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Experimental validation of aircraft fuselage sections by testing at the stiffened panel level

Authors

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The paper discusses a reliable, high versatility, cost efficient approach for performing full-scale fuselage panel testing and validation of the respective novel stiffening design concepts, as well as the way to confidence enhancement in computational models towards safer and more light-weighted aircraft designs. A methodology to mature low-cost testing technologies for demonstration of the structural integrity of representative aircraft fuselage panels in representative static and fatigue loadings, for the next generation Aircrafts is presented.

To mature up to Technology Readiness Level TRL6 the environmentally friendly manufacturing and surface treatment technologies developed in the metallic materials technological stream of Clean Sky 2 core project ecoTECH project [1], a high versatility, cost efficient approach for performing full-scale fuselage panel testing is required. The new manufacturing technologies include Friction Stir Welding for the replacement of riveting and mechanical milling for the replacement of chemical milling. The above-mentioned methods are combined with new surface treatments like the Chromium free anticorrosive surface treatments, developed and performed by Hellenic Aerospace Industry, Thin film Sulphuric Acid Anodizing and AC131 sol gel developed with a totally free Cr preparatory steps of cleaning and etching, and a totally Cr free post treatment step of Sealing after the anodizing. The basic anticorrosive surface treatments are combined with a new Chromium free primer, developed and industrialized by AKZO NOBEL with the commercial name: Aerolith CF Primer 2210, and water based top coat.

The steps to scale-down the experimentation at the stiffened panel level and provide the opportunity to effectively validate state-of-the-art designs than previously attainable are presented in the present paper, as part of Clean Sky 2 project Demonstrate which is CfP of ecoTECH [2]. The proposed methodology comprises the development of a test bench and its application for the execution of static tests on advanced metallic curved integrally stiffened full-scale panels, representative of a business jet fuselage structure; and the execution of an endurance test on an integrally stiffened 4th generation Al-Li curved panel, under a realistic load spectrum representative of the aircraft mission profile. The design of the rig and the experimental process are supported by validated multi-scale simulation models, focusing on the predictions of static, buckling and post buckling deformations, as well as on the crack initiation and damage growth. The virtual testing methodology was used for the definition of the stiffened panels boundary and loading conditions, such that they are fully representative of the aircraft full-barrel fuselage in-flight loading conditions. It can be concluded from the performed research activities, that the development of the innovative, cost-efficient, and easily adaptable to a wide range of curved panel lengths and curvatures fuselage panel full-scale test bench concept, has been proven capable to introduce the desired representative boundary / loading conditions and successfully validate the novel manufacturing and surface treatment processes.

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1. Introduction

The activities of the work described in this paper have been carried out to achieve two main objectives. The first was the full-scale testing of two airframe section demonstrators, i.e. two metallic fuselage panels, incorporating the newly developed 4th generation Al-Li Alloys in static loading conditions. The second target was the demonstration of the structural integrity of these representative aircraft fuselage panels, by advanced simulation methodology correlated with experimental data.

In order to achieve the above mentioned objectives, a number of enabling technologies have been developed, which resulted to the realization of an efficient, reliable and cost-effective test bench suitable for the full-scale testing of curved aeronautical panels. More specifically, these goals comprise:

1. The development of a virtual testing methodology for the definition of the stiffened panels boundary and loading conditions, such that they are fully representative of the aircraft full-barrel fuselage in-flight loading conditions.
2. The further development of an innovative, cost-efficient, easily adaptable (to a wide range of curved panel lengths and curvatures) fuselage panel full-scale test bench concept, capable of introducing the desired representative boundary / loading conditions.
3. The development and/or adaptation of a wide range of novel measurement techniques, explored to monitor the panel deformation and to capture onset / growth of damage.
4. The development and application of advanced simulation methodologies, focusing on specific issues related to the panels novel material systems and their integral stiffening concepts.

The activities described in this paper are included in a wider context of research work inside the Clean Sky 2 AIRFRAME Integrated Technology Demonstrators (ITD) program. In particular, the activities k are part of ‘Eco-Design’, which is devoted to the development and maturation to technology readiness levels of 4 and 5 of technologies to reduce the environmental impact for the non-operational phases of the aircraft lifecycle, aiming in lowering the environmental impact all along the aircraft lifecycle, operation phase excluded. Technology development activities cover materials and processes, manufacturing, maintenance and end-of-life. The research conducted in the present work (being part of the activities of the DEMONSTRATE program) have created full-scale experimental test data and related technologies, which are used to validate fuselage concepts of high technology readiness levels for both metallic and thermoplastic experimental curved-stiffened panels. An important benefit from developing an optimized test-bench for performing tests on panel level is the parallel maturation of low-cost testing technologies for demonstration of the structural integrity of representative aircraft fuselage panels in representative static and fatigue loadings, for the next generation Aircrafts. In this frame, one of the intended objectives of the work was to contribute to a faster, more thorough completion of the design-cycle, through the provision of test data with quantified uncertainties and the robust detailed correlation of measurements with predictions, derived by lower cost testing processes.

