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Tyre Impact on Optimized Composite Wing

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Abstract

Thanks to the confidence gained in the numerical simulation methods through correlation with a wide range of tests, nonlinear "realistic simulations" are taking more and more place in the design and sizing of aeronautical components during development and Certification phases. Airworthiness Authorities agree more and more to use the "virtual testing" or "realistic simulations" as means of compliance for all the items for which an acceptable level of validation of methodologies has been demonstrated.

The main objective of the TIOC-Wing project supervised by the Topic Leader DASSAULT-Aviation is the development and the validation of criteria and a virtual testing methodology that will allow to predict the resistance of a representative stiffened composite wing panel subjected to the impact of tyre debris and the residual strength capability of the damaged structure.

This will be reached by means of a test program focused on tyre debris impact events on composite aircraft structures and using the acquired experimental data to develop and validate numerical computational tools. The Consortium of TIOC-Wing project joins expertise in composite material knowledge, testing and manufacturing, in tyre tread impact testing and numerical simulations from 3 partners: SONACA, DGA-TA and CENAERO coming from Aeronautical Industry, referenced Test Laboratory in foreign objects impact capabilities and Research and Technology Center in advanced numerical simulations.

TIOC-Wing will give the opportunity for the partners of the Consortium to enhance the level of expertise in the field of foreign objects impact aircraft vulnerability. For the industrial partners, the anticipation of such particular risks in the early stage of the development of an aircraft will reduce inherent costs due to possible modifications in a more advanced phase of the program, needed to satisfy the Certification requirements. This also enables to increase the competitiveness through innovation by the integration of advanced computational tools in the sizing loop. Decrease of development tests will have as consequence the decrease of non-recurrent costs.

Finally, during future development of the next generation of aircraft thanks to less conservative approaches, TIOC-Wing offers the means for possible optimization of design concepts and weight savings strategies with reducing the CO2 emissions."

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1. Introduction

Foreign impact damage is an important issue for safety in the aircraft industry. Indeed, in the field of the Civil and Military aviation, vital components of structures are potentially vulnerable to impact events (engines, wings slat leading edges and flap trailing edges, vertical and horizontal tail planes, front fuselage including the cockpit area). Figure 1-1 illustrate some examples of foreign objects impacts encountered by aircraft during flight.

Tyre impact ***Engine rotor failure*** ***Hailstone on nose fuselage and cockpit***

Figure 1-1: Foreign object on aircraft observed in service

High velocity projectiles generally induce more severe damages. Concerned “outside of aircraft” projectiles are bird and hail. Metallic projectiles can also result from the failure of aircraft components like rotating elements of an engine (rotor burst or fan blade out). Furthermore, in particular during taxing and take-off runway phases, foreign objects (like stones, bolts or other metallic fragments) can be encountered and thrown against the aircraft structure. Failure of aircraft wheels and tyres has the potential for generating high velocity impact tyre and metallic debris on critical aircraft parts and could lead to catastrophic consequence as illustrated by the example of the Concorde crash as illustrated by the

Figu

Figures 1-2: Tyre debris object on aircraft wing lower cover observed in service
The example of Concorde

The foreign object impacts are considered in the airworthiness requirements of the European Aviation Safety Agency (EASA) and the US Federal Aviation Authority (FAA). Top level requirement is that, after impact, safe continuation of flight and subsequent landing must be ensured. Consequently, foreign object impacts are treated in the aircraft level as particular risks and they are considered in the early stage of the aircraft development program. The reason of that is they provide guidance on prudent design considerations and they have a major impact on the systems and the equipment installations and also on the structure sizing and weight. From the design to the Certification phase of the aircraft, aerospace industries adopt as means of compliance the so-called test pyramid (or building block approach) which contains 5 levels of tests from material test on coupons in level 1 up to full aircraft structures in level 5 as shown in the Figure 1-3 below.

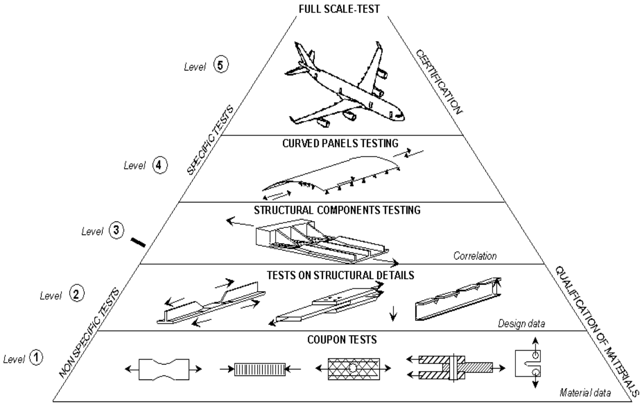


Figure 1-3 : Pyramid of physical tests used by the aerospace industries

When considering aircraft vulnerability issues such as foreign objects impacts including hail, runway debris (stone), tyre and metallic debris, tests are required at each level of the pyramid:

- At level 1, materials properties for design analysis are determined at level 1 on standard coupons.
- At level 2 and 3, the complexity of the specimens is increased including more structural details and performing more specific tests. The elements with particular configurations are tested such as panels with co-cured stiffeners.
- At level 4, sub-components extracted from full-scale structures and representing the real items are tested.
- At level 5, it is necessary to carry out impact testing on full-scale structure using realistic foreign objects as required by airworthiness rules.

During the last decades, in the aerospace industry, the use of composite materials takes more and more important place in the design of the structural components. These materials replacing the conventional metallic materials leading to lighter structures, contribute to the reduction of the CO_2 emissions and to the production costs. For example, the Figure 1-4 shows the increasing proportion of composite materials in the civil and military aircrafts over the past 30-40 years.

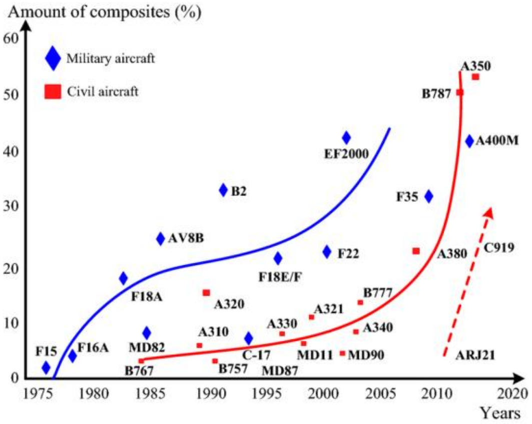


Figure 1-4 : Amount of composite materials in the civil and military aircrafts

Consequently, the aeronautical structures have been subjected to increase constraints in terms of quality, cost and time, in addition to the technical requirements themselves. Faced with this fierce competition, it is vital for the European aeronautical companies to stand out on the one hand in terms of costs (study and manufacturing) by advanced technologies and secondly in terms of quality and innovation of solutions proposed to the major customers.

