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Drop test simulation and validation of a full composite fuselage section of a regional aircraft

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Abstract

In the aircraft industry, the use of fiber reinforced materials for primary structural components over metallic parts has increased up to more than 50% in the recent years, because of their high strength and high modulus to weight ratios, high fatigue and corrosion resistance. Currently, the need of lowering weight and fuel consumption is pushing the world's largest aircraft manufacturers in the design and building of structures entirely made of composites.

Fuselage structure plays an important role in absorbing the kinetic energy during a crash. Through the deformation, crushing and damage of fuselage sub-floor structure, a survivable space inside the cabin area should be preserved during and after a crash impact in order to minimize the risk of passengers' injuries.

In this work, a Finite Element (FE) model of a full-scale 95% composites made fuselage section of a regional aircraft under vertical drop test is presented. The experiment, conducted by the Italian Aerospace Research Centre (CIRA) with an actual impact velocity of 9.14 m/s in according to the FAR/CS 25, has been numerically simulated. Two ATDs (Anthropomorphic Test Dummies), both 50th percentile, seats and belts have been modelled to reproduce the experimental setup. The results of the simulation, performed by using LS-DYNA® explicit FE code, have been validated by correlation with the experimental ones. Such comparisons highlight that a good agreement has been achieved.

The presented FE model allows verifying the structural behavior under a dynamic load condition and also estimating the passive safety capabilities of the designed structure. Since the experiment is expensive and non-repeatable, a FE model can be used for Certification by Analysis purposes since, if established, it is able to virtually demonstrate the compliance to the airworthiness rules.

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1. Introduction

The consequences of an aircraft emergency landing on the ground can be dramatic. In the last decades, significant efforts have been carried out to increase the aircraft level of safety in the event of accident. Crashworthiness, therefore, has been becoming more and more one of the fundamental themes in aircraft design and certification.

One of the most important safety characteristic that an aircraft must accomplish is the capability to absorb as much energy as possible through structure deformations and failures, in a way to preserve the survivable space as well as allow passengers to not entrap themselves and escape the aircraft, after a crash impact. At the same time, the current design practice is addressed to limit the loads involving the passengers during a crash and, then, to limit the risk of passengers' injuries (Obergefell et al. (1988), Ruan et al. (2001), Wismans et al. (1994), Mertz et al. (1996)).

With the increasing composite material applications in both primary and secondary structures of commercial transport aircraft, up to more than 50%, in the recent years, it has been needed the establishment of a new design practice, since the different energy-absorbing mechanisms. Composite materials behavior is hardly predictable, respect to metals, due to the wide variability of response under different kinds of loadings (Califano (2018)) and to the complexity of the failure mechanisms that can occur: fiber fracture, matrix cracking, fiber-matrix de-bonding, and delamination (Riccio et al. (2017) - Composites Part B, Riccio et al. (2016), Riccio et al. (2017) - Engineering Failure Analysis)). The brittle failure modes of composite materials can make the design of energy-absorbing crushable structures tricky. Furthermore, a crash impact response is highly nonlinear, in terms of both geometry and materials (Xiaochuan et al. (2014)). Consequently, specific passive safety criteria are necessary to predict and improve the energy absorption capabilities of primary and secondary composite aircraft structures during a crash as well as to improve the crashworthiness. Moreover, compliance with regulations and crashworthiness requirements has influenced the design philosophy of the latest generation of aircrafts, and it will keep affecting the future, leading to an improvement in passive safety.

Crash tests are, in most of the cases, conducted on components under simpler boundary conditions. Full-scale tests are rarely conducted due to the high cost, so very few works are available in literature. As a result, numerical modelling is founding increasing application in the sectors where the demonstration of the crashworthiness capabilities assumes a key-role. In the last years, thanks to the continuous progress of the commercial Finite Element (FE) codes, several works have been presented in literature, aimed to make faster and less expensive the design practice. Contributes presented in literature can be listed in the following topics: virtual certification of aeronautical and automotive seats (Guida et al. (2018) - Multibody System Dynamics, di Napoli et al. (2018)); dynamic response of aircraft subjected to crash loading condition (Caputo et al. (2018), Lawrence et al. (2008)); prediction of both seat and occupant responses under different dynamic loading conditions; prediction of the probability of occupants' injuries (Ekman et al. (2018)) and evaluation of both structural behavior and failures under various crash scenarios (Waimer et al. (2013 – Composite Structures, Waimer et al. (2013) – CEAS Aeronautical Journal), not economically feasible with full-scale crash testing. Delsart et al. (2016) investigated experimentally a composite sub-cargo fuselage section of a commercial aircraft. Haolei et al. (2014) developed a numerical study of the crash performance of a hybrid metallic/composite fuselage section subjected to vertical crash. However, the only composite part of the purely virtual fuselage section was the fuselage skin, while all the other parts, such as cargo floor, frames, stringers and wave-plates were aluminum made. Guida et al. (2018) – Progress in Aerospace Science, developed a simplified finite element model of a typical composite fuselage able to predict the energy absorption capabilities of the structure during an emergency crash landing. Jackson et al. (2018) investigated the energy absorption properties of composite airframes structures both experimentally and numerically using a multilevel approach (component specimens and barrel section). In addition, they described a crash test of a full-scale composite helicopter with its landing gears; numerical simulations were presented and the results compared with the experimental ones.