2. Concept and methodology

The concept of the present work aims in demonstrating the structural integrity of advanced 4th generation Al-Li alloy fuselage panels, using the developed efficient test bench to perform testing under quasi-static loading of two airframe section demonstrators. The testing was performed by Applus Laboratories in Barcelona, Spain, and the deformation of the panels was monitored during the tests by advanced metrology equipment, such as Digital Image Correlation (DIC). The early detection of cracks was performed by acoustic emission and Acoustic Camera while the evolution of damage growth was assessed by means of DIC. The preparation of this test campaign requires the prediction of the behaviour of the test bench and the panels. For this purpose, extensive pre-test simulations were performed by advanced multi-level Finite Element models, which were experimentally validated and used for various purposes. First to define the test panel boundary and loading conditions, then to assist in the design, development, and adaptation of the test bench, afterwards to model the panel behaviour during testing and finally to evaluate damage growth.

The advancement of the design and modelling process of large-scale experimentation of aeronautical parts was achieved by the special design of the proposed test bench, which enabled the reliable application of the fully representative tension / compression, bending, torsion and shear loads, simultaneously with pressure differential loads, at a cost and time efficient way. An additional novel aspect of the work is the adaptability of the proposed full-scale panel test bench, that can accommodate a wide range of panel geometry (sizes and

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curvatures), at reduced setup time and test execution costs. What is more, the use of a virtual test methodology and an optimization algorithm to define loading and boundary conditions for the stiffened panels testing, which are fully representative of the full fuselage section in flight, are all custom-made for the needs of this research. Additionally, important novel aspects of the work are the development and validation of advanced FE models for the metallic panels, which will also include the main test rig components, in order to enable the fit-for purpose adaptation of the test bench. More specifically, the panel FE simulation models, incorporateδ the 'as build' characteristics of the panels, to enable accurate predictions of panels deformation and damage growth. A flowchart representation of how to scale down from the entire aircraft to more specific structural components is depicted in **1.**

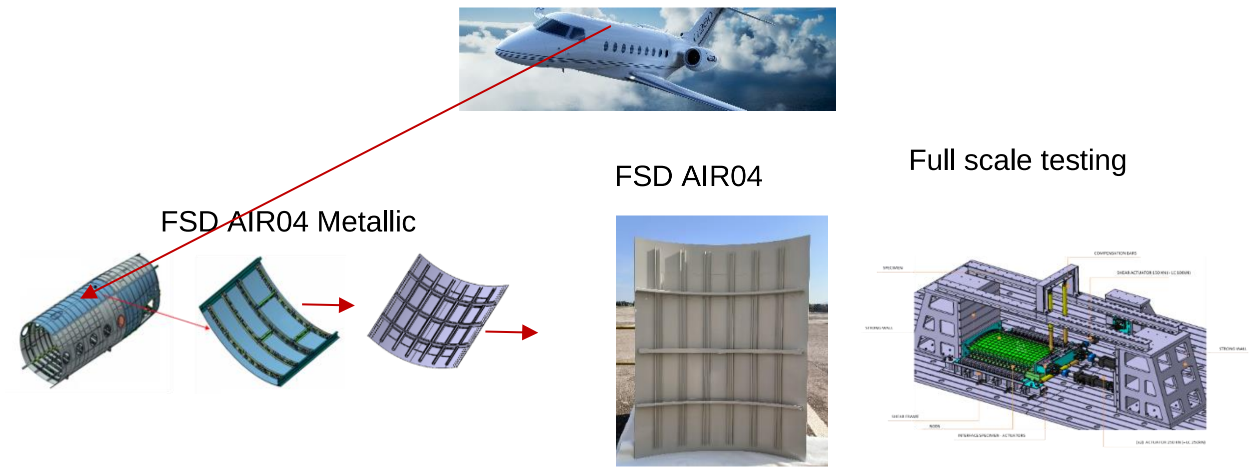

Figure 1: Scaling down process to focus on design elements and components of a fuselage [Clean Sky2 AIRFRAME FSD AIR04: Flagship Metallic fuselage demonstrator]