However, in the design of the aircraft structures, the constructors are concerned by the vulnerability of their structures. Nevertheless, such materials in primary structures are particularly vulnerable to foreign objects impacts due to their brittle properties. Therefore, for composite structures, Certification requirements are more conservative and a building block approach including a huge number of tests is required. Furthermore, foreign objects impacts cannot always be fully assessed through testing for cost and feasibility reasons. On one hand, the test even at component level, are very expensive, on the other hand, the number of scenarios to be investigated is numerous, it is therefore convenient to support design and Certification approaches numerically in order to significantly reduce the development times and cost for new transport aircraft, especially when new material classes or innovative structures are being considered. Since the last decade, due notably to the significant increase of computational performance, advanced nonlinear analysis methodologies are widely used providing more accurate results and allowing the decrease of conservative assumptions. The development of numerical platform integrating virtual design tools and advanced numerical simulations have raised the importance of the virtual testing which requires a high level of confidence in the commercial computational softwares (ABAQUS, LS-DYNA, …), methodologies, analysis process, people skills and experience. The validation of numerical simulations is judged accomplished when it exists a building block approach showing accurate predictions for various levels of the pyramid validation from “coupon” level to “aircraft component” level.

For business jets, the development of a composite wingbox contributes to the weight reduction of the aircraft. This is an attractive solution that fits with one of the main goals of the CLEANSKY 2 program i.e. the reduction of CO_2 emissions. However, this solution represents a major design change when compared to a conventional metallic design and additional requirements are formulated by the certification authorities. One of them is the demonstration of sufficient robustness of the exposed parts of the composite wings in case of tyre burst with tyre components hitting the wing surface. Requirements and threats to be considered are detailed in paragraphs CS 25.734, CS 25.963(e) and related AMC 25.734 and 25.963(e). In the frame of this Call for Partners, works will be focused on impacts of small and large tyre debris as defined in AMC 25.734 on wing fuel tank zones. Main objectives will then consist in minimizing penetration, deformation and leakage risks, as well as demonstrating the residual strength and damage tolerance. It is important to be able to adequately integrate these requirements on the wing design in an optimized way to avoid compromising the assets of the composite solution.

2. TIOC-Wing objectives

The main objective of the TIOC-Wing project is the development and the validation of criteria and a virtual testing methodology that will allow to predict the resistance of a representative stiffened composite wing panel subjected to the impact of tyre debris and the residual strength capability of the damaged structure. In order to assess the technical success of the project, the Virtual Testing methodology will be used to quantify the cost efficiency by replacing a tyre impact physical test on a fully (including panel curvature) wing component (at aircraft level) by the corresponding Virtual Testing validated on a representative wing panel sub-component. Expected impact from the TIOC-Wing project will be quantified for the cost efficiency showing the benefit brought by the use of Virtual Testing methodology validated on aircraft sub-component. Based on tyre impact and mechanical test campaign of typical configurations, both simulations and failure criteria will be developed for damage and residual strength predictions capability. This development shall lead to a simple methodology applicable to support the design of composite wing panels, allowing to take into account certification constraint while minimizing weight penalty. This exercise will be performed on a panel geometry provided by the Topic Manager. This objective will be reached by means of a pyramidal test program focused on tyre debris impact events on composite wing aircraft

structures and residual strength assessment of damaged structures. The acquired experimental data will be exploited to develop and validate numerical models for Non Linear Finite Element Analyses using a reference commercial ABAQUS/Explicit computational code. Due to the availability of more accurate design tools, the level of conservatism will also be reduced allowing optimized design with potential weight saving, better performance and lower fuel consumption during future development of the next generation of aircraft. Furthermore, the anticipation of such particular risks in the early stage of the development of an aircraft will reduce inherent costs due to possible modifications in a more advanced phase of the program, needed to satisfy the Certification requirements. This also enables to increase the competitiveness through innovation by the integration of advanced computational tools in the sizing loop. Decrease of development tests on large representative sub-component will have as consequence the decrease of non-recurrent costs.
The Consortium of TIOC-Wing project joins expertise in composite material knowledge, testing and manufacturing, in tyre tread impact testing and numerical simulations from 3 partners: SONACA, DGA-AS and CENAERO coming from Aeronautical Industry, referenced Test Laboratory in foreign objects impact capabilities and Research and Technology Center in advanced numerical simulations.

3. Overall approach and methodology

The R&D strategy of TIOC-Wing project is based on the establishment of a new test program for tyre debris impact events on composite structures and to the use on the acquired experimental data to validate Non Linear Finite Elements Analyses [NLFEA] using high level and innovative modelling techniques developed in a computational reference codes (SAMCEF/Mecano, ABAQUS/Standard and ABAQUS/Explicit) widely used in the aeronautic industry. The validation of numerical simulations developed with the TIOC-Wing project is based on a building block pyramidal approach showing the 5 levels of the pyramid validation from "coupon" level to "wing component" level illustrated in the Figure 3-1 :

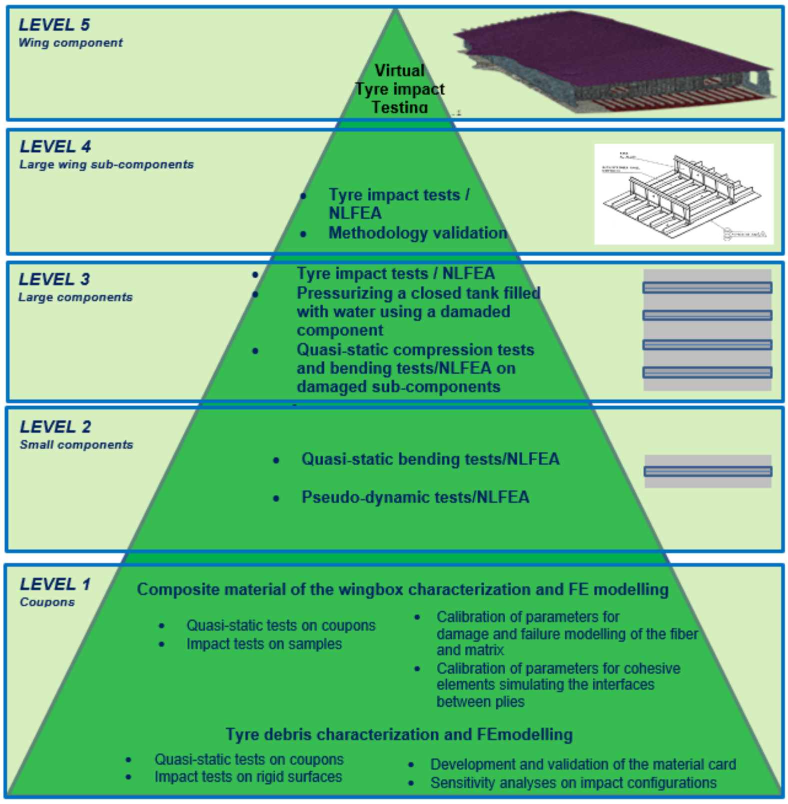


Figure 3-1: Building block pyramidal approach of TIOC-Wing project

4. Mains results

An overview of the main results obtained from the TIOC-Wing project are presented hereafter for the following levels of the building block pyramidal approach.

