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Procedia Structural Integrity 2 (2016) 2198–2205

Structural Integrity
Procedia

www.elsevier.com/locate/procedia

21st European Conference on Fracture, ECF21, 20-24 June 2016, Catania, Italy

Crash Testing of a CFRP Commercial Aircraft Sub-Cargo Fuselage Section

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Abstract

The paper addresses the testing at the ONERA (Office National d'Etudes et de Recherches Aérospatiales) crash tower of a sub-cargo demonstrator representative of new generation CFRP (carbon fiber reinforced polymer) commercial aircraft. The project was conducted within a technological platform coordinated by AIRBUS Germany, which aimed at designing, simulating and testing an innovative crashworthy sub-cargo structure. Technical activities were shared between AIRBUS Germany for the demonstrator design and manufacturing, DLR (German Aerospace Center) for the numerical analysis and ONERA for the crash test. The demonstrator was based on single aisle aircraft geometry and comprised 2 Integrated Cargo Units (ICU) equipped with Triggered Tube Segments (TTS) dedicated to energy absorption and CFRP stringer-stiffened skin. The crash concept was based on an integrated structural design which applied the "bend-frame-concept" where the cargo cross-beam acts as a bend frame and withstands the dynamic loads introduced by the TTS components. The testing configuration - loading system and instrumentation - was defined on the basis of numerical analysis performed by DLR at the fuselage section level. In that frame, a kinematic model with a 2-frames typical fuselage section and ICUs involving the "bend-frame" concept was numerically simulated, with the main objective to identify the loading conditions that apply at specific sections, notably those surrounding the ICU-frame coupling areas where the test fixtures were to be implemented. As the outcomes of these numerical works showed that bending/compression loading, at a specific ratio, shall be targeted in priority, the accordingly designed loading system thus consisted of articulated rigs maintaining both ends of the demonstrator. The testing was performed at the ONERA-Lille crash tower at a 6,7m/s impact velocity, with a 1050 kg trolley mass. The acquisition system cumulated a total of 48 channels, including force sensors (6), strain gauges (36), displacement laser sensors (5) and an accelerometer (1). Besides, 4 high-speed cameras were implemented to visualize the rupture phenomenon likely to develop during the crash test. Results confirmed the expected crash scenario, with the bending of the cargo cross-beams and the resulting progressive crushing of the TTS components.

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10.1016/j.prostr.2016.06.275

Peer-review under responsibility of the Scientific Committee of ECF21.

Keywords: CFRP; aircraft; crash,;testing

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1. Introduction

In the field of aircraft crashworthiness, experimental validation of innovative fuselage concepts still stands as a key milestone despite the continuing progress of integrated numerical tools that have permitted, through the past few years, to drastically accelerate the entry-into-service of new technological solutions. Such concern is especially effective in the field of composite structures which exhibit - when considering crashworthiness - specific failure modes that are hardly predictable even by the most sophisticated numerical models. When experimental validation at full-scale level is considered, most testings are yet to be conducted - for cost reasons - on fuselage sections, thus possibly making crucial the question of how the loading is introduced to the specimen. In most cases, crash-tests are indeed usually conducted under simply supported/guided conditions, or, at the opposite, under fully clamped conditions; such conditions may be adapted when the loading at the free edges of the sub-structures does not strongly control the behavior of the specimen, as can be illustrated in Delsart et al. (2004). These works indeed describes the testing of an airliner composite fuselage section for which the upper section situated above the passenger floor could be neglected, insofar only the lower part of the fuselage was supposed to deform and absorb energy during the crash. Thus, the structure could be tested in free fall conditions without specific maintaining or guiding system.

