Final Report Publishable Summary

More Affordable Aircraft structure through eXtended, Integrated, and Mature nUmerical Sizing

1.1 Executive Summary

The aim of MAAXIMUS is clearly mirrored in the project's full name "**M**ore **A**ffordable **A**ircraft structure through e**X**tended, **I**ntegrated & **M**ature n**U**merical **S**izing". The Consortium strives to demonstrate the fast development and right-first-time validation of a highly-optimised composite airframe. This overall objective was to be achieved through coordinated developments on:

- A physical platform (PP), to develop and validate the appropriate composite technologies for low weight aircraft
- A virtual structure development platform (VP), to identify faster and validate earlier the best solutions.

The dual approach of simultaneously working on virtual and physical enablers was absolutely necessary to develop both platforms with their specific and dependent needs, and to cross-validate their respective achievements. MAAXIMUS project constitutes a unique chance to demonstrate the **efficiency of virtual structure development** in the context of a real **innovative composite airframe** structure development. This approach is expected to introduce a "**cultural change"** in the way airframes will be developed in Europe.

The proper demonstration of the Full Scale Demonstrator with many challenging technologies and assessment of their benefits have been essential for MAAXIMUS and for a potential short-term and mid-term application in current and future aircraft programs.
Although the Physical Platform (PP) was running into a significant delay in period 7 due to some adverse circumstances, further impacts both on the integration of the VP and PP platforms and the associated validation work were successfully mitigated in the last period 8. The high complexity of the Full Scale Demonstrator and the numerous challenging technologies to be implemented were reflected in a re-scheduled timeline as part of the overall extension of the project duration to 102 months. Thus, it can be stated that the challenging project objectives regarding weight savings, manufacturing and assembly R/C reduction, section FAL time reduction, cost and overall time reduction in development, manufacturing, simulation and validation were widely achieved. MAAXIMUS technical activities led to numerous results of high importance which is also reflected by the achievement of all Phase II milestones.

MAAXIMUS was a key enabler of Fast Development of Right First Time innovative aircraft:

- Major step forward in design robustness and predictive capabilities
- Leap forward in the aircraft structure optimisation foundations
- Integrated CAD-CAM-CAE framework for aircraft development
- Demonstration on a full-scale composite fuselage demonstrator

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1.2 Context and Objectives

Composite materials provide higher stiffness and strength to density ratios than metallic ones. They permit the design of more integrated structures, with fewer fasteners. They are less prone to progressive damage under in-service fatigue loads with current design rules and are also less sensitive to corrosion. Therefore, composite solutions can deliver **lighter structures** with less maintenance and are increasingly used on business jets, regional and commercial aircraft. Composites represent 26% of the Airbus A380 structural weight. Up to 55% can be considered for the Boeing 787 and the Airbus A350 XWB. Nevertheless, increasing the percentage of composites in the airframe structure is not sufficient to achieve lighter and more cost efficient airframes: areas already in composite can be further significantly optimised in terms of cost and performance, and the various knock-on effects of a 'more composite' aircraft should also be considered.

Firstly, many fasteners remain in the design of today's composite structures as a legacy of metallic design approaches. Additional weight reductions can be achieved by reducing the number of fasteners: **the assembly of many small parts is substituted by a single one-shot large part**. However this one-shot technology route must be **economically sustainable**. Secondly, as the aircraft in-service performance demands more one-shot composite components, the **final assembly line process** must be adapted to their specific properties (**lack of ductility, higher stiffness)**. Otherwise, the production rate would be significantly lower than for metallic designs, creating an uneconomic industrial bottleneck. Thirdly, due to their laminate nature and the wide range of possible fibre reinforcements, composite materials offer **a huge range of design options**, with a strong dependency with manufacturing. Finding the manufacturing cost / in-service performance **optimum** in a so wide and complex design space and in the shortest possible period of time is a real challenge for the aircraft industry. Today, this process relies heavily on time-consuming and expensive physical tests; with a risk of late and costly design changes. **Simulation-based design** would provide a faster and less expensive path but current simulation capabilities do not provide the **appropriate level of confidence and cycle time**.
Lastly, composites have much lower thermal and electrical conductivities than metals. Due to their massive use, the aircraft system protection against lightning strikes, overheating or electro-magnetic fields is no longer 'naturally' ensured as with metals. **More attention on** is therefore necessary to avoid additional weight for system protection.

The aim of the MAAXIMUS project (More Affordable Aircraft structure through eXtended, Integrated, & Mature nUmerical Sizing) was to demonstrate the fast development and right-first-time validation of a highly-optimised composite airframe. This was to be achieved through coordinated developments on:

- A physical platform (PP), to develop and validate the appropriate composite technologies for low weight aircraft
- A virtual structure development platform (VP), to identify faster and validate earlier the best solutions.

The dual approach of simultaneously working on virtual and physical enablers is absolutely necessary to develop both platforms with their specific and dependent needs, and to cross-validate their respective achievements. This project constitutes a unique chance to demonstrate the **efficiency of virtual structure development** in the context of a real **innovative composite airframe** structure development. This approach is expected to introduce a "**cultural change"** in the way airframes will be developed in Europe.
It will enable for the airlines, aircraft with **lower acquisition and operating costs**, a **reduced Time-to-Market** and a **reduced environmental impact**. MAAXIMUS strongly contributed to strengthen the European aeronautical industry, in line with the objectives defined in paragraph AAT.2007.4.4.1 of the FP7 Work Program.

The MAAXIMUS contribution is also in line with the SRIA of the ACARE Council, regarding cost efficient aircraft. It also addresse the MANUFUTURE SRIA regarding acceleration of technological innovation in the field of manufacturing. It is fully complementary to demonstration oriented JTI.

The MAAXIMUS objectives related to the **highly-optimised composite airframe** were to:

- Enable a high-production rate: 50% reduction of the assembly time of large composite sections by an increased use of robotics for assembly automation and tolerance management. Demonstrate this achievement through the assembly of two composite sub-components representative enough of composite fuselage final assembly context.
- Reduce the manufacturing and assembly **recurring costs by 10%** compared to the ALCAS equivalent reference, as a result of more integrated structures
- Reduce the **structural weight by 10%**. Acoustics, lightning strikes, thermal effects, production ramp-up and rate, increased maintenance interval will be considered together with weight.

The MAAXIMUS objective related to a **faster development** was to:

- **Reduce by 20% the current development timeframe** of aircraft structures from preliminary design up to full-scale test (ALCAS reference), and **by 10% the corresponding non-recurring cost**, by a much higher integration of structure disciplines, with a higher fidelity and confidence in the virtual assessment of structural behaviour during the numerical optimisation process.

The MAAXIMUS objectives related to the **right-first-time structure** were to:

- Additionally reduce the airframe **development costs by 5%** through the delivery of a predictive virtual test capability for **large composite structures** up to failure **with a quantified level of confidence**. This capability will be assessed and validated through an exhaustive comparison with a pre-existing full-scale physical test of a composite fuselage barrel. A new Certification Philosophy, based on Virtual Testing, will be also assessed. It will also consider the structure as it is actually manufactured and assembled and not only as it is designed.
- Avoid late and costly changes due to unexpected test results. **Virtual Testing will be a major asset to freeze a trouble–free design** earlier than today. It will provide more mature aircraft to the customers at Entry Into Service, with fewer Service Bulletins or post-entry into service modifications. This will be a key asset for airliner satisfaction.

The Consortium of **57 partners** from **18 countries** was made up of aircraft **manufacturers**, **material** behaviour specialists, **software** developers, **computational mechanics** experts and **test centres**, both from industry and academia. The combination of such experience and know-how ensures proper capitalisation of results from past and current national and international projects.
The MAAXIMUS project was originally planned to run from April 2008 for 60 months but was subsequently and step-wise extended to 102 months. The reason for this extension was to accommodate changes in the components to be included in full scale physical demonstrator.

The project which contained over 60 WPs and several hundred tasks was broken down into six sub-projects (SPs) for the first phase of activities: aircraft requirements, design, analysis and verification, manufacturing and assembly, NDT and on-line process monitoring and lastly Test, correlation and validation. All of the activities within these sub-projects contributed to the abovementioned project objectives. To be able to measure and ensure compliance against the project milestones, the project activities where organised into the following themes:

- Advances in **Composite Technology**
- **Virtual aircraft Engineering and Manufacturing**
- Generic **Numerical technologies** for optimisation and analysis (computational mechanics)
- IT **framework** development, for a successful **multi-skill integration** of new methods into a coherent working environment

These four themes are transverse to the previously mentioned six sub-projects and are broken down into five distinct 'Hubs' in the project. Each work package is affiliated to a hub. Three of these thematic hubs will constitute the **Virtual Platform**, the remaining two will constitute the **Physical Platform**.

Virtual Platform:

- Hub A – Virtual Aircraft Structure Engineering and Manufacturing
- Hub B – Numerical Technologies for Optimisation and Analysis
- Hub C – Multi-skill Integration Framework

Physical Platform:

- Hub D – Advanced Composite Technology
- Hub E – Fuselage Design & Sub-Component Demonstration

Each work-package was affiliated to a hub where its results had the strongest influence on the expected results of the work package.

Hub D addressing **Advanced Composite Technology**

Based on a set of initial requirements, the main work in this area was the successive design, sizing, manufacturing and testing of a wide range of coupons, structural details and panels aimed at **evaluating the physical feasibility and performance** of innovative technologies or design principles.

Hub A addressing **Virtual aircraft Engineering and Manufacturing** development

The main focus here was the development and validation of new approaches for the airframe **virtual development**. This includes definition of airframe requirements, development and validation of design rules and **sizing criteria** (static analysis, fatigue and damage tolerance, thermal analysis, crash and impact), identification of the way to **numerically capture** useful manufacturing data (including defects), test **definition** to ensure method validation. As opposed to the previous hub, which is focused on physical evaluation, this hub is focused on defining and using the best **numerical information** in the development process.

Hub B addressing Generic **Numerical Technologies** for optimisation and analysis

The main challenge in this hub was the development of the high-level **numerical technologies** breakthrough that will enable the aircraft engineers involved in the previous topic to **use** much more powerful methods. These **breakthroughs** include **optimisation algorithms and strategies** to link the different design levels of the test pyramid and design stages, the **numerical techniques** to decompose huge finite element models into smaller ones, the mathematical means to estimate **error bounds** in these finite element models, or the mathematical techniques to estimate probabilities of failure, from global barrel scope through panel level, down to material scale.

Hub C addressing IT **framework** development, for **multi-skill integration**

The main focus here was the improvement of IT technology and software solutions to Composite Virtual Structure Development requirements, together with the **integration** of improved methods and modelling approaches in a coherent design - analysis – manufacturing – test **numerical framework**. The typical skills involved were **IT and software developers**.

Hub E addressing **Fuselage Design & Sub-component Demonstration**

Hub E performs the **design**, **sizing, manufacturing, control and testing up to failure of the full-scale composite barrel**. It will demonstrate the expected accuracy and confidence of the virtual platform. This hub will give the drumbeat to the project. The skills that bring the critical innovative elements will be composite manufacturer specialists, assembly and physical test (full-scale) specialists.

Therefore the overall MAAXIMUS strategy was to simultaneously address the two dimensions of the development:

- **'airframe development' skill** view from the Sub-Project view. The different sub-projects contained all the project work packages
- **'capability development'** view from the 'Hub view', to give a transverse vision on the project and to create the connection between Sub-projects.

For each hub, a set of challenges and associated use-cases were defined allowing the progress towards the achievement of the project objectives to be "assessed".

1.3 Main Results / Foreground

Given the large number of activities performed within the project corresponding to almost 6,000 Person-Months (PM) of effort, it is not possible to provide an exhaustive description of all project results. In this chapter, only the most significant results are briefly presented per sub-project (SP), making reference to the fulfilment of transversal expectations or challenges.

Results from the aircraft requirements sub-project

Requirements used by all of the project were established in the early phases of the project for the components of the physical platform (typically applicable regulations, overall architecture definition, Sub-component specific requirements (windows, frame, stringers, door surround etc); Material, process and fastener catalogue; manufacturing tolerances; test philosophy (sequence & categories of load); Design and sizing rules; CAD and Simulation Tools (including release identification) and design variables for optimization loop. Similarly requirements for the PAX doors (Type-A) and thermal aspect requirements were also provided. In the same way for the needs of the virtual platform, a generic model for the giga-dof challenge was developed. It consists of a fuselage slice (one frame-bay) with appropriate structural details inserted (windows, passenger floor, cargo floor, material data etc). This representative CAD model was used as reference for all solver developers.

Also, the requirements of the multi-level framework referred to as the VP were also expressed, for example, the capability to solve a Finite Element model of a barrel with a mesh made of 10^9 degrees of freedom hence the giga-dof challenge. Current industrial standards for Finite Element models are around 10-20 millions d.o.f., two orders of magnitude smaller. Another important aspect concerned multi-level optimization, providing the capability to federate all design activities across the various companies involved in the aircraft development within a consistent framework.

Results from the Design sub-project

Optimisation techniques for panels with tailored lay-up

Various project partners worked on the the optimisation of composite stacking sequences at panel level under the simultaneous consideration of post-buckling, strength and manufacturing constraints. Several approaches and the associated numerical methods and algorithms (together with the resulting code) were proposed, from different classes of techniques, from purely discrete and evolutionary algorithms or heuristics (ant colonies) to reformulations for gradient-based optimisers.

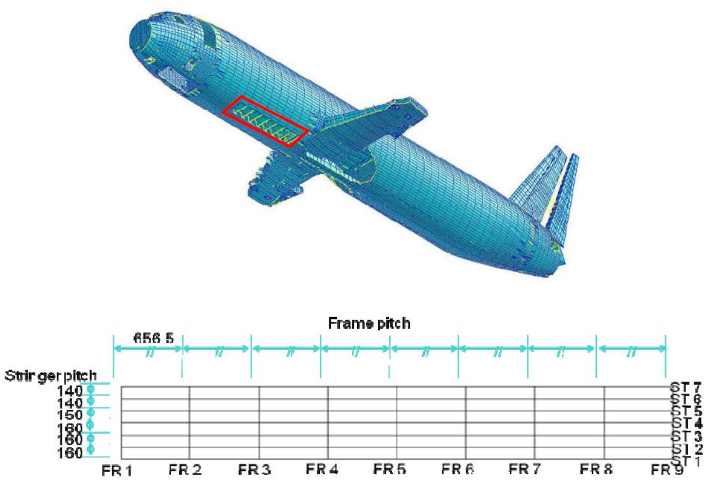


Figure 1: Extracted panel considered for panel use case

These innovative optimization methods were then integrated in a single platform, namely BOSS quattro. Different approaches were proposed because of the discrete structure of stacking sequences, a natural approach consists in applying discrete methods for the optimization of sequences: this is the case of GEOPS, based on genetic algorithms, and the backtracking generator for stacking sequence tables, a variant of enumeration-tree approaches. In contrast with GEOPS and backtracking, a re-formulation of the problem in terms of continuous design variables (laminate parameters of SIMPlike formulation) was performed. Partner (6) AI-UK restarts from the results of this continuous optimization to adapt the sequence itself, while partner (44) SAMTECH uses a "guide" generating variants of a common "parent" stacking sequence. Whatever the method selected for composite sequence optimization, it may prove expensive in terms of function evaluations, i.e. calls to the analysis tool, e.g. for buckling analysis. This is the reason why it may prove useful to replace the original simulations with surrogates, which speeds up the process. This is the goal of the original "mixture of experts" method presented by ONERA (partner 40).

