energy.

• Bearing Failure: Bearing failure mode is a method used to provide controlled energy dissipation at predictable load levels. The ACAP landing gear lateral strut attachment uses a joint design where lateral impacts result in non- catastrophic bearing failure of the attachment frame. Energy can be absorbed in a similar manner at other mechanical joints throughout the structure.

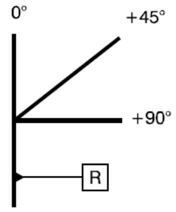
• Foamed Plastics: These materials indicate no prominent peak stress at the start of crushing action and very little difference in stress-strain characteristics with variations in velocities over the range of interest, but static tests generally show a decrease in available energy absorption capacity. As expected, there is a rapid increase in energy absorption with increased density but usable strokes are limited and rebound energies are significantly increased when large stroke values are used.

3. Material and reference model

The crash absorber prototype integrates an element of composite material, and it is comparable with the features and performance of a landing gear oleo-pneumatic shock absorber traditionally produced by Magnaghi Aeronautica. The Crash absorber (CRABS), made of composite material (carbon fiber), appears to be the essential part of the system crash integrated into a shock absorber capable of absorbing impact energy in case of extreme crashes.

The layup, see Table 1, and mechanical properties of the material, see Table 2, used to define CRABS prototype is described below.

Table 1 Mechanical properties of the material



Ply number	Sequence	Material	Fiber Orientation
P1	S10	HexPly 914/40%/G803	0
P2	S20	HexPly 914/40%/G803	+45
P3	S30	HexPly 914/40%/G803	-45
P4	S$0	HexPly 914/40%/G803	+45
P5	S50	HexPly 914/40%/G803	0

Table 2 Mechanical properties of the material (Normalised to 60% fibre volume, except for ILSS)

Weft (dry & RT)	Tensile	flexural	ILSS	Compression
Strength (MPa)	550	790	68	550
Modulus (GPa)	65	58	-	59
Test method	EN 2597	EN 2562	EN 2563	EN 2850 B

NB: Flexural result are not normalised

In reference (Guida *et al*. 2014) this material and the layup were used to design a tube subjected to quasi static analyses at low speed crushing (about 1 mm/s). Different layups, materials and manufacturing technologies to joint the fibres were studied and correlated to define the best crashworthiness configuration.

This research study has been initially performed on aluminium alloy specimens with different geometries and thickness, and then on carbon fibers. To find a consistent comparative benchmark, an extensive campaign of quasi-static tests was carried out to correlate the numerical analysis and to define a numerical model able to simulate the real behaviour of the tubes under static load.

Fig. 1 shows the different tubes investigated. Initially a 200 mm tube length was chosen to experimentally determine the buckling load, the results have been repeated with two different thicknesses of 1 and 1.5 mm. The experimental tests performed on the metallic tubes were correlated with the results for the composite specimens with same lengths but with different tube junctions. The correlations have been performed considering a tube with end-closed heads, then tubes that presents an overlap of 20 mm and finally with an overlap of 10 mm of junctions.

These results allowed to define a new tube in composite material with a different length and an overlap of 20 mm that under a buckling load the maximum stress value decreases with a reduced length.

The validation problem was defined to maximize the absorbed energy of a cylindrical tube with the final scope to obtain a maximum design load. These results were obtained adopting the strategy one factor at a time (OFAT), this approach is based on the choosing an initial set of baseline levels for each factor in succession and to vary the levels of each factor in its range of variation, keeping all other factors constant at their base level, Montgomery (2007).

Regarding to the application of the crash absorber tubes, the geometrical variables of the tube such as thickness, diameter and length have been verified by comparing they with the experiment, and the design variables have been validated to obtain the best result. For the first design cycle, the diameter levels are 50 mm, thickness of 1, and 1.3 mm, and the length is 200 mm. The correlations of the maximum load were performed for aluminium alloy and composite cylinder, this last was manufactured in two different ways, overlap and end-closed heads. Design variables depend on the material and manufacturing process, so the selection of design range can have a major effect on the response. On the basis of the experimental results obtained during the compression test on the crash absorber in aluminium alloy and composite materials, the main effects and interactions of the design variables are evaluated by means of the total absorbing as well as the mean axial impact force with respect to the design variables.

The optimum results of the first design cycle showed an increasing of 24.2% in specific absorbed energy of the overlap composite cylinder compared to the aluminium cylinder, also the overlap composite offer the benefits of 15.3% in decrease in tube mass and also 6.4% decrease in the mean crash force.

Therefore, in the second design cycle, on the basis of numerical results, the limits of thickness and diameter have been enclosed and the value of L has been decreased up to 50 mm to obtain a maximum design load of 13 kN. The optimum results of the second design cycle indicated that the new optimum tube in overlap carbon fiber has higher capacity of energy absorption, lower weight and also lower mean crash force for a geometry as shown in Fig. 2, with a length of 103 mm, thickness of 1.2 mm and an inner diameter of 53.5 mm.

