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Procedia Structural Integrity 24 (2019) 788–799

Structural Integrity Procedia

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AIAS 2019 International Conference on Stress Analysis

Numerical Drop Test of a Full Composite Fuselage Section Having Two Components of Velocity

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Abstract

In the present work two different crash scenarios have been numerically investigated in order to evaluate the structural behaviour of a full-scale composite made fuselage section of a regional aircraft under dynamic load conditions. The developed Finite Element model has been validated with respect to the experimental results obtained during a test campaign performed at Italian Aerospace Research Centre (CIRA). The reference experimental test consisted in a 4.26 m vertical drop with an impact velocity equal to 9.14 m/s. Starting from the FE model validated respect to the pure vertical drop test condition, in this work, a new impact scenario onto a rigid surface has been simulated applying both horizontal and vertical velocity components, resulting in an overall impact speed of 22 m/s. The FE explicit solver LS-DYNA® has been used to perform the simulation. The results, in terms of global deformations, failures and local accelerations, have been compared with the numeric pure vertical drop test ones in order to evaluate how more complex impact conditions could influence the structural behaviour of the fuselage section with a focus of improved crashworthy components in Certification by Analysis (CbA) point of view.

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Keywords: crashworthiness; drop test; combined velocity; FEM; composite fuselage section.

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10.1016/j.prostr.2020.02.070

1. Introduction

The safety, in terms of both structural and occupants one, is fundamental in all types of transport. Particular emphasis, however, must be paid especially in the aeronautical field, in which the risk of accidents in quite low even though the magnitude of danger could be very high. In the last decades, many studies have been performed in order to improve the crashworthy of aircraft structures and the survival probability to accidents, leading to renewed and extended safety regulations such as the Federal Aviation Regulation (FAR) by the Federal Aviation Administration (FAA) and the Certification Specification (CS) (CS-25, 2014) by the European Union Aviation Safety Agency (EASA).

Following the building block approach (Guida et al. 2018), the experimental tests start from the material characterization at coupon level and finish with the full-scale drop test (Caputo et al. (2011), Caputo et al. (2014), De Luca et al. (2016) and Riccio et al. (2016)). The drop test consists in a free fall from a prescribed height of the entire aircraft or subcomponents (such as fuselage or its section) on more or less rigid surfaces to assess the structural response to impact. It is clear that such kind of test is very expensive and time-consuming and, also, it demands for considerable technical, organisational and economic efforts.

Since the '60s, military drop tests have been conducted by the U.S. Army to certify the passive safety of helicopters according to Military Standard rules (MIL-STD, 1998) which establish combined velocity conditions. In 1999, according to Jackson et al. (2006), at NASA Langley's Impact Dynamics Research Facility (IDRF) a drop test of a prototype helicopter having 11.58/9.60 m/s (vertical/longitudinal) combined velocity loading conditions was conducted. Moreover, the authors performed helicopters falling simulations for the purpose of Certification by Analysis (CbA) and discussion of new regulatory requirements. Two main conditions of the landing gear were analysed: extended and retracted, and the effect of different loading condition, such as impact directions, speed values and impact surface types were set up. In particular, initial velocities of 12.80 m/s and 8.23 m/s, along the longitudinal and vertical directions with respect to the ground, have been adopted to investigate a high drop down angle scenario and 4.27 m/s and 30.48 m/s, along the longitudinal and vertical directions with respect to the ground, to investigate a low drop-down angle scenario. The authors stated that a long work for a CbA must be still carried out and they made proposals for more innovative analytical models to be used in the future.

Caputo et al. (2018 - Frattura ed Integrità Strutturale, Advances in Material Science and Engineering) developed an established FE model to simulate the static and the dynamic behaviour of a landing gear of a regional aircraft. In 2012, NASA began the Transport Rotorcraft Airframe Crash Testbed (TRACT) performing drop test crashes of two helicopter airframes. In Annett et al. (2014) the first crash test, named TRACT1, was performed with 7.62/10.06 m/s combined velocities with the aim to assess the crashworthiness capabilities of structures and to develop novel data acquisition techniques, which obtained crash data to perform a comparison with the second test. TRACT2 was executed in Annett (2015) with approximately the same velocity conditions and the same impact position but with a different impact surface and different sub-floor energy absorbers to evaluate their crashworthiness performances. Subsequently, numerical simulations have been executed by Littell et al. (2016).