Reliability-based design optimisation (RBO)

Activities aimed at developing and integrating advanced optimisation tools comprising of novel sensitivity analysis strategies for RBO of composite fuselage structures and demonstrate these capabilities on panel and fuselage level for different design stages.

Probabilistic optimization methods

A study was performed by ENGINEOUS – now linked to DS (partner 12) – to highlight the diferent elements required for a probabilistic optimization, namely the simulation model, the stochastic model – distribution function, the probabilistic assessment – MCS, MVFO, FORM, SORM, the optimization algorithm and the approximation technique.

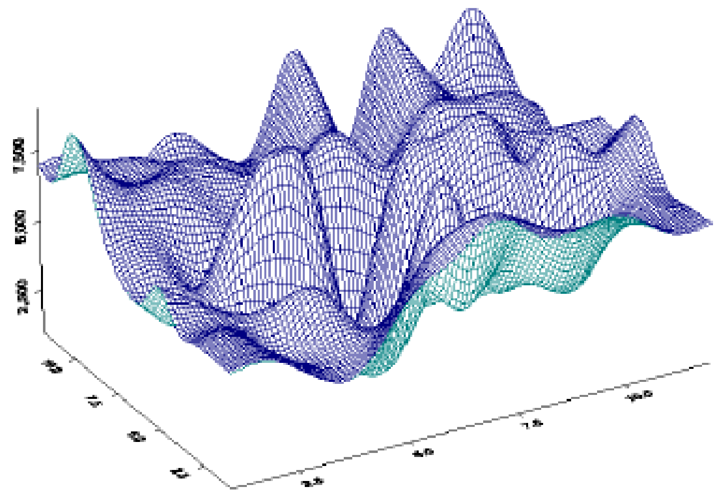


Figure 2: Stochastic optimisation algorithm use-case

Choosing a fitting combination of all the pieces is the key to a successful application of probabilistic optimization. All items should be on the same level of fidelity. It does not make sense to use a very high fidelity Monte-Carlo-Simulation-Study, if the distribution functions are only very roughly known. In these cases any attempt to calculate very unlikely events will fail. Also the choice of the optimization algorithm needs to fit. Since the results of MCSs are inherently noisy, gradient based algorithms will often fail. If the reliability is taken into account and there are two or more constraints, often situations will occur, where the MPP fluctuates between multiple constraints, generating a difficult to solve optimization problem. Most success was obtained in choosing pattern search algorithms and increasing the values for the probabilistic constraint during the course of the optimization, from a one sigma to a three or four sigma design. The test cases of the panel lead for each reliable design to an increase in mass, compared to the deterministic design. From a design standpoint it would be interesting to determine the trade off between weight and manufacturing costs. Since in the panel case the uncertainties enter the problem mostly through the manufacturing process, controlling this process better could lead to a smaller input parameter variance and hence to a lighter design.

Reliability-based Optimisation

A new RBO scheme was implemented by partner (49) NLR and successfully applied to a number of test problems following a step wise approach. The probabilistic approach, including the Reliability-Based Optimisation (RBO) scheme, was demonstrated by means of the NLR in-house tool RAP++ on several test problems of increasing complexity and compared against the deterministic approach following a standard procedure. The first two test problems consisted of a 10-bar truss and a 25-bar truss frequently used in literature to demonstrate optimisation schemes. Next, two different

composite fuselage panels were analysed demonstrating the probabilistic approach for realistic problems. The probabilistic results were compared against results obtained with a typical deterministic optimisation approach and showed that an improved optimal design can be obtained with a predetermined reliability level. It has been demonstrated that RBO of structural design problems can be performed successfully, although against substantial computational costs. Hence, its application is feasible for smaller component level problems (e.g. fuselage panel) rather than on large components (e.g. barrel level) or even on a full scale aircraft model. It was demonstrated that a probabilistic approach taking into account uncertainties (scatter/variability) in geometry, loads and material properties can (substantially) improve the design of structures compared to the traditional deterministic approach in combination with scatter and safety factors, which often yield a too conservative design. A probabilistic analysis can provide the reliability level and the best directions to improve the design.
In composite structures design, the larger variability observed in composite materials requires different scatter and safety factors and often the design principles are based on a worst-case scenario increasing the deterministically obtained conservatism even further. A probabilistic approach on the other hand requires sufficient data to characterise the variability in the dominant random variables, for which currently often the data is lacking. In these cases an upper bound can be selected for the variability yielding more conservative results.

Mathematical techniques for sensitivities in manufacturing or load variation
An improvement of the feasible direction technique has been developed in order to get approximate optimum solutions without carrying out a new optimization loop. The linearization of inactive constraints about the optimum solution allows updating the set of active constraints. The results obtained with this new approach are significantly better than without updating the set of active constraints. In order to check this method, parameters of different natures were chosen in the study. After checking the method in two bar structures, it was applied it in the panel use case provided by partner (49) NLR obtaining good results. The following conclusions were drawn of this work:

1. This approach to get approximate optimum solutions may be an efficient tool for estimate the evolution of optimum solution when a parameter changes its value.
2. Computational time is small compared to the optimization process.
3. The three bar truss example shows the efficiency of tracking active constraints. Satisfactory results were obtained for the ten bar truss example even for large parameter variations.
4. A stiffened panel representing a fuselage component has been used also as an application example. Again the accuracy of the approximate solutions is also adequate.
5. In the aluminum panel example, it is observed than the set of active constraints can change substantially for small parameter variation (5% when $p=r$), being not valid the initial technique. This issue is corrected by tracking active constraints.
6. In the composite panel, the approximate optimum solutions are good for small parameter variations. For large parameter variations the obtained design is far from being the optimal solution in some cases.
7. If slenderness constraints are not considered in the optimization problem the thickness of flanges and webs leads to their minimum value.
8. The panel optimization considering frame pitch and stiffener pitch as design variables produces an appreciable decrease of the objective function value (mass/m^2).
9. If only buckling and slenderness constraints are considered the value of the optimal solution decreases substantially while the application of strain constraints leads to a heavier solution.

Optimisation tools for multi-criteria stochastic problems
This work presents a new stochastic design methodology that aims at enabling accurate design decision-making over time, in the presence of uncertainty. It provides affordable solutions in multi-

variable and multi-criteria problems. On the contrary to the contemporary state-of-the-art multi-objective tools, the VSLCD is able to cope with non-deterministic parameters whose values are governed by a certain distribution over time. Moreover, VSLCD is capable of providing accurate solutions within a considerably short-time, compared with traditional multi-objective tools. This work demonstrates the capability of VSLCD tool to cope with multi-criteria problems. The presented example incorporates three non-deterministic variables that affect two contradicting criteria. Simulation results show the proof-of-concept. Further work can be done towards the criteria trade-off after a first solution has been obtained based on the certain given criteria weights and bounds. This process takes place whenever the initial decision made by the tool does not fully satisfy the designer or the designer wants to further explore different potential solutions.

Feasibility for barrel stress sizing optimization (preliminary/detailed)

The objectives of these activities was the implementation and establishment of a prototype multi-level optimization framework for fuselage sizing for the preliminary and detailed design phases: “Virtual design framework” able to handle large scale data management. A very Large Size Optimization algorithm has been developed by partner (44) SAMTECH based on a multi-grid approach. The algorithm has been developed and integrated in BOSS Quattro. Tests are on-going on a representative test-case of the barrel (panel test-case).
An innovative algorithm (Maximum Entropy Principle) has been successfully completed by University of La Coruna, integrated in BOSS Quattro (optimization kernel of MAAXIMUS framework) and demonstrated on a representative test-case: detailed finite element model of a panel built by partner (49) NLR. Similiarly, another innovative approach for multi-level optimization of structures has been completed by partner NLR with extensive use and expertise of surrogate models. Two kinds of finite element models have been used:

- a Global Finite Element Model for the extraction of internal loads.and the global optimization based on surrogate constraints
- a Detailed Finite Element Model for the calculation of the buckling behavior and the local optimization to build the surrogate constraint for the global level.

A demonstration has been run on a barrel representative use-case (stiffened panel use-case).

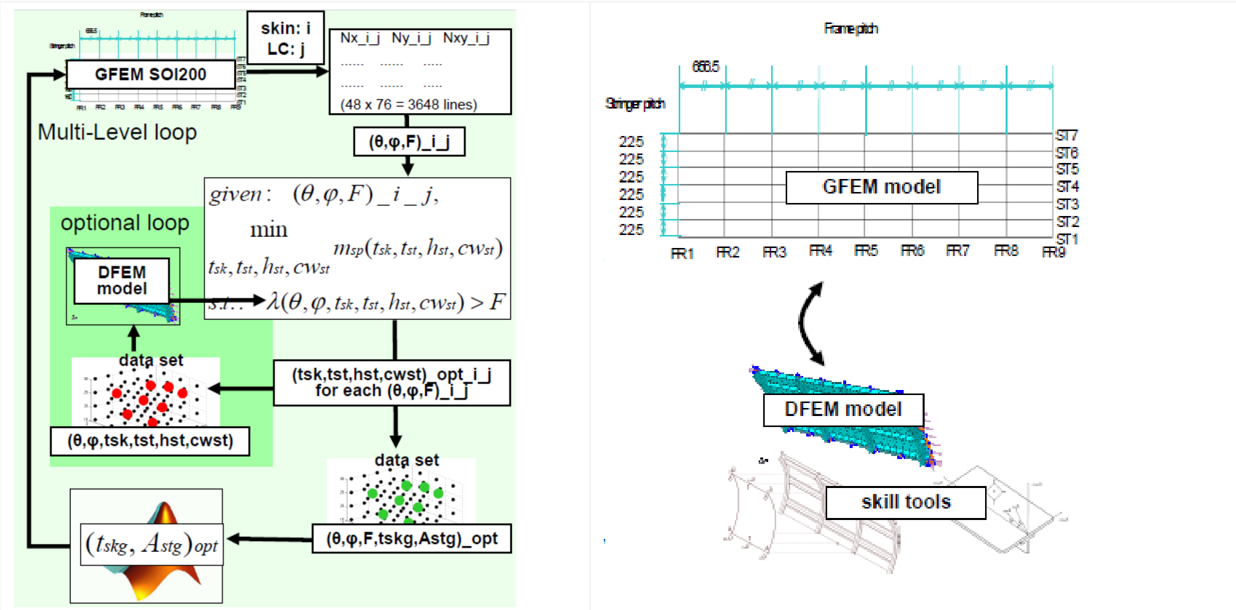


Figure 3: A bi-level global-local optimization scheme with surrogate models

Rapid sizing and pre-sizing results have already been demonstrated over the past years. Two multi-level strategies have also been clarified, implemented and integration is on-going in MAAXIMUS framework (through BOSS Quattro). They are not fully equivalent. One based on surrogate models is

probably appropriate for rapid sizing. The second one base on an "optimization of optimization" approach is more dedicated to detailed design (because more accurate).
All partners have solved comparable use-cases (panel level test-case) both in a multi-level way and in a single level way. A quick analysis capability has been delivered for post-buckling of a fuselage section.

Common engineering parametric model

This activity aimed to specify and prototype a framework architecture for a full design loop for composite components including automatic iteration between design, simulation and manufacturing (CAD-CAE). This would support the virtual platform enabling composite applications and the communication through a unified hub.
A multi-skill integrated framework was developed which offered the following innovative features:

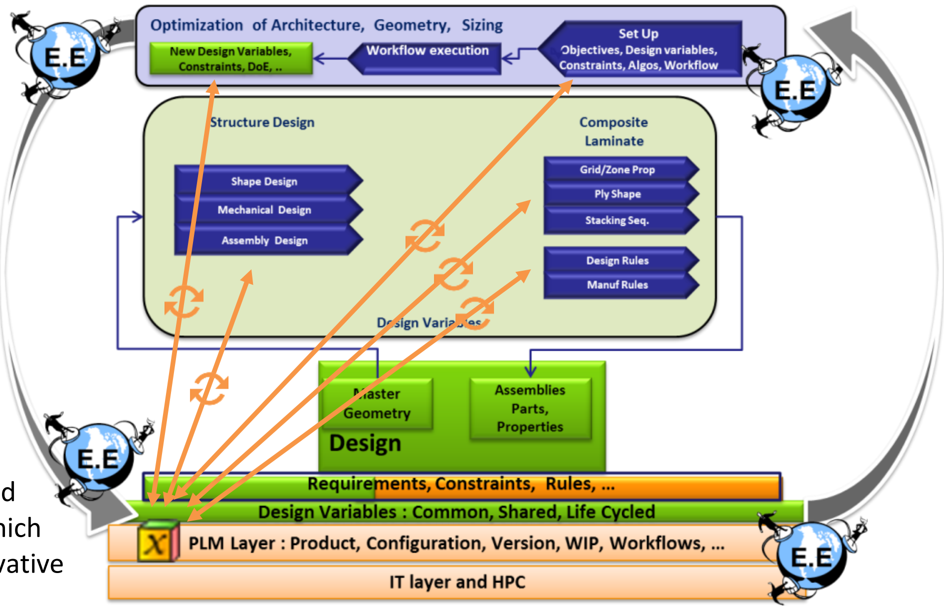


Figure 4: Parameters management with PLM parameters

- **Innovative methodology to design composites structures.**

The grid approach developed by partner 12 DS in CATIA allows "relational design" to be applied to design composites structures. Thanks to the "grid" and "virtual stacking" managed by CATIA at early stages of design, optimization of thickness laws and/or stacking sequences can be shared directly between design and analysis. Design variables are managed independently from geometry to provide increased optimisation flexibility.

- **Common master design model shared by designers, analysts and optimizers**

Design process and concepts are now adapted to the analysts' « way of design » and optimization. Again, this is made possible by the grid and virtual stacking which are managed by designers and which also match analysis and optimization entities. Design variables have been made independent of geometry to be shared across disciplines i.e. design and analysis today and manufacturing tomorrow.

- **PLM Environment supports « Close Design-Analysis Loop »:**

The following PLM functionalities are key in this analysis design loop: Role and right management, Data management, Process flows, Check-in/check-out, Traceability, Impact analysis, Configuration, Versioning, Maturity. Extended Enterprise (EE) is supported. Design Variables are managed by PLM independently from the geometry. Life cycle management applies to Design Variables.

- **«Close Design-Analysis Loop » applies to skill tools (analytical) as well as to « FEA Analysis »**

- **Sharing across multi disciplines of parameters specific to composites part**

The parameters defining the laminates (thickness law or stacking sequence) available for a composites design are exposed at a higher level in the composites design part, as opposed to their previous encapsulation in the design itself. Thanks to the "extended laminate", the above mention laminate parameters are brought in the PLM layer and as such become shareable, visible and supported by the Extended Enterprise.