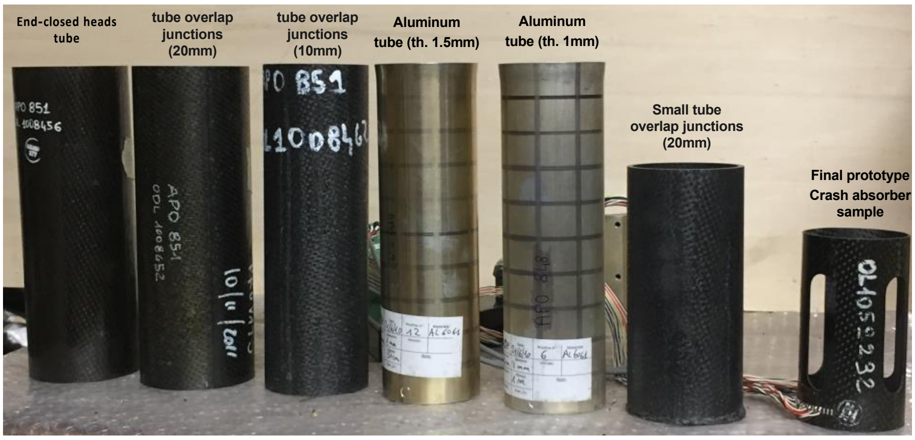


Fig. 1 Example of tested specimens

Fig. 2 Crash Absorber sample

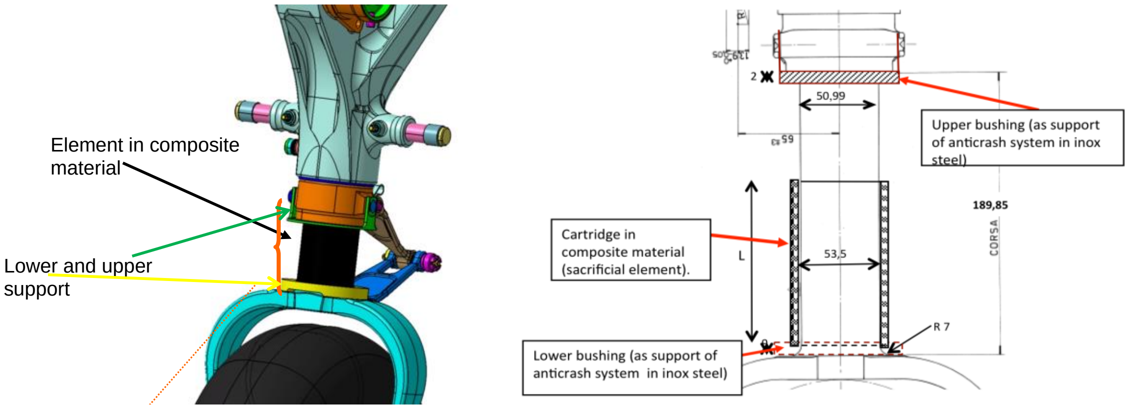


Fig. 3 Installation of the dissipative device

It is compared with a conventional oleo-pneumatic shock absorber, designed to withstand a crash load, which has a greater longitudinal dimension, incorporating a chamber of high pressure, able to ensure the extra stroke for the absorption and dissipation of impact energy.

A special crash absorber was specifically designed to absorb part of the energy produced in the vertical impact, Fig. 3. The design solution installs the CF absorber around S/A Rod and fixed on the fork. The shock absorber works in oleo-pneumatic manner for a maximum stroke of 190 mm.

Starting from the results obtained during the landing gear drop test without crash absorber and considered that the inner diameter is 53.5 mm, to obtain a maximum design load equal to 13 kN, the length of the absorber of carbon fiber/epoxy matrix 914/40%/G803 resulted in 103 mm.

From the comparison of the results, it resulted that this simple crash system can be a valuable alternative to the traditional one with advantages in terms of weight, maintenance and reliability at the same performance. The crash system is basically a composite material cartridge integrated into the oleopneumatic shock absorber avoiding the high pressure chamber.

The advanced composite cartridge (carbon fiber pre-preg fabric) is a sacrificial element of cylindrical shape, installed coaxially to the cushion landing gear prototype, (then in series with it) and rests in its lower part on a support metal grooved and even coax it to the stem. The system crash is also constituted by a metallic support installed to the lower base of the body of the carriage, which ensures a homogenous impact of the lower part of the body with the cartridge during the crash.

The cartridge starts working when the oleopneumatic cushion has completed its stroke, and reaches the mechanical stop at the top of the cartridge muffling the peak of impact load (“crash”).

This crash system has achieved a weight reduction of about 20%, compared to the high pressure system of the traditional oleo pneumatic shock absorber, which is made of steel and copper.