About aircrafts, at Landing and Impact Research (LandIR) Facility, belonging to NASA Langley Research Center (LaRC), Jackson et al. (2017) discussed about many full-scale drop tests, pure vertical and not, arranged over the decades and, also, they affirmed that it is the unique facility able to impart combined horizontal and vertical velocities onto test articles. In 2015, a Cessna 172 airplane was impacted onto the soil trough 7.01/18.35 m/s combined velocities and a pitch angle of 1.48° (nose high). After that, a second test with a similar airplane model was dropped crashing with 8.75 m/s vertical velocity, 20.91 m/s longitudinal velocity and a pitch angle of 12.2° (nose down). Lastly, a third experiment adopted a similar test article which resulted having at the impact instant a vertical/horizontal velocity equal to 7.19/17.34 m/s and a pitch angle of 8.0° (nose up). Results, discussed in Littell and Annett (2016), were focused on the investigation of a possible survivability of occupants. Finite Element (FE) models, representative of the three test articles, were developed and analysed in Annett et al. (2016) and Jackson et al. (2017). During the 2017, a full-scale drop test onto a sloping soil of a Fokker F28 wingbox fuselage section was conducted. The difference between the test article attitude and the impact surface angle was used to simulate a horizontal component of velocity. At the impact instant, the measured horizontal velocity was 0.34 m/s, while the vertical impact velocity was 8.87 m/s, as reported in Littell (2018). During the summer of 2012, accompanied with a significant media impression, at the Sonoran Desert in Mexico, an entire full-scale unmanned Boeing 727-212 was staged to crash, including dummies and instrumentation for acquisition data. At the impact point, the aircraft had a 2° nose down, a vertical velocity equal to 10 m/s and a horizontal velocity of 68 m/s, as mentioned in Song et al (2018). Scientists showed that cheap seats could be safer than first-class ones. In June 2019, at LandIR, NASA dropped a whole Fokker F-28 transport aircraft equipped with dummies and cameras in order to obtain passenger response data and to study injuries of occupants. Essential information can be found in Maede (2019) but technical documentation is waiting to be released.

The present work aims to investigate the structural response of a composite fuselage section under two different impact conditions, from a numerical point of view. The adopted numerical model was validated against experimental results in previous works (Perfetto et al. (2018) and Perfetto et al. (2019)) and in this context the main aspect was reported for sake of clarity. In particular, the validated numerical model regards a drop test, and starting from this model a new boundary condition, such as a longitudinal component of velocity, has been applied to investigate the mechanical behaviour in an alternative impact condition.

Nomenclature

FAR	Federal Aviation Regulations
FAA	Federal Aviation Administration
CS	Certification Specifications
CbA	Certification by Analysis
FE	Finite Element
CFRP	Carbon Fibre Reinforced Polymers
ATD	Anthropomorphic Test Dummy
Acc	Accelerometer

2. CIRA experimental test

As part of the research project "Virtual Certification Methods Applied to Innovative Solutions" (CERVIA) funded by the Italian Ministry of Research, in 2017 a pure vertical drop test of a regional aircraft full-scale composite made fuselage section from a height of 4.26 m was performed at Impact Tests Laboratory of Aerospace Structures (LISA) of the Italian Aerospace Research Centre (CIRA). The purpose of the experiment was to acquire the physical data of interest (local accelerations and deformations) during the impact of the fuselage section in order to develop and validate numerical models able to simulate the dynamic phenomena with a high level of accuracy and to define crash design methods.

The main characteristics of the test article were: radius 1725 mm (Fig. 1a), length of 4726 mm (Fig. 1b) and a mass of about 550 kg (fuselage barrel structure only).

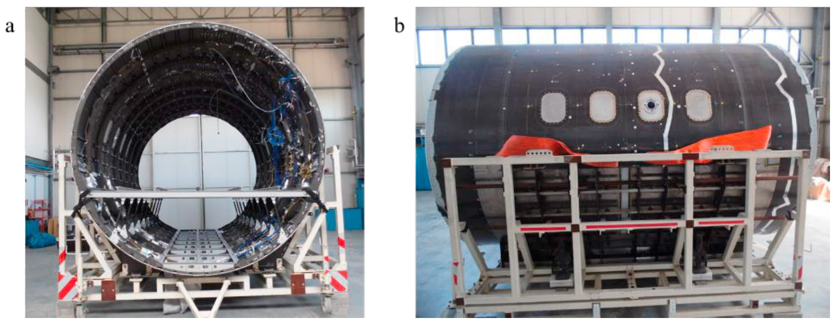

Fig. 1. Fuselage barrel: (a) front view; (b) lateral view.