On the contrary, the present project concerned a crash concept for which the loading introduction at the free edges of the investigated demonstrator appeared to be essential to enable the appropriate functioning of the energy absorption devices and the development of their actual crash performance. The studied demonstrator, representative of the sub-cargo area of a CFRP commercial aircraft fuselage, was investigated within a technological platform coordinated by AIRBUS Germany. Technical activities were shared between AIRBUS Germany for the demonstrator design and manufacturing, DLR for the numerical analysis and ONERA for the demonstrator crash test. Works described hereafter most directly relate to the crash-test activities which thus targeted at defining a specific experimental protocol permitting to account for the realistic loading conditions actually encountered by the structure in a crash situation. The testing principle - loading system and instrumentation - was thus defined and dimensioned on the basis of numerical analysis performed by DLR at the fuselage section level, with the main objective to identify the loading conditions introduced to the demonstrator when considered in its full structural environment.

Nomenclature

ICU	Integrated Cargo Unit
TTS	Triggered Tube Segments
CFRP	Carbon Fiber-Reinforced Polymer

2. Sub-cargo demonstrator

The sub-cargo demonstrator uses the baseline of a single aisle aircraft geometry and implies an integrated structural crash concept for the sub-cargo area called ICU (Integrated Cargo Unit), which applies the “bend-frame-concept” where the cargo cross-beam acts as a bend frame and withstands the dynamic loads introduced by local TTS (Triggered Tube Segments) crash absorbers. In such concept, the loading generated at the connection with the upper frames and transmitted to the cargo floor beam therefore directly affects the cargo floor beam and its interaction with the TTS components.

The demonstrator comprises 2 ICUs, for an approximate 1900x750mm total dimension, each ICU being equipped with two TTS components, CFRP stringer-stiffened skin and a cargo floor beam. The TTS components consist of CFRP half-tube crash absorbers exhibiting high energy absorption capacities which can be adjusted so that the resulting crushing force of the ICU fulfills specific crash requirements.

Within the project, large test programs were preliminary conducted at DLR to investigate the crushing performances of such TTS components, for different variants involving major dimensioning parameters such as the thickness, lamina type, trigger design and angle of integration into the ICU, as can be seen in detail in Waimer et al. (2013/1). Tests were conducted on the one hand on isolated half-tube specimens and on the other hand on specimens connected to their ICU struts (Fig. 1b) so as to check if and how the specific crushing performance of these TTS specimen could be affected once integrated with the surrounding structure. This permitted to select the appropriate crash absorbers as a compromise between energy absorption capacities and maximum force levels acting on the cargo crossbeam. In the reference crash scenario considered within the project, the TTS components were thus designed so that the sub-cargo area could absorb a significant amount of the energy generated by a crash at a 6,7m/s vertical velocity.

Fig. 1. (a) Sub-Cargo Demonstrator ; (b) TTS specimen mounted on ICU strut.

3. Test setup dimensioning

Pre-test simulations were performed by DLR in order to provide information for the preparation and definition of the test set-up configuration - loading system and instrumentation. This was achieved by simulating a kinematic model (Abaqus code) involving linear-elastic material modeling approach and macro elements for the description of the energy absorbing devices, thus allowing very flexible and effective analysis for various crash conditions, see Waimer et al. (2013/2). The model included a 2-frames typical fuselage section and ICUs based on the “bend-frame” crash concept (Fig. 2a), with the main objective to identify the loading conditions (in terms of bending/compression and shear/compression ratios) that apply at specific sections during the initial phase of the fuselage crash sequence (sub-cargo crushing), notably those surrounding the ICU-frame coupling areas where the test fixtures were to be implemented. In that goal, different load sections were thus generated through the model, from which the force tensor that applied at these locations could be post-treated. As visible in Fig. 2b, this included sections positioned around the ICU-frame coupling area and on both sides of the fuselage, left (CS08/CS10) and right (CS09/CS11), with sections CS08/CS09 located within the ICU coupling area, and sections CS10/CS11 located outside the ICU coupling area.