This work presents the development of a FE model of a full-scale 95% composites made fuselage section of a regional aircraft under vertical drop test. The experiment, conducted by the Italian Aerospace Research Centre (CIRA) with an actual impact velocity of 9.14 m/s in according to the FAR/CS 25, has been numerically modelled, included two 50th percentile male Anthropomorphic Test Devices (ATDs), seats and belts, to reproduce the exact experimental setup. The simulation results, carried out by performing a LS-DYNA® explicit simulation, have been validated by correlation with the experimental data. Such comparison highlights that a good agreement has been achieved.

Nomenclature

FE	Finite Element
CFRP	Carbon Fibre Reinforced Polymers
CbA	Certification by Analysis
OPB	One Piece Barrel
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
CS	Certification Specifications
AC	Advisory Circular
CAD	Computer-Aided Design
ATD	Anthropomorphic Test Dummy
hcl	Free fall height
Acc	Accelerometer
SAR	Coupling & release system remote control

2. Test article description

A vertical drop test of a full-scale composite fuselage section of a regional aircraft, provided by Leonardo Aircraft Division, was conducted at LISA (Laboratory for Impact testing of Structures in Aerospace field) by the Italian Aerospace Research Centre (CIRA), in July 2017, with an actual impact velocity of 9.14 m/s, in according to the FAR/CS 25 (FAA (2006)).

The barrel, shown in Fig.1, is 4720 mm long and has a 4350 mm diameter circular section, for a weight of 534 kg. The test article is 95% CFRP (Carbon Fiber Reinforced Polymers) composite made obtained by means of OPB process. In particular, the skin, the stringers and the frames are made of thermosetting material while the main floor and the cargo floor beams are made of thermoplastic material. Stingers and skins are co-cured in the OPB process, while the other components are fastened to each other by means of titanium rivets. The thermoplastic material has been used also for the window frames. Fig. 2 shows several structural details of the test article, like the internal surfaces (skin, stringers and frames), the window frames and the cargo floor beams.

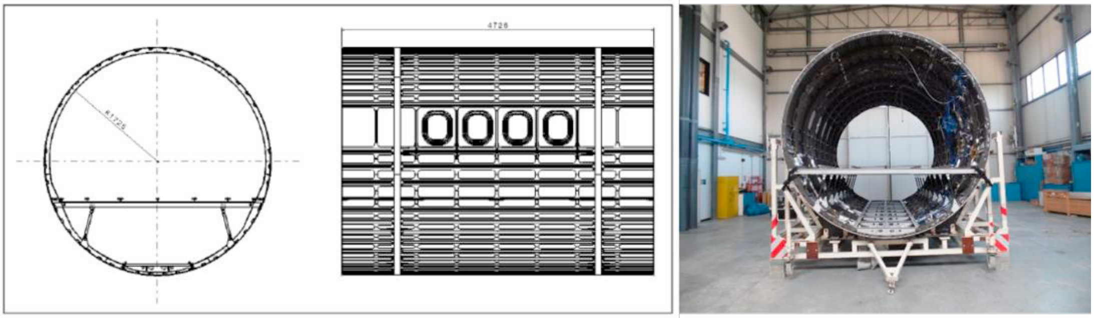


Fig. 1. Test article.

In order to lift the test article, four metal covers with handles were installed on the central windows, two per side. In this way, no intrusive systems were necessary.

In order to acquire useful data for the analysis of the dynamic behavior of the test article, the following measurement equipment was used: data acquisition system; anthropomorphic dummies (with cell load and accelerometers); impact signals measuring sensors (accelerometers and strain gauges) and two high speed cameras. The experiment was performed to verify the structural behavior under a dynamic load condition as well as to estimate the passive safety capabilities of the designed structure. For such purpose, two different types of dummies were used: Hybrid II (74 kg) and FAA Hybrid III (77 kg), both 50th percentile male. The ATDs were settled on aeronautical seats installed on the seat rail in correspondence of the central bay (Fig. 3.a) in order to reduce the need of installing balancing masses. The dummies were positioned respectively on the central seat and on the corridor-side seat (Fig. 3.b).

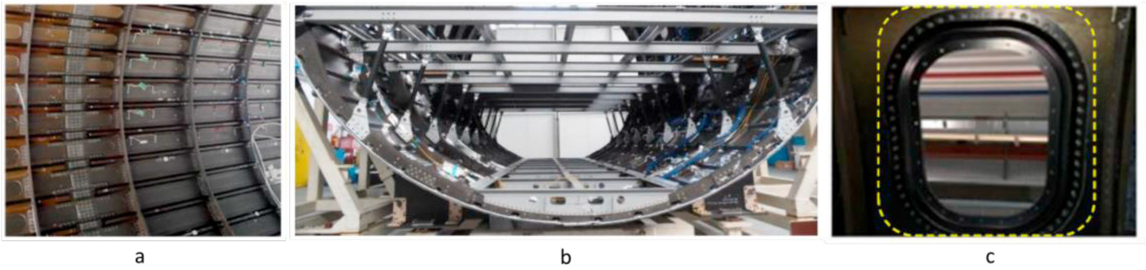


Fig. 2. Some structural details: (a) frames; (b) cargo zone; (c) window frame.