All the above partial innovations, contribute to the main innovation, i.e., the realization of an adaptable, cost-efficient and reliable test bench for full-scale testing of curved aircraft panels. The test campaign was structured following the internal APPLUS procedures, which is based on the Airbus Structural Test Quality procedure, to reinforce the Test Program definition and to provide the monitoring of key desired outputs. The process followed the distinct steps described hereafter:

1. The test-panels were manufactured, prepared and delivered as will the loading cases at the full barrel level. FE models were built to perform simulations at the fuselage barrel level and at the stiffened panel level, from which the loading and boundary conditions of the stiffened panel, representative to that of the complete fuselage section have been defined.
2. The FE models were validated before their application, through their correlation with experimental results of a specially defined small-scale test campaign at the APPLUS Laboratories.
3. Based on the virtual test (simulation) results, APPLUS designed, adapted and instrumented the cost-efficient test bench assembly, which was used to execute the test campaign and provide the experimental results reports for the three panels. In parallel, the FE models were extended to include damage and damage growth in of the metallic panels.
4. These models were validated using the final panel experimental testing campaign results at the APPLUS Laboratories.

3. Manufacturing building blog approach

The main objectives of the performed work within the frame of ecoTECH were:

- Designing, manufacturing, and testing a novel fuselage concept based on an existing reference panel from an upper fuselage business jet.
- Integrating advanced manufacturing and surface treatment technologies, developed within the metallic materials technological stream of ecoTECH, into the demonstrators to reach a Technology Readiness Level (TRL) of 6. These technologies include:

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- Manufacturing technologies:
  - Friction Stir Welding for the replacement of riveting and
  - Mechanical milling for the replacement of chemical milling
- Surface treatments:
  - Chromium free anticorrosive surface treatments, developed and performed by Hellenic Aerospace Industry: Thin film Sulphuric Acid Anodizing and AC131 sol gel developed with a totally free Cr preparatory steps of cleaning and etching, and a totally Cr free post treatment step of Sealing.
  - a chromate-free primer developed by AkzoNobel with the commercial name: Aerolith CF Primer 2210.

Cr free surface treatments | Cr free Primer | Mechanical Milling | Friction Stir Welding

Figure 2 : New developed technologies within the frame of CS2 ecoTECH project

In order to achieve a Technology Readiness Level (TRL) of 5 prior to final testing, a progressive building block methodology was employed, starting from the coupon level and advancing to the element and demonstrator levels. Validation testing was conducted at each stage. The approach followed for each technology is depicted in the accompanying figure (Figure 3).

4. Definition of test boundary and loading conditions at panel level

A portion of an aircraft's fuselage undergoes complex loading, along multiple axes and of various types, such as bending, shear and differential pressure loads. Novel fuselage structural concepts can be validated more efficiently and with less effort and risk at lower scales of the test pyramid, i.e., at the level of a typical stiffened panel, which should comprise all critical and complex structural features of the fuselage barrel. Experimental campaigns carried out at the component level comprise of quasi-static tests at multiple loading combinations up to ultimate final failure, in addition to endurance tests using a fatigue loading sequence representative of the operational conditions of an aircraft's flight profile. Performance of these kinds of tests requires advanced and adaptable test-rigs, capable to smoothly and correctly introduce the multi-axial forces, indicative of the fuselage complex loading, and the representative boundary conditions on the tested experimental panels. Appropriate decisions have to be made about the encompassing supporting structure, the interfaces and the rest of the components and elements of the test-bench so that a reliable recreation of the surrounding fuselage structure's stiffness can be realized. Likewise, load combinations should be imposed in such a way so that they induce a response in the test panel, which closely approximates that of the respective full-scale fuselage barrel under real flight conditions.

The present experimental stiffened panel concept was based on the virtual testing at both the 'full-scale fuselage barrel' level, as well as the 'curved stiffened panel' level. Detailed simulations of the physical tests of both the 'fuselage barrel' and the 'stiffened panel', incorporating all crucial features of the test rig, were performed using detailed Finite Element (FE) models. Starting from the geometry, structural definitions and loading cases of the full-barrel section and the test panel geometry provided by Hellenic Aerospace Industry, extensive parametric model studies about panel loading and boundary conditions, achievable by the APPLUS panel test bench, were carried out. The most promising loading concept was further parameterized and inserted in an optimization algorithm, which led to the optimal definition of boundary conditions and loading systems leading to panel responses, which are as close as possible to those of the fuselage barrel in-flight.

