Development of a prototype test system for certification of curved fuselage panels

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Abstract. A prototype test system with capacity to reproduce combined loads representative of real loading cases of a curved fuselage panel has been developed. This prototype test system allows the structural validation of curved fuselage panels to be accomplished. The developed system is able to apply combined mechanical and pressurization loading states under quasi-static and dynamic loading conditions. It has been designed using CAD models and calculated with the aid of Finite Element models to ensure its integrity. A data acquisition system synchronized with a control system enables real time monitoring of test parameters.

1. Introduction

The most recent designs of regional aircraft primary structures are made of carbon fibre reinforced polymers (CFRP) due to their excellent mechanical properties and low weight ratios.[1] To achieve the certification of a primary structure, extensive validation and verification campaigns are required, which combine experimental and virtual tests. Typically, these campaigns are distributed in a building block approach from obtaining design allowables for basic material properties (coupon level), followed by testing at detail and sub-component levels, up to testing the full-scale structure.[2]

Information gathered from these test campaigns is crucial if new developments are intended to be included in a commercial aircraft. When a new aircraft model is developed, it must obtain a type certificate from the responsible aviation regulatory authority before entering into operation. The European Aviation Safety Agency (EASA) is responsible for the certification of aircraft in the EU and for some European non-EU Countries since 2003.[3] In the United States, the Federal Aviation Administration (FAA) certifies the design of the aircrafts and components that are used in civil aviation operations.[4]

Aircraft fuselage is a primary structure of complex geometry where different requirements in terms of design stresses must be satisfied. During its service life, it is subjected to different operations (take-off, landing, taxi, etc.) which cause actual stress conditions that cannot be experimentally obtained by means of simple loading conditions. The combined loads sustained by the aircraft fuselage panels in real operation conditions cause complex stress states that need to be evaluated to validate the structural integrity of the panels. Consequently, different load combinations must be taken into account at validation stage to reproduce the conditions that may appear in the fuselage panels' in-service life.

At experimental stage, the most common test method uses big size mono-axial universal testing machines. To validate the complex loading cases acting on the component in real operation conditions, an engineering solution commonly used is to divide the combined loading cases in several simpler loading cases in which only one main axial load is applied in different directions. However, this approach leads to high increments of testing time and costs, since several aircraft structures need to be manufactured and tested.

Additionally, fuselage panel undergoes the aircraft inner-pressure. This introduces a change in stress status of the structure and thus, this condition must be reproduced simultaneously in combination with other external loads.

Test facilities to accommodate combined loading tests have been previously developed. The NASA Langley COmbined Loads Test System (COLTS) is capable of testing fuselage barrels up to 4.6 m diameter and 13.7 m long with combined mechanical, internal pressure, and thermal loads.[5] In Europe, NLR test facility allows fuselage skin sections to be subjected to biaxial loading conditions during static and fatigue tests,[6] while IMA-DRESDEN test bench enables to apply tensile and pressure loads as well as thrust loads.[7]

This work presents the development of a test system with capacity to reproduce combined mechanical (static and dynamic) and pressurization loading states, representative of real loading cases of a curved fuselage panel. The prototype is intended to allow the structural validation of fuselage curved panels up to 5 m long to be accomplished. It has been designed using CAD models and calculated with the aid of Finite Element models to ensure its integrity.

2. Test requirements and prototype test system specifications

Composite structure certification is based on the stress, strain and damage tolerance evaluation requirements. According to CS 25.571,[8] damage tolerance and fatigue evaluation of a composite structure in large aeroplanes must show that catastrophic failure due to fatigue, environmental effects, manufacturing defects, or accidental damage will be avoided throughout the operational life of the aeroplane. The definition of load cases for damage tolerance assessment is based on design load levels, i.e., limit load and ultimate load. The experimental test system must be capable of applying sufficient loading in order to reach limit, ultimate and failure loads of the specimens.