Other advantages are also in terms of cost, varying from 15 to 30% (depending on the type of landing gear and the aircraft on which it is installed), for the reduction of the metal parts and expensive special manufacturing processes like galvanic surface protection. Moreover, it eliminates the need for a high pressure inflation valve and the conditioning times cushion (room charge high pressure).

The elimination of the high-pressure chamber entails a decrease of the maintenance costs (of the order of 15%) and an increase of 'operational reliability (of the order of 34%) since it reduces

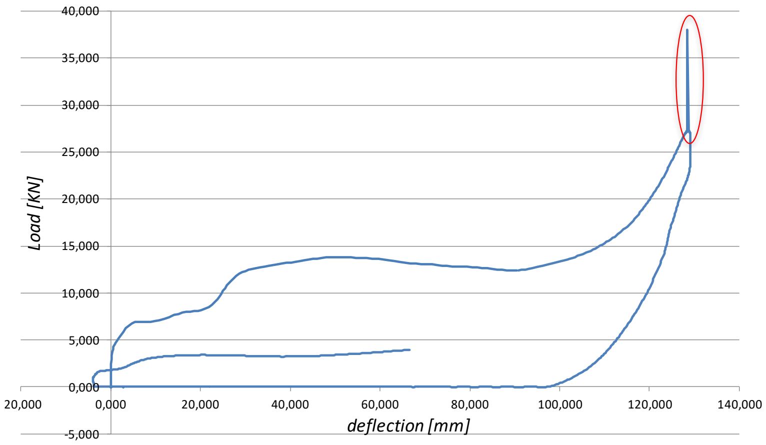


Fig. 4 Vertical Load - S/A stroke without CRABS

The number of seals that separate the high and low pressure volumes and the possibilities of leakage of gas and hydraulic oil.

4. Composite crash energy absorption

The selected test article is the landing gear of the military jet pilot trainer SIAI Marchetti S211. The crash test condition consists to drop a total weight of 418 kg so to obtain a vertical speed of 11m/s and a load factor of 7 g, in order to record a shock absorber with a stroke of about 1.5 m) On the other hand, with a simple crash absorber system, with fewer element and lower cost, integrated in the landing gear structure, it is possible to obtain the same performance of a traditional S/A.

Several preliminary drop tests were performed at different heights to estimate the stroke of the landing gear, and the entity of the reaction forces, using an instrumented torque plate at the base of the drop tower. The objectives of the testing program were to simulate a crash condition in which the shock, after completing the total mechanical travel with nitrogen and hydraulic fluid compression, be able to absorb the impact energy reaching the mechanical stop. The efficiency of the shock absorber decreases increasing the landing vertical speed, producing an increase of the peak load, Fig. 4.

Based on the characteristics of the available drop tower, the required vertical speed of 30 ft/s (10 m/s) for crash testing this landing gear has been translated, through a comparative energy analysis, to 100 ft/s (3 m/s), maintaining the same weight but adopting a lower admissible impact stroke. This, indeed, is the main parameter which needs to be correctly defined in order to dissipate a specific amount of energy for an imposed load factor.

For this reason, a 10 ft/s (3 m/s) drop test was conducted with a free drop height of 0.459 m and with a drop weight of 418 Kg (computed including landing gear and wheel).

From the drop test, the recorded value of the stroke has been 0.146 m, with an inertial load factor equal to 7 g, and a maximum load for the mechanical bottoming of 38 KN. Since the load value recorded just before reaching the crash condition has been about 10 kN, a crash absorber with such buckling load should be designed and installed. This would protect the fuselage attachments from being loaded by excessive force values.

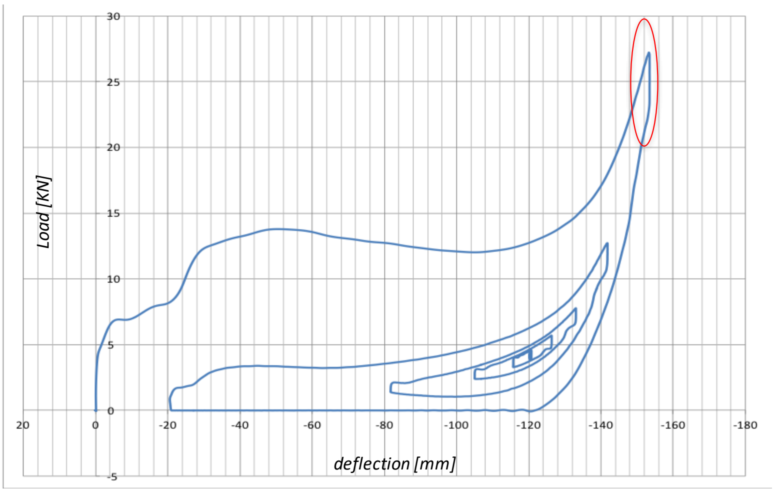


Fig. 5 Vertical Load - S/A stroke with CRABS

The drop test campaign has shown that a stroke of 128 mm was the limit before reaching the mechanical stop and the consequent load increase. Installing a sacrificial composite material element would be able to absorb the surplus of kinetic energy, avoiding any extra-stroke and controlling the peak load as shown in the Fig. 5).