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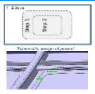
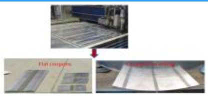
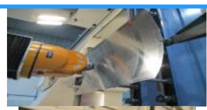
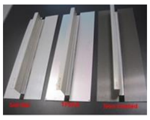
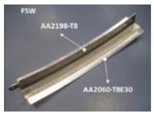
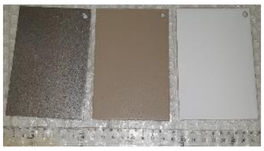
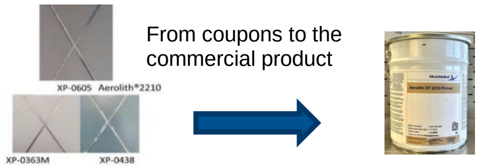
Technologies	Coupons	Elements	Demonstrator
Pocketing by mechanical milling by IAI, to replace mechanical milling			
Stringer-skin, frame - skin welding (Friction Stir Welding) by LORTEK to replace the riveting in order to further reduce the weight of the structure			
Cr-free anticorrosive surface treatments (Thin Film Sulphuric Anodizing and Sol-Gel) developed by HAI, including all the cleaning steps and the sealing for the case of anodizing			
Application of Cr-free primer and top coat developed and industrialized by AKZO NOBEL			

Figure 3 : TRL evolution of involved technologies

Two preliminary concepts for substituting the omitted fuselage section with a dummy structural arrangement were investigated, followed by their evaluation using FE method. According to the first concept, a dummy structure based on a bar structural assembly was introduced, as shown in **Figure 4**. The stiffness of the bars that horizontally join the two side edges of the panel, as well as of the bars joined at their lower vertex to compose a triangular shaped structure, were adapted such that they can recreate the stiffness of the missing circumferential section of the full barrel. The main advantages of the first proposed test rig concept comprised:

1. The zero stiffness of the bar assembly in the axial direction, as the bars are attached on a slider to be free to move in the axial direction.
2. The realization of a smooth edge loading by appropriately adjusting the stiffness of each bar.
3. Its bench adaptability to panels of different length or curvature thanks to the possibility to easily modify the length of the bars.
4. The capability of a localized monitoring of the loads passing through each one of the bars (by means of instrumenting and calibrating each bar with strain gauges), which allows the local reaction forces monitoring in a precise way.

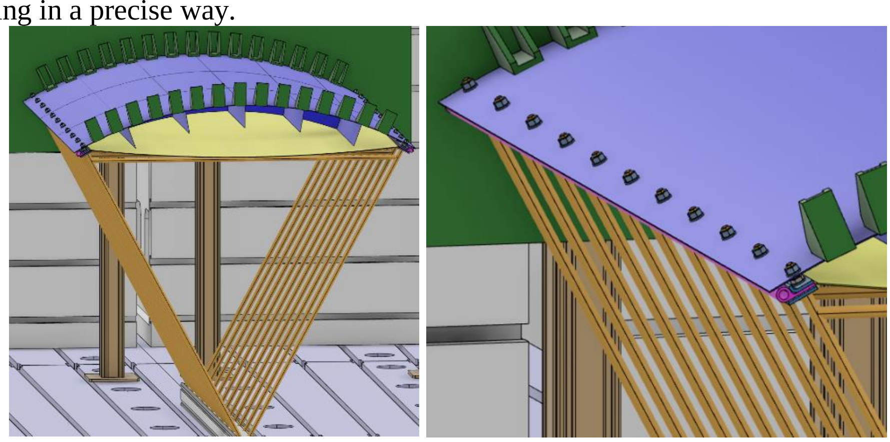


Figure 4: Bar structural assembly representing the omitted barrel segment (concept 1)

The second concept considered the arrangement based on a rod’s structural assembly shown in **Figure 5**. The stiffness of the rods that circumferentially join each side edge of the panel, to the ground, are adapted such that they can recreate the stiffness of the missing circumferential section of the full barrel.