4.1. LEVEL 1 [COUPONS]

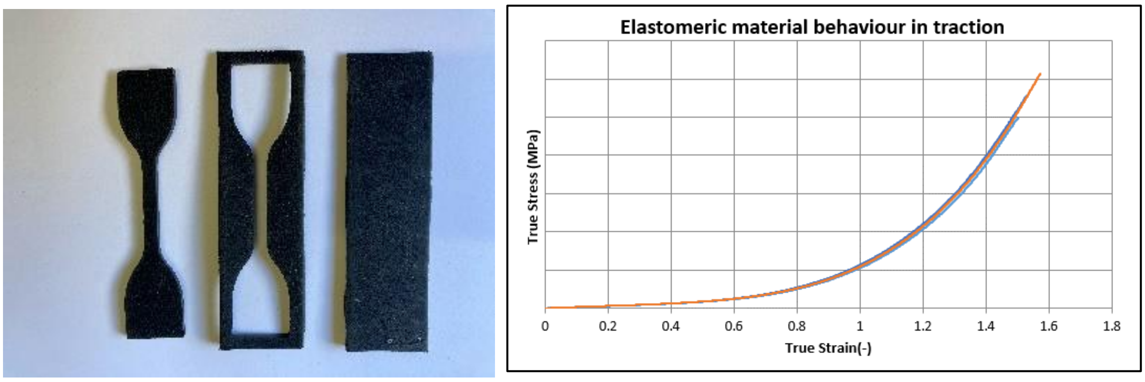
The level 1 supports the modelling methodology on the one hand of the tyre debris and the second hand of the impacted structure made with composite material that are used for the different components of the pyramid.

Tyre debris modelling

Based on the evaluation of the certification and structural requirements, a tyre debris model has been established to be used in the project as a reference projectile. This debris extracted from a typical aeronautical tyre illustrated in Figures 4-1 contains an elastomeric part and a reinforced part and is therefore representative in terms of geometry, materials composition and stiffness.

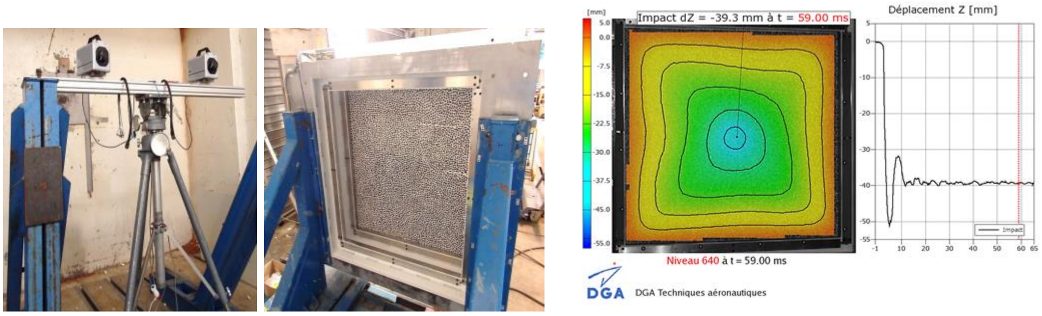
Figures 4-1: WP1 – Tyre debris model

A complete survey on the modelling methodology has been done for the tyre debris including several material modelling approaches and the selection of the most suitable approach in terms of simulating the physical behaviour and the computational efficiency. Knowing that the behaviour of elastomeric materials can be strongly influenced by external parameters as temperature, strain rate, maximum strain, loading history (Mullins effect), a definition of the field of use and the surrounding parameters is therefore essential to ensure the reliability of the model. Consequently, in order to provide a generic database of material properties to feed the numerical models and to assess sensitivity of physical parameters on material behaviour law, an extensive static and dynamic characterization testing program on tyre debris coupons conducted by DGA-AS has included uniaxial tensile tests, uniaxial compression tests, cyclic loading tests, relaxation tests. The Figures 4-2 illustrate a typical coupon manufactured to perform a tensile test and the corresponding result showing the true stress function of the true strain resulting of a tensile test.



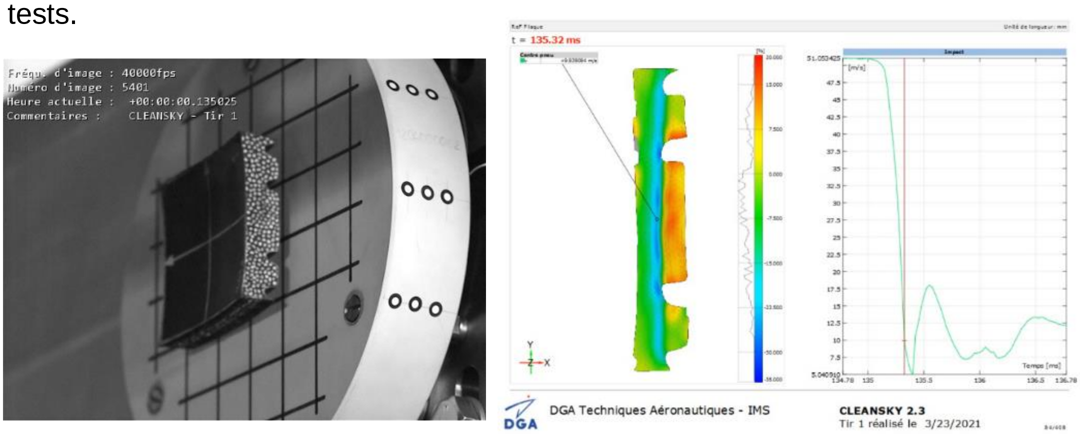
Figures 4-2: Tyre coupons for material characterization

In parallel of the tyre model development, the experimental mean to perform tyre debris impact tests has been enhanced with the objective for DGA-AS to develop a robust chain composed by a pneumatic gun able to launch on a test article representative of an aircraft sub-component different types of tyre debris covering the range of mass and speed parameters according to requirements provided by the aeronautical industry. Reliable measurement systems to record accurately the impact speed of the tyre debris and a set of advanced measurement systems using high-speed camera for stereoscopic techniques were developed to acquire during the impact testing, measurements used as means for the correlation with numerical simulations results.



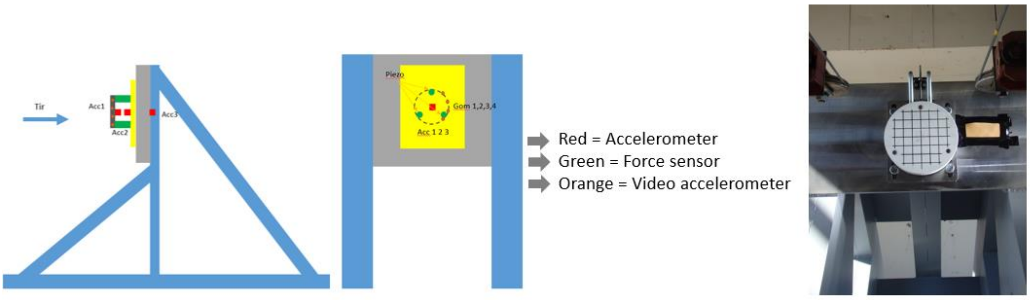
Figures 4-3: DGA-AS high-speed cameras for 3D DIC (Digital Image Correlation)

Impact tests on a rigid frame with speeds varying from 50 to 100 m/s were carried out using the reference tyre impactor presented earlier. For this first impact test campaign, speed of the fragment was measured by laser barrier. Strain and strain rate of the tyre debris were measured with 3D DIC instrumentation. An analysis of the results obtained using stereo correlation allows to know the level of compression as well as the maximum deformation rate during the tests.