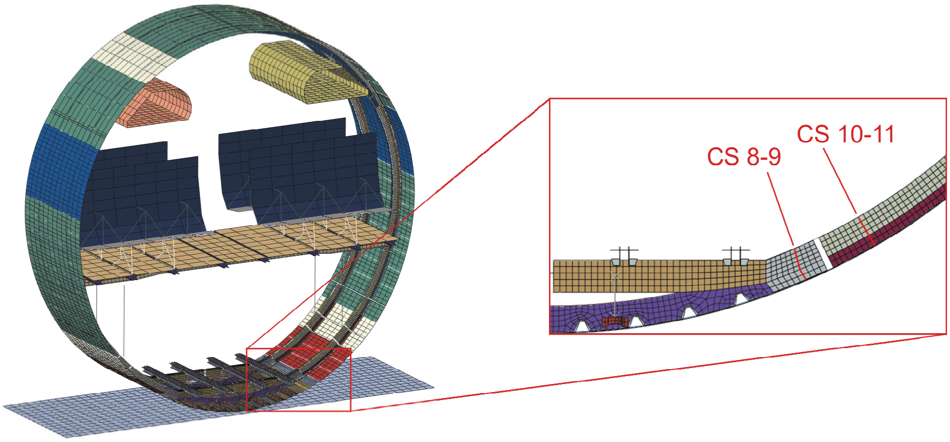

Fig. 2. (a) Kinematic model ; (b) Load sections at the ICU/Frame coupling area.

Results in terms of bending/compression and shear/compression ratios are illustrated in Fig. 3. Within the crash sequence, most emphasis was brought to the crushing phase of the sub-cargo structure which occurs between t=10ms and t=35ms and which is basically characterized by quasi-constant loading ratios.

- Regarding the bending/compression ratio, the average range evolved, in the considered time window, around approximately 60 for sections CS08/09 and 150 for sections CS10/11.
- The shear/compression ratio showed an average range evolving between approximately 0,6 for sections CS08/09 and 0,4 for sections CS10/11.

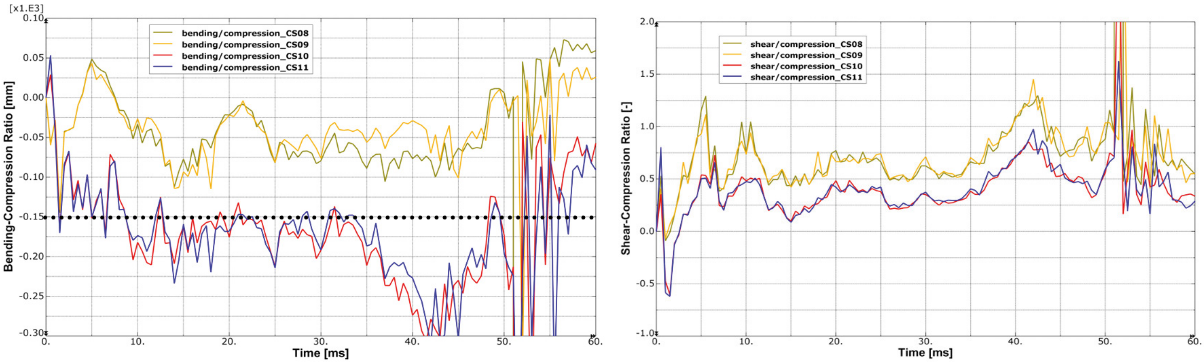

Fig. 3. (a) Bending/compression ratios at the ICU-coupling ; (b) Shear/compression ratios at the ICU-coupling.

In terms of practical application, such bending/compression loading could be generated thanks to articulated rigs with a deported axis with respect to the frame mid-line. Basically, 2 options could be foreseeable, with fixed or moving (in the lateral direction) axis so as to account for the flexibility of the upper fuselage frames.

In a first step, the “fixed axis” option was investigated and a parametric analysis relative to the influence of the vertical and lateral position of the load introduction axis on the bending/compression and shear/compression ratios was conducted. Outcomes of this analysis showed a negligible influence of the lateral rig axis position while a significant influence of the vertical rig axis position (lateral/vertical with respect to a local coordinate system which is orientated parallel to the ICU coupling cross-section). This relation (that depends on the test setup as well as on the demonstrator structure) was caused by a reaction force vector in the test rig axis that was almost perpendicular to the cross-section of the ICU coupling. Hence, a separate adjustment of bending/compression and shear/compression ratio only by varying the test rig axis position was not achievable in this case.