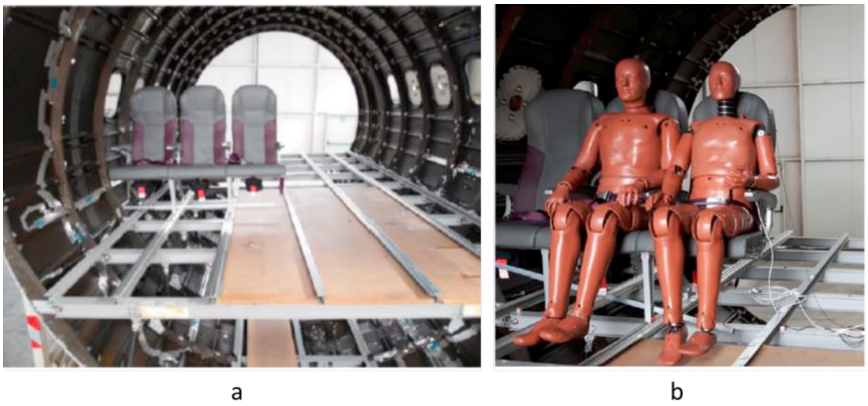


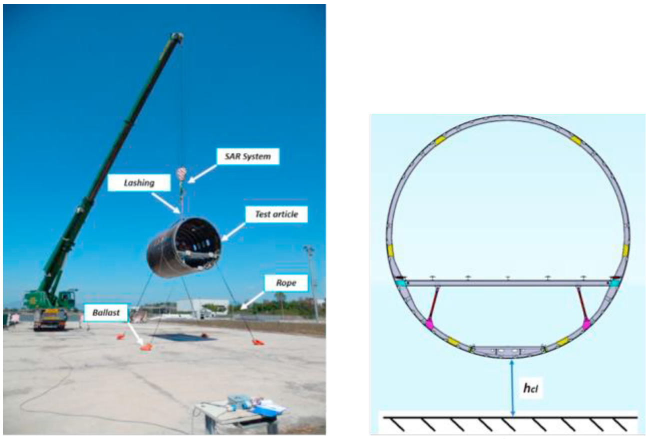
Fig. 3. Positioning of (a) seats and (b) dummies.

The total mass of the two dummies with the seats is about 185 kg, the acquisition system with the energy absorbing system have a total mass of about 42 kg, the two balancing masses with the support plate have a total mass of about 134 kg, the cables and bolts have a total mass of about 10 kg. Finally, the four metal covers with a handle installed on the central windows have a total mass about 23 kg.

In order to monitor the dynamic structural response of the test article, 11 piezoresistive accelerometers were installed so that the main floor beam was symmetrically monitored with respect to the roll and pitch axes. Each accelerometer was positioned and fixed on an aluminum block which was installed on the test article through mechanical joints as well as the accelerometer on the block. The connection between the test article and the SAR was carried out using four lifting bands, making their ends converge in a single anchorage point through which the release of the test article was activated with an electric remote control from the crane. In order to avoid oscillations and to stabilize the test article four ropes were used.

The test article was lifted to the prescribed free fall height, "h_{cl}", of 4260 mm and the configuration before the execution of the drop test is shown in Fig. 4. The SAR was used to release the test article and to active the data acquisition system. The data were acquired by setting a cutoff frequency of 1650 Hz for the single channel and by using a sampling frequency of 10 kHz, according to the SAE J211 standard.

Two high speed cameras, able to acquire images at a rate of 500 frames per second, were used to monitor the test from both frontal and lateral viewpoints. Furthermore, the cameras were used to record the video of the impact, useful in the post-process phase to provide displacement, velocity and acceleration time-history curves of the section during impact, by using several image markers applied on the frontal and lateral sides. The markers were used also to evaluate the roll and pitch angles at the impact instant.



a

b

Fig. 4. (a) testing configuration; (b) free fall height "hcl".

3. Numerical simulation of fuselage section drop test

In this section, the developed numerical model of the tested fuselage is presented. Since the experiment under investigation is expensive and non-repeatable, an established FE model can be a helpful tool for designers to investigate numerically several types of crash scenario, under a CbA (Certification by Analysis) point of view. Once the reliability of the numerical model has been demonstrated, designers can use it to understand numerically the effects of some few minor structural changes as well as the different aircraft attitude at the impact on the passengers' passive safety. This approach allows designer and manufacturers to save costs and time and, if established, to virtually demonstrate the compliance to the airworthiness rules (Olivares (2011)).

The here presented drop test finite element analysis has been performed using the commercial nonlinear, explicit transient dynamic, LS-DYNA® FE code.

3.1. Components modelling

The model of the fuselage section includes, as in the experiment, all the important structural features of a transport aircraft: frames, outer skin, stringers, beams, cargo floors and stanchions absorbers.

Shell elements have been used to model the fuselage skin, frames, floor and the supporting beams, as well as stringers and floor reinforcements, while solid elements have been used to model seats and dummies. In details, Quad4 and Tria3 shell elements (from LS-Dyna® Element Library) have been used: 4-nodes and 3-nodes elements, respectively, whose degree of freedom is six.