Likewise, the test system must be able to reproduce inner aircraft pressurization. Maximum cabin pressure differential, ΔP, depends on the aircraft model. Depending on the aircraft model and its maximum operation altitude, a short range of pressure differential is observed. For example, in the case of ATR 72 regional aircraft, the limit design level for differential pressure is 0.45 bar (25000 ft), whereas the operational differential pressure for Boeing 787-8 is 0.65 bar (43100 ft).

When the fuselage is subjected to internal pressure, circumferential (hoop reaction) and longitudinal stresses are produced in the structure. Since the curved panel is a section of the aircraft barrel, equivalent loads to reproduce this stress state must be considered in the test. Moreover, the load transmissions at each case must be fully representative of real loading cases to which the full system is subjected. Test boundary conditions that depend of the specimen such as pressurization chamber, anti-buckling and stabilizers (hoop stress) are addressed in a separate work.

Additionally, displacement requirements must also be fulfilled. Flat panel tests have been conducted at Element Seville facilities with a maximum level of absolute strain of 5400 μm/m at failure. If these results are extrapolated to a 5 m curved panel, a displacement of approximately 20 mm is obtained when a pure tension or compression load case is applied. For load cases where torsion load is applied, numerical FEM of the test provides information on expected displacements.

Finally, the dimensions of the curved panel section to be tested must be taken into account. Length, width and diameter of the test sample vary depending on the specific program. As an example, the ATR 72-600 has a diameter of 4.5 m, [9] while the largest diameter, of 7.14 m, is found in the Airbus A380. [10]

Following the guidelines for composite structure certification, the prototype test system is designed to conduct static and fatigue tests. The loading capabilities of the prototype test system are summarized in Table 1. The prototype test system design is intended to offer versatility in terms of capability of testing different specimen dimensions. The maximum dimensions of the curved panels which can be tested through the prototype test system are 5000 x 1700 mm (length x width) and 1500 mm radius.

Table 1. Prototype test system capabilities

Pure axial loading	±2000 kN
Max. displacement	±100 mm
Pure torsion	±200 kN·m
Max. torsional rotation	7°
Max. internal pressure	+ 3 bar

3. Design and calculus of sub-components

Once test requirements and prototype test system specifications were defined, the design of the test rig was addressed. As shown in figure 1, the test system structure can be divided into three sub-components: a. Supporting structure, b. Load introduction frame, and c. Reaction beam.

The loading introduction is performed by means of a hydraulic actuation system that is able to apply combined loading solicitations with components of different magnitude. Axial load is created by four hydraulic actuators connected to the supporting structure in one end and to the load introduction frame in the opposite. The torsional load is created by two actuators installed in the load introduction frame. Their connections with this sub-structure will be described in a following section.

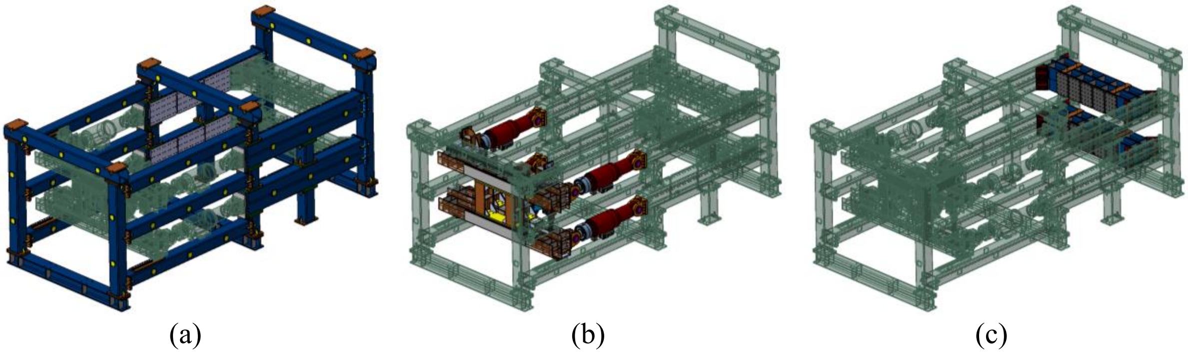

(a) (b) (c)

Figure 1. Sub-components of the test system structure: (a) supporting structure, (b) load introduction frame and (c) reaction frame.