In a second step, the "moving axis" option was investigated so as to evaluate the influence of a lateral flexibility of the test rig axis. In addition to the rigid configuration previously studied, an additional configuration was thus analyzed, with a lateral flexibility between the rigs axis that was estimated by numerical analysis of the fuselage upper frames model. The analysis showed a significant effect of this parameters on both ratios (bending/compression and shear/compression), meaning that the introduction of an appropriate device making it possible to account for a lateral flexibility between the test rig axis would permit the adjustment of both ratios as identified in the fuselage section model, inclusive an accurate load distribution along the frame coupling and the cross-beam.

Though permitting a more accurate representation of the actual loading conditions, the introduction of a lateral flexibility between the test rig axis was however not considered, in order not to jeopardize the project with too high complexity in the test set-up. Therefore, the priority was given to the bending/compression ratio ; with respect to the rig system configuration i.e. the position of the load introduction axis relatively to (CS08/09) and (CS10/11) sections, and the outcomes of the above numerical analysis, a bending/compression ratio of 150mm was therefore considered as the main dimensioning parameter for the test fixture.

Besides the support to the definition of the loading principle, the numerical analysis also aimed at investigating different crash scenarios (with a prescribed 6,7m/s vertical velocity), involving variants of the fuselage configuration, notably in terms of mass - starting from the maximal total weight of the considered fuselage section i.e. 1400 kg - with fully/partially loaded overhead compartments and seats rows. In parallel, the analysis also studied different scenarios in terms of energy absorption repartition between the sub-cargo and the cargo areas (where additional specific crash concepts, e.g. in the frame, could also be implemented). However, in the scope of the project, only the sub-cargo area was focused on. These works finally led to the selection of an intermediate fuselage configuration with a total weight of 1050kg, which was proved to provide enough kinetic energy for realistic representation of the loading rate during the whole crash sequence and to achieve convenient failure of the dedicated components.

4. Crash test

4.1. Test facility and requirements

The testing was performed at the ONERA-Lille crash tower (Fig. 4a) which is equipped with vertical rails that permit to guide the trolley during its fall, thus ensuring the control of the impact conditions. Each rail is supported by a set of 4 synchronized mechanical jacks that permit to adjust the crash zone and use trolleys of variable dimensions and mass, according to the test requirements. In the present project, the trolley dimensions were 1000x1500mm. The test area is basically 2x2m² and is made of a metallic table embedded into a suspended and damped 80 tons concrete mass, permitting to isolate the test area from the laboratory environment. Due to the size of the demonstrator, an additional longer metallic table was fixed over the existing one to receive the specimen + rigs assembly. The main characteristics of this facility are a 15m maximum drop height, a 1 Ton maximum trolley mass, a 15m/s maximum impact velocity, for a 100 kJoules maximum impact energy according to the combinations. As defined previously, the crash-test was to be performed at a 6,7m/s impact velocity, with a 1050 kg trolley mass (Impact energy: 24 kJ).

4.2. Loading principle

The loading system was designed accordingly with the outcomes of the DLR numerical analysis and thus consisted in articulated rigs maintaining both ends of the demonstrator and introducing bending/compression at the targeted ratio of 150 (Fig. 4b). The specimen was maintained at its free edges inside aluminium jaws, and was positioned and tested in upside-down position (skin side impacted by the trolley), and the normal and tangential components of the resulting force at the load application axis were made independent thanks to a system of vertical and horizontal rods, thus allowing to separately measure both components.

Besides, an energy absorption system was implemented to decelerate the trolley once the specimen was crushed over a targeted height - free stroke - so as to prevent its complete destruction and allow post-test inspections. This absorption system consists in 4 metallic tube absorbers that surround the specimen and absorb the residual energy of the trolley. The allowable free stroke was determined by pre-test analysis so as to permit the development of the expected crash sequence, hence the crushing of the TTS components in parallel to the bending of the cargo cross-beam.