- **Manufacturability assessment of composites part**

The assessment of the manufacturability of a composites part, if performed at the end of the detailed design phase, usually requires the design to be modified so that it becomes manufacturable. The composites data model is now enhanced and support the manufacturing parameters to be applied during the preliminary phase of the design, and as such, permits the assessment of the manufacturability at an earlier stage of the process:

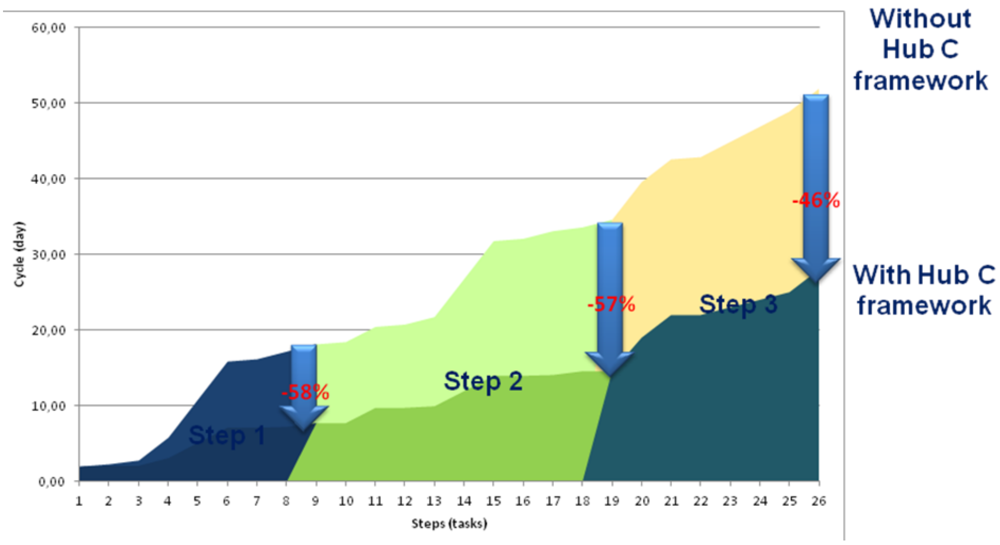


Figure 5: Impact of multi-skill framework on development cycle

Extended entreprise framework

Results in this area were target at two different levels:

- from the analysis integration platform, develop the capability to distribute the computations over a network;
- at a higher level, insert the analysis integration platform into a global process including the management of users and access rights.

During several project reviews live demonstrations of the the various couplings which can be industrialised in a straightforward way were made:

- The link between CAESAM (as analysis integration platform – provided by partner 44 SAMTECH) and an SLM (ENOVIA – provided by ENGINEOUS, now partner 12) in such a way that the stress analyst work is part of a complete simulation management framework.
- Added to CAESAM was also the capability to use another tool provided by ENGINEOUS, namely FIPER, for the remote and distributed analysis runs.

Static Analysis

Results in this field included the integration of several multi-scale damage models, for example from partner 3 ALE going from micro level (fibres and matrix) by homegenisation according to the Mori-Tanka resulting in the compliance on the meso level (ply level). Also, partner (57) ULIM provided 3D bolted joint models. These models werr subsequently integrated into a ABAQUS user material routine (UMAT) were refines were made to include SLS (solid like shell) visualisation and sub-modelling. These models were tested by industrial partners such as Airbus on relevant use cases.

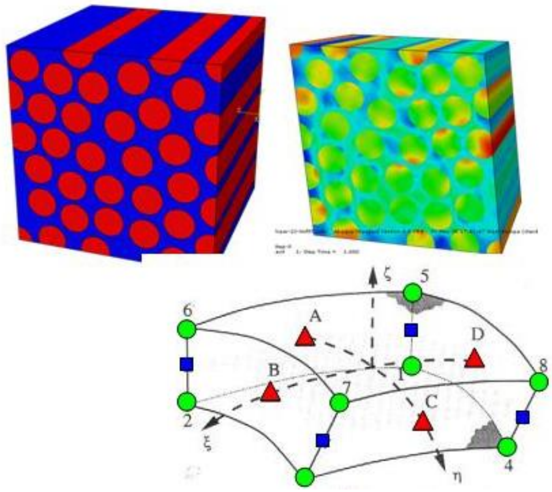


Figure 6: Multi-scale model (Mori Tanaka) for coupons and panels

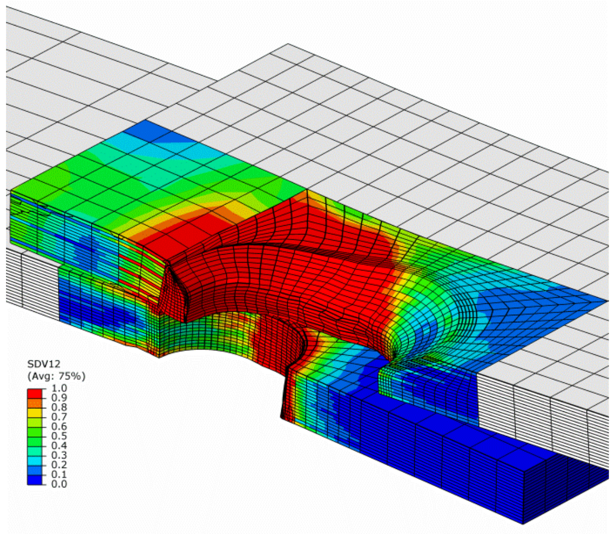


Figure 7: Damage pattern in single bolt joint (bolt removed for visibility) of carbon fibre composite

Fatigue and Damage Tolerance

Fatigue methods for bonded joints and bolted joints were developed and implemented in two major commercial FE-systems as summarised in the table below:

Partner	Type	Software used	Remarks
(58) LTSM-UP	Damage 1-models of plain weave, NCF material, Coupons	ANSYS	UserSupplMatMod
(10) CIRA	Buckling-induced delamination 0-growth, Panel	ANSYS	Software Development
(55) FOI	Fatigue in complex bolted joints, debonding 0, Panel, Frame	In-House	Software Development
(26) IMPERIAL	Damage laws for interface elements	ABAQUS	Constant Law

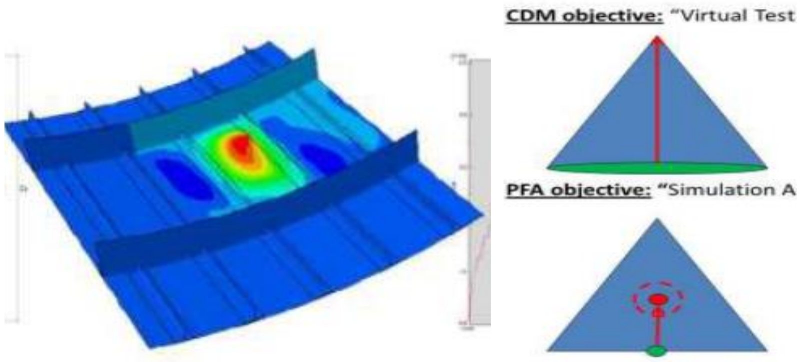
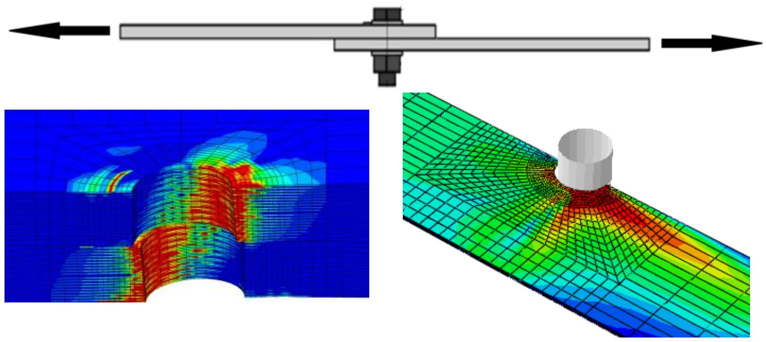
Partner	Type	Software used	Remarks
(26) IMPERIAL	Fatigue life prediction 0 in adhesive bonds, Coupons	ABAQUS	Software Development
(40) ONERA	Multiple-delamination growth in laminate subject to compression	In-house	Unique in MAAXIMUS

Classical fracture mechanics based techniques were used to analyse multiple delamination growth. Significant results in this area include:

- Improved laws for damage growth in bonded joints (26 IMPERIAL)
- Verified damage growth model based on fast and novel high-accuracy numerical methods for multiple damage growth in bonded joints (55 FOI)
- Skill tool for buckling delamination analysis and a novel numerical tool for single delamination growth analysis in stiffened structures (10 CIRA)

Low Velocity Impact/High Energy Impact

Numerical schemes/models for analysis of low-velocity impact on stiffened shells and on bolted frames were developed and partly verified. Significant results include:

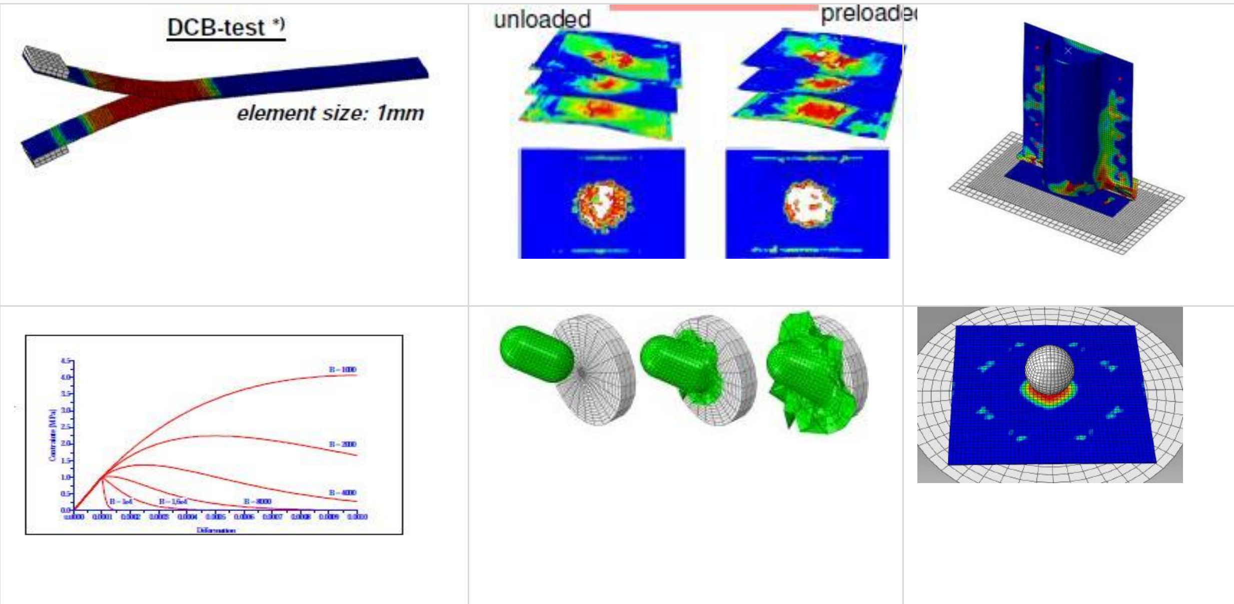
A novel concept for prediction of damage after impact on realistic fuselage sec-tions was developed and partly verified (17 AGI-F).	
Several numerical schemes based on the most advanced da-mage models avai-lable were developed and validated for analysis of complex bolted joints (57 ULIM)	

Vulnerability (Crash and high energy impact)

Advanced damage models have been implemented in form of user-supplied material-models in commercial software and in in-house software. The effectiveness and the accuracy of the software and the damage models have been investigated by analysing various aircraft components and the numerical results have been compared with experimental data. Significant results from these activities include (see also images below):

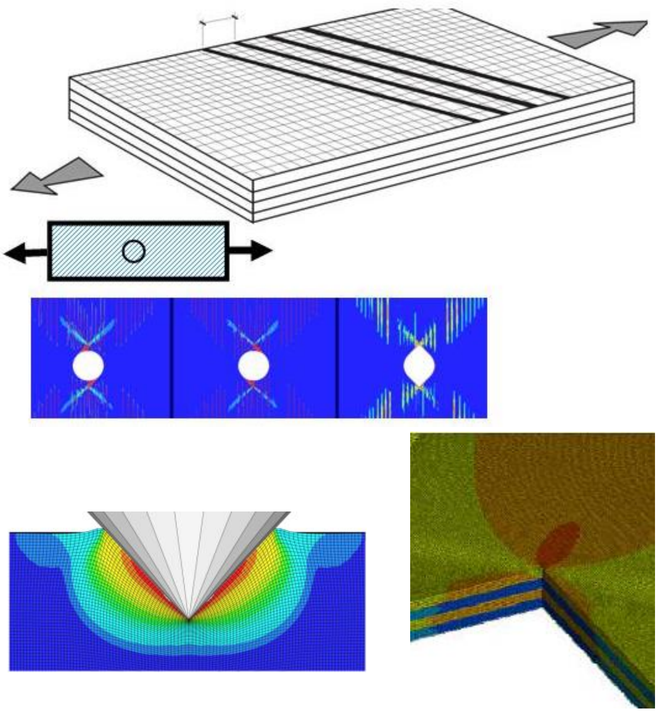
- Better models for high velocity impact modelling (40 ONERA)

- Characterisation of IMA/M21 material for vulnerability analysis (15 DLR)
- Selection of the optimum numerical scheme for vulnerability analysis when ABAQUS software is used (16 AIRBUS DS-D)



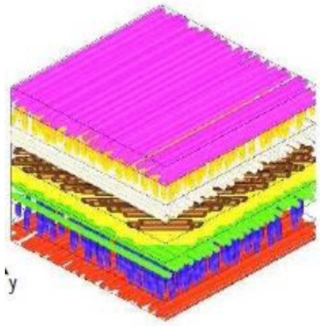
Environmental Effects on Material Properties

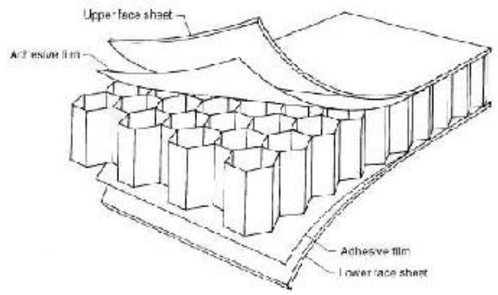
Several models for simulation of hot/wet conditions on mechanical behaviour and damage growth in composite materials were developed. The models were used to increase the understanding of the influence of hot and wet processes on material properties and damage growth (59 IMDEA Materiales).



Thermal and Electrical Conductivity

Models (based on the most recent homogenisation theory) and software have been developed for determination of homogenized thermal properties (4 AIRBUS OPERATIONS) for composite laminates and sandwich structures (29 INSA).