The prototype test system design also incorporates a pressurization chamber attached to the specimen assembly allowing internal pressure loads to be applied. Pressurized air is introduced in the pressure chamber, causing a uniform constant pressure in the inner side of the curved panel. Joints between the panel and pressure chamber are sealed.

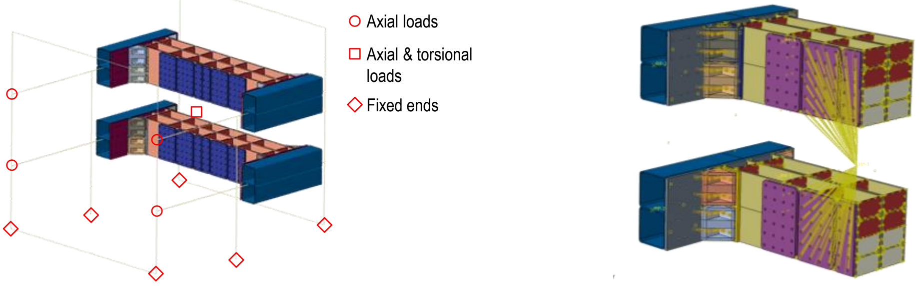
Several preliminary designs were analysed until the final design described above was achieved. The stress analysis has been carried out with the aid of Finite Elements (FE) models implemented in Abaqus. Preliminary models using mainly beam elements were used to define the size of the beams and final calculations were carried out with detailed models using mainly solid elements. The definition of the loads, boundary conditions and interactions between the different sub-sections has implied the use of special elements, like fasteners, using connector elements, multipoint constraints and contact conditions. Consequently, in many cases, a non-linear solution of the models has been required.

In the following sub-sections, the design of the subcomponents of the test system structure is commented in more detail and results of the FE analysis carried out are shown.

3.1. Reaction frame

In figure 2, the FE model of the final design of the reaction frame can be observed. Solid elements are employed in the FE model to be able to determine the stress concentrations in the beams, the reinforcement plates and the stiffened angles connecting the reaction frame and the supporting structure. In order to reduce the size of the model, beam elements are employed to model the supporting structure in the parts not connected to the reaction frame. The connection of the beam elements and the solid elements is carried out using a multi-point constraint (MPC) for each connection. The load introduced by the sample into the reaction frame is applied in a control node and transmitted to the reaction frame using also a MPC, see figure 2(b). Own weight of the structural elements is considered in all models.

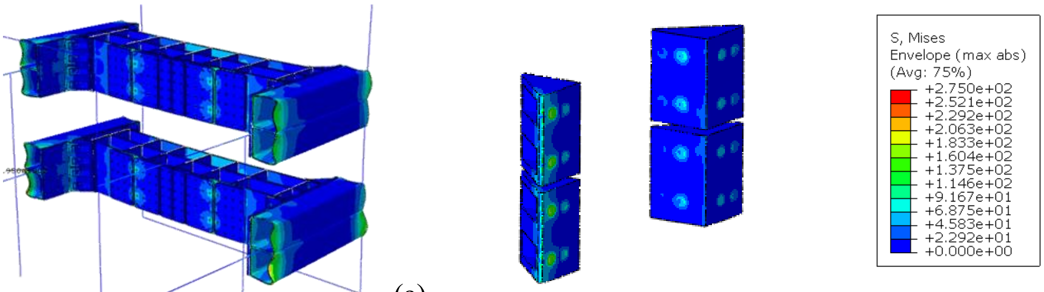
During testing, reaction beam is kept in a fixed position. Notwithstanding, connection with supporting structure is detachable to adapt the test configuration to panels with different lengths. Thus, the elements modelling the supporting structure, the stiffened angles and the reaction frame are not directly connected. Special elements are employed to model the bolted joints between these elements. Additionally, contact conditions between the stiffened angles and the elements modelling the supporting structure and the reaction frame are considered.