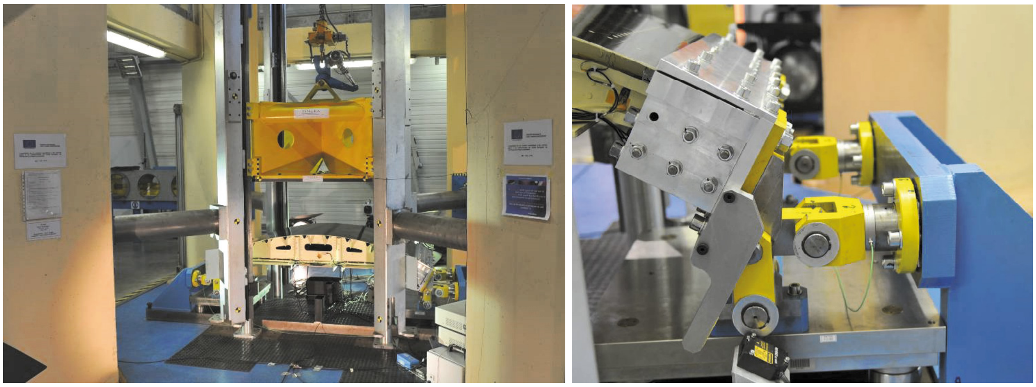

Fig. 4. (a) Sub-Cargo Demonstrator crash-test set-up; (b) Test fixtures.

4.3. Acquisition system

The acquisition system consisted of 4 multi-channel transient analyzers that are designed for synchronized acquisition of different signal sources and for data analysis. The data processing from the transient analyzer and the post-treatment for graphical representation was performed using the FAMOS environment. The trigger of the acquisition systems was controlled by 2 contactors activated by the trolley when reaching the position of impact; it also permitted to synchronize the start of the high-speed cameras. The acquisition system cumulated a total of 48 channels, including force sensors (6), strain gauges (36), displacement laser sensors (5) and an accelerometer (1). Besides, 4 high-speed cameras were implemented to visualize the rupture phenomenon likely to develop during the crash-test.

4.4. Crash-test results

The crash sequence is illustrated in Fig. 5 with snapshots from the high-speed cameras, showing both faces of the specimen at increasing times. Generally speaking, results confirmed the expected crash scenario, with the bending of the cargo cross-beams and the resulting progressive crushing of the TTS components (see Fig. 6). Once the trolley got into account with the metallic absorbers surrounding the testing area, almost 75% of the impact energy was already absorbed by the structure - while the TTS components were crushed over around 60mm - which appeared to be fully compliant with the considered crash scenario and the expected performance of the ICUs. At this stage, the bending of the cargo cross-beam, measured at its center, reached 25mm. Finally, the analysis of the tangential and vertical force signals measured at the load application axis proved that the resultant force was oriented as predicted i.e. the loading applied at the frame sections was introduced in accordance with the numerical pre-test analysis.