Thermal Analysis with respect to Equipment

A powerful and accurate scheme for heat flow optimization in the crown compartment has been created based on response surfaces derived by using computational fluid dynamics methods (57 ULIM). Several new reduced heat flow models have been developed (partners 4 AIRBUS OPERATIONS and 40 ONERA), see also images below:

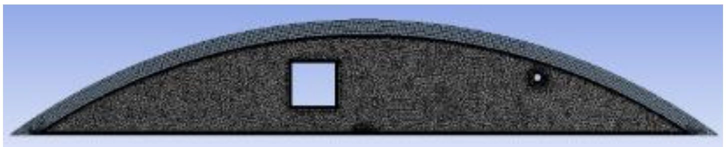


Figure 8: Use of CFD to create design space (ULIM)

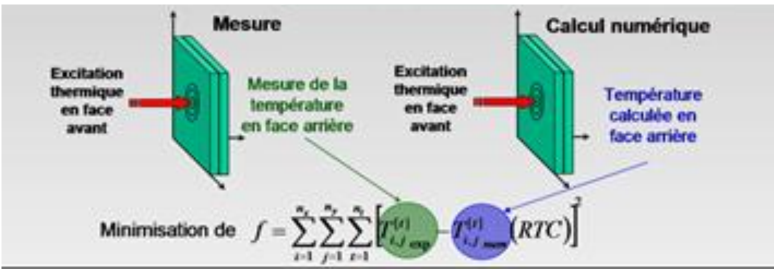


Figure 9: Mod. Flame impingement (ONERA)

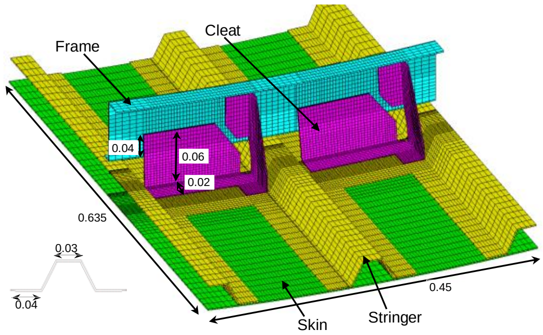
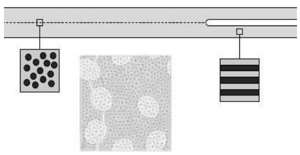
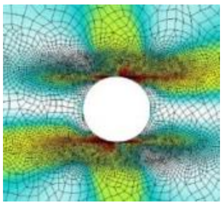
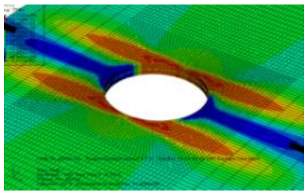
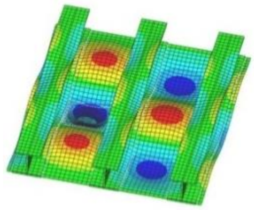
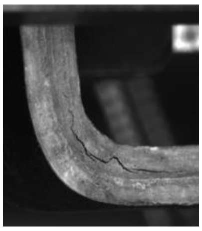
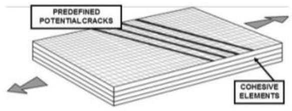
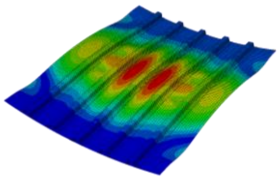
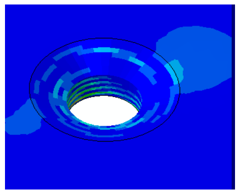


Figure 10: Multi-scale reduced models (AIRBUS OPERATIONS)

Advanced Damage Modeling

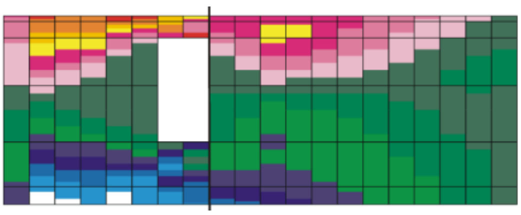
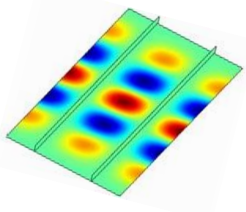
This was the largest WP in MAAXIMUS project in which a menagerie of damage models were created. The activities ranged from rather basic research to development of methods for applications and data base creation. Work contents are: Use of advanced damage modelling (ADM) for panel

design (63 ALA), basic work in order to understand the effects of defects as voids, stability, fibre waviness (35 LUH), characterisation of IMA/M21E static/dynamic material properties (57 ULIM), improved and verified ADM modelling in commercial software SAMCEF (9 CENAERO and 44 SAMTECH), new method for statistical ADM analysis of complex joints (38 ENSC), numerical schemes for multiple delamination growth (10 CIRA), catalogue/database of observed type/size manufacturing during aircraft production (1 AI-D), a method for damage analysis of bolted joints of NCF/braided composites.
The significant results come from this activity can be summarised as:

Novel path following algorithm stability / damage (53 TUE)	Improved model for damage and rupture in composites (40 ONERA)	Advanced ADM analysis of inter/intra damage in flat plates with multiple bolts/fasteners (57 ULIM, 38 ENSC)	Multiple delamination growth in stiffened flat plates (10 CIRA)
			
Creation of database of effects of defects observed during manufacturing (1 AI-D)	Scientific approach to analyse effects of defects (59 IMDEA Materiales)	Novel computational scheme for analysing effects of defects on micro-scale (35 LUH)	Verification/validation of ADM analysis methods in bolted joints (17 AGI-F)
			

Fast Methods of Sub-Components and Fuselage Sections at Preliminary Design Stage

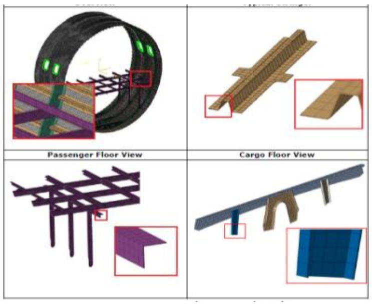
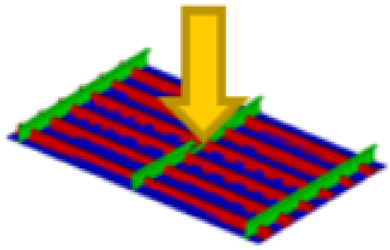
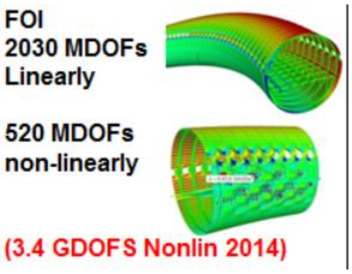
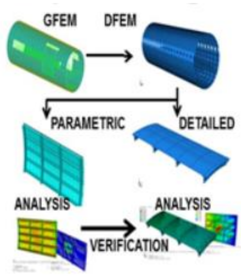
Several important developments were obtained in this WP: FE-systems for large-scale nonlinear damage analysis of complex joints (58 LTSM-UP), fast semi-analytical tools (41 POLIMI and 15 DLR) for stiffened plates and full fuselage (43 RWTH), a better shell finite element (28 USTUTT), a finite element for advanced damage analysis (53 TUE), and an evaluation of the efficiency of three damage models for use in stiffened shell analysis (DLR). Especially noteworthy are the results from RWTH and POLIMI as well as the comparison made by DLR.

Fast and accurate tool for barrel analysis/optimization (43 RWTH)	Fast semi-analytical tool for buckling optimisation of stiffened plates (41 POLIMI)
	

Advanced Computational Mechanics Strategy for Aircraft Sub-Components and Structures

Several partners (2 ABQ, 9 CENAERO, 55 FOI, 40 ONERA, 44 SAMTECH, 28 USTUTT) tried to develop effective solvers for solution of nonlinear fuselage problems of size 1 GDOF (10^9 degrees of freedom). Two partners worked with automated systems for the creation of large fuselage meshes (2 ABQ, 12 DS), two partners developed novel numerical schemes for nonlinear (38 ENSC) and dynamic (29 INSA) analysis and finally a framework for multilevel optimisation of fuselage structures was developed (49 NLR).

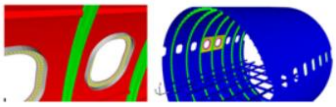
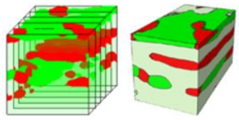
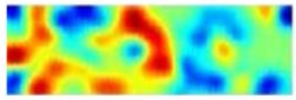
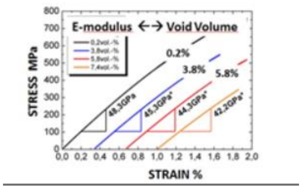
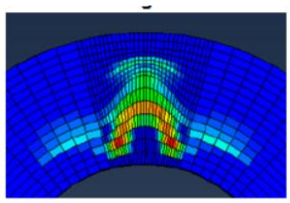
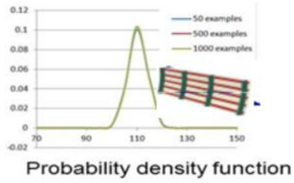
The large-scale capacity of the commercial software ABAQUS and SAMCEF were increased so very large (few hundred MDOF) nonlinear problems could be solved (2 ABQ, 44 SAMTECH, 9 CENAERO). The large-scale capacity of a research code was increased so the 'GDOF challenge' target could be reached by solving nonlinear 2-GDOF fuselage problems in short time using a CRAY systems with >10 thousand cores effectively (55 FOI). A novel dynamic code coupler was developed which allow analysis of models consisting of different meshes and different time steps (29 INSA). A novel and general multi-level system for fuselage optimisation was developed within this work package (49 NLR).

Partners 2 ABQ and 12 DS solutions	29 INSA dynamica code coupler
	
55 FOI solutions	49 NLR framework for ML optimum design
	

Robust Analysis: from Sensitivity Analysis to Statistical Analysis including Stochastic Analysis

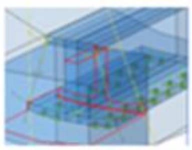
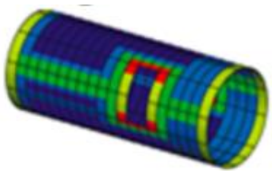
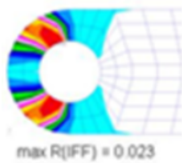
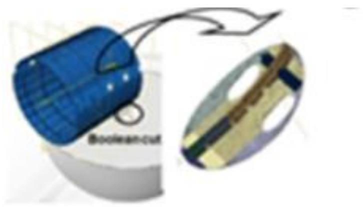
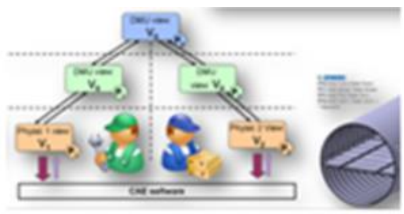
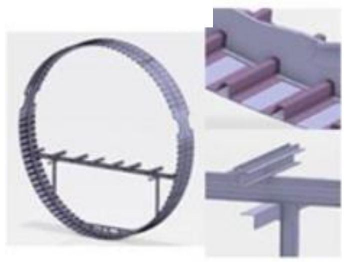
Activities included the development of a module for statistical input data generation to be used for Monte Carlo type statistical analysis with ABAQUS (2 ABQ), the development of a system based on stochastic Galerkin methods (51 TUBS) which together with experimental data (52 TUHH) made it possible to create statistical void distributions, a multilevel approach was used to calculate the effects of manufacturing defects (1 AI-D), a general system setup was created for modelling with variability and stochastic fields (17 AGI-F) and finally, scientific methods and a framework for large-scale statistical multi-site fatigue analysis (metals) of full fuselage sections were developed (55 FOI).

55 FOI multi-scale scheme for statistical bolt fatigue	51 TUBS Stochastik Galerkin method	17 AGI-F Modelling with variability and stochastic

		modelling
		
52 TUHH Analysis of manufacturing defects	1 AI-D Multi-level approach manufacturing defects	21 FICG Stochastic analysis of structures
		

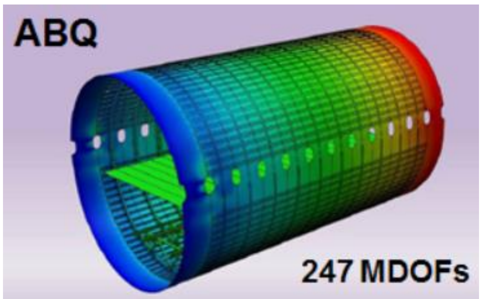
CAD_CAE-CAD process & automatic meshing

A set of software tools for the Hub C platform was developed, i.e. automatic generation of input data for contact surfaces (2 ABQ) making true large-scale analysis practically possible, automatic transfer of boundary conditions data (global → local) when so called sub-modelling is used (ABAQUS) which saves time for smaller problems and avoids errors, semi-automatized methods for fast geometry input data generation for full fuselage sections with a-priori well-defined geometries (partner 12 DS) need for large scale nonlinear analysis, a fast and accurate analysis tool for barrel optimisation was developed (43 RWTH) permitting preliminary design optimisation of large structures such as fuselages and finally a feedback technology for tailored-fibre-placement (54 TFP) was developed (15 DLR) permitting reliable analysis of TFP structures.

2 ABQ Automatic selection of contact surfaces	43 RWTH Analysis (optimisation) of fuselages	15 DLR Feedback of TFP data
		
2 ABQ Automatic sub-modelling	17 AGI-F Multi-physics / scale FE-analysis	12 DS Meshing and modelling
		

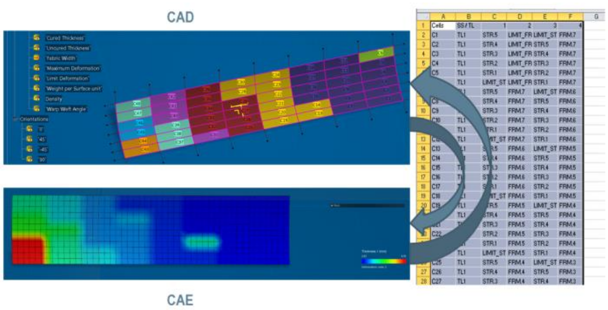
Large–scale Analysis Post-processing

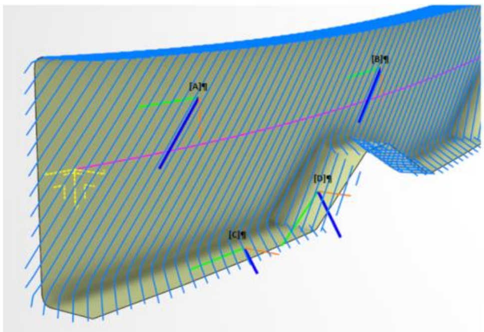
The postprocessor capability to ABAQUS was rewritten in order to post-process much larger models than hithertho. The work was absolutely necessary in order to take advantage of the new large-scale analysis capabilities in ABAQUS resulting from MAAXIMUS work.