This event occurs when the shock absorber has reached the mechanical bottoming, which could result in a potential catastrophic collapse of the fuselage (crash landing condition).

Therefore, when the stroke of the shock absorber is not sufficient to absorb the kinetic energy required in this emergency condition, the presence of a specifically tailored element can absorb the surplus of kinetic energy reducing the load transmitted (as shown in, thus avoiding the need for more sophisticated devices, gaining benefits in terms of overall dimensions, weight, cost and maintenance procedures.

Fig. 5 shows how the peak load, with the introduction of the sacrificial element, can be effectively controlled, reduced in intensity and completely absorbed.

The objective is therefore to develop a system crash with cylindrical element in composite material (carbon fiber) to be integrated in a prototype of the landing gear.

It reduces the peak load due to high velocity impact and prevents the transfer of loads to the structure with catastrophic damage also in compliance with the requirements of the standard rule in case of a crash landing conditions. This type of solution is also reliable from the structural point of view and has a lay-out very simple and with low cost and weight and reduced environmental impact.

The integration consists to install the cylindrical element internally or externally the landing structure depending on the architecture of the landing gear, the entity of the vertical speed and load factor, the efficiency of the shock absorber.

An experimental study of failure mechanism on the energy absorption capability of metallic and different layup of CFRP tubes under axial compression was described by (Guida *et al*. 2014). The conclusions of this study were that a traditional tongue-in-groove joint tends to create interlaminar shear loads, which are hard to resist with a sandwich construction and can lead to breakage. Then the fiber carbon tubes show a typical brittle fracture mode comprising transverse shearing and splaying modes. The transverse shearing crushing mode is characterized by a wedge

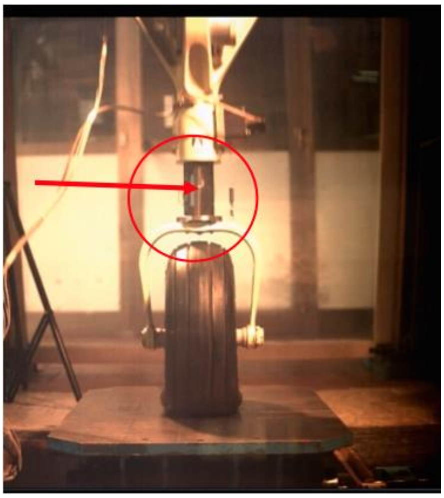


Fig. 6 Experimental test of the S/A stroke with CRABS element

shaped laminate cross section with one or multiple short interlaminar and longitudinal cracks that form partial lamina bundles. The splaying mode is characterized by very long interlaminar, intralaminar, and parallel to fiber cracks, with a fracture of the lamina bundles. During the experimental test related to the quasi-static crushing tests, the tubes crushed by the brittle fracture mode absorb energy by various modes such as propagation of center interlaminar cracks, bending of fronds, fracture of lamina bundles and friction between fronds.

As a conclusion, the experimental results by (Guida *et al*. 2014) also defined the best solution in terms of layup sequence and useful to define a configuration of the absorber, to be installed on the landing gear and that would meet the installation and performance requirements.

5. Evaluation of the failure models with real tests

Fig. 6 reports the experimental test, it showed the instant in correspondence of the local failure of the antic rash system, which completely deforms until to the total collapse because of the local instability.

The performance of the plasticity and damage models selected for this investigation is herein evaluated. In order to achieve global convergence and affordable analysis times, implicit analysis has been selected for all simulations. Initially the focus is on a tube FE model, fully meshed by shell elements. Intralaminar failure in the multi-layered composite shell elements is covered by Hashin (1980) for damage initiation and a fracture energy-based formulation for damage evolution, based on stress components; beyond the failure surface, elastic properties are degraded according to laws defined by the material model.

The boundary conditions were defined corresponding to the experimental crash tests with a compressive load of 10 KN, which is the value read in correspondence of the tube attacks and corresponding to the force value that should be absorbed by the crash absorber.

The layup of the carbon fiber cylinder absorber consists of five pre-preg carbon fiber plies (Hexply 914/40%/G803) laminated at (0, +45, -45, +45, 0) degrees resulting in a thickness of 1.49 mm (=0.298 mm×5 plies). The manufacturing process provides a finished product with an effective thickness of about 1.78 mm taking into account the overlap configuration used, therefore it was modeled as made up of 6 plies.

The dimensioning of the absorber defining the design, geometry and thickness distribution was studied introducing the load acting in correspondence of the lower and upper attack of the absorber, so the cylinder was subjected to the compressive load. The simulation has shown stress concentrations in correspondence of the cutting of the tube. This suggests that the main contributors to the energy absorption are represented, in this model, by the cohesive elements and the damage and delamination modes under bending. Again, it has to be recalled that the real physical process of fragmentation cannot be properly represented by this FE model, but just approximated.