For the fuselage section an average element size of 10 mm has been set, for a total of 1231801 elements. The properties of the composite materials of skin and cargo beams have been represented using LS-DYNA® Mat54 material card, which allows defining arbitrary orthotropic materials, modelling the failures with the Chang-Chang criteria. It should be noted that Mat54 includes some parameters which have been estimated entirely on converge studies carried out on simpler components. The Mat116 card, allowing the modelling of the elastic response of the composite based on standard composite lay-up theory, has been used for lag and stanchions. The aluminum components, such as lag connecting beams and stanchions, reinforcement strips, have been modelled through the material card Mat24: an elastic-plastic material formulation that considers the strain rate effects by using the Cowper-Symonds law. Rivets and others simpler components have been instead modelled by means of Mat1 material card which allows defining a pure elastic material behaviour. A list of the mechanical properties of the materials is provided in Table 1 and Table 2.

Table 1. Aluminum properties.

	AA2024-T351	AA7075-T6
Density [kg/mm^3]	2.78e-6	2.85e-6
Young Modulus [GPa]	73.1	71.7
Tangential Modulus [GPa]	0.805	0.770
Poisson ratio	0.33	0.33
Elongation at break	0.20	0.11
Ultimate Tensile Stress [GPa]	0.324	0.503

Table 2. Composites properties at lamina level.

	AS4/3501	TC1100
Density [kg/mm^3]	2e-6	2e-6
Longitudinal Young Modulus, E_1 [GPa]	144.4	134
Transverse Young Modulus, E_2 [GPa]	10	134
Poisson ratio, ν_{21}	0.0201	0.33
In-plane Shear Modulus, G12=G13 [GPa]	7	5
In-plane Shear Modulus, G23 [GPa]	5.76	5
Longitudinal Tensile Strength, X_t [MPa]	2200	2020
Longitudinal Compressive Strength, X_c [MPa]	1700	1100
Transverse Tensile Strength, Y_t [MPa]	60	2020
Transverse Compressive Strength, Y_c [MPa]	400	1100
Shear Strength, S_c [MPa]	180	180

Components that are not co-cured together have been assembled by mean of titanium rivets. A surface-to-surface contact algorithm has been implemented between the rivets and the lags. The other bolted connections have been modelled, instead, with rigid elements (constrained nodal rigid body) to save computational costs.

The seats, made almost entirely of aluminum alloys with a total mass of 34 kg, have been reproduced as show in in Fig. 5. Quad4 and Tria3 element types (from LS-Dyna® Element Library) have been used for 2D shell elements while Tetra4 element type (from LS-Dyna® Element Library) have been used for 3D elements, for a total of 92,745 elements. The materials properties of the seats have been reported in both Table 1 and Table 3.

Table 3. Material properties of the seats.

	AA7050-T7651	Foam
Density [kg/mm^3]	2.83e-6	8.5e-8
Young Modulus [GPa]	71.7	0.005
Tangential Modulus [GPa]	0.689	-

Poisson ratio	0.33	-
Elongation at break	0.11	-
Ultimate Tensile Stress [MPa]	490	-

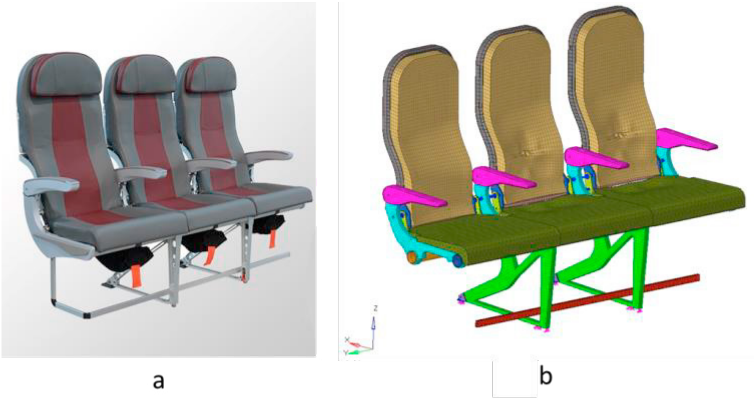


Fig. 5. (a) seats used in the experiment; (b) modelled seats.

As aforementioned, accelerometers sensors have been used in order to monitor the dynamic structural response of the test article during the test. Each accelerometer was experimentally installed on an aluminium block (Fig. 6.a), in order to simplify the installation procedure and to assure a correct installation. The aluminium blocks were installed on the test article through mechanical joints as well as the accelerometer on the block. Numerically, only 4 piezoresistive accelerometers have been modelled as shown in Fig. 6.b.

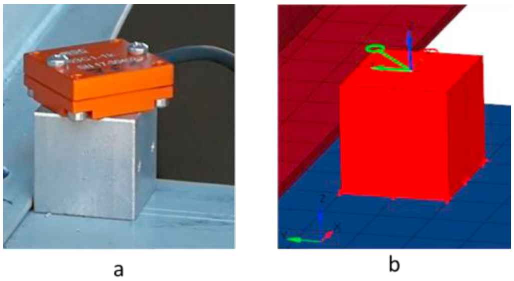


Fig. 6. (a) accelerometer used in the experiment; (b) FE model of the accelerometer.

3.2. Assembly

In this section, the assembly of the complete numerical model is described. The full FE model has been prepared by assembling the fuselage section structure, seats, dummies, seat belt and accelerometers. The initial conditions of the finite element model, including the impact velocity and positions, have been set up in order to reproduce the experimental drop test conditions.