Figures 4-4: DGA-AS tyre impact tests on a rigid frame – Use of stereo correlation

The rigid frame was instrumented with different load sensors to measure the time history of the impact load as illustrated by the Figures 4-5.



Figures 4-5: Tyre debris impact tests on rigid frame – Test setup and measurements

The Figure 4-6 illustrates the maximum impact loads measured during impact tests performed at different speeds (varying from 50 to 100 m/s) compared to the theoretical maximum load derived from the elastic shock theory.

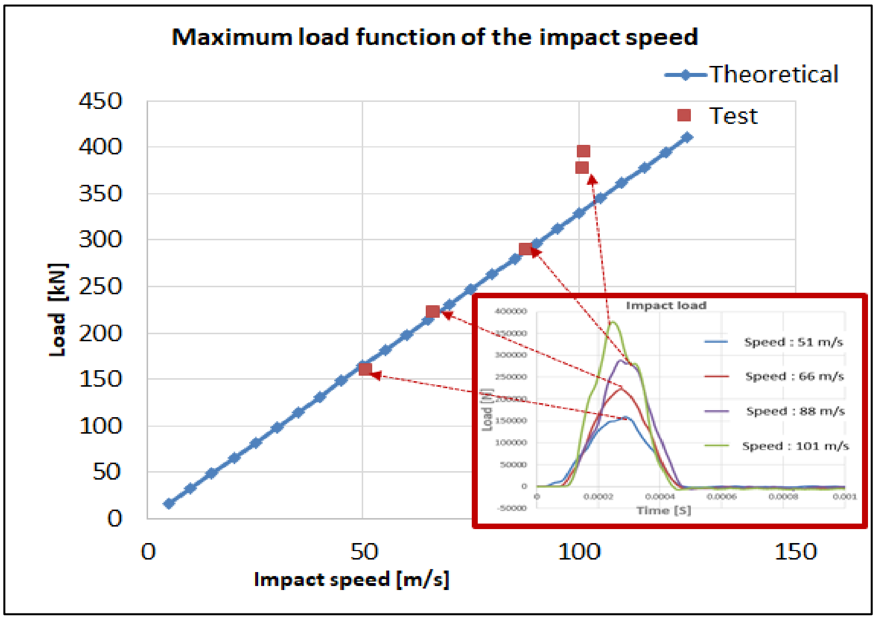


Figure 4-6: Tyre debris impact tests on rigid plate – Correlation between maximum experimental test and theoretical load derived from the elastic shock theory

Those measurements allow defining a methodology to validate the suitable tyre debris modelling. Since high fidelity modelling of the fragment including geometrical details like tyre grooves and curvature is time consuming, various sensitivity studies have been made to generate a simplified model without curvature and groove of tyre debris able to simulate with an acceptable level of accuracy the impact behavior by correlation with test results. As presented by the Figure ***4-7***, the time history of impact forces measured by load cells recorded during tests are compared to the numerical simulation results using both types of tyre models (detailed vs simplified).

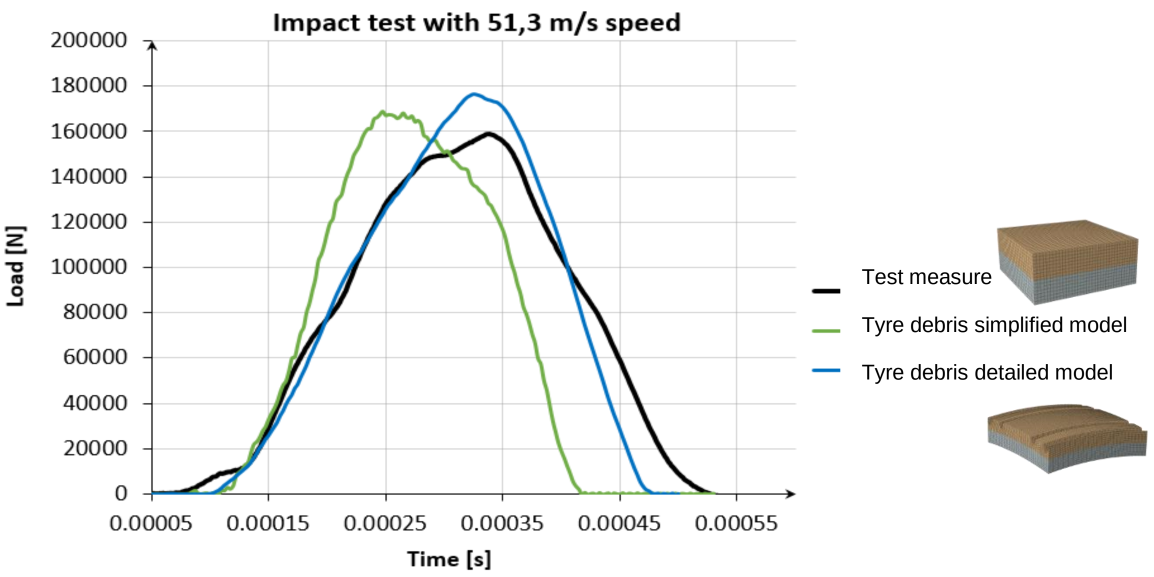


Figure 4-7: Tyre impact numerical simulations – Correlations with test results

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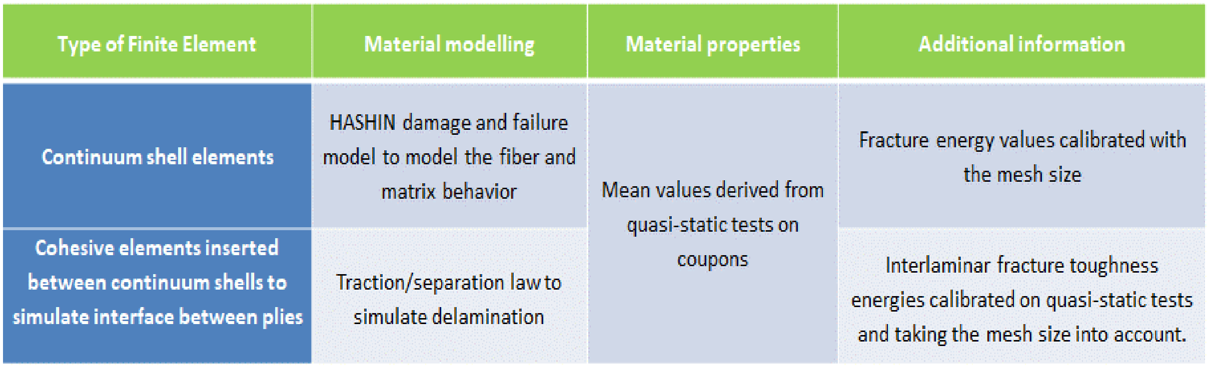
From material to structure modelling of the impacted components

The typical structure representative of a wing box lower skin is idealized as a stiffened flat panel containing stiffeners co-bonded using adhesive with the skin. In particular M21EV/IMA prepreg tape from Hexcel are used for the skin and stiffeners. A generic database has been established to feed and to validate the material models. It contains properties coming from traction, compression, intra-laminar and inter-laminar shear quasi-static tests and interlaminar fracture toughness obtained from Double Cantilever Beam, End Notched Flexure and Mixed Mode Bending quasi-static tests results.