In order to ensure similar target buckling load (10 kN where the S/A stroke is 128 mm), the cylinder have been properly shaped by applying a large cut out along its main axis.

Following an iterative approach the optimum solution have been achieved considering #4 rectangular hole of 46×17 mm with circular fillet of 8.5 mm, which ensure a reduced effect of stress concentration and complies with actual manufacturing process used for this item.

Nastran SOL105 have been adopted to compute the buckling eigenvalue. The following Fig. 7 and Table 3 show, respectively, the boundary conditions and the applied load together with the resulting computed output load.

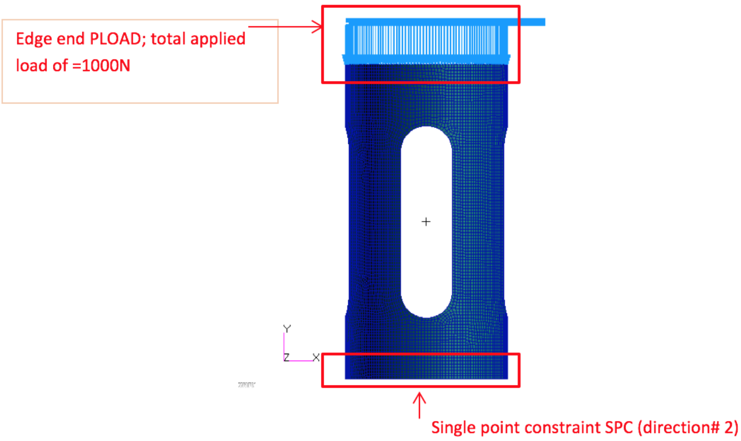


Fig. 7 FEM detail of constraint and force

Table 3 FEM detail of OLOAD

Load Type	T1	T2	T3	R1	R2	R3
Fx	0	-	-	-	0	0
Fy	-	-9.99999E+02	-	5.400125E-13	-	-2.586376E-12
Fz	-	-	0	0	0	-
Mx	-	-	-	0	-	-
My	-	-	-	-	0	-
Mz	-	-	-	-	-	0
totals	0	-9.99999E+02	0	5.400125E-13	0	-2.586376E-12

The FEM is modelled using only QUAD4 element ensuring a maximum element length of 1 mm. Finally, each element has been associated with PCOM properties as described in the following Fig. 8 and Table 4.

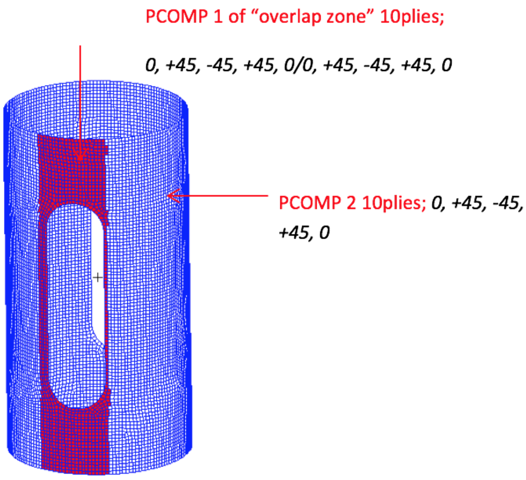


Fig. 8 FEM detail of constraint and force

Table 4 FEM material and laminate properties

			$Baseline material			
MAT8	1	65000.	65000.	.4	1910.	
			$laminate overlap zone			
PCOMP	1	0.			0.	0.
1	0.298	45.	YES	1	.298	-45.
YES						
1	0.298	45.	YES	1	.298	-45.
YES						
1	0.298	45.	YES	1	.298	-45.
YES						
1	0.298	45.	YES	1	.298	-45.
YES						
1	0.298	45.	YES	1	.298	-45.
YES						
			$Baseline laminate			
PCOMP	2	0.			0.	0.
1	0.298	45.	YES	1	.298	-45.
YES						
1	0.298	45.	YES	1	.298	-45.
YES						
1	0.298	45.	YES	1	.298	-45.