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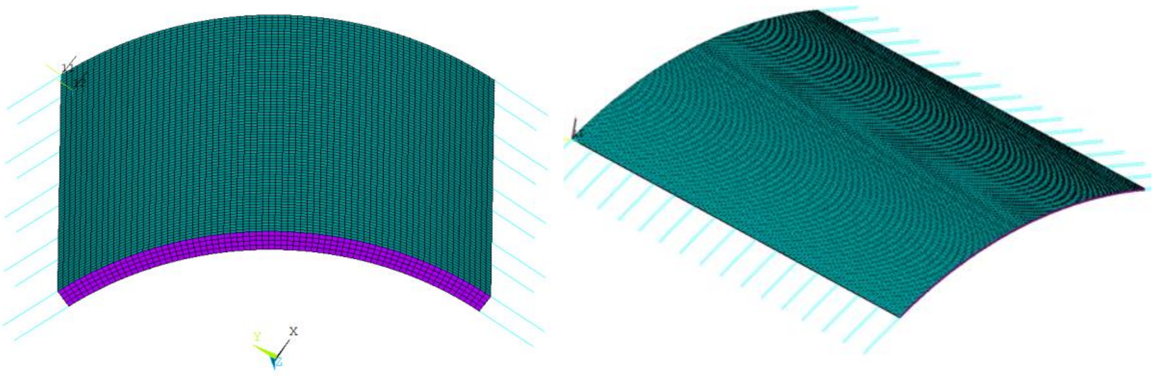
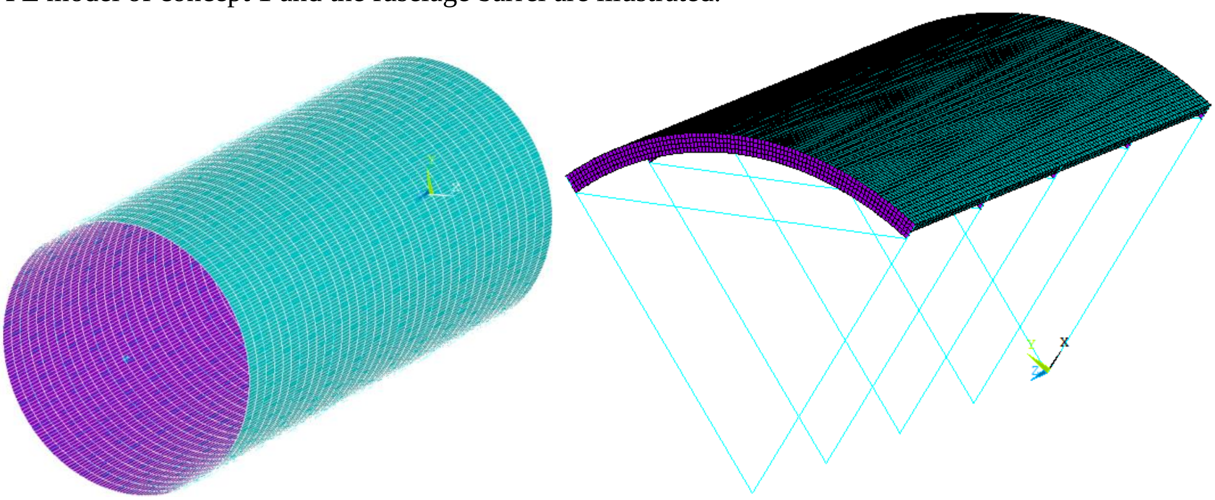


Figure 5: Arrangement of rods representing the omitted barrel segment (concept 2)

Finite-element simulations were performed for the particular loading scenario of uniform inner pressure for the fuselage barrel section, as well as for the two concepts shown in **Figure 4** and **Figure 5**, in order to assess the representativeness the concepts and their ability to approximate the real panel behaviour when it is placed into the fuselage barrel. In **Figure 5** the FE model for concept 2 is presented, while in **Figure 6**, the FE model of concept 1 and the fuselage barrel are illustrated.



(a) (b)

Figure 6: FE models of fuselage barrel (a) and test-rig concept 1 (b)

All finite-element-models were parametrically programmed in ANSYS APDL, using shell elements for the skin. In the case of the fuselage, beam elements were selected for the stiffeners having typical profiles, while for the panel models, equivalent stiffness blades made of shell elements were used. After imposing a differential pressure equal to 0.124 MPa in all cases, post-processing of the out-of-plane deformation took place, where the deformed shapes of the panels were compared with a fuselage section. The comparison of the radial, out-of-plane displacements is depicted in **Figure 7**, where the qualitive correlation of results displays concept 1's inability to produce a uniform field due to undesired bending of the skin. On the other hand, concept 2 develops radial displacements that match very well with the fuselage, proving its suitability for the pressure load case.