CAE models Integration for Composites

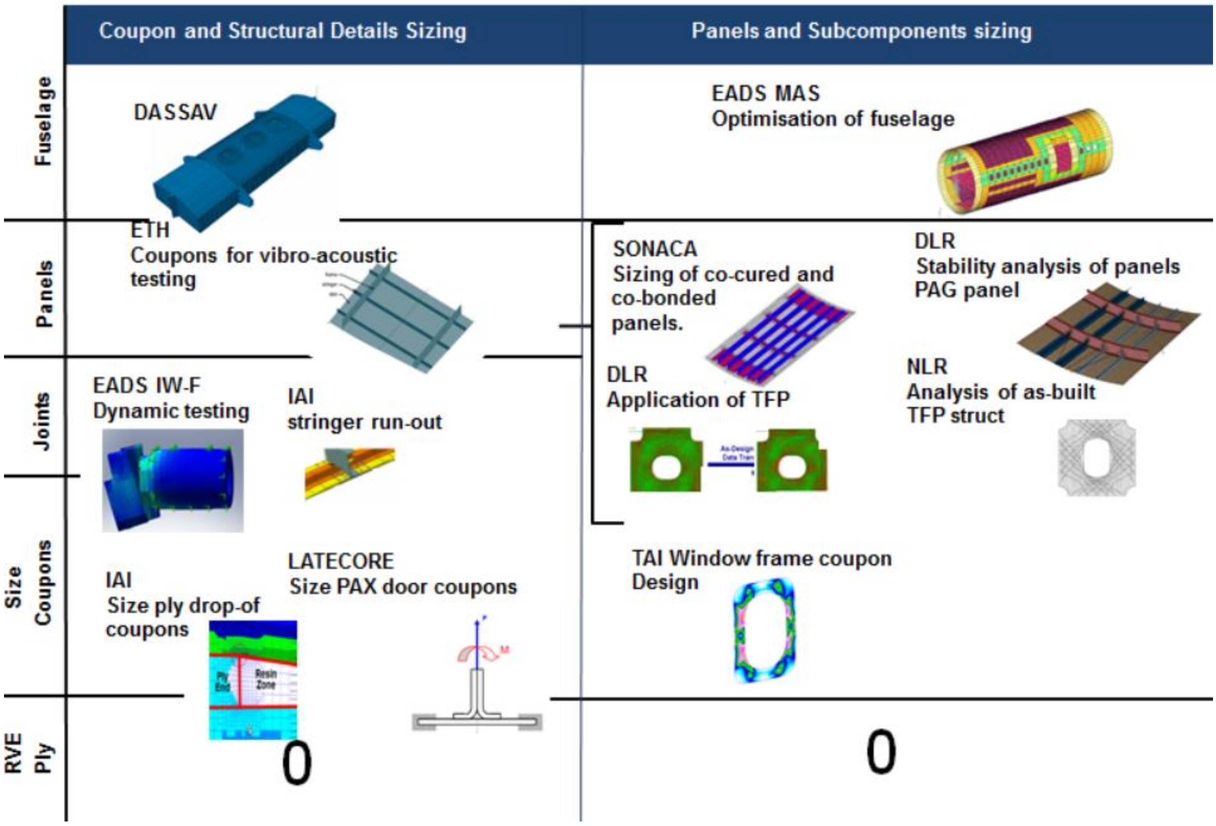
Activities were related to the development and implementation of two damage models in the commercial software SAMCEF and ABAQUS (3 ALE, 38 ENSC). Two partners (2 ABQ, 44 SAMTECH) provided software support to several other partners (40 ONERA, 29 INSA, 15 DLR, ...). However, the main activity was the development of an enhanced composite data model (ABQ) and its integration into an integrated CAE framework (44 SAMTECH). Of special importance is the adaption of the data structure and the CAE-framework for effective analysis of as-built composite structures (12 DS). An enhanced composite data structure was defined, a general software interface developed and the internal data structure in ABAQUS revised accordingly to form a new powerful part of the CAE-framework (2 ABQ, 44 SAMTECH, 12 DS). Functionalities for analysis of as-manufactured composite structures were integrated in the multi-skill framework (12 DS).





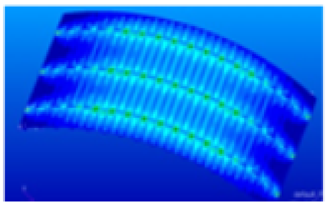
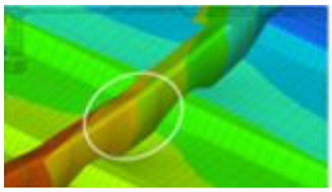
Panels or sub-components sizing to support and verify high fidelity structural analysis methods

Activities were focused on the verification of predictive capabilities for analysis and optimisation (16 AIRBUS DS-D) of window frames (56 TAI) and stringer stiffened panels (48 SONACA, 15 DLR) where improved stiffener and material lay-up modelling are used, to test and evaluate existing sizing techniques and special purpose FE-meshing/modeller for tailored fibre placement (15 DLR, 49 NLR) in actual frame and stringer stiffened panels and finally, to size a number of stiffened panels to be tested. Tailored fibre placement technologies were significantly developed and applied (DLR, NLR).



Sizing of components for testing at panel level & for integration at barrel level

The focus of activities was on the door surround area. Improvements in framework (1 AI-D) for composite fuselage optimisation were made, two PAX doors (34 LATECORE, 19 AIRBUS HELI) were sized with partly new technologies and software, significant efforts were put into improved frame design (3 ALE, 20 FACC) and several window designs were sized (56 TAI, 33 NIAT).

34 LATECOERE Size Pax door 1	63 ALA Stress analysis of frame	20 FACC Frame stress analysis in undisturbed area
		
56 TAI Sizing window frames and skin panel	33 NIAT Sizing of window T- and L-frames	19 AIRBUS Heli Size Pax door 2

Analysis of panels for low loaded areas of a barrel

The objective is to evaluate the structural efficiency of the panel designs of WP2.12 for low loaded areas of a barrel. Nonlinear analysis of grid-stiffened panels were performed (15 DLR) and a full fuselage were sub-modelling were applied (49 NLR). The efficiency of designs were grid-stiffening is used were quantified. First steps in developing an analysis framework for stress analysis of complete fuselage with grid stiffened panels was achieved (NLR).

Results from the manufacturing and assembly sub-project

Manufacturing defects

This activity sought to develop material behaviour laws (constitutive properties and failure criteria) considering the effects the degree of cure and temperature for prediction of manufacture defect and damage formation during curing and cooling phases of the manufacture, as well as subsequent damage tolerance. Partners 46 SICOMP with 19 AIRBUS HELI developed a micro-meso analysis approach with a modification of Puck's criteria for modelling of NCF composites hierarchical structure which opens up the possibility of a broader understanding of the relevant mechanisms that governs failure of NCF composite structures.

The set of MF criteria was deemed a suitable candidate for more accurate modelling of NCF (bundle) strength due to its capability of handling more complex stress states, however results showed the transverse compressive strength (utilising FE RUC models) could not be accurately captured using the proposed methodology.

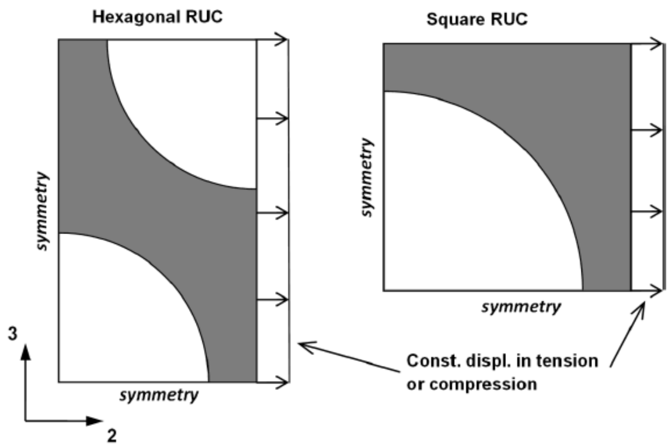


Figure 11: Hexagonal an squre fibre arrangement used in the micromechanical analysis (46 SICOMP / 19 AIRBUS HELI)

Manufacturing simulation tool

The objective of this work package was to develop and validate a simulation tool for thermoset Fibre Placement (FP) /Winding process, accounting for the geometric parameters of the process (in particular number, width and cutting strategies of tows) that may cause defects in the component.

The following figures represent some configurations proposed by 10 CIRA and manufactured by 49 NLR.

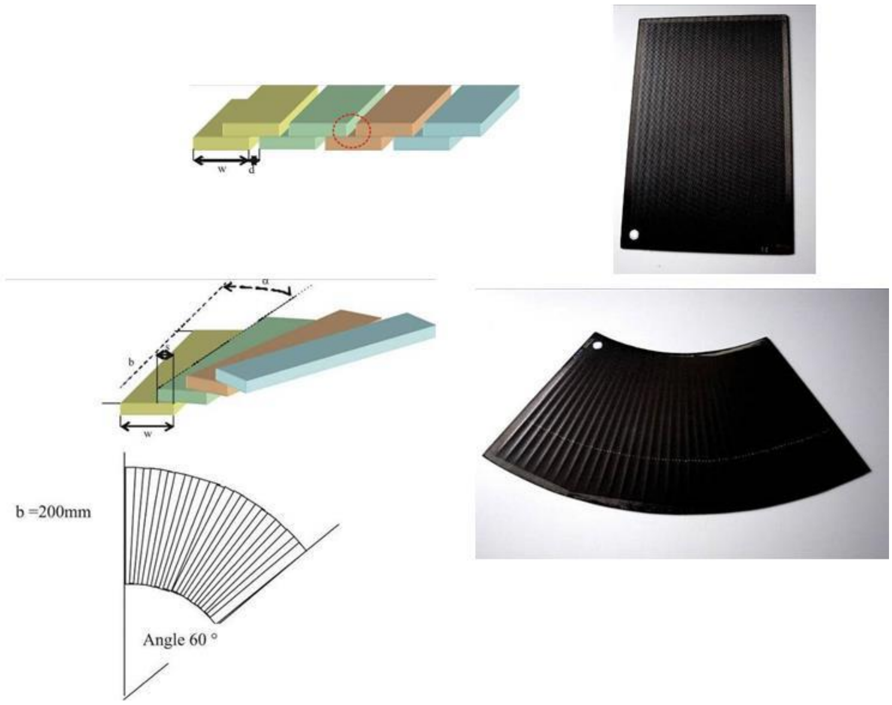


Figure 12: Selected configurations of parallel tows deposed by FP on a flat surface (10 CIRA proposal, 49 NLR manufacturing)

Residual Stress Calculation

This activity was focused on the development and verification of manufacturing process simulation (MPS) techniques for arbitrary shaped thermoset composites. The objective was to develop models and methodology for accurate prediction of manufacturing induced residual stress. Additionally, a dedicated autoclave manufacturing ESI simulation software was to be developed. Ultimately, it was hoped that the use of MPS could predict the distortions and adapt the tooling to minimize them.
Results from this WP include: A new element formulation developed by partner (18) ESI in SYSPLY, curing kinetic was implemented in CFD-ACE+, and for autoclave and distortion simulation, validation and sensitivity analysis were performed. Experimental results achieved were used to validate the residual stress methodology developed by partner (46) SICOMP. Validation of residual stress prediction on real structure (aircraft door structure) manufactured by partner 19 AIRBUS HELI. A numerical method to assess distortions was proposed and applied on a FACC part (partner 20) by AGI-F (partner 17).

Assembly tolerances and scatter

The objective of the WP was to develop flexible models and simulations for virtual final assembly processes taking into account the mechanical constraints in the assembly and the parts behaviours in order to optimize the assembly process and anticipate on issues thanks to realistic simulations. A global method was defined and tooled. It enables to perform tolerance optimization and best fit. The method has been applied on an AGI-F (partner 17) use case: the assembly of two panels.

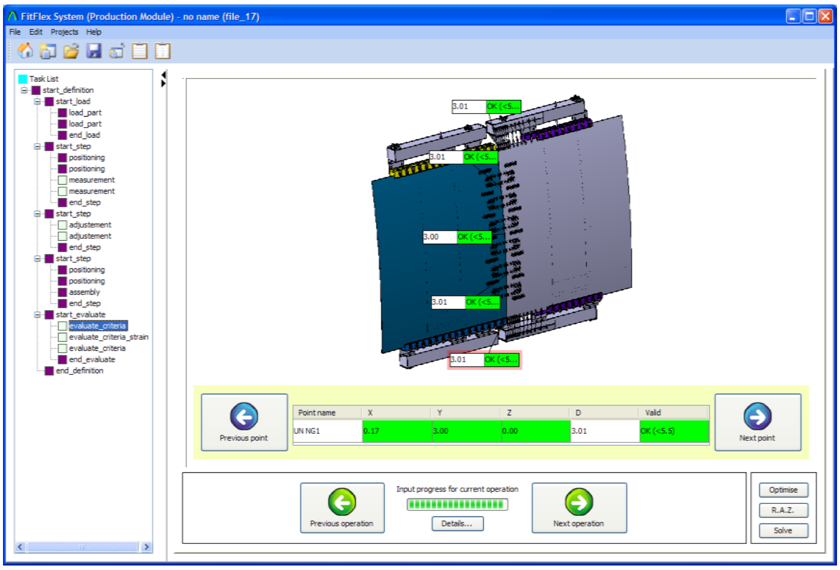


Figure 13: Results vizualisation with FitFlex; a software developed by 17 AGI-F

Two methods were developed enabling realistic simulation of the assembly process in order to avoid concessions & delays in assembly lines. They specifically enable to:assess the assembly feasibility, optimize the assembly sequences, get a perfect match of parts during the assembly process through optimization, check geometrical conformity in any fixturing and hosting configurations and most importantly validate and optimize tolerance intervals.

As-built data for modelling

The goal of this WP was to specify the extensions of the "composites data model" and workflow to capture "as built" manufacturing data, at early stage of the development process, based on "manufacturing constraints and variables" and at final certification stage, based on "as programmed" manufacturing machine operations. Results were only achieved in the extension of the composite data model by DS who developed improvements on the "producibility" feature to allow several producibility features to be created and managed under each ply for test purposes.

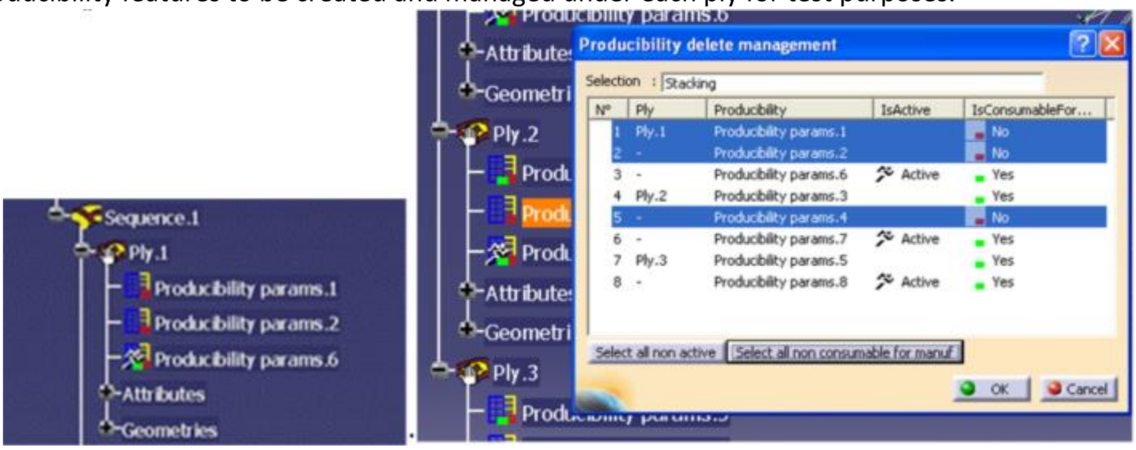
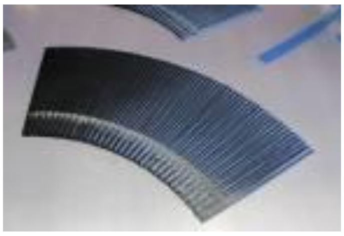
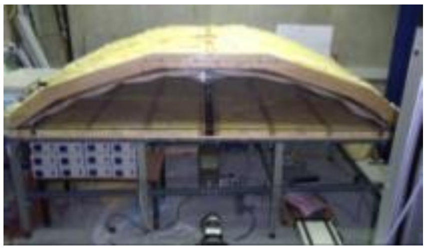


Figure 14: CAA APIs to access and manage the producibility (12 DS)

Coupon and Structural details manufacturing for trade-off

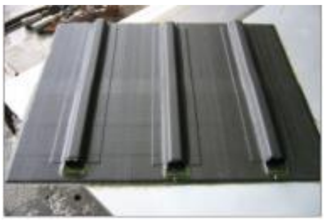
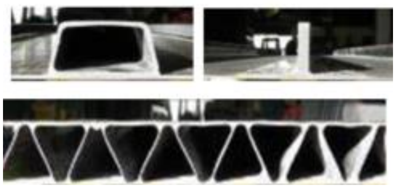
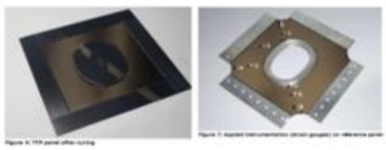
The purpose of this work package was to manufacture a variety of test coupons and small structural parts so that a number of tests and characterisations could be performed typically: material, thermal conductivity and fire characterisation, low and high-energy impact and residual strength, assess the effects of manufacturing defects on mechanical properties, calculate design limits for different preforms, for frames and their series production. Examples are shown below:

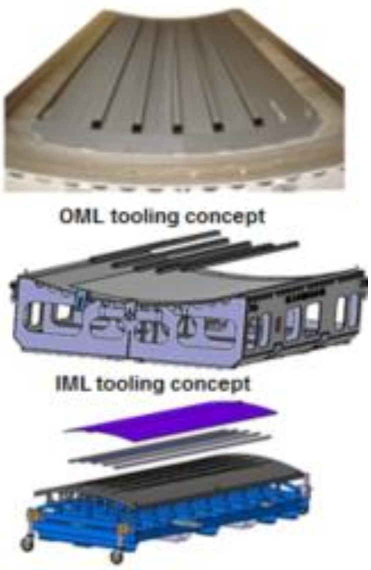
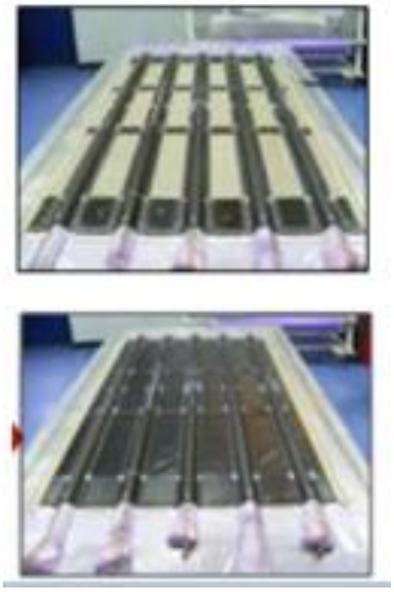
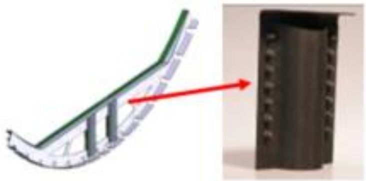
20 FACC produced 24 trial frames for establishing infiltration process.	34 LATECOERE carried out all coupons (170) representatives of the PAX Door	32 IAI have manufactured all specimens with ply drop-off PDO to reduce transition zone	32 IAI have manufactured all specimen T Stringer RunOut SRO
			

49 NLR produced trial coupons and panels in FP for assessment with simulation process.	57 ULIM Manufacturing of Crown Compartment for heat transfer
	

Panels or sub-components manufacturing to support and validate high fidelity structural analysis methods

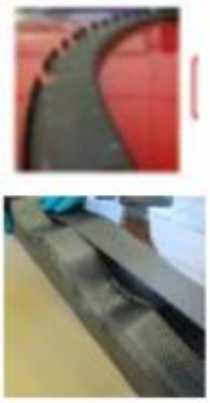
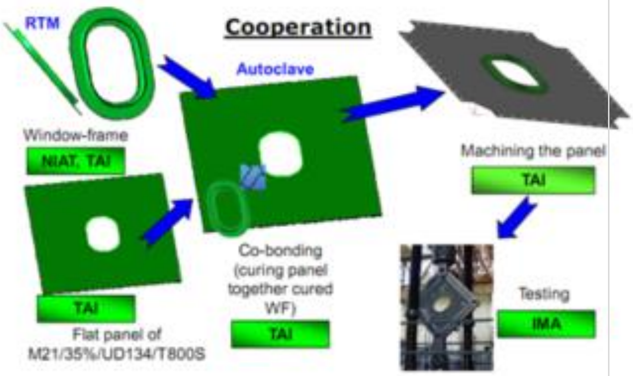
Similarly to WP4.6 this work package focused on the novel manufacturing of structural parts such as panels with different types of stringer configurations (co-cured or co-bonded). Examples include:

32 IAI Ω Stringer Runout panels SRO	45 BOMBARDIER manufactured 3 panels with RTI using different stiffening techniques	49 NLR manufactured innovative panels with load controlled fiber lay-up
		
48 SONACA - IML (inner mould line) and OML (outer mould line) in co-cured/co-bonded process => 4 panels manufactured	15 DLR – all specimen of sub cargo structure are manufactured	63 ALA – Two RFI co-cured stringers panels for static and fatigue compression

Frames, window frames and door manufacturing

Manufacture the integrated composite PAX Door structure using innovative materials and manufacturing processes and associated production jigs. Processes focused on the improvement of the manufacturing parameters to decrease time and scrap and increase the level of quality. The activities included the development of an innovative specific lip seal using all usual aeronautical requirements as well as the manufacturing of all the associated accessoires: stop fittings, guide rollers, brackets. This work package also manufactured window-frames using injection technology process which also addressed tolerances and system integration constraints. Finally is also manufactured braided frame preforms, using textile preform technologies and manufactured all frames for frame tests and one-shot section in undisturbed areas.

PAX Door (34 LATECOERE)	Frames and stiffened panels (16 AIRBUS DS-D, 20 FACC, 63 ALA)	Window frames (56 TAI and 33 NIAT)
		

Manufacturing of panels for low loaded areas of a barrel

The purpose of this work package was to manufacture the panels designed for the low loaded areas of the MAAXIMUS virtual barrel. Six panels were designed and manufactured by partner 15 DLR, using J and blade stiffeners. In these frame-stringer stiffened panels, the skin and the stringers are CFRP prepreg parts (IMA/M21E). The frames are aluminum parts. The stringer are bonded onto the skin by using film adhesive FM 300. Besides the frame-stringer stiffened panels, also grid stiffened panels were made. Two panels were designed by DLR using 10mm high grid stiffeners, and were manufactured by partner 49 NLR using Advanced Fibre Placement (AFP). Three panels were designed by NLR using 2mm high grid stiffeners, and were manufactured by NLR using AFP. Attention has been paid to advanced manufacturing methods, with respect to high levels of automation in manufacturing and assembly, advanced process monitoring and control and low cost manufacturing solutions. For example, the applicability of the AFP process to rather complex grid stiffening structures was evaluated.

Figure 15: High grid, low grid shear and low grid compression panels as manufactured

Two-panels assembly

The goal was to specify and develop an innovative and high production rate assembly process in order to perform the circumferential joint between the two panels of the demonstrator using a fully automated autonomous system. AIRBUS defined the requirements and definition of the automated system. Partner 60 TECNA performed the detailed design, production and testing of the robotic system. Partner 1 AI-D manufactured and assembled the test specimens, as well as perform the final two-panels assembly.

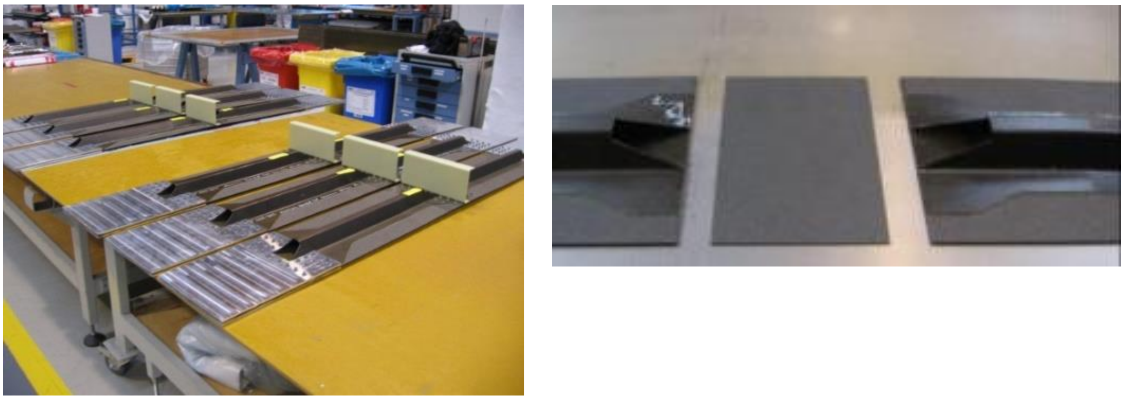


Figure 16: Manufacturing of test specimens (1 AI-D)

Figure 17: Assembly of the external butt strap test specimens (1 AI-D)

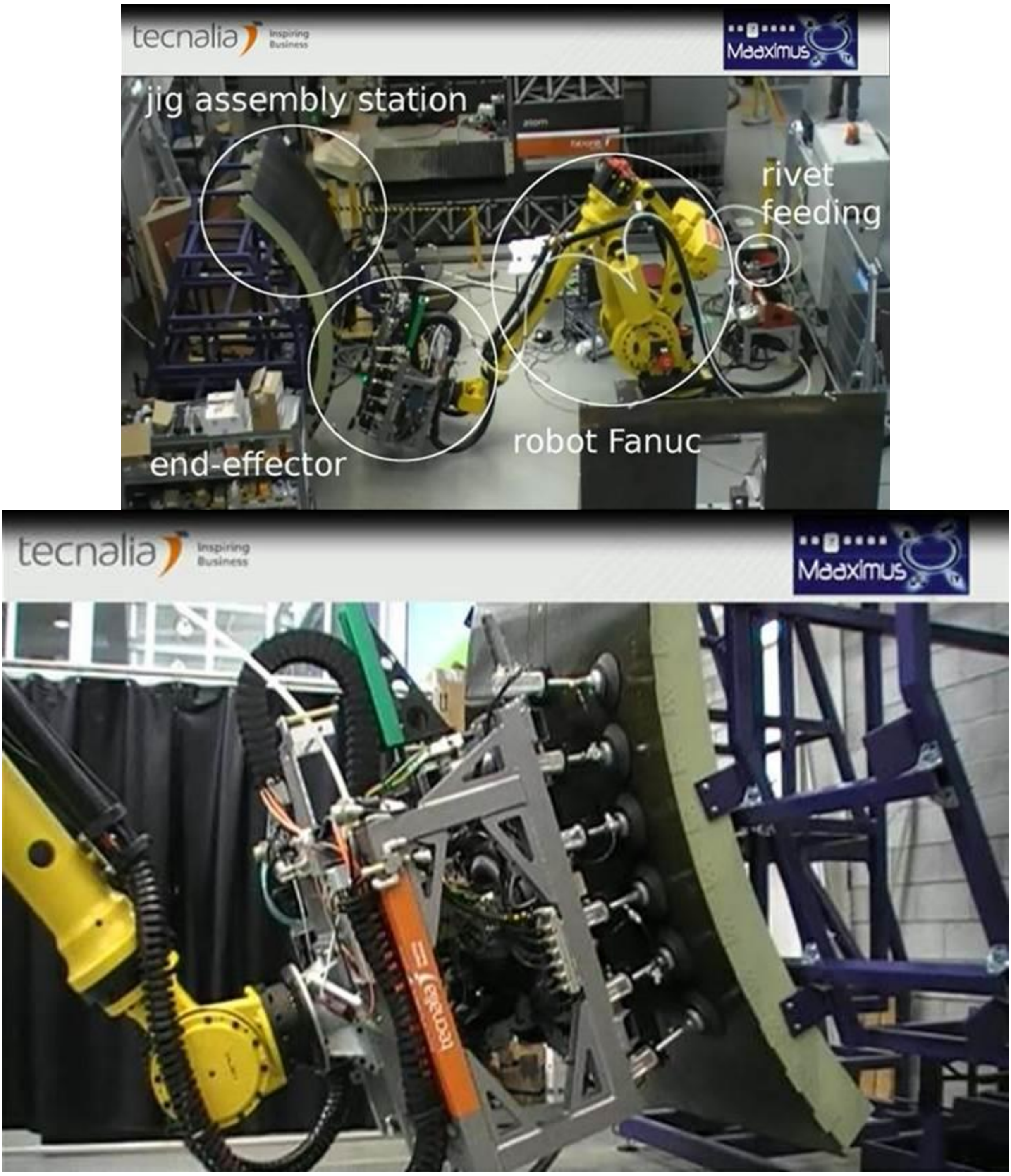


Figure 18: Assembly station at partner 60, TECNA

All design activities of this WP were achieved. The complete automation system deployment on a full scale fuselage was achieved in concept and simulated.
The automation system was prototyped and tested: all performance indicators have been achieved and improved (demonstrated on a reduced number of fastener installations, and on a mockup of CFRP fuselage).

Results from the NDT and on-line process monitoring sub-project

Manufacturing and Assembly Process Data Capturing

The objective of this work package was to develop methodologies in order to establish the link between NDI findings and numerical sizing tools and also develop an NDI simulation platform for obtaining defect distributions. A software tool has been developed for the transfer of defect data from ultrasonic NDI to an existing ABAQUS FE-model. It uses a client-server architecture with a damage database as its central component. The client is written in JAVA and runs on all platforms, for which a Java Runtime Environment is available. It can access the database over a network. A simple example demonstrates the capabilities of the software.

Figure 19: Identification of damage using the software

The database holds damage information in the form of its three-dimensional extension and the damage type. Additionally, it holds data about the composite structure containing the damage.

Manufacturing Defect Analysis

This work package activity consisted in (a) defining appropriate manufacturing defects and appropriate formats to exchange this information between WPs, (b)defining key NDI parameters to record and best suited NDI methodology, (c) correlate manufacturing defect occurrence with the process and its parameters and (d) to analyse Dielectric Sensing data of the selected manufacturing processes and evaluate process parameters.

During the manufacturing of composite parts it is very often that air or volatile substances create air pockets or voids that are trapped within the material. The void formation was studied and characterised and the correlation with the processing parameters for autoclave parts identified. From the analysis of process monitoring dielectric data from on line measurements it will be possible to derive key process points (resin arrival, max. flow, degree of cure, end of reaction) and perform feasibility analysis for cure cycle optimisation to determine “best practice” routes for assurance and reproducibility of prescribed quality parts.

CFRP laminates were cured with different autoclave pressure levels to achieve various void contents. The flaws have been investigated by different destructive and non-destructive inspection methods to get further information about the morphology and distribution of voids in the composite.