(a) (b)

Figure 2. Detailed global/local FE model of the final design of the reaction frame: (a) complete model, (b) detail.

In figure 3(a), results obtained in the FE model of the final design of the reaction frame are shown. The colour represents the value of the von Mises equivalent stress at each point when maximum axial and torsional loads are simultaneously applied. Results obtained in all stiffened angles are nearly identical. Consequently, in figure 3(b) for the sake of brevity, only the value of the von Mises equivalent stress in a single set of stiffened angles is shown.



(a) (b)

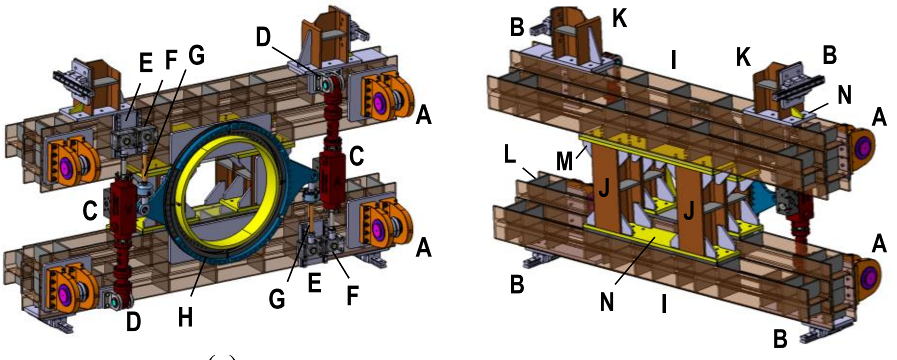
Figure 3. Von Mises equivalent stresses obtained in (a) the FE model of the final design of the reaction frame; (b) one set of stiffened angles connecting the reaction frame and the supporting beam.

3.2. Load introduction frame

As can be seen in figure 4, the load introduction box is composed of two main horizontal beams (I) connected by two vertical beams (J). In fact, the horizontal beams are composed by three welded H beams and the vertical beams by two welded H beams.

The axial actuators' clevises (A) in which the axial loads are applied, are located at the ends of the horizontal beams, where are also located the linear bearings (B) which connect the load introduction frame and the supporting structure, enabling only the axial movement of the frame. A double pin connection is used between the hydraulic actuators and the load introduction frame to prevent bending in the hydraulic actuators. In the lower part of the frame, the axial linear bearings are directly connected to the horizontal beam, while in the upper part a supporting H beam (K) is employed to connect the horizontal beam and the axial linear bearings.

Torsional load is introduced by the torsion actuators (C), attached at one side to one of the vertical beams using two clevises (D). At the other end, the torsion actuators are connected to linear bearings (F) that can move along the vertical guides (E) placed at the opposite vertical beam. Two auxiliary rods (G) transmit the torsional load to the main bearing (H) to which the sample is attached. Where needed, beam web reinforcement plates (L), gussets (M) and plates (N) are employed.



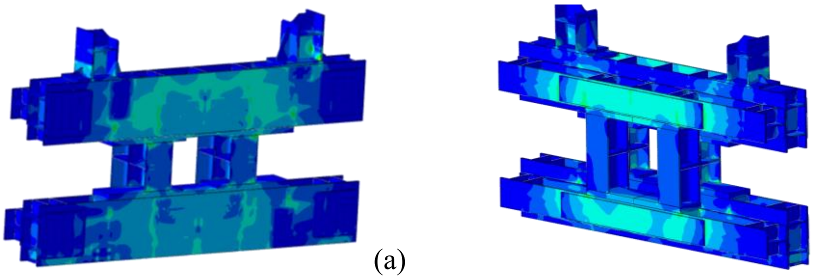
(a) (b)

A: Axial actuators' clevis
B: Axial linear bearings
C: Torsion actuators
D: Torsion actuators' clevis
E: Torsion guides
F: Torsion linear bearings
G: Torsion rods
H: Loading plate bearing
I: Horizontal beams
J: Vertical beams
K: Top guides' support beams
L: Web reinforcement plates
M: Reinforcement gussets
N: Reinforcement plates

Figure 4. Final design of the load introduction frame: (a) front view, (b) rear view.