A step by step progressive approach has been used for the structure modelling made with composite material, starting first with simplified models. Therefore, pre-test numerical simulations are based on a macroscopic approach using multilayered shell elements to support test. This basic approach is judged adequate to predict the overall scenario including the global elastic response until the failure of the component. However, it will actually be necessary to define an area of the panel which will be enriched by more advanced modeling. The mesoscale approach for composite modelling to increase the accuracy of predictions (damage and failure characteristics of specimens) is planned for post-test simulations activities and is summarized in the Table 1.



Type of Finite Element	Material modelling	Material properties	Additional information
Continuum shell elements	HASHIN damage and failure model to model the fiber and matrix behavior	Mean values derived from quasi-static tests on coupons	Fracture energy values calibrated with the mesh size
Cohesive elements inserted between continuum shells to simulate interface between plies	Traction/separation law to simulate delamination		Interlaminar fracture toughness energies calibrated on quasi-static tests and taking the mesh size into account.

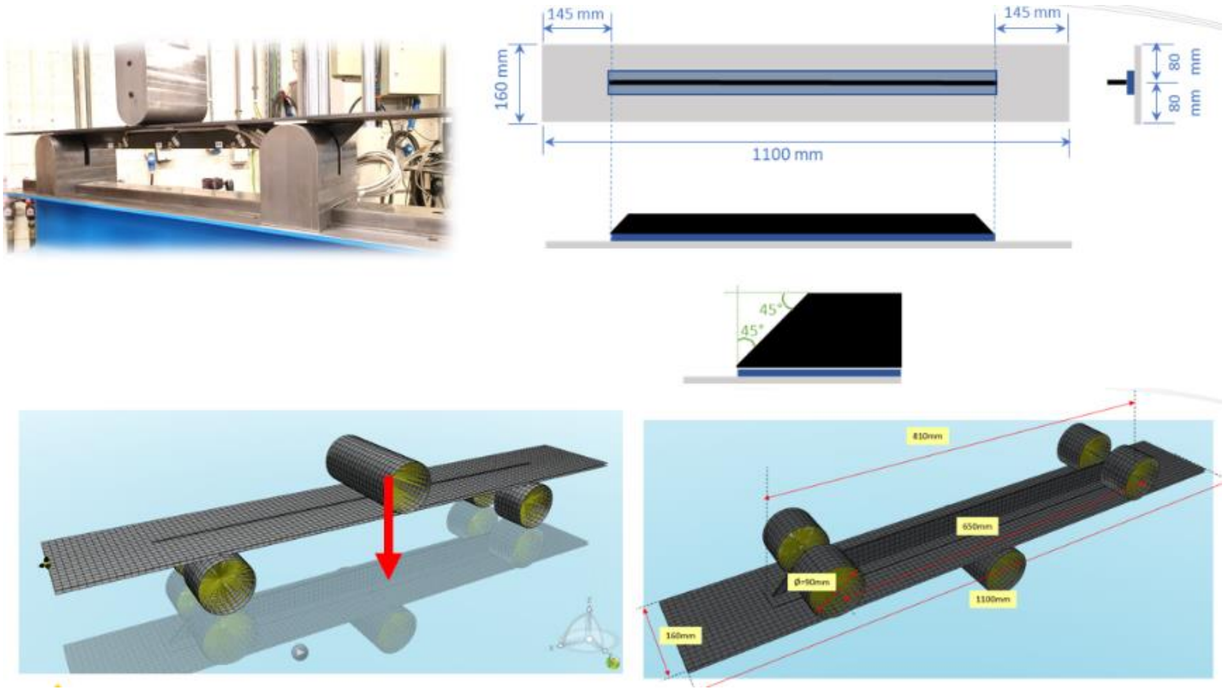
Table 1 : Composite material modelling – mesoscale approaches

4.2. LEVEL 2 [SMALL COMPONENTS]

The first test campaign at Level 2 consisted in 4 quasi-static 3 points bending tests on small components (1100mmx160mm stiffened flat panel containing only one stiffener) has been performed at SONACA in September 2021 with the objective to characterize for the composite stiffened panel, the global response and the local behavior (damage and failure mode, location and size) analyzed by the means of strain gauges bounded on each specimen. The Figures 4-8 illustrate the test setup.

Figures 4-8: Quasi-static 3 points bending tests on stiffened panels – Test setup

The modelling using macroscopic approach has been created including the boundary conditions, the detailed geometry representation by the use of material card, appropriate finite elements and meshing. The numerical simulations using SAMCEF/ASEF for linear analysis, SAMCEF/MECANO and ABAQUS/Standard for nonlinear analyses of the component subjected to quasi-static bending have been performed to support the test definition and to predict the load function of displacement until failure.



Figures 4-9 : Quasi-static 3 points bending test numerical modelling on stiffened panels

The Figure 4-10 provides the comparison between the predicted numerical simulation using linear analysis (SAMCEF/ASEF) with the four test results and shows that the correlation with the use of measured strain failure provides the adequate failure load and displacement of the subcomponent.