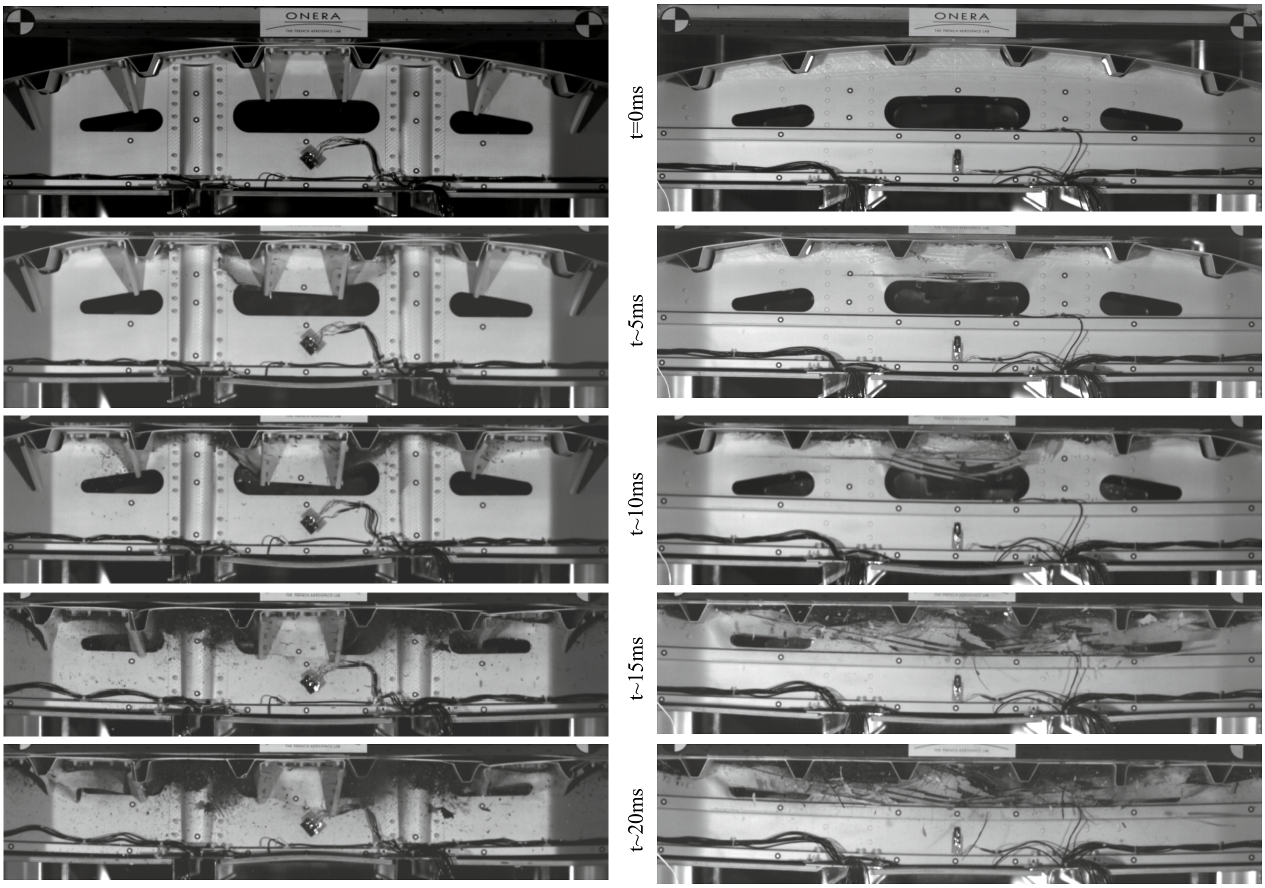

Fig. 5. Crash sequence of the Sub-Cargo Demonstrator (a) Front view; (b) Rear view.

Fig. 6. TTS components after test (a) Rear left ; (b) Front left ; (c) Front right; (d) Rear right.

5. Conclusions

The project, coordinated by AIRBUS Germany, targeted the development of a crashworthy sub-cargo demonstrator to be implemented in new generation CFRP commercial aircraft. Among activities defined in the work-program involving AIRBUS Germany, DLR and ONERA, an experimental validation step at the full-scale level, described in the present paper, aimed at crash-testing the demonstrator in realistic loading conditions i.e. likely to be imposed when integrated in a real structural environment.

To support these works, numerical analysis was performed by DLR through a kinematic model allowing efficient parametric modeling, and permitted, after selecting a relevant crash scenario, to identify the loading conditions that shall be considered, mostly characterized by a combination of bending and compression. As a result, the test principle involved articulated fixtures, which permits to submit the specimen with a combination of force and moment loading, similar to what was numerically proved to actually apply on the demonstrator edges. The sub-cargo demonstrator test performed within the project thus provides an innovative test setup that permits to evaluate the actual energy absorption performance of the sub-cargo crash concept. As a perspective, the introduction of a lateral flexibility between the test rig axis. which would account for the upper fuselage mechanical interaction, would constitute the further step to get closer to reality.

Acknowledgements

The authors wish to acknowledge the French Ministry of Defense, the FEDER and the Région Nord-Pas-de-Calais for their financial support.

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