The seats have been positioned and fixed inside the fuselage trunk replicating the actual configuration. Then, it has been defined the contact algorithm that simulates the junction between the seat rails and the floor transverse beams as a spotweld one.

As aforementioned, two ATDs were installed in the experimental test case in order to evaluate the survival conditions during the impact event. However, it is imperative that, during an emergency landing, all occupants wear safety belts to ensure that they are not violently projected towards fuselage parts or other passengers, with fatal consequences. So, the ATDs were restrained in the seats by a torso belt oriented almost horizontally: in this way, a minimum vertical movement of the passengers can be guaranteed. AC25.562-1B requirements have been considered (FAA (2006)) for the correct positioning of the experimental and numerical ATDs. In the FE model, once the dummies were placed, the seat belts have been implemented too (Fig. 7.a).

In the experiment, the position of the passengers-seats system was chosen in order to reduce the unbalance of the whole fuselage section with respect to the pitch axis. So, the additional balancing mass has been modelled by means of an aluminum block (186 kg) positioned as in the test case and constrained to the floor by the spotweld contact algorithm (Fig. 7.b).

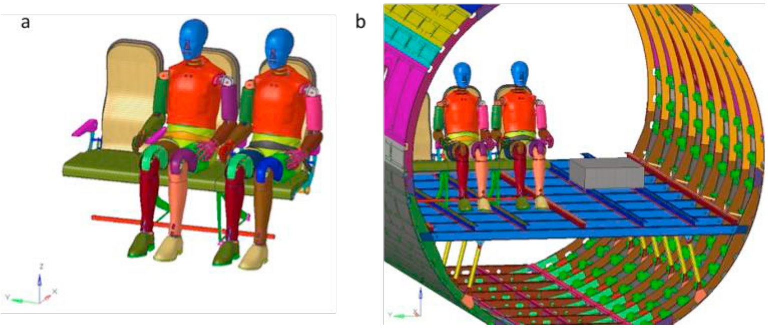


Fig. 7. (a) positioning of ATDs and seat belts; (b) positioning of balancing mass.

Fig. 8 shows the 4 accelerometers mapped numerically as to reproduce those installed on the test article. In particular, the accelerometers have been installed on the intersection between the transversal and longitudinal beams of the cargo and passengers floors at the fuselage central section (frame 4).

Actually, the test article impacted the ground in a non-symmetric mode showing pitch and roll angles equals to 2.28° and 0.89°, respectively. Therefore, the entire FE model has been adjusted in order to replicate the configuration of the fuselage trunk at the moment of the impact. In addition, it has been decided to model the ground as a constrained rigid surface.

A velocity of 9.14 m/s, matching the experimental measured fuselage velocity an instant before the ground impact, has been assigned to all nodes of the model, and the gravity acceleration has been applied to the whole structure too.

A master-surface to slave-node contact algorithm has been defined between the impact surface (the rigid wall) and the lower part of the fuselage section.

The overall finite element model, consisting of 2025786 nodes and 2410651 elements, is reported in Fig. 9. It has a total weight of 929.53 kg, which is slightly heavier than the test article one (927 kg).

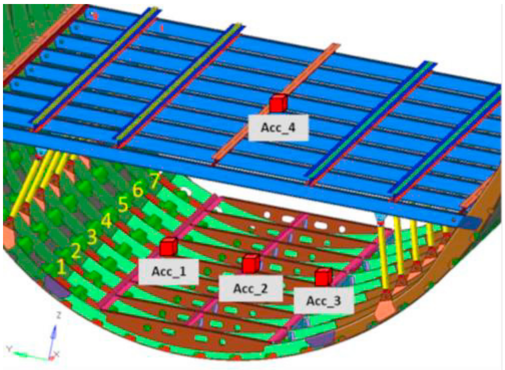


Fig. 8. Map of accelerometers on the cargo and passengers floors.

For each element, according to its characteristic size, density and stiffness, it is possible to calculate the time-step. For a stable simulation the time-step must be less than or equal to the critical time-step, which is provided by the smallest element of the whole mesh of the model. The solver allows freely choosing the value of the time-step, but this involves a recalculation of the material density and, so, of the mass. In general, the adoption of a time-step higher than the minimum one involves an increase in the mass of the model. In the carried-out simulation, the time-step value has been set in such a way to limit the increase of the added mass up to 3%.

The total simulation duration is 150 ms. About 50 hours are necessary to perform the numerical simulation by means of a HPZ820 workstation (16 CPU).

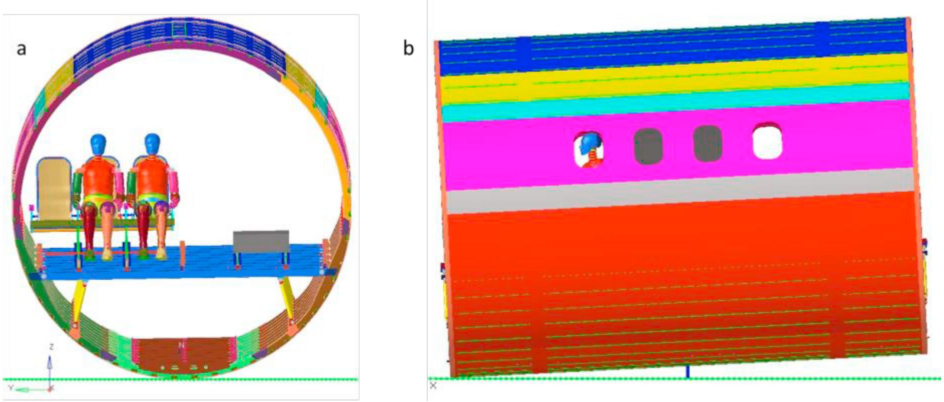


Fig. 9. Impact configuration: (a) frontal and (b) lateral views.