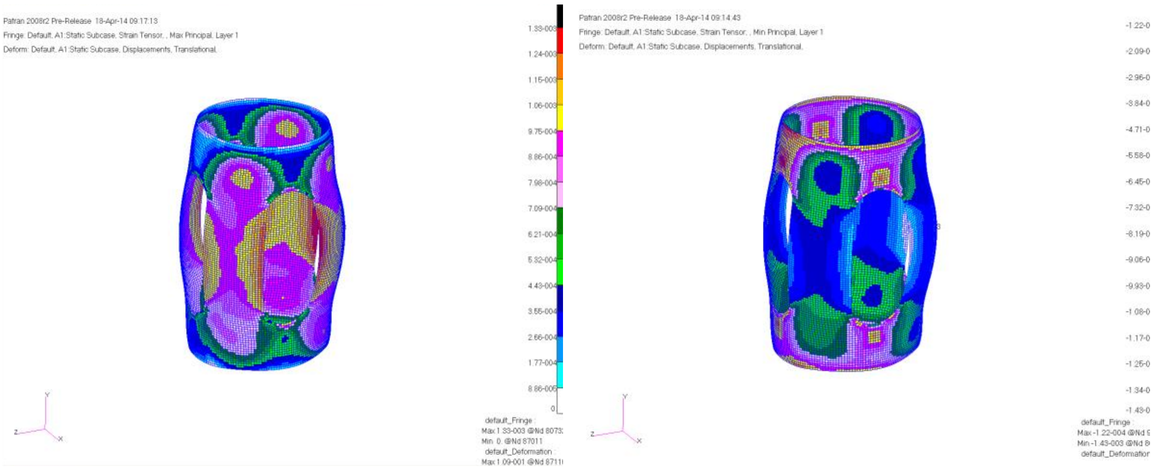


Fig. 9 Stress concentration (Maximum and minimum principal)

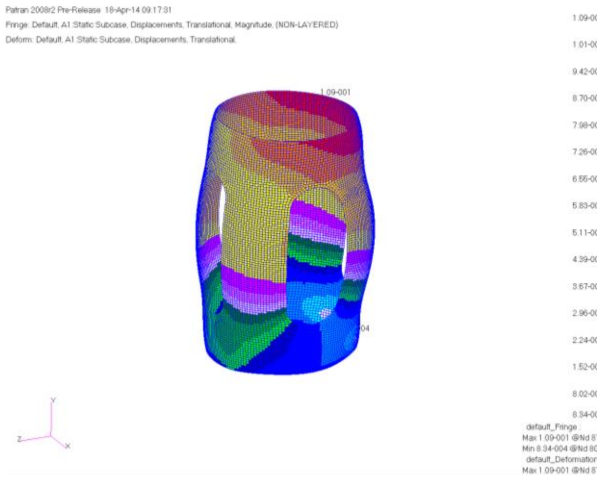


Fig. 10 Maximum axial displacement

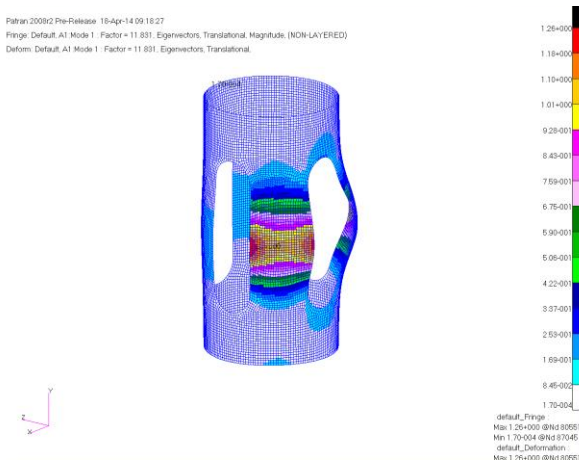


Fig. 11 Buckling instability during the compressive load

Table 5 FEM Real eigen values

Real Eigen Values						
Mode no.	Extraction order	Eigen value	Radians	Cycles	Generalized Mass	Generalized stiffness
1	1	1.183109E+01	3.439635E+00	5.474349E-01	4.033448E+01	4.772008E+02

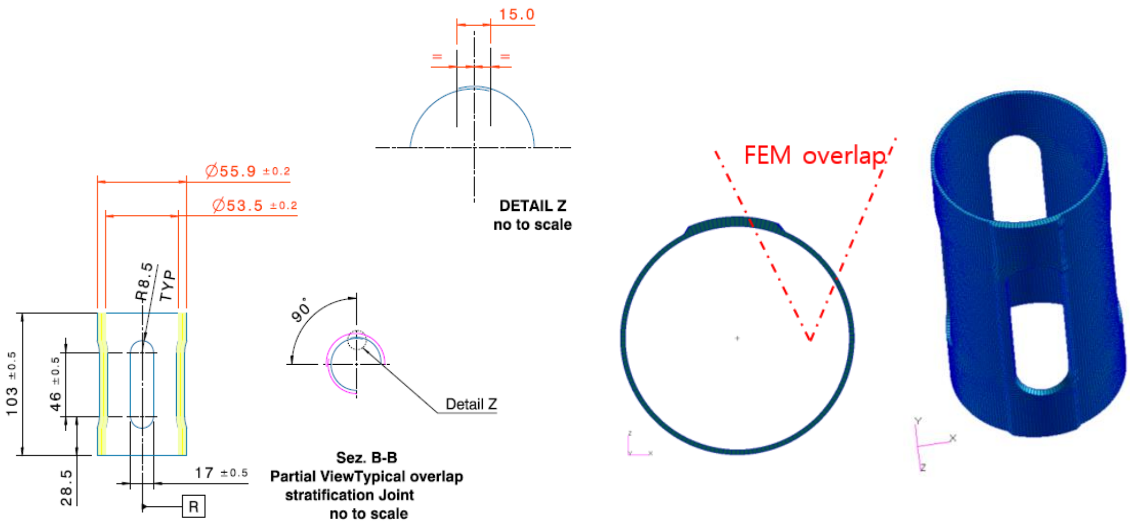


Fig. 12 Details of the wall thickness because of the overlap

The first eigenvalue associated with the configuration analysed is 11.8 (See Table 5).