The entire barrel was made in carbon fibre reinforced polymer (CFRP) material. In particular, the skin, stringers and frames were made in thermosetting material (Fig. 2a), while the passengers and the cargo floor beams were made in thermoplastic material (Fig. 2b).

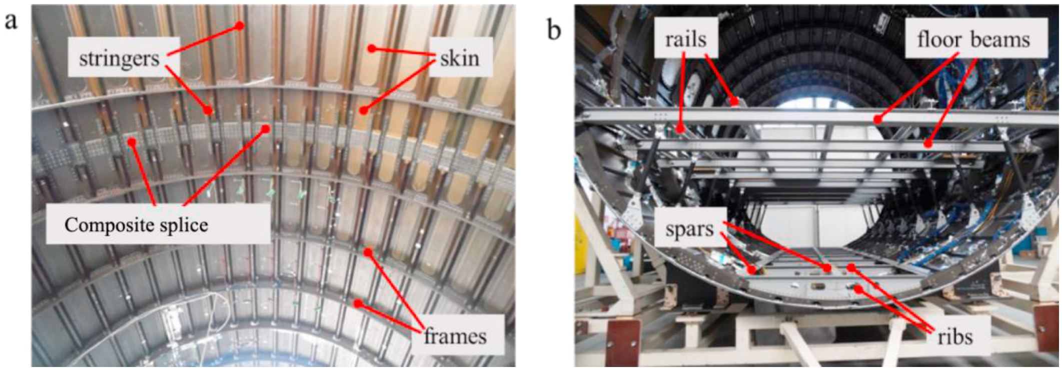

Fig. 2. (a) barrel description; (b) floor beams and cargo sub-floor parts.

The test article is composed of a central section and two smaller extremal sections, connected each other by means of dedicated composite splices (Fig. 2a). In addition, the sub-floor zone is connected to the main structure by means of composite struts and aluminium alloy lags (Fig. 3a). On the right side (referencing to global longitudinal axes) of the passenger area, a three seats row was installed on rails with two belted Anthropomorphic Test Dummies (ATDs), a Hybrid II and a Hybrid III, both 50th percentile male (Fig. 3b).

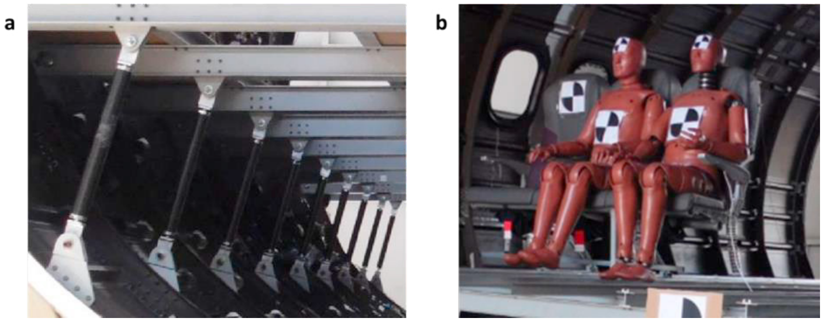

Fig. 3. (a) connecting struts; (b) seats with dummies.

Seats' rails and structure were also made of aluminium alloys. To balance this load, on the left side, a balancing mass was added. Finally, an acquisition data system and sensors (accelerometers and strain gauges) were set up to collect the impact information. The final total mass was roughly 927 kg.

The test was carried out by raising the fuselage section up to 4.26 m, in order to achieve the desired vertical impact speed of 9.14 m/s. The test article impacted the hard soil with a pitch angle of 2.883° (nose down) and a roll angle of +0.891°, despite the initial position was checked to be null.

3. FE model description

A detailed FE model (Fig. 4a) was developed in Ls-Dyna® environment by Perfetto et al. (2018) and Perfetto et al. (2019). The test article was modelled to make it as faithful as possible to the real component, using Tria3 and Quad4 shell elements. Passengers' level is composed of seats, floor beams, rails and balancing mass (Fig. 4b). The skin, stringers, frames and reinforcement strips make up the barrel (Fig. 4c). Five accelerometers were modelled through 3D rigid elements (Fig. 4d) and arranged as shown in Fig. 5. The cargo zone consists in ribs, spars and frames (Fig.

4e). Finally, the titanium bolts of main floor and stanchions' supports were modelled with 3D solid elements Tetra4 (Fig. 4f).