4. Results and discussion

In this section, an analysis aimed to investigate damages and failures that affected the structure is carried out by comparing the experimental and numerical results. In addition, also a kinematic analysis, focused on the signals acquired by the accelerometers is discussed. The recorded accelerations have been post-processed according to the SAE J211 standard.

4.1. Damages and failures investigation

In order to provide representative data of the state of the damages involving the structure after the drop test, the residual deformations involving the frontal section have been assessed. The undeformed fuselage section is perfectly circular with a diameter equal to 3445 mm. Fig. 10 shows the variation of the horizontal and vertical diameter: 305 mm along the vertical direction and an increase of 25 mm along the horizontal direction were recorded experimentally. Numerically, these variations have been well predicted, with a deviation of 88 mm and 50 mm along the horizontal and vertical directions, respectively.

As predictable, the most amount of the kinetic energy is absorbed through both failures and strains involving the cargo floor area, while frames, stringers and skins within the passengers' area do not present large failures/deformations. It is clear that, due to the non-symmetrical fall, which induces the front section to touch the ground before than the rear one, the front section reports more damages than the rear one. As a result, the forward section of the lower lobe absorbs a higher amount of impact energy. After the first impact, the structure settles down to the ground in a less abrupt way.

Moreover, also the manikins' positions after the test have been numerically well reproduced, as shown in Fig. 11.

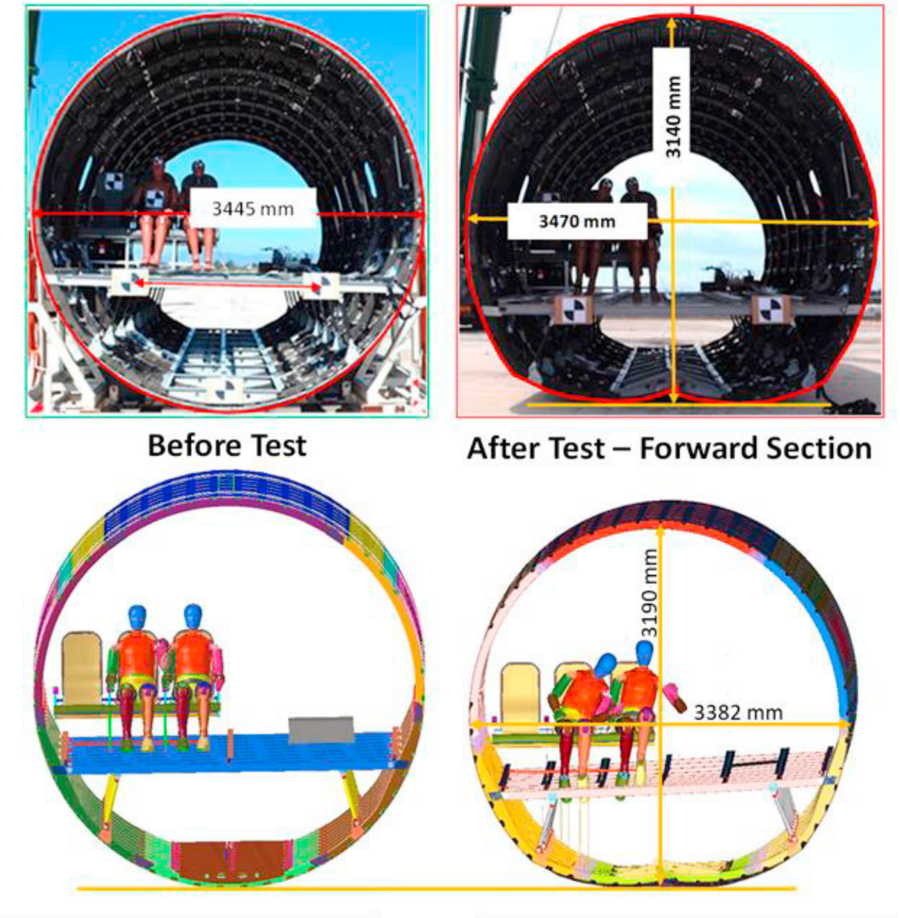


Fig. 10. Configurations before and after the test: experimental vs numerical.