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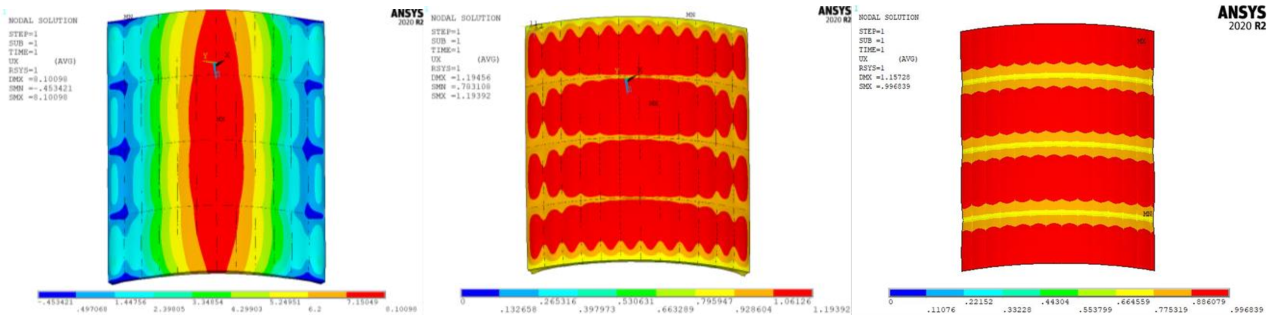
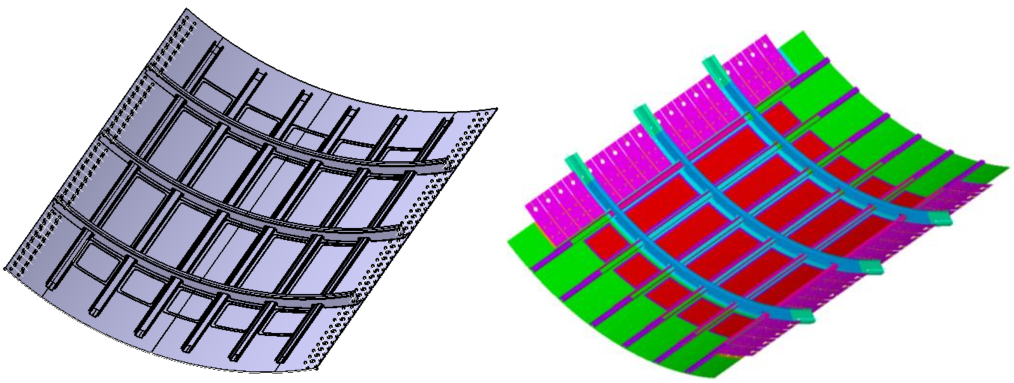


(a) (b) (c)

Figure 7: Radial displacements distributions for concept 1 panel (a), concept 2 panel (b) fuselage section (c)

5. FE model of the metallic panel and its test-rig and its validation for the compression load case

Focusing on the metallic panel, its initial design comprised 3 frames and 11 stringers. A modification improvement by HAI was implemented, which resulted in a reduction in the width of the panel by introducing 8 stringers instead of 11. Furthermore, the modified panel design introduced pockets of reduced thickness at bays located between the three frames of the panel. This design was further optimized, and the finalized version included 6 stringers and additional skin pockets after the first and last frame. The 2nd modified design of the metallic stiffened panel along with its respective developed FE model are presented in **Figure 8**. The FE model incorporated the reduced thickness pockets, along with other details such as the frame's cutouts. The detailed FE model was parametrically built in Ansys Mechanical APDL. The material properties used for the simulation are presented in **Table I**. The FE model comprised all geometrical details of the stiffened panel (Z-frames, Hat-stringers, pockets with reduced thickness, etc.), using approximately 236,000 shell elements for the simulation of all components of the panel.



(a) (b)

Figure 8: CAD drawing of 2nd modified panel design, provided by HAI (a), FE model in ANSYS APDL (b)

Table I: Material properties of Al-Li 2198-T8

E_t [GPa]	E_c [GPa]	F_{ty} [MPa]	F_{cy} [MPa]	F_{tu} [MPa]	F_{bry} [MPa]
62	80.9	420	503	524	703

The optimized panel was then placed inside the test-rig, which was developed based on concept 2 (**Figure 5**), by Applus Laboratories in Barcelona, Spain. To facilitate the application of a lateral, shear load parallel to inner pressure (with the use of an inflatable airbag) a shear frame was inserted into the assembly, whose side beams were free to rotate in-plane and the frontal transverse bar was able to move sideways while maintaining the frame's shape. Rods were hinged via clevis joints to the straight edges of the panel and connected through