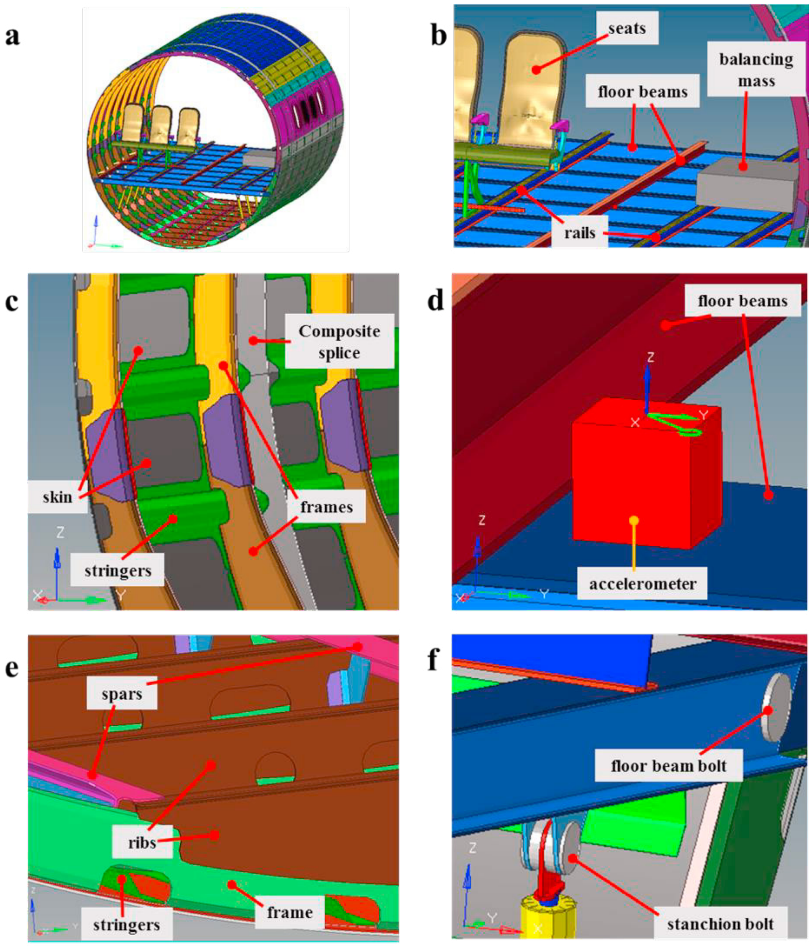

Fig. 4. FE model details: (a) global view; (b) passengers' floor; (c) barrell external structure; (d) accelerometer; (e) cargo sub-floor; (f) bolts.

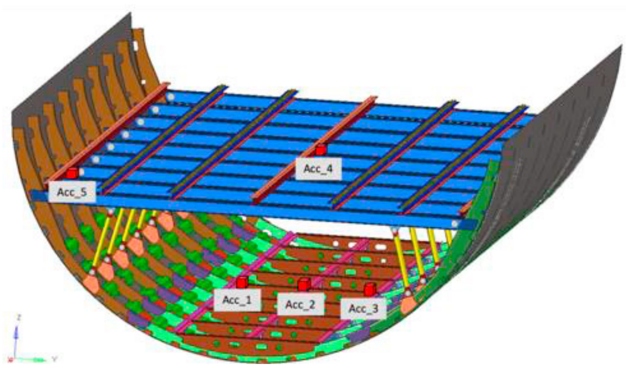

Fig. 5. Arrangement of accelerometers.

The remaining bolted/rivetted parts of the structure were modelled as spot-weld contacts (which allows the continuity between the parts by projecting the nodes of the slave surface on the master one) or as rigid constraints to connect the seats and the balancing mass on the rails and to link floor beams with stringers and skin. The stanchions, described in more detail in Perfetto et al. (2019), are shown in Fig. 6. Respect to the previous work of Perfetto et. al (2018), the only difference was the substitution of the mannequins with rigid masses on seats (Fig. 7) in order to save computational time. In the end, the total mass was 930 kg, very close to actual one, and the FE model consisted of 2031764 nodes and 2426312 elements.