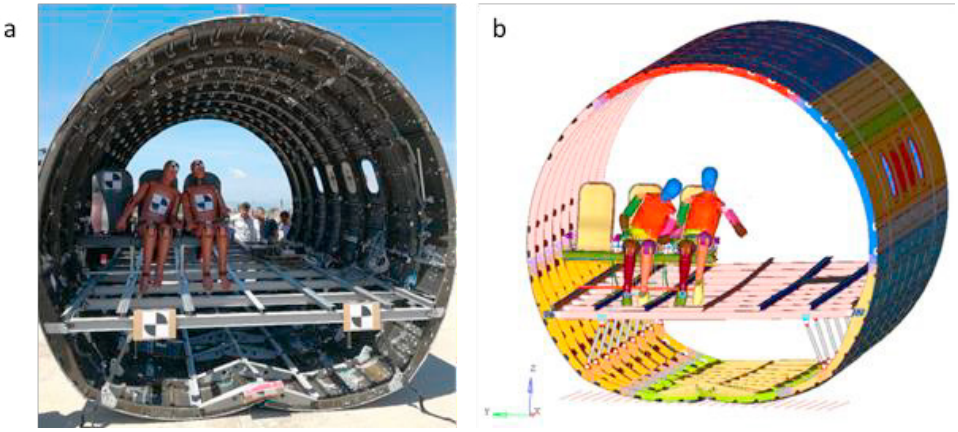


Fig. 11. Manikins' positions in experimental test (a) and numerical simulation (b).

4.2. Kinematic analysis

As reported, the accelerations field of the barrel has been monitored through 4 accelerometers, placed on the floor of the passenger section and on the floor of the cargo area, at the central section of the fuselage trunk. All experimental and numerical acceleration signals have been filtered with a CFC60 filter and, then, compared to each other (Fig. 12). The highest acceleration peak has been recorded from accelerometer 2 placed in the cargo zone. This result is justified by the fact that the accelerometers placed in this zone are the closest to the contact zone, and, consequently, they do not benefit from the dissipation of energy provided by the structure. Only one frame and a thin skin, in fact, are interposed between the accelerometers and the rigid ground.

The trend of the numerical signals seems to reproduce the experimental one; also, the acceleration peaks can be considered in good agreement, taking the complexity of the simulation into account.

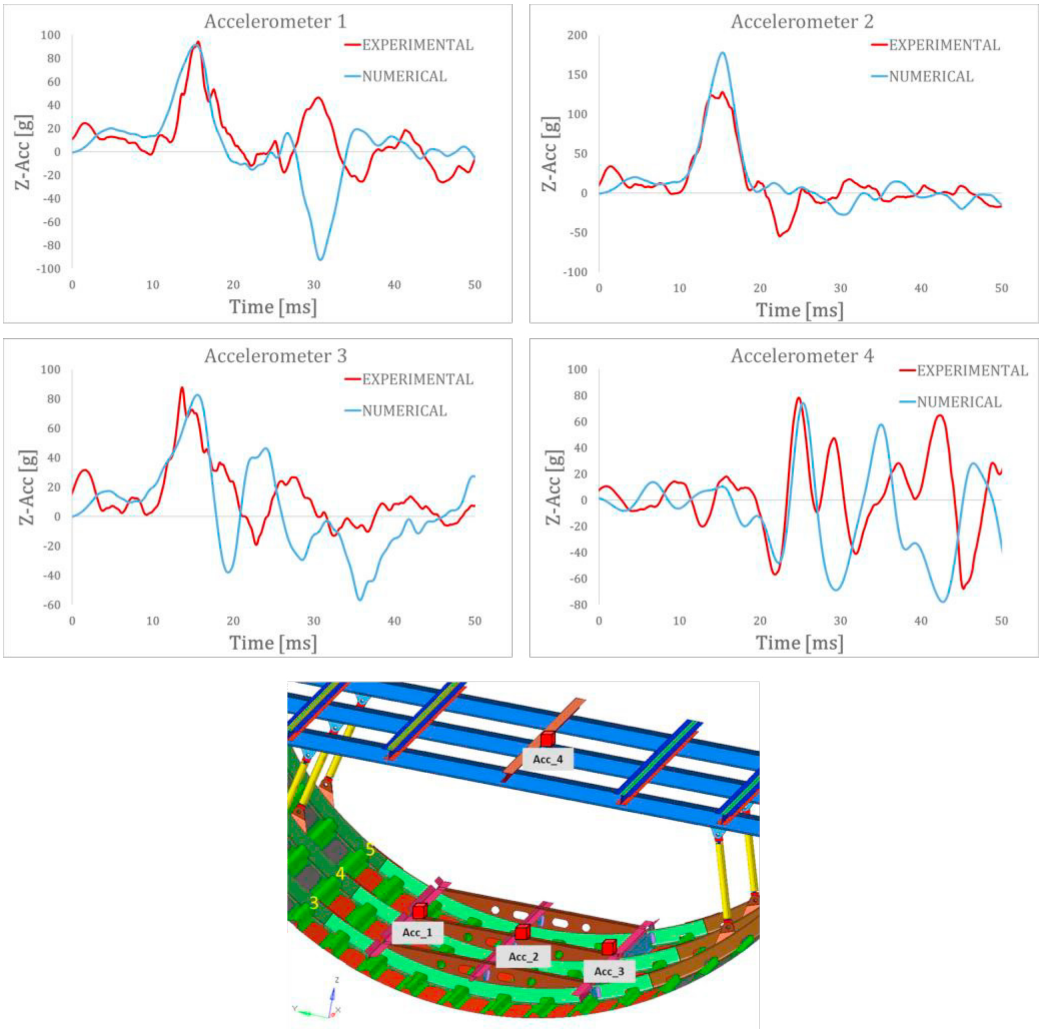


Fig. 12. Accelerometers data: experimental vs numerical results comparison.