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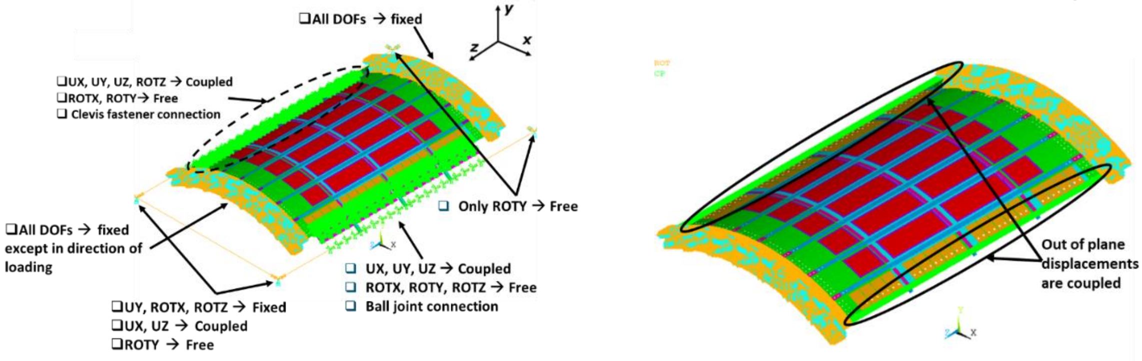
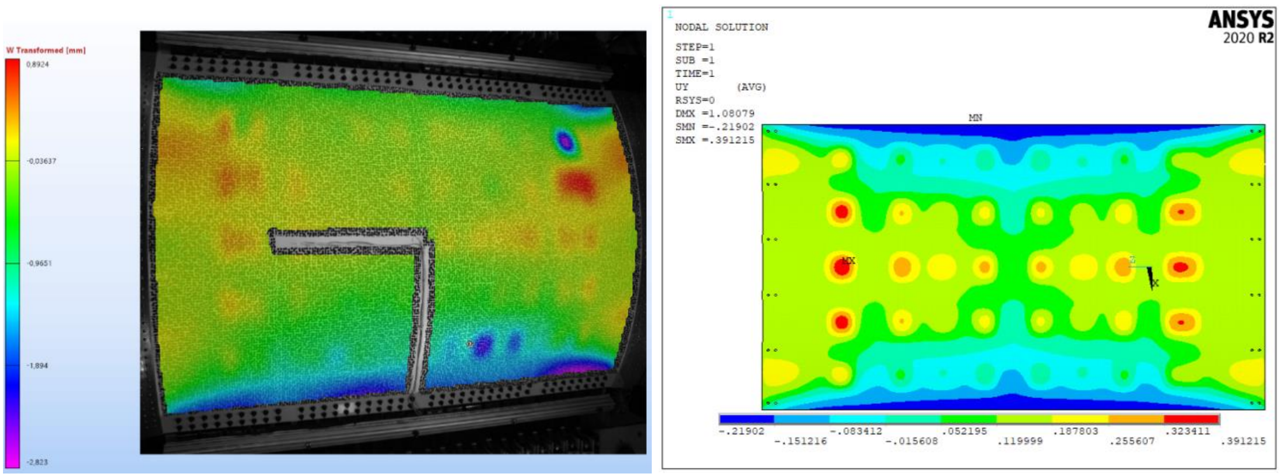
ball-joints to the shear-frame. These joint systems together with the interfaces were simulated in the FE model by using appropriate nodal couplings, the shear frame and rods were modeled as beam elements. For the load case of compression, the surrounding structure of the shear frame and the rods were removed, and an anti-buckling device was installed in the straight edge boundaries preventing localized out-of-plane deformation of the skin. This configuration was simulated via coupling the out-of-plane displacement of all nodes located at the straight edges. An overview of the boundary conditions and couplings can be seen in **Figure 9**.



(a) (b)

Figure 9: The FE model of the panel inside the test-rig including BCs and couplings (a), the FE model of the panel with the simulated anti-buckling device (b)

The next step was to run simulations of the tests performed on the final design of the experimental panel. For the purposes of this research the load case chosen was the simple uniaxial compression one. Compression was introduced by loading a load-bearing plate with two actuator hydraulic jacks. The panel was bolted to the plate with a fitting block. The compressive force was decided to be 100 kN, based on fuselage's limit loads after multiplying them with appropriate safety factors. They were multiple strain gauges and rosettes installed on characteristic locations on the panel for monitoring strains during the static test. However, the validation of the FE model depended more heavily on achieving a comparable to the experiment global panel response. The global data, captured from the test, was in the form of Digital-Image-Correlation (DIC) images, which were processed into contours and were compared with the FE displacement results. **Figure 10** and **Figure 11** show side-by-side the deformations from the experiment and the FE analysis. In **Figure 12**, the force-displacement curves are plotted for the test and the FE simulation.