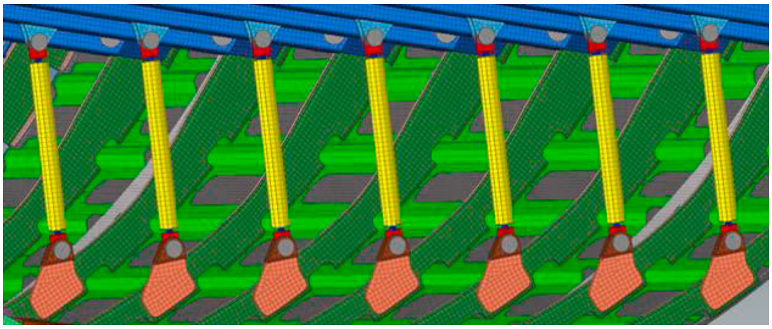

Fig. 6. Stanchions arranged between frames and beams.

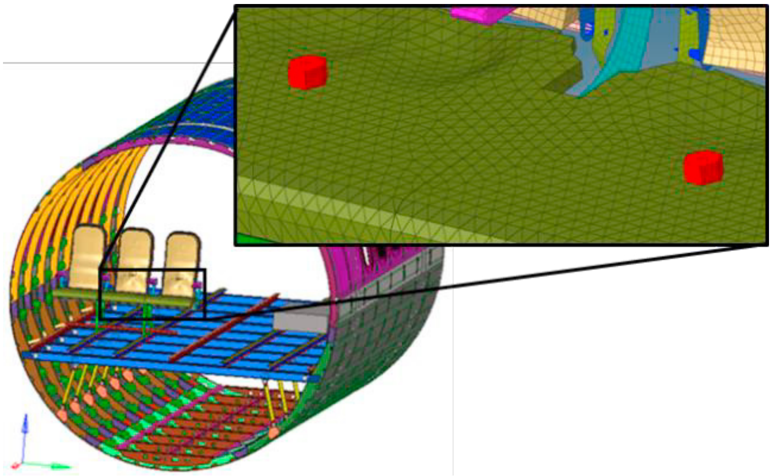

Fig. 7. Concentrated rigid masses substituting dummies on seats.

To model properly the structural behaviour of composite materials, the MAT54 material model was adopted. It provides the possibility to simulate orthotropic materials, like composites indeed, with Chang-Chang failure criteria, used in the proposed FE model, which distinguish matrix and fibre failure in both tensile and compressive cases, as described in the Ls-Dyna® material library (Ls-Dyna® R7.1, Keyword User's Manual).

Main material parameters adopted for composites can be found in Perfetto et al. (2018).

Aluminium alloys were implemented by means of MAT24 material model, able to define an elastic-plastic formulation, that considers the strain rate effects by using the Cowper Symonds law (Perfetto et al. (2018)), while the rigid masses used to replicate the dummies and the accelerometers, have been modelled thanks the MAT20 material card. The FE model plotted by components is shown in Fig. 8.

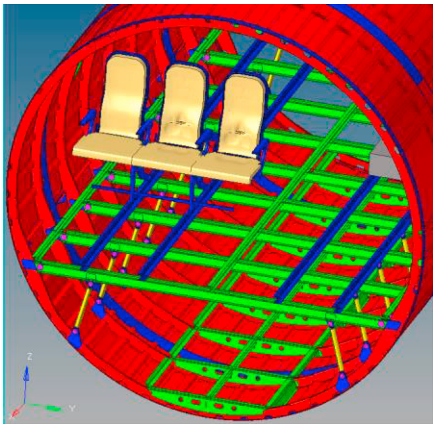

Fig. 8. FE model plot by components: skin and main structure (red); cargo and passengers' floor structure (green); rails, composite slices and lags (blue); stanchions (yellow); bolts (purple).

Model's position at the impact moment was set up (Fig. 9) as descripted in the previous Section as well as the gravity acceleration and the vertical impact velocity (Z-axis direction), whereas the impact concrete surface was modelled as a rigid wall. Moreover, a friction coefficient of 0.3 and opportune contact algorithms have been set. The friction coefficient has been estimated by authors according to the literature and it is representative of the interaction between composite fuselage skin and ground. A good numerical-experimental correlation in terms of both breakages and acceleration values was reached. For the sake of brevity only the final damage state occurred in the cargo zone is reported in Fig. 10. However, deeper descriptions regarding the numerical model can be found in Perfetto et al. (2018) and Perfetto et al. (2019).