As shown in the Figs. 9 and 10, due to the axial asymmetry because of the overlapping region, the stiffer area is less loaded. As expected and shown during the test, the buckling instability is much more evident in the area far from the overlap.

The experimental failure mode of the cartridge, see Fig. 11, reveals the first instability at break of the walls of the slits arranged diametrically opposite to the overlap of the plies. The overlap, Fig. 12, is requested to ensure correct closure and mechanical sealing of the cartridge obtained during the pre and post treatment in autoclave. This manufacturing process yields the initial failure starting in the walls of the absorber.

Furthermore, an important correlation between different configurations confirmed the necessity to investigate a non-metallic solution comparing the force and displacement when the compressive load of 10 KN is imposed, this value corresponds to the force value that should be absorbed by the crash absorber.

The different configurations were investigated by numerical simulations to characterize the material behaviour:

• Crash absorber in aluminum material with 1.2 mm of thickness;
• Crash absorber in aluminium material with 1.0 mm of the thickness;
• Crash absorber in CFRP with 1.2 mm of thickness.

Considering the target force of 10 KN, the choice of CFRP is more appropriate. The underlying area is, in fact, greater while maintaining lower load levels.

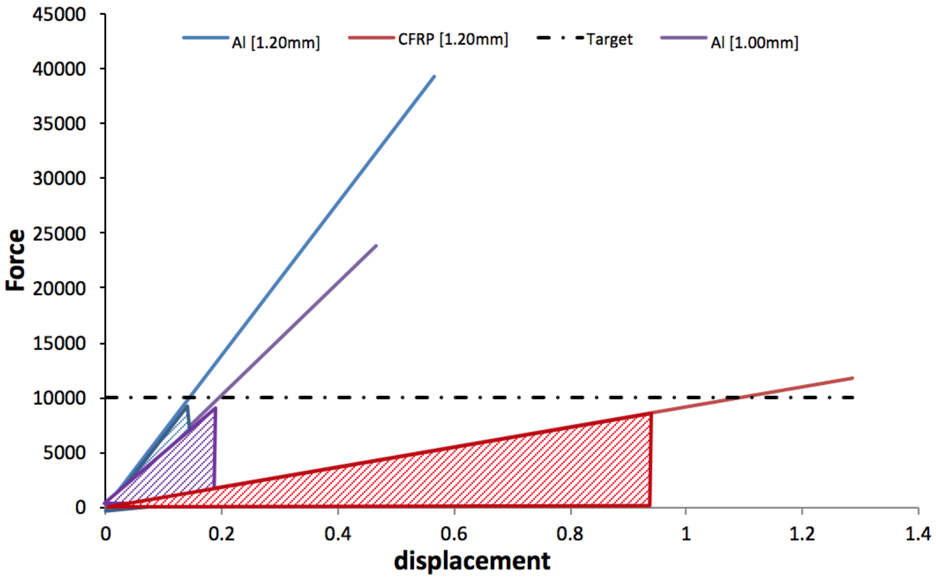


Fig. 13 Force-displacement curve about different samples under compressive static test

6. Conclusions

When designing a structural member for energy absorbing purposes, it is important that the initial peak load be kept low to minimize the transmitted forces while the sustained crush load be kept high as the damage progresses to maximize the energy absorption.

A lightweight composite crash absorber was developed to improve the crashworthiness behaviour of a landing gear. A prototype cylinder crash tests under normal loading conditions provided consistent results within all requirements and showed a very high degree of robustness and reproducibility of the results.

The results show a general improvement in terms of the energy absorption, and the composite crash-absorber prototype has shown the best results. The sensitivity of its parameters on the total specific energy absorption has been studied to prevent catastrophic failure of a landing gear during an emergency landing.

The peculiar feature of the absorber device is its capability to absorb major part of the total impact energy in crash conditions.

The achieved results are perfectly inline with what was expected and therefore very promising for future applications with adequate design. The resulting crash absorber system resulted to be very simple, low weight, low impact in terms of functional and assembly of the landing gear and it can be fitted, as it is, to a direct or telescopic landing gear, designed on the maximum take-off weight.