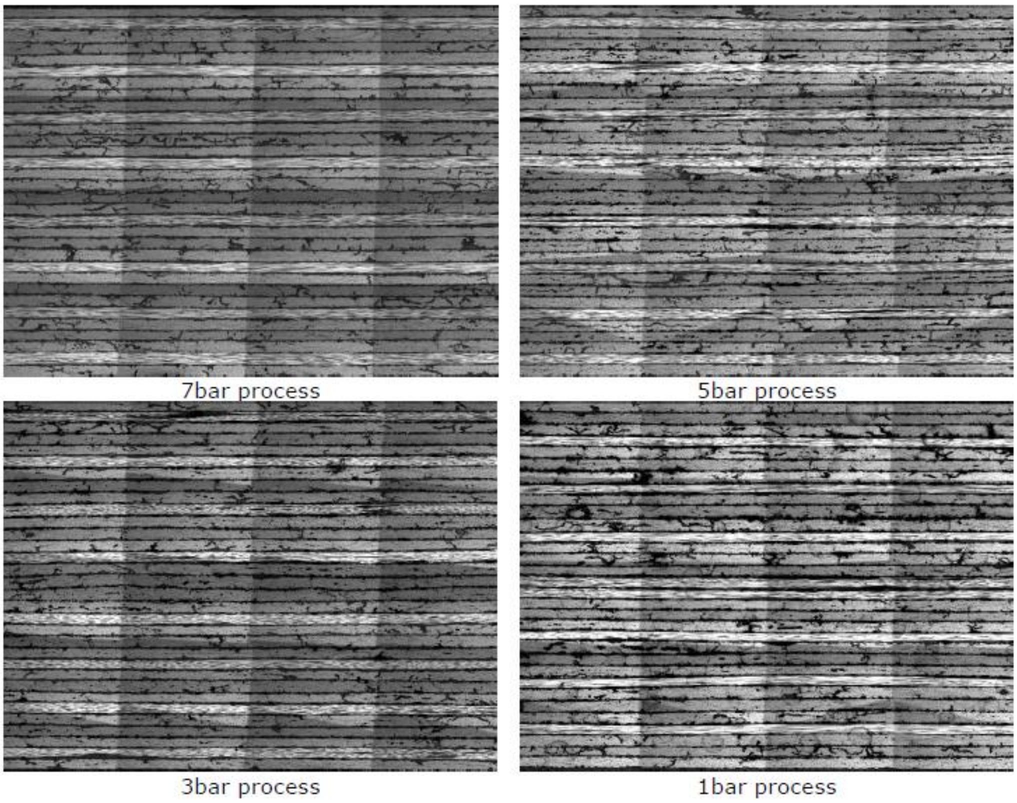


Figure 20: Polished cross-section from panels produced by different autoclave pressures

The application of dielectric process monitoring in the manufacturing process is highlighted for the case of a stiffened panel made by Resin Transfer Moulding (RTM) technique. The materials that have been used are the same as in the anticipated Composite Frame use case. The resing property grids are derived and the measured data are used to derive important process parameter milestones such as maximum flow point, vitrification point, end of cure identification.

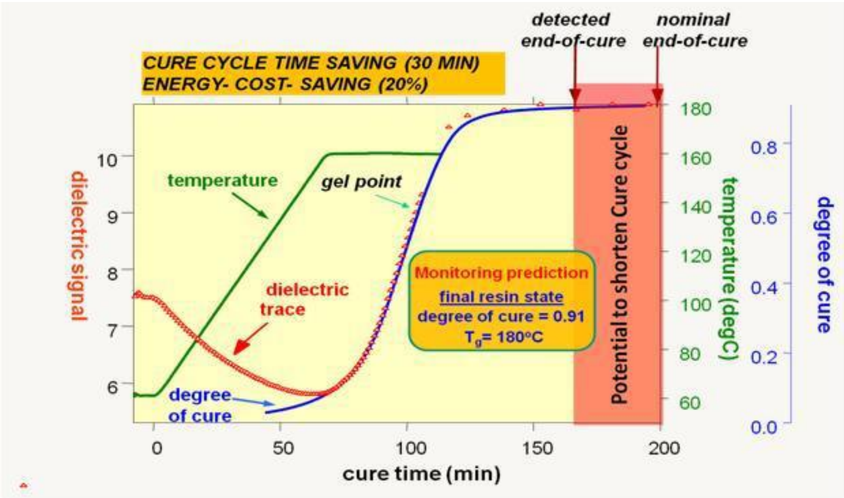


Figure 21: RTM-6 degree of cure - dielectric measurement correlation

It has been possible to correlate the dielectric signals with the material status during the polymerisation process and build a material state map for an infusion resin that is widely used in the fabrication of high end aerospace components. Further to that a generic methodology has been developed that allows the creation of a materials library that can be used to suit many applications.

A cure cycle optimisation tool is available that can derive the optimum cure profile based on cure kinetics that can be directly applicable to the process under consideration. It can be combined with material state map to derive the link of the processing parameters to the desired physical properties. Furthermore it is possible to perform cure cycle optimisation based on the actual material properties, in terms of shorter production time or desired properties. The material state mapping and the cure optimisation tools are the key enablers, together with the monitoring system, for an automatic closed loop control of the fabrication process, based on the actual material properties rather than the temperature readings as the current state-of-the-art.

Fibre Placement is a special composite manufacturing process which allows to obtain very large components with complex geometries. Due to its special carbon fibres deposition method, the fibre placed composites are affected not only by the typical defects that could occur during common manufacturing processes, but also by defects that are directly related to the design chosen by the customer. In particular the deposition geometries involving overlapped tows have been deeply studied, because from the NDI results, they have shown the occurrence of the porosity.

Using the general theory of the ultrasonic attenuation within the materials, the attenuation c-scans obtained by the application of a specific NDI technique, ultrasonic DTT, have been converted in thickness c-scans by creating a Matlab tool. That method has allowed to visualize the defect which is responsible of the increased attenuation (the porosity) as a thickness variation, and, to identify where the defects arise with respect to the deposition geometry of the tows. This have led to achieve a more accurate analysis of the porosity distribution. In particular, the configurations with a progressive overlapping of the tows seem to be responsible not only of local variations of the thickness, but also of the occurrence of the porosity in specific parts of the final manufacture. On the contrary, the panels where the tows are totally or partially overlapped without variations of the overlap areas, are not affected by porosity.

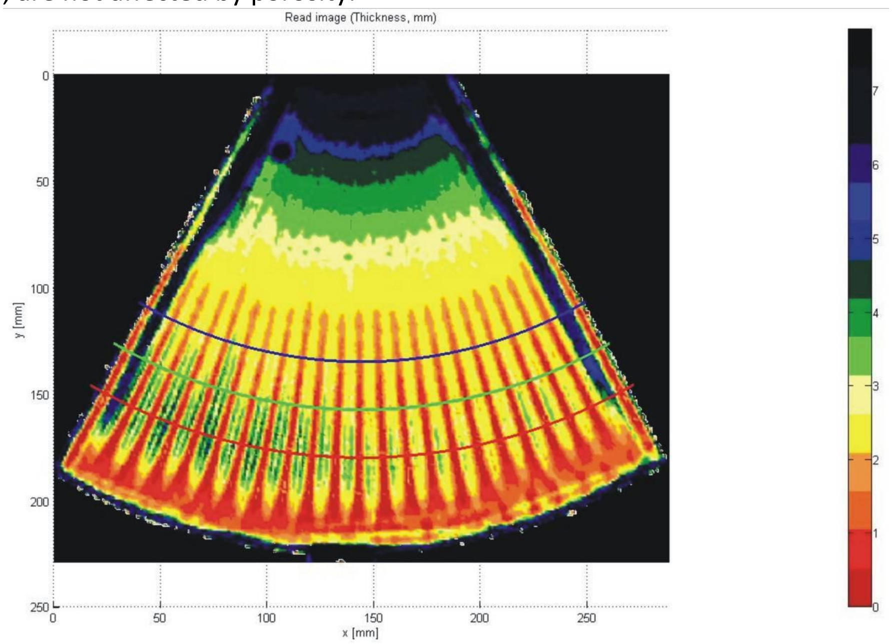


Figure 22: Thickness c-scan of the OL3 panel and its colour-thickness palette

NDI Scatter – Uncertainty

Work performed concerns the development of a virtual tool to assess the development of a simulation tool for US propagation modelling through composite materials (17 AGI-F) and complement the activities in WP5.1 and 5.2.

An ultrasonic testing for composites simulation approach has been developed based on a the identification of the major physical features of ultrasonic propagation in composites, leading to the choice of a Finite Difference in Time Domain (FDTD) numerical scheme to solve the propagation problem. Description of the propagation medium (composite) and of possible defects has been investigated. Defects dealt with are delaminations, porosity and waviness.

Very encouraging validation results have been obtained on a safe reference block as well as in a shaped configuration (composite stiffener radius).This work has increased the partners' experience and practice of such simulation code in very complex configurations. A major difficulty has been identified for a use in an engineering environment: the material description and defect description can be very tricky and time consuming without the help of a specific pre-processor and a specific GUI. Secondly, in some configurations for which the water path of ultrasound is large compared to the material thickness, the FDTD performances are strongly penalized by long propagation in the water cumulated to numerical dispersions arising in long run simulations. This integration includes a dedicated GUI for composites definition and gives the possibility to run an FDTD computation via a semi-analytical / numerical coupling.

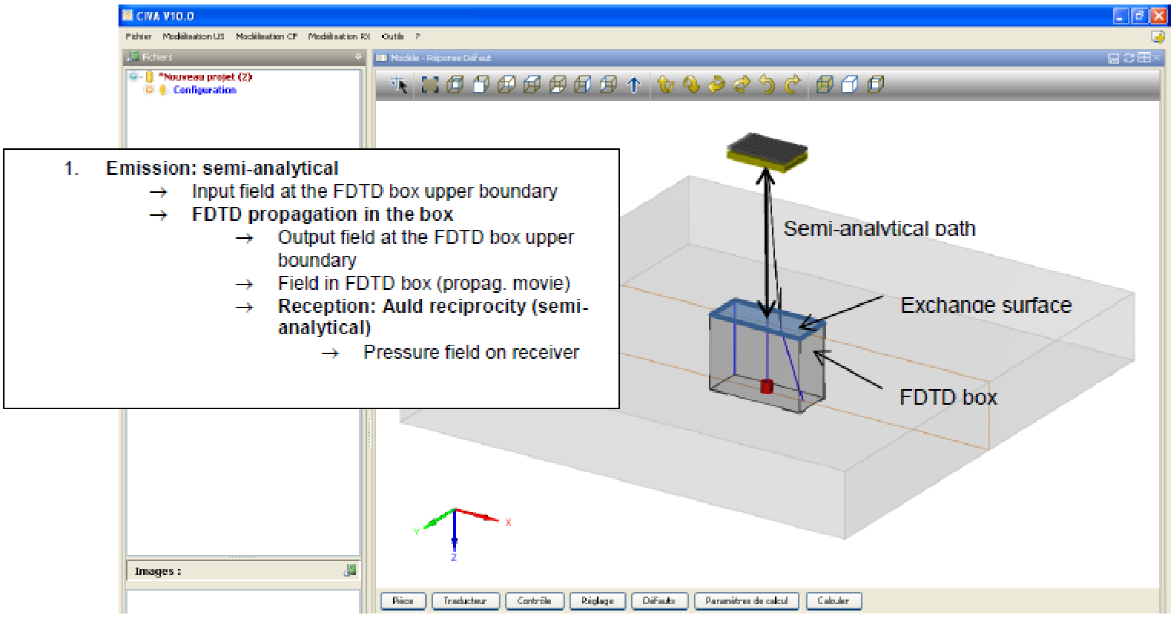


Figure 23: Semi-analytical / numerical coupling in CIVA

The dedicated GUI, in its first version, will enable the user to define 2.5D shaped parts and to describe the associated lay-up and materials properties. In particular, the description of resin interfaces for the ultrasonic model has been made possible through this GUI.

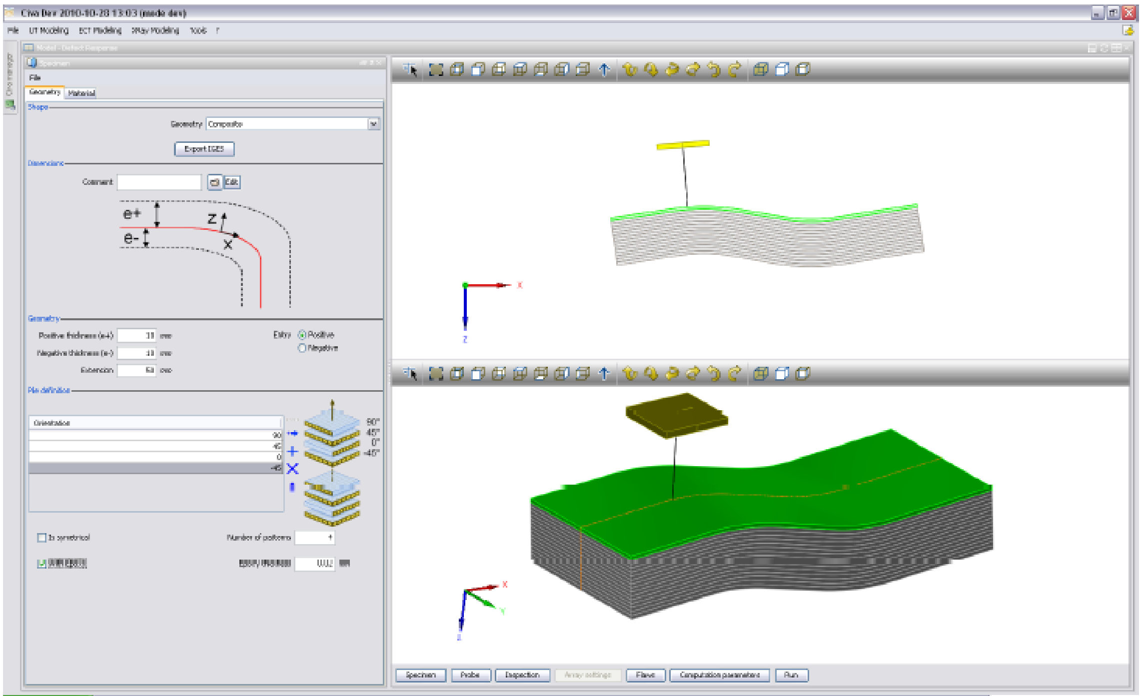


Figure 24: 2.5D part definition with associated lay-up

Integration of NDI data in the framework for High-Fidelity Modelling

The specialized software tool MCODAC from DLR allows the transfer of NDI-data to FEModel and enables the evaluation of the effect of damages through nonlinear FE simulation. The created damaged model can be used directly to evaluate the damage influence. Furthermore the model could be used as local model in a global-local-approach for more complex structures or it could be used as basis for an additional mapping on FE-models with another discretization, e.g. a discretization by shell elements for larger-scale and more complex structures.

The integration of this software tool onto the multi-skills integration framework is possible, with various degrees of integration. But this integration task can go beyond and remove some of the user input that is currently necessary but somewhat redundant, such as the composite layup information, the material data, and the panel geometry. It could also evolve so that already defined Abaqus input files are used straight as input to MCODAC, with extensions to accommodate Cartesian coordinate systems.

Additionally, damage data and calibration information can be stored in the PLM infrastructure. Once stored, one can imagine that the damage data can be reused, for instance to perform probabilistic studies or Design of Experiments on damage positioning ("what if this damage happens in a nearby area? Is my part still structurally sound?").

By connecting NDI measured data to the FE analysis standard in the Hub C multi-skill integration framework (thus enabling FE analysis on as-inspected part, and triggering earlier changes on a design or manufacturing process leading to unreliable parts), and by ensuring the traceability of data and the workflow of information, controlling the input and the output, these enhancements brought within this WP to the Hub C platform do contribute to reducing the development time and cost of composite structures. More specifically, the C3 challenge of the Hub C, focussing on close loop between design, analysis, manufacturing and NDI was to contribute to the reduction of the development time and cost, with a respective contribution of 2% and 1.5% of the quantified high level objectives.