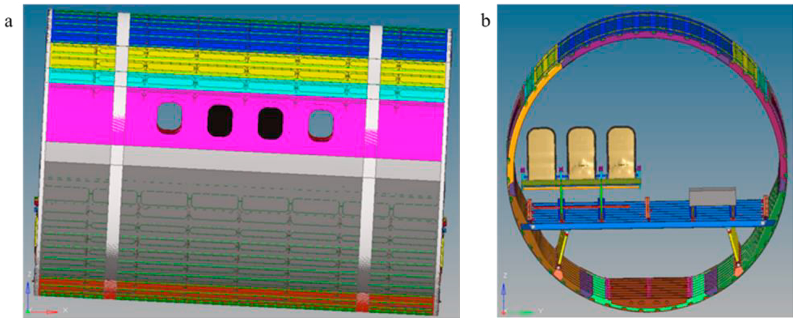

Fig. 9. Position of the model: (a) pitch inclination; (b) roll inclination.

Fig. 10. (a) experimental vs. (b) numerical damages.

4. Combined impact load condition

Starting from the descripted FE model, validated for a particular load condition (vertical drop test), a new simulation has been performed in order to further verify the reliability of the numerical model under different impact conditions and to evaluate the energy absorption capabilities of the whole composite structure under a new accident scenario. The new boundary condition consists in a new impact velocity with both vertical and horizontal components. Riccio et al. (2019), using a similar FE model, performed the numerical drop test with two different position conditions: pitch angle of 0° and 3°, both nose down.

To assess the FE model versatility respect to different load conditions and taking into account the state-of-art described in Section 1, a longitudinal velocity equal to 20 m/s has been applied, while the vertical velocity has been fixed to 9.14 m/s, obtaining a global velocity equal to 22 m/s. In this new simulation, the barrel initial position has been set to 0° in pitch and roll angles. Moreover, the gravity acceleration and the friction between the test article and the ground have been applied too.

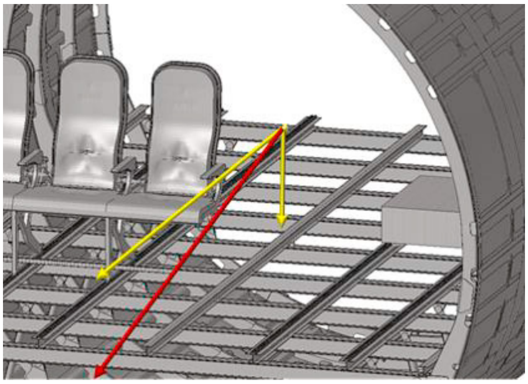

Fig. 11. Components of velocity (yellow) and their resultant (red).

4.1 Numerical Results

In this section the numerical results, regarding the new impact load condition, are presented. The total simulation time has been set to 300 milliseconds, which is big enough to capture the entire phenomena but on the other hand it allows to have a reduced computational cost. Fig. 12 reports some steps of the analysis in order to highlight the structural behaviour of the test article during the crash event. In particular, 4 step frames are reported: a) beginning of the analysis; b) first impact instant; c) tilt of the fuselage; d) rebound. The phenomenon can be resumed as follows: the combination of the impact energy and the direction of the velocity causes the deformation of the bottom part first (Fig. 12b); then, the fuselage section slides forward on the rigid surface and, after a certain horizontal motion, it tilts until a certain angle due to the horizontal velocity component (Fig. 12c); lastly, the elastic return begins, due to the intrinsic characteristics of the structure, and the consequent rebound occurs (Fig. 12d).

Fig. 13 reports a comparison between pure vertical and combine impact conditions, in terms of global deformations. From the comparison it is clear that ribs, spars and frames are more affected by deformations and breaks than the pure vertical case. The horizontal velocity produces a sliding and thus the reaction forces push on the barrel both in the vertical and in the horizontal directions. All that lead to dissipate energy in a different way, involving more components. Indeed, unexpected results have been pointed out in upper floor. In fact, the previous simulations, performed in Perfetto et al. (2018) and Perfetto et al. (2019), did not cause relevant damages to the main floor, in contrast with the current one, which shows widespread deformations on seat rails, floor beams and seats structure (Fig. 13). These results suggest that the main floor has the capability to dissipate a greater amount of energy by means of elastic and permanent deformations before to incur in total failure, with respect to the pure vertical drop.