Axial loads are applied to the pivot rods of clevises (A). The motion of the load introduction frame is restricted by considering the contact of the axial linear bearings (B) with fixed solids simulating the linear guides. Moreover, a cylindrical dummy sample is connected with the loading plates H (not shown in figure 4 for clarity). The torsional actuators introduce two distinct loads in the load introduction box: firstly, a force (in the direction of the actuator), applied at the pivot rods of the corresponding clevises (D) and, secondly, a moment in the linear bearings (F). This latter element has not been included in the FE model, and the moment has been transmitted to linear guides (E) using a multipoint constraint.

In figure 5, results obtained in the FE model of the final design of the load introduction frame are shown. The colour represents the value of the von Mises equivalent stress at each point (using the same scale shown in figure 3) when maximum axial and torsional loads are simultaneously applied.



(a) (b)

Figure 5. Von Mises equivalent stresses obtained in the FE model of the final design of the load introduction frame: (a) front, (b) rear.

3.3. Supporting structure

Loads applied to the supporting structure come from three different sources. Firstly, from the axial actuators, applied at the location of the clevis connecting these actuators and the supporting structure. Secondly, from the connection of the sample with the reaction frame, applied at a control node and distributed over the beams modelling the reaction frame with the aid of a MPC. Finally, from the connection of the load introduction frame and the supporting structure. The latter have been calculated from the reactions obtained at the fixed solids modelling the linear guides employed in the FE model described in the previous section, and introduced as point loads and moments at their corresponding locations.

In figure 6, results obtained from the FE model of the final design of the supporting structure are shown. For a better visualization of the results, a 3D representation of the actual 1D FE elements is employed. In each section of the beams the colour represents the maximum value of the von Mises equivalent stress within that section (using the same scale shown in figure 3).

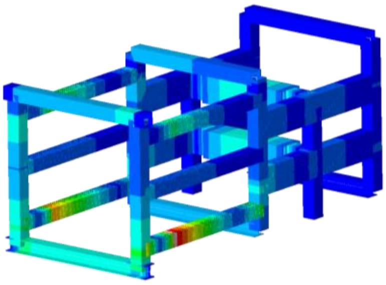
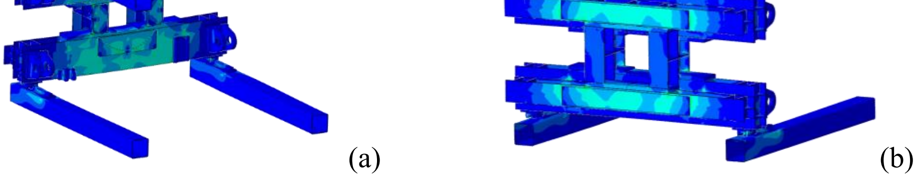


Figure 6. Von Mises equivalent stresses obtained in the preliminary FE model of the final design of the supporting structure.

As it can be seen, the sections in which highest stresses are observed are those in which the load introduction frame is connected to the supporting structure. Notwithstanding, it has to be taken into account that decoupling the FE model of the load introduction box and the supporting structure has been carried out substituting the supporting structure by fixed boundary conditions in the axial linear guides. Thus, reactions obtained in these fixed solids may be significantly higher than those actually transmitted through the connection. To obtain a better estimation of the stresses in the beams to which the load introduction frame is connected, they have been included in the detailed model of the load introduction frame described in the previous section. The solids modelling the axial guides have been attached to these beams and contact between the linear bearings and the guides is considered. To prevent the motion of the beams of the supporting structures, their ends have been fixed.