(a) (b)

Figure 10: Out-of-plane vertical displacement contours, DIC (a), FE (b)

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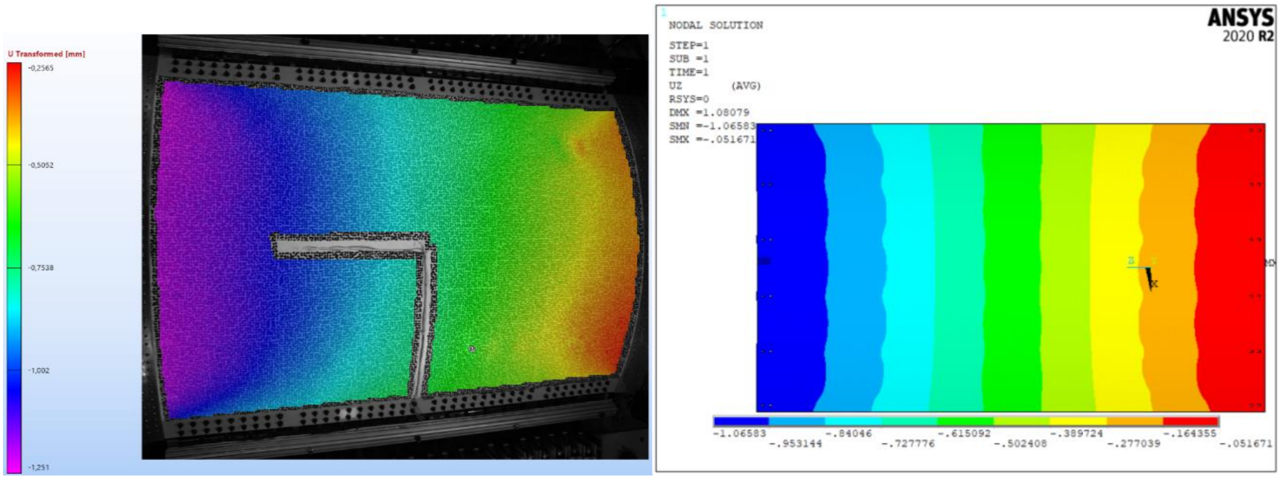

(a) (b)

Figure 11: Axial displacement contours, DIC (a), FE (b)

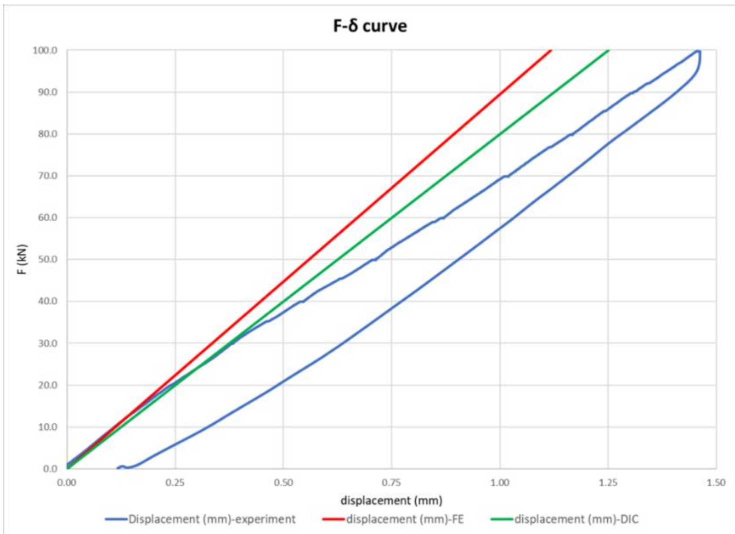

Figure 2: Force-displacement curves of experiment (LVDT), DIC and FE

There exist two comparative criteria by which to evaluate the capability of the model to capture the stiffness of the experimental panel. One of these is the correlation of the deformed contour shapes while the second is by quantitatively measuring the accuracy of the model via calculating errors at specific areas. According to the first approach the out-of-plane contours of **Figure 10** showcase a satisfactory agreement in regard to the amount and the location of the deformed skin pockets at the front and the rear. When observing the DIC data in **Figure 11**, the gradient from the highly compressed loaded side to the fixation side is similar to the FE model prediction. In **Figure 12** the experimental force-displacement curve is characterized by a decrease in slope as force is raised, thus causing deviations from the FE linear analysis, this could be attributed to the rig's tolerances and slack. Maximum deviations of the FE are about 20% from the measurements of the LVDT sensors and approximately 10% from the DIC maximum value.

6. Conclusions

A test-bench capable to perform static and fatigue experiments on state-of-the-art integrally stiffened optimized fuselage panels was developed. The preliminary studies concerning different configurations to constraint the straight edge boundaries of the test panel, employed the FE method to evaluate the structural response of each panel and correlated it to that of a reference fuselage model. After finishing the design iterations of the experimental assembly, the test campaign was initiated and the validation process of the models for a simple compression load case was achieved. The structural behavior of the novel metallic integrally stiffened panels

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will be further investigated, with respect to compression, shear, pressure loading and their combinations, to derive and useful conclusions about their capability to safely undertake typical fuselage loads.

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[2] https://www.horizon-demonstrate.eu/

Acknowledgments

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