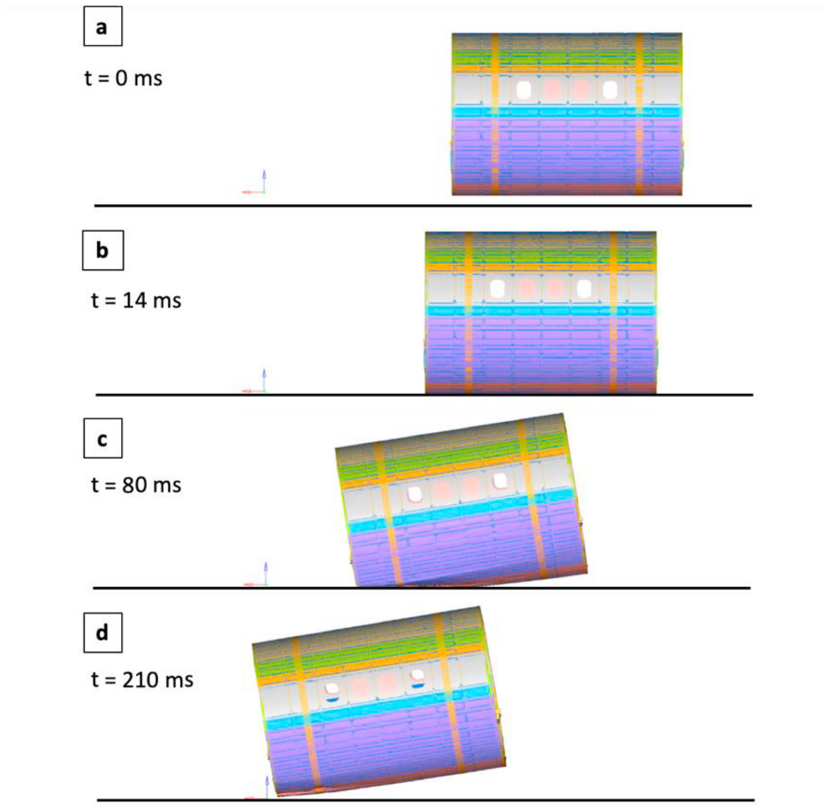

Fig. 12. Sequences of the simulation: (a) beginning of the analysis; (b) touchdown; (c) sliding and inclination; (d) rebound.

In addition, almost all stanchions fail (Fig. 14), pointing out that they are very critical components. Nevertheless, the connection between the passenger's floor beam and the main structure is still available due to the metallic lags.

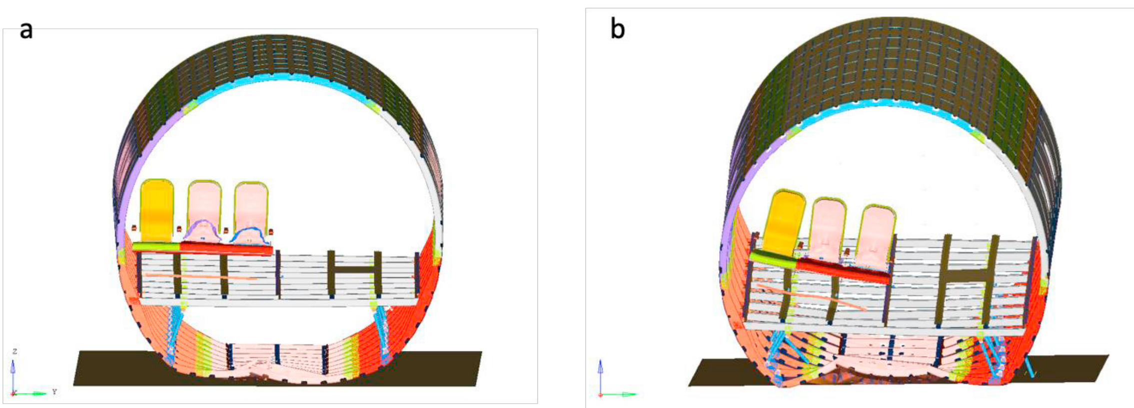

Fig. 13. Global deformation in (a) pure vertical impact condition and (b) combined impact condition.

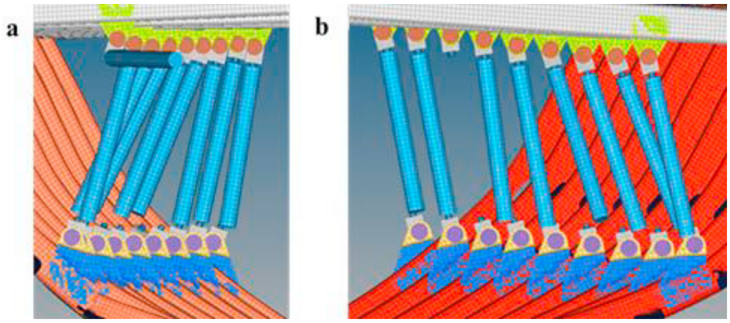

Fig. 14. Stanchions damages: (a) left side; (b) right side.