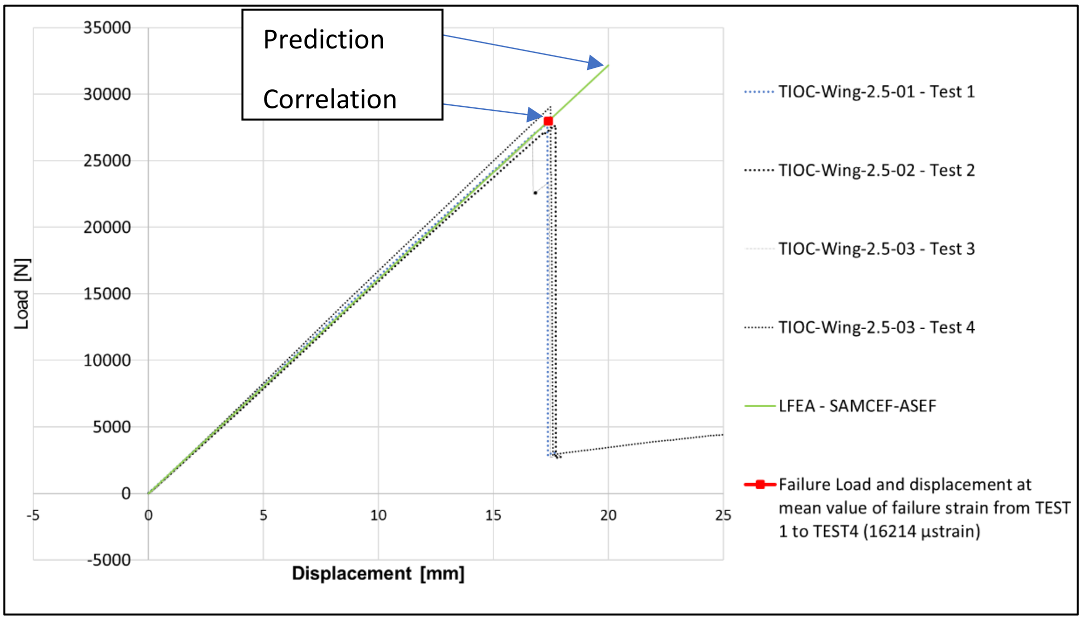


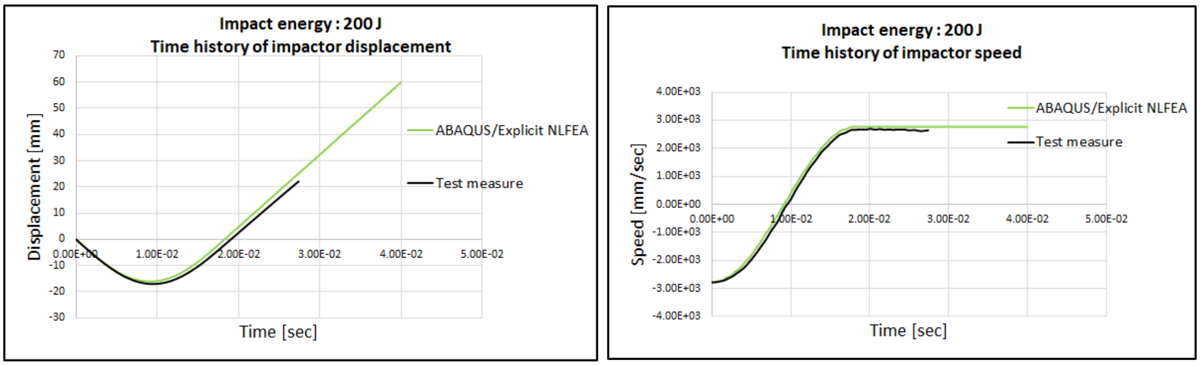
Figure 4-10: Quasi-static 3 points bending simulations on stiffened panels - Pre-test simulations – Load function of displacement predictive result to support test definition

The second test campaign at Level 2 consisted in 4 drop-weight impact tests as illustrated by the Figures 4-11 on small components having the same geometry and boundary conditions than those tested for quasi-static 3 points bending tests described previously. These tests have been performed at DGA-AS in October 2021 with the objective to characterize for the composite stiffened panel, the global response and the local behavior (damage and failure mode, location and size) under low velocity impact. The impact energy was established in relationship with the failure energy obtained for the quasi-static 3 points bending tests. A range of impact energy 200J to 400J was established to perform the tests and to characterize the failure energy of the subcomponent. The time history of the load, the out-of plane displacement and the speed of the impactor have been measured.

Figures 4-11: Pseudo dynamic tests on stiffened panels – Real test setup and specimen description

The same modelling was applied as for that used for the 3 quasi-static points bending tests on small components. The numerical simulations using ABAQUS/Explicit have been performed in order to circumvent the energy leading to the failure of the specimen. Sensitivity analyses on the impact parameters including speed, impact locations have been done to support the test definition. Correlations between test results and predictive results using macroscopic approaches have been done. The jack load function of displacement, damage and failure of the panel characteristics has been used for the comparison with the numerical simulations results.

Figures 4-12 and Figure 4-13 provide for the impact energy of 200J the comparison between the predicted numerical simulation using NLFEA (ABAQUS/Explicit) with the test result for the time history of the impactor displacement, speed and acceleration.



Figures 4-12: Pseudo dynamic tests on stiffened panels – Pre-test simulations – Time history of impactor displacement and speed - predictive result to support test definition

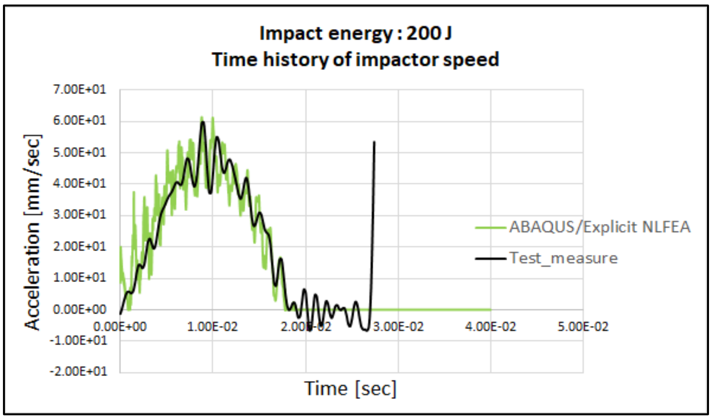


Figure 4-13: Pseudo dynamic tests on stiffened panels – Pre-test simulations
Time history of impactor acceleration - predictive result to support test definition

4.3. LEVEL 3 [LARGE COMPONENTS]

The first test campaign at Level 3 consisted in 5 tyre impact tests with different impact energies on large aluminium components (1100mmx1100mm stiffened flat panel as illustrated by the Figure 4-14) and has been performed in June 2021 at DGA-AS with the objective to characterize the global response and the local behavior analyzed by the stereo correlation as illustrated by the Figures 4-15.