The knowledge that tubular elements made of carbon fiber are excellent for absorbing energy under the action of a compressive load, such as for a front collision of the installed safety cell on F1 cars, is well known. The use of such element in a complex landing system to withstand the extreme conditions of a crash, resulted in an original application for both civil and military aircraft.

The complexity of such system, with all associated problems, has been solved by the lightweight, inexpensive and environmentally sustainable composite cartridge.

References

Alkbir, M.F.M, Sapuan, S.M., Nuraini, A.A and Ishak, M.R. (2014), "Effect of geometry on crashworthiness parameters of natural kenaf fibre reinforced composite hexagonal tubes", *Mater. Des.*, **60**, 85-93.

Brady, C. (2014), *The Boeing 737 Technical Guide*, 69 edition, Tech Pilot Services Ltd, U.K.

Currey, N.S. (1988), *Aircraft Landing Gear Design: Principles and Practices*, 4th Edition, American Institute of Aeronautics and Astronautics, U.S.A.

Daryadel, S.S., Ray, C., Pandya, T. and Mantena, P.R. (2015), "Energy absorption of pultruded hybrid glass/graphite epoxy composites under high strain-rate SHPB compression loading", *Mater. Sci. Appl.*, **6**(6), 511-518.

MIL-STD-1290A (AV) (1986), *Light Fixed-and Rotary-Wing Aircraft Crash Resistance*, Dept. of Defense, U.S.A.

Farley, G.L. (1991), "The effect of crushing speed on the energy-absorption capability of composite tubes", *J. Compos. Mater.*, **25**(10), 1314-1329.

Farley, G.L. (1983), "Energy absorption of composite materials", *J. C. Mater.*, **17**(3), 267-279.

Foye, R.L. and Shipley, J.L. (1981), "Evolution of the application of composite materials to helicopters", *J. Am. Helicopter Soc.*, **26**(4), 5-15.

Ghasemnejad, H., Blackman, B.R.K., Hadavinia, H. and Sudall, B. (2009), "Experimental studies on fracture characterizations and energy absorption of GFRP composite box structures", *Compos. Struct.* **88**(2), 253-261.

Gilbert, E.D. and Deyerling, G.P. (1966), *US 3265163 A1*, U.S. Patent and Trademark Office.

Guida, M., Marulo, F., Montesarchio, B. and Bruno, M. (2014), "Innovative anti crash absorber for a crashworthy landing gear", *Appl. Compos. Mater.*, **21**(3), 483-494.

Hadavinia, H. and Ghasemnejad, H. (2009), "Effects of mode-I and mode-II interlaminar fracture toughness on the energy absorption of CFRP twill/weave composite box sections", *Compos. Struct.*, **89**(2), 303-314.

Hashin, Z. (1980), "Failure criteria for unidirectional fiber composites", *J. Appl. Mech.*, **47**(2), 329-334.

Lavoie, J.A. and Kellas, S. (1996), "Dynamic crush tests of energy absorbing laminated composite plates", *J. Compos. Part A-Appl. S.*, **27**(6), 467-475.

Mahdi, E. and Sebaey, T.A. (2014), "An experimental investigation into crushing behavior of radially stiffened GFRP composite tubes", *Thin Wall. Struct.*, **76**, 8-13.

Mamalis, A.G., Manolakos, D.E., Demosthenous, G.A. and Ioannidis, M.B. (1998), *Crashworthiness of Composite Thin-Walled Structural Components*, CRC Press, U.S.A.

Mamalis, A.G., Manolakos, D.E., Demosthenous, G.A. and Ioannidis, M.B. (1996), "The static and dynamic axial collapse of fibreglass composite automotive frame rails", *Compos. Struct.*, **34**(1), 77-90.

Montgomery, D.C. (2007), *Design and Analysis of Experiments*, 6th Edition, Wiley, U.S.A.

Oebermann, S. (2010), *General Familiarization Boeing 777*, AeorEd and Aircraft Technical Book Co., U.S.A.

Priem, C., Othman, R., Rozycki, P. and Guillon, D. (2014), "Experimental investigation of the crash energy absorption of 2.5D-braided thermoplastic composite tubes", *Compos. Struct.*, **116**, 814-826.

Roskam, J. (2007), *Airplane Flight Dynamics and Automatic Flight Control Part I*, DAR Corp.

Thornton, P.H. (1979), "Energy absorption in composite structures", *J. Compos. Mater.*, **13**(3), 247-262.

Thuis, H. and Metz, V.H. (1993), "The influence of trigger configurations and laminate lay-up on the failure mode of composite crush cylinders", *J. Compos. Struct.*, **25**(1-4), 37-43.

Zahran, M.S., Xue, P., Esa, S.Y., Abdalwaheb, M.M. and Guoxing, L. (2017), "A new configuration of circular stepped tubes reinforced with external stiffeners to improve energy absorption characteristics under axial impact", *Lat. Am. J. Solids Struct.*, **14**(2), 292-311.

EC