Indeed, examining and comparing vertical accelerations (global Z-axis direction) given by the accelerometers, these evidences are confirmed consulting Fig. 15, in which, for the sake of clarity, only the first 50 millisecond acceleration vs. time curves are reported. First peaks of accelerations (normalised respect to gravity acceleration), recorded by the accelerometers placed both in cargo zone and passengers' floor, are quite higher than a pure vertical drop test as aforementioned in the Section 3. That indicates how these conditions of crash would be unlikely survivable for eventual occupants.

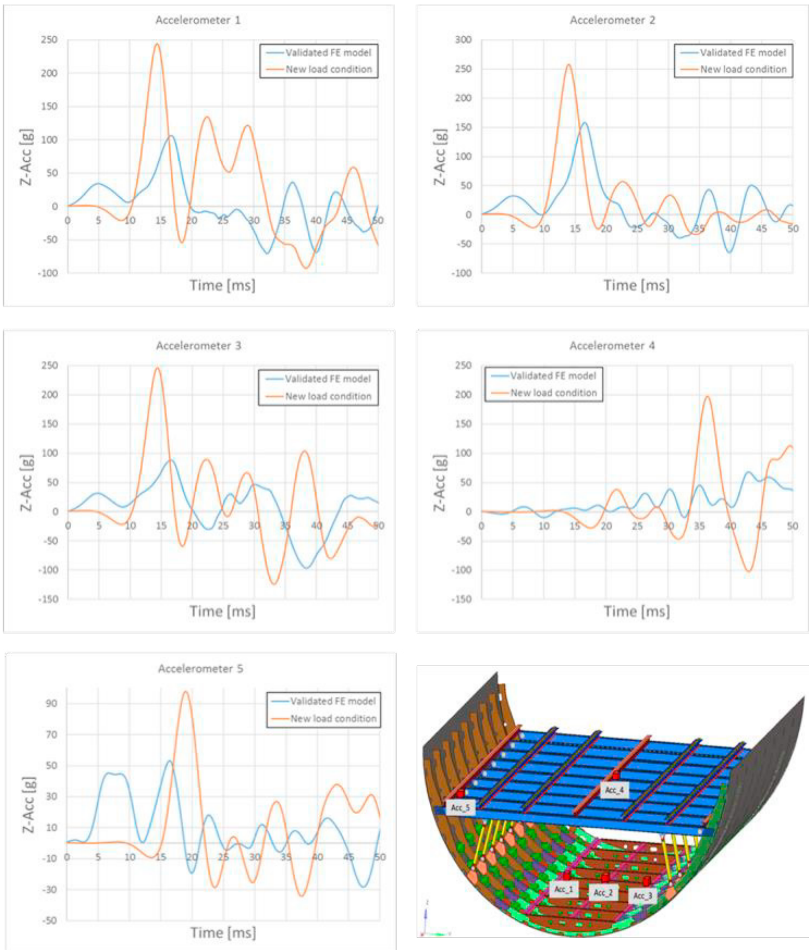

Fig. 15. Comparison of vertical accelerations between pure vertical and combined impact conditions.

5. Final considerations

In this work, the reliability of a developed FE model, previously validated respect to a pure vertical drop test case, has been assessed under a combined impact load condition. The results obtained indicate that the presence of horizontal velocity component of 20 m/s, in addition to the pure vertical component of 9.14 m/s, causes accelerations and loads transmitted to the passenger area much higher than a pure vertical velocity case and, therefore, much more dangers for the safety of occupants. In particular, skin, struts and floor beams result markedly damaged and more damages affect the passengers' floor as well. In the end, the finite element model has proved to be appropriate and effective also to simulate more critical impact conditions, providing realistic results, which are consistent respect to the reference data.

Future developments could lead a better characterization of the FE model to perform the falling with oblique trajectory in a more realistic way with respect to experimental tests, i.e. taking into account the remaining part of the fuselage in order to simulate an entire aircraft drop test.

Acknowledgements

The study has been funded in the framework of Italian Minister Research Program PON 2007-2013 through the POR - FESR funds managed by Regione Campania, promoted by DAC (Distretto Aerospaziale della Campania), within the CERVIA (Innovative and Advanced Verification and CERtification methods) project, in partnership with CIRA SCpA and coordinated by Leonardo Aircraft Division. The authors would like to acknowledge all the involved partners.

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