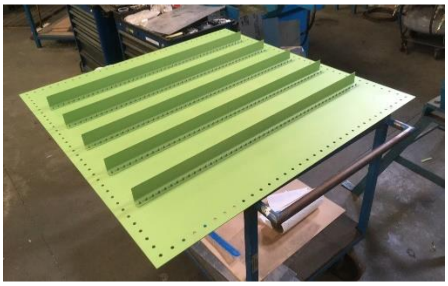
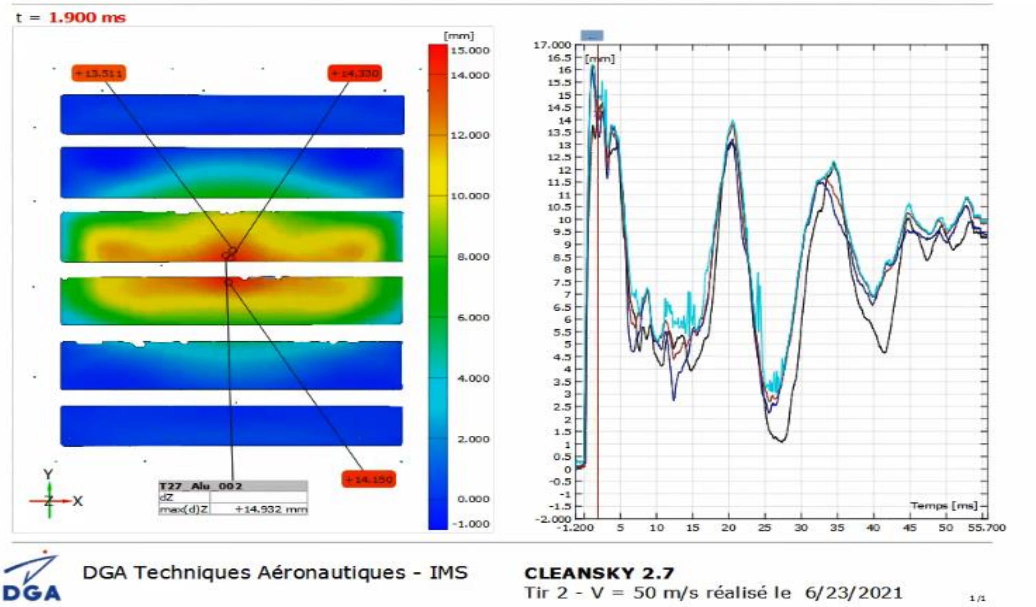
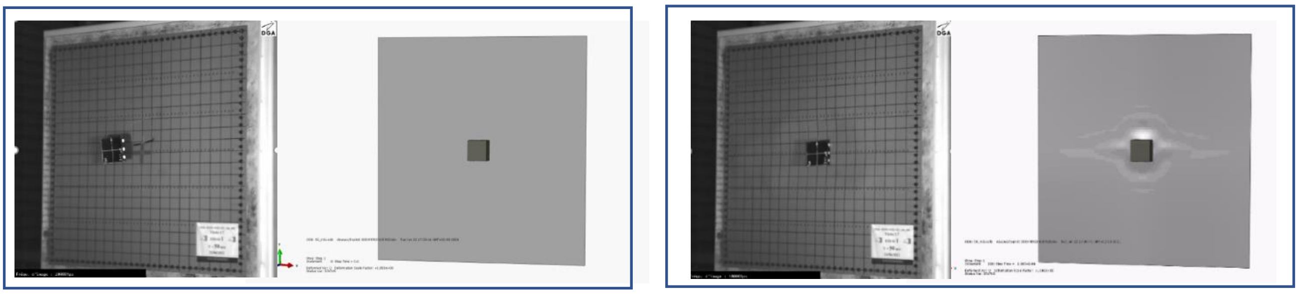


Figure 4-14: Tyre impact test on stiffened metallic flat panels – Test specimen

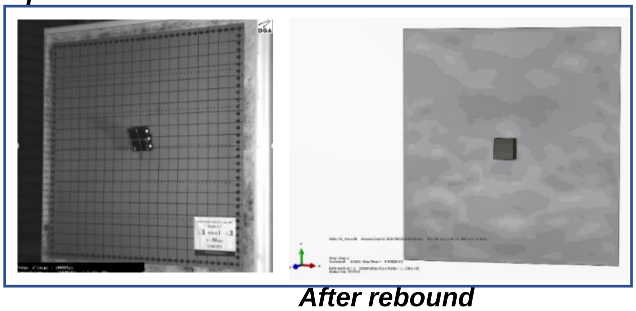


Figures 4-15: Tyre impact test on stiffened metallic flat panels – Use of stereo correlation

The Figures 4-16 provide some views illustrating the impact scenario extracted from the high-speed camera and compared to the results of numerical simulation using NLFEA (ABAQUS/Explicit).



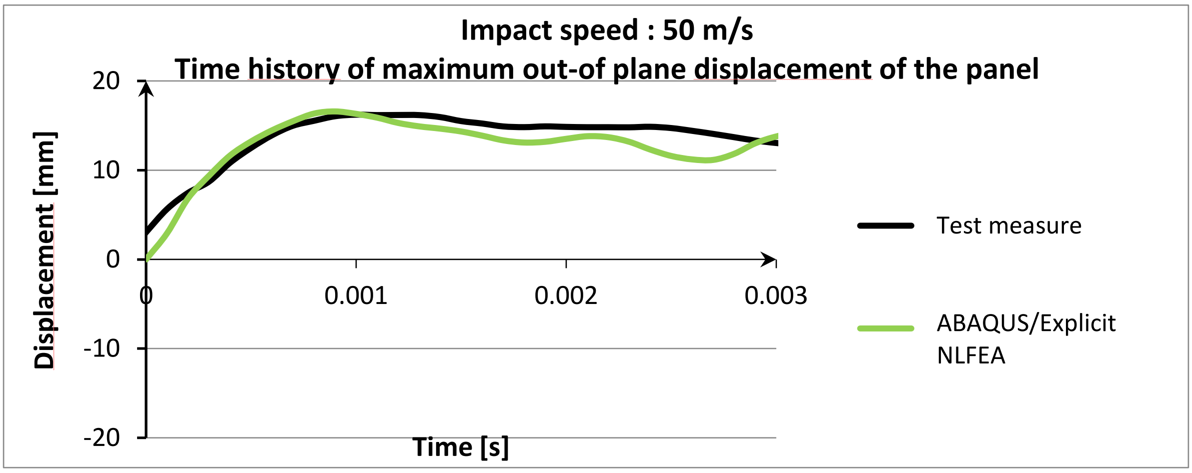
Before impact ***Initial contact***



After rebound

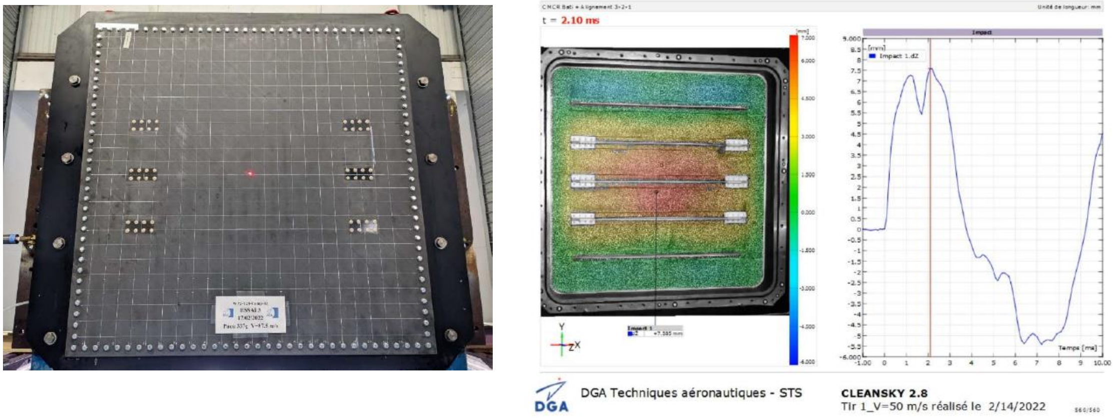
Figures 4-16: Tyre impact test on metallic flat stiffened panels – Impact scenario
Test result NLFEA result (ABAQUS/Explicit)

Figures 4-12 provides for the impact speed of 50 m/s the comparison between the predicted numerical simulation using NLFEA (ABAQUS/Explicit) with the test result for the time history of the maximum out-of plane displacement of the panel.