5. Conclusions

The article reports the numerical results of a drop test of a full-scale fuselage section of a regional aircraft made entirely in composite material. The aim of this work is the development of a finite element model and its validation by comparing the results with those of the experimental test. In detail, only four accelerometers have been numerically reproduced and the results can be considered in good agreement with the experimental ones, according to the simulation complexity.

In addition, in order to save computational costs, several simplifications have been made, such as the bolted and glued connections, which have not been modeled in detail. This, together with the materials failure criteria modelling, explains the slight disagreement among the compared experimental-numerical results. As a consequence, this model must be considered as a preliminary stage for a more detailed one. Therefore, one of the possible future developments is to simulate the material behavior through more accurate and complex material models, paying particular attention to the cargo area, considering that the roll and pitch angles have a strong impact on the numerical results.

References

Califano, A., 2018. Modelling the fatigue behavior of composites under spectrum loading. AIP Conference Proceedings 1981, 020144 (2018).

Caputo, F., De Luca, A, Greco, A., Maietta, S., Marro, A., Apicella, A., 2018. Investigation on the static and dynamic structural behaviours of a regional aircraft main landing gear by a new numerical methodology. Frattura ed Integrità Strutturale Volume 12, Issue 43, 191-204.

di Napoli, F., De Luca, A., Caputo, F., Marulo, F., Guida, M., Vitolo, B., 2018. Mixed FE-MB methodology for the evaluation of passive safety performances of aeronautical seats. International Journal of Crashworthiness (TCRS).

Ekman, S.K., Debacker, M., 2018. Survivability of occupants in commercial passenger aircraft accidents. Safety Science 104, 91-98.

Federal Aviation Regulation FAR 25.562, 2006. Emergency landing dynamic conditions. Federal Aviation Administration FAA.

Guida, M., Manzoni, A., Zuppardi, A., Caputo, F., Marulo, F., De Luca, A., 2018. Development of a multibody system for crashworthiness certification of aircraft seat, Multibody System Dynamics, Volume 44, Issue 2, 191-221.

Guida, M., Marulo, F., Abrate, S., 2018. Advances in crash dynamics for aircraft safety, Progress in Aerospace Sciences 98, 106-123.

Jackson, K. E., Fasanella, E. L., 2018. 8.15 Design, Testing, and Simulation of Crashworthy Composite Airframe Structures at NASA Langley Research Center, Comprehensive Composite Materials II, Volume 8, 2018, 286-307.

Lawrence, C., Fasanella, E.L., Tabiei, A., Brinkley, J.W., Shemwell, D.M., 2008. The Use of a Vehicle Acceleration Exposure Limit Model and a Finite Element Crash Test Dummy Model to Evaluate the Risk of Injuries during Orion Crew Module Landings. NASA/TM – 215198.

Mertz, H.J., Prasad, P., Nusholtz, G., 1996. Head Injury Risk Assessment for Forehead Impacts. SAE International Congress and Exposition, SAE Paper No. 960099.

Mou, H., Zou, T., Zhenyu, F., Ren, J., 2014. Crashworthiness simulation research of fuselage section with composite skin, Procedia Engineering 80, 59-65.

Obergefell, L.A., Gardner, T.R., Kaleps, I., Fleck, J.T., 1988. Articulated total body model Enhancements, Volume 2: User's Guide.

Olivares, G., 2011. Crashworthiness of Composites – Certification by Analysis. JAMS Workshop Technical Review.

Riccio, A., Damiano, M., Raimondo, A., Di Felice, G., Sellitto, A., 2017. A fast numerical procedure for the simulation of inter-laminar damage growth in stiffened composite panels. Composite Structures 145, 203-216.

Riccio, A., Di Costanzo, C., Di Gennaro, P., Sellitto, A., Raimondo, A., 2017. Intra-laminar progressive failure analysis of composite laminates with a large notch damage. Engineering Failure Analysis 73, 97-112.

Riccio, A., Sellitto, A., Saputo, S., Russo, A., Zarrelli, M., Lopresto, V., 2017. Modelling the damage evolution in notched omega stiffened composite panels under compression. Composites Part B: Engineering, 126, 60-71.

Ruan, J.S., Zhou, C., Khalil, T.B., King, A.I., 2001. Techniques and Applications of Finite Element Analysis of the Biomechanical Response of the Human Head to Impact. CRC Press LLC.

Waimer, M., Kohlgrüber, D., Hachenberg, D., Voggenreiter, H., 2013. Experimental study of CFRP components subjected to dynamic crash loads, Composite Structures 105, 288-299.

Waimer, M., Kohlgrüber, D., Keck, R., Voggenreiter, H., 2013. Contribution to an improved crash design for a composite transport aircraft fuselage – development of a kinematics model and an experimental component test setup. CEAS Aeronautical Journal 4, 265-275.

Wismans, J.S.H.M., 1994. Injury biomechanics. Eindhoven University of Technology, Division of Fundamentals (WFW).

Xiaochuan, L., Jun, G., Chunyu, B., Xiasheng, S., Rangke, M., 2015. Drop test and crash simulation of a civil airplane fuselage section. Chinese Journal of Aeronautics, 28(2), 447-456.