In figure 7, results obtained from the FE model of the connection between the load introduction frame and the supporting structure are shown. The colour represents von Mises equivalent stress (using the same scale shown in figure 3). In the plot it can be clearly appreciated how, as expected, including the actual stiffness of the beams in which the linear guides are supported instead of considering them rigid, reduces the load transmitted through the guides and, consequently, the stresses in the beams supporting them.



(a) (b)

Figure 7. Von Mises equivalent stresses obtained in the detailed FE model of the load introduction frame and the supporting structure: (a) front view, (b) rear view.

4. Prototype manufacturing and assembly

Once design is finalized, a drawings set is generated in order to launch manufacturing of the prototype. The designed prototype has been manufactured and fully assembled at ELEMENT SEVILLE, the full system being approximately 2.5 m height, 4 m wide, and 7 m long.

The structural testing workshop was conditioned to include the prototype, enabling a new high pressure oil line for supplying hydraulic actuators and adapting control and monitoring channels to be able to control the new test system. Loading actuation system are comprised of a group of synchronized hydraulic actuators for providing static and dynamic loading and data acquisition is carried out through acquisition system, which is also synced to the control system. Safety systems have been included in order to prevent from any accidental event.

The assembly process is divided in different stages, first the supporting structure is assembled together, then the load introduction frame is introduced into the supporting structure and the reaction beam is installed in the correct position. Laser dimensional control technique was used to check test set-up installation. Joining of parts is mainly welded to form sub-assemblies. Sub-assemblies were joined together by means of bolts. To do so, a specific screwing tool with capacity of applying the correct torque was used. Next, safety equipment is installed. Finally, actuators are pinned and sensors are mounted. Hydraulic connections are made and control-monitoring system is set up in the last stage. As shown in figure 8, the full structure is levelled and to fix the full structure, it is drilled to the technical floor of the workshop.

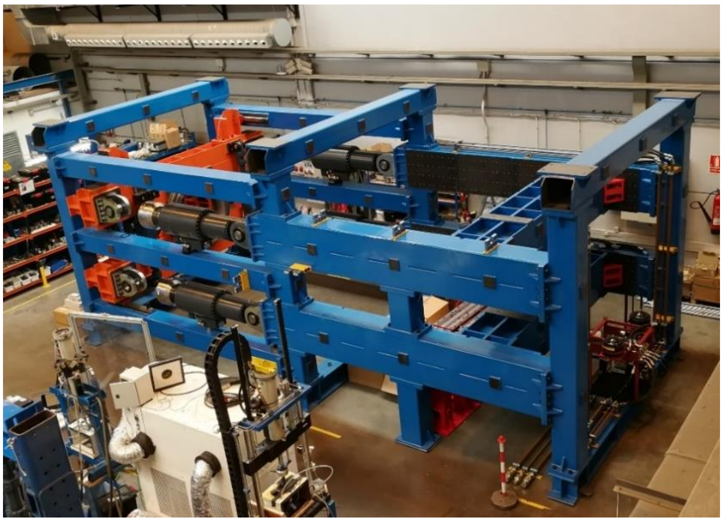


Figure 8. Prototype test system.

5. Conclusions

A prototype of test system for experimental certification campaigns of curved fuselage panels has been developed. It allows the cost of certification tests to be decreased, as well as the lead times to be improved. Test requirements were established according to the aero-structure certification guidelines and real operational conditions of the aircraft. Subsequently, specifications were defined to outline the test system preliminary concept.

Detailed design and calculus iterative phase was carried out in order to ensure structural integrity and system functionality at the same time than optimizing size and weight of the system’s parts. A set of drawings was generated and parts were manufactured and assembled. Hydraulics and pneumatics were assembled, and control & monitoring systems synchronized.

As a result, a prototype with capability to apply axial, torsional and pressurization loads, representative of in-service loads of curved fuselage panels up to 5 m long has been developed. The system provides the necessary boundary conditions, so that the load transmissions at each case are fully representative of actual loading cases to which the full system is subjected. This development is used in research & development activities part of Clean Sky 2 program with the purpose of validating new aero-structures configurations concepts.

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