Figures 4-17: Tyre impact test on metallic flat stiffened panels – Pre-test simulations
Time history of the maximum out-of plane displacement of the panel

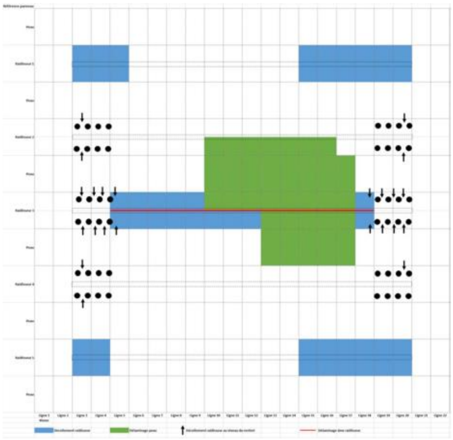
The second test campaign at Level 3 consisted in 5 tyre impact tests with different impact energies on large CFRP components (1100mmx1100mm stiffened flat panel as illustrated by the Figure 4-18 – left side) and has been performed at DGA-AS in February 2022 with the objective to characterize the global response and the local behavior analyzed by the stereo correlation as illustrated by the Figure 4-18 (right side). The panels were installed on a watertight tank in order to check their tightness after the impact.



Panel on the watertight tank ***Stereo correlation***

Figure 4-18: Tyre impact test on stiffened CFRP flat panels – Test specimen

A pressure measurement to check the post tightness impact and NDT analyses were carried out. The damage of the tested panels was characterized essentially by stiffener debonding from the panel skin and by the appearance with the increase in impact energy of delamination of the stiffener web and the skin at the area of impact. The following figure illustrates the resulting damage obtained after NDT of one of the panels subjected to the highest impact energy.



Blue parts show detachment of the stiffener from the panel
Green parts show delamination of the panel skin
Red line shows the “opening” of the stiffener web
Black arrows show detachment around the rivets

Figure 4-19: Tyre impact test on stiffened CFRP flat panels – NDT analyis

The pre-test simulations using the macroscopic approach with ABAQUS/Explicit had made it possible to predict qualitatively the appearance of delamination in the bonding zone between the panel and the stiffener as illustrated in the figure below:

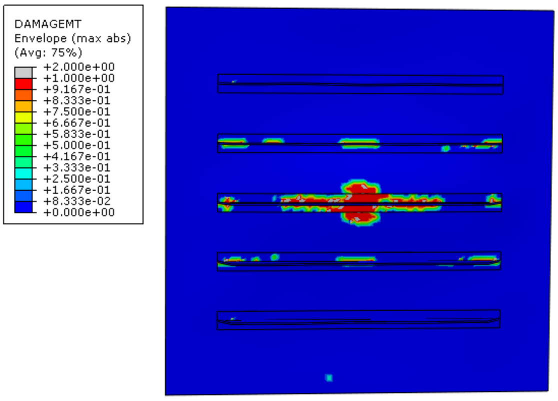


Figure 4-20: Tyre impact test on stiffened CFRP flat panels – Predictive numerical simulation

5. Conclusions and next steps

This paper has provided a general overview of the TIOC-Wing project currently in progress. Based on the building-block approach, the different stages of the validation pyramid have been presented for level 1 to level 3. The next steps of the project will focus on the continuation of the test campaigns in the level 3 and level 4.

In the Level 3, quasi-static tests in compression and in bending on composite stiffened panels damaged by tyre will assess the residual strength capability.

In level 4, it is planned in the next coming months to perform two tyre impact tests on 2 representative wing sub-components as illustrated by the Figure 5-1. It is also to carry out a comparative experimental evaluation which will make it possible to analyse the effect of the presence of the fluid on the response of the structure and on the damage of the multi-stiffened composite panel. To do this, a watertight box filled with water will be used during one of the tests.

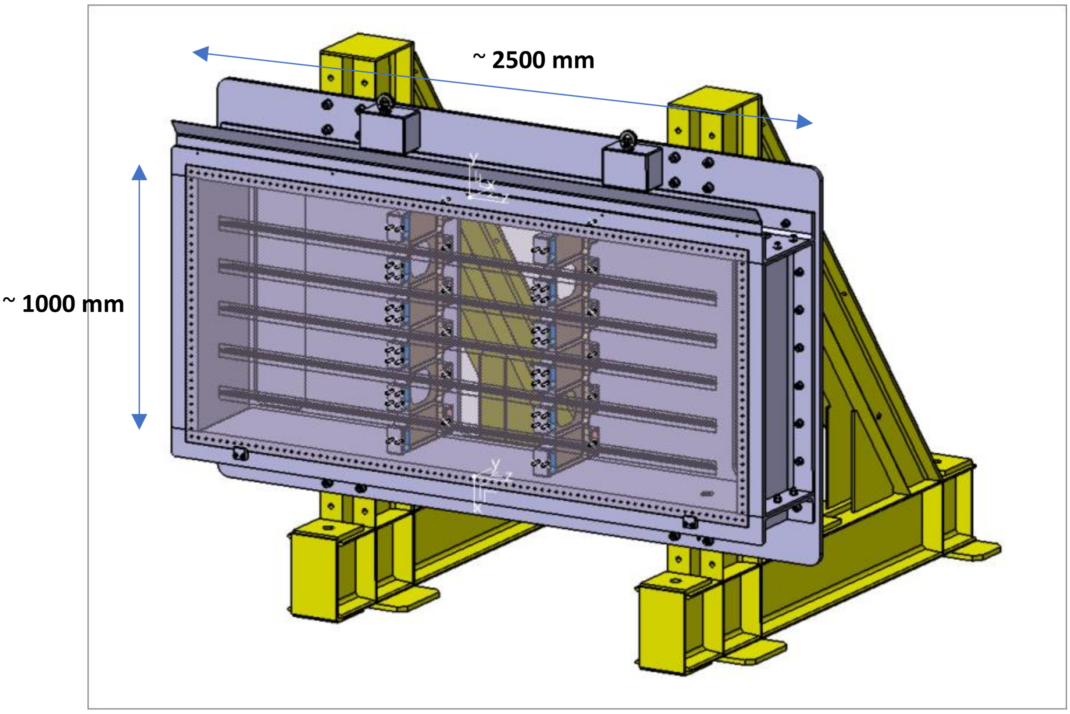


Figure 5-1: Multi-stiffened panel wing sub-components for tyre impact tests

Regarding numerical simulations tasks, current activities are focusing on the development and validation of more advanced approaches for modelling composite materials in order to better predict the various damages observed in previously performed tests.

Taking into account the uncertainties and variability on the parameters of the numerical models used, which is also part of one of the objectives of the project, is currently the subject of sensitivity analyses in order to identify the influence of these on the global response and on the damage of the structures studied.