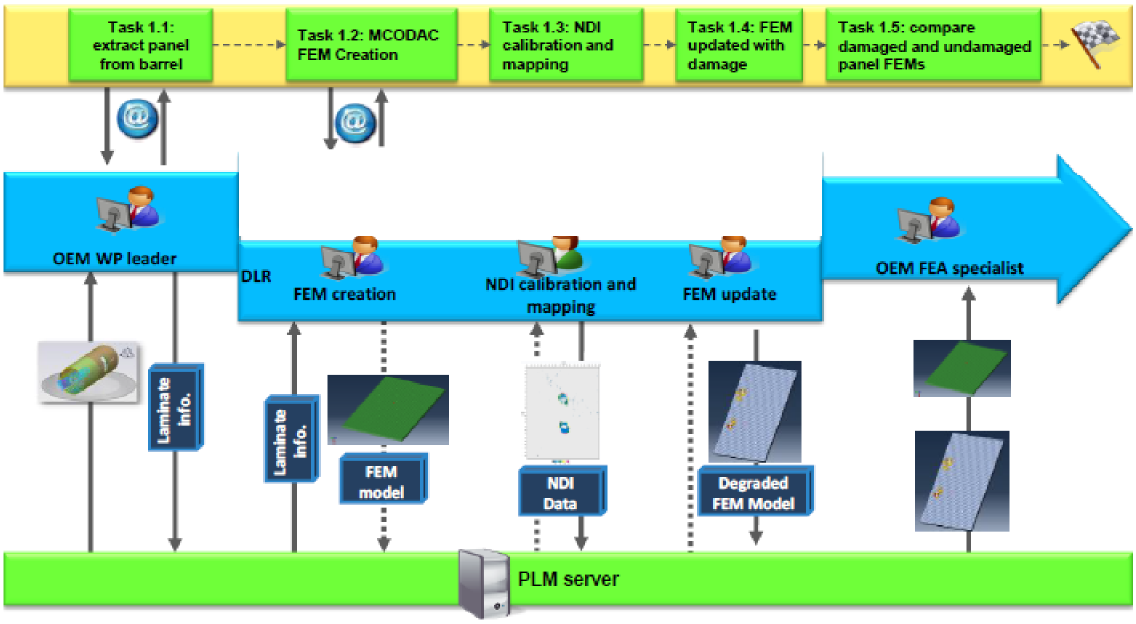


Figure 25: Demonstration scenario and baseline for the MCODAC first level of integration in the integrated platform

Coupon, structural details, panels quality control

The activity in this work package deals with NDI and microscopy of coupon, scaled components and panels with the aim to check the conformity with the predefined quality standards as well as to extract information regarding the effect of defects on the "as build" structure, and the progression of damage in test specimens.

ULIM (partner 57) worked on NDI/Microscopy findings on bolted joint coupons, material model whilst partner (34) LATECOERE worked on testing of components representative of the PAX door.

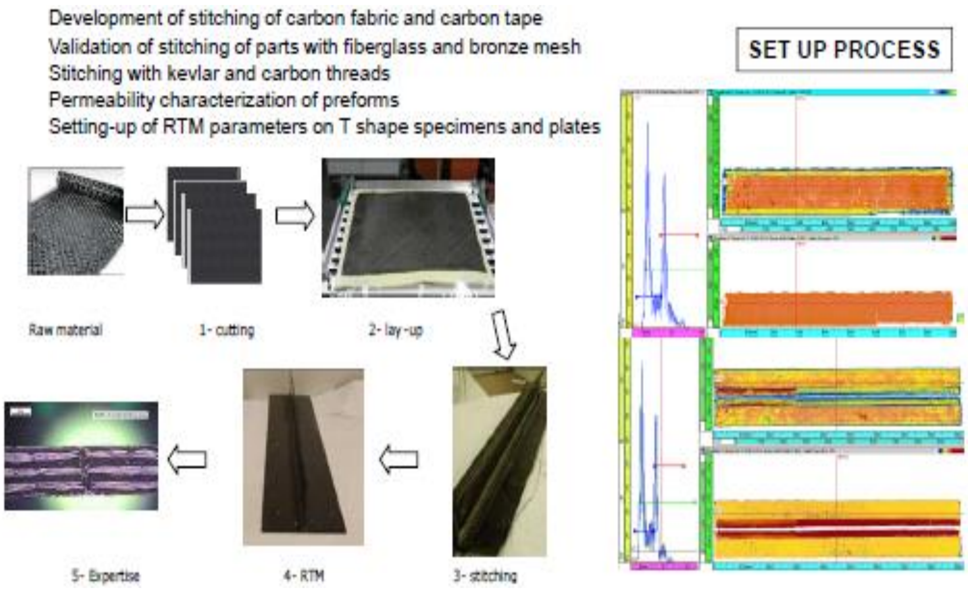


Figure 26: Trials and experiments made on 15 component representative of the PAX door, stitching and RTM trials on T shape specimens and plates (T4.6.2 and T5.6.1)

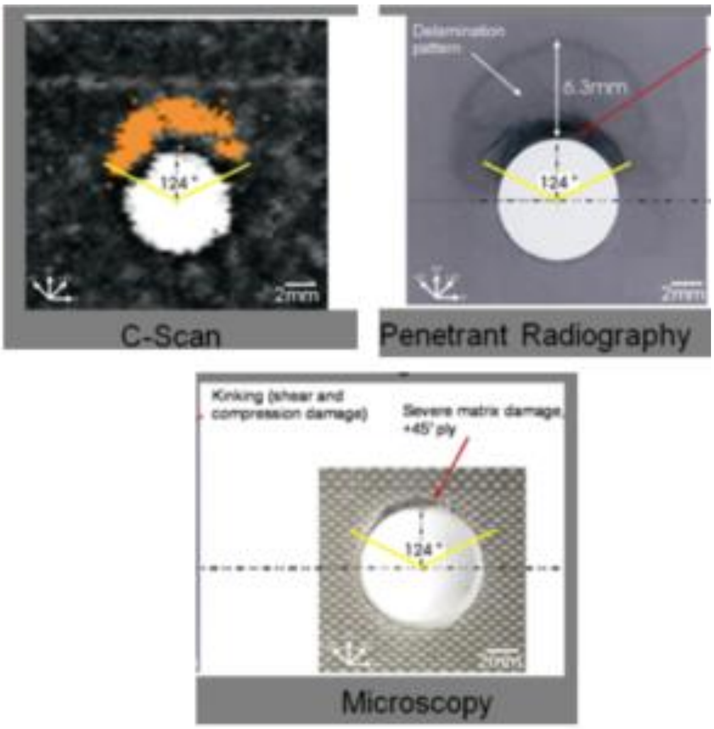


Figure 27: NDI analysis of bearing failure in bolted joint (57 ULIM)

Quality-Assurance and Inspection

Activities in this work package were concerned with the adaptation of industrially available NDI methods in order to inspect subcomponent and fuselage section elements for quality assurance.
The monitoring strategy for assessing the infusion process of the braided composite frame of FACC was identified. Partner (27) INASCO's DIAMON plus system was used encompassing four flexible dielectric sensors for flow and cure monitoring and four thermocouples for temperature measurements.

Figure 28: US inspection using A-Scan

Overall the different test method for the inspection of the integrated mouse hole frames used on the side panel for testing has highlighted two issues: the resin rich areas on the outer flange after infusion of the parts, the Spring In effect of the frame is different between the inner and outer flange. The NDI test method is not fully applicable in some areas of the integrated mouse holes regarding that the shape of the part will separate the ultrasonic signal.

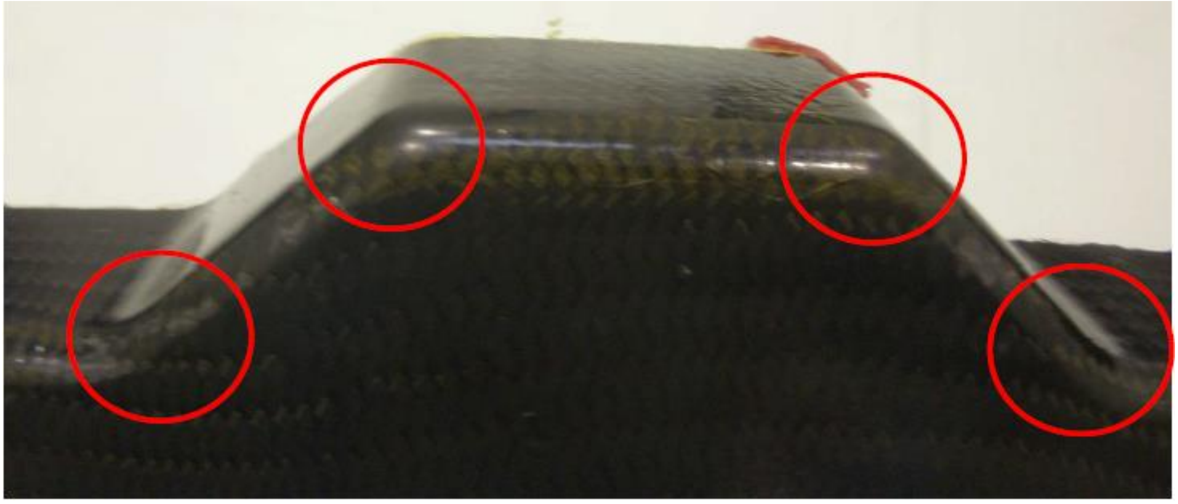


Figure 29: Zones of comples NDI analysis

Also, non-destructive inspection of RTM window frames (WF) and co-bonded panels was also performed. Three TAI manufactured window frames (partner 56) and three co-bonded panels with TAI WFs have been assessed as to meet the defined quality requirements via those inspection processes. Also the co-bonded panels with partner (33) NIAT's WFs have been inspected via USI process. Inspected co-bonded assemblies have been forwarded to IMA to be tested according to the defined specification. There were three assemblies featuring NIAT WF and three more with TAI WF.

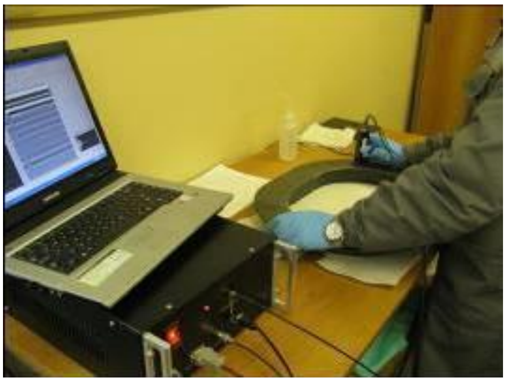


Figure 30: First phase of scanning

Figure 31: Second phase of scanning

Partner (63) ALA inspected two composite stiffened panels with seven and fifteen co-bonded stringers and three bolted integral frames were inspected by standard ultrasonic methods in order to evaluate the quality of manufactured parts. Some acceptable defects were observed but only two stringers, because of one detected void and one detected delamination were scrapped. The integrated Z-shape frames were manufactured with an innovative Hand Lay-up process that shows good results from a manufacturing quality point of view.

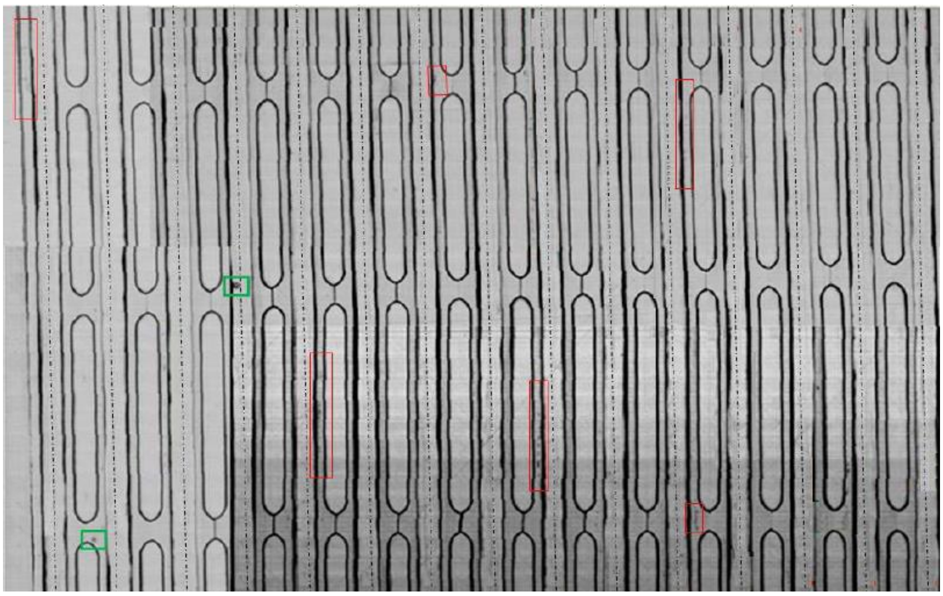


Figure 32: Panel NDI results (63 ALA)

The PAX Door #1 Composite structure and its equipments were manufactured and inspected by LATECOERE (partner 34).

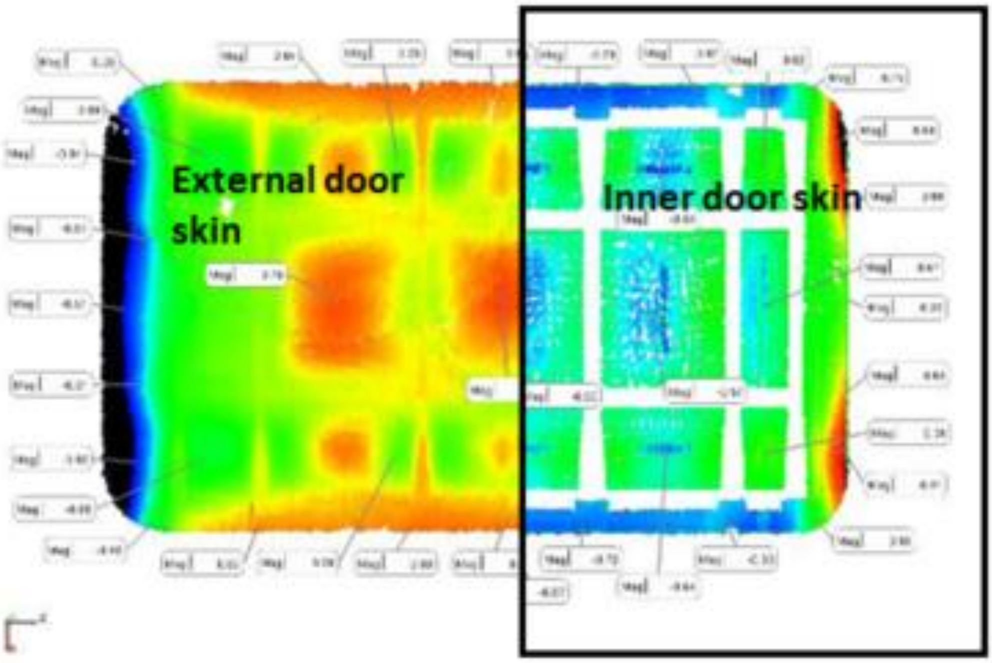


Figure 33: A-scan and C-scan US testing of PAX door

Non destructive inspection of panels

Six panels were designed and manufactured by partner (15) DLR, using J and blade stiffeners. Two panels were designed by DLR using 10mm high grid stiffeners, and were manufactured by NLR using Advanced Fibre Placement (AFP). Two panels were designed by partner (49) NLR using 2mm high grid stiffeners, and were manufactured by NLR using AFP. C-scan NDI was applied to investigate the structural quality of these panels. The six J and blade stiffened panels were inspected by DLR. The four grid stiffened panels were inspected by NLR. The manufacturing quality of the high grid and low grid panels was found to be satisfying.

Figure 34: Test setup for ultra-sonic inspection of the stiffened panels

Figure 35: Detail of the bonding of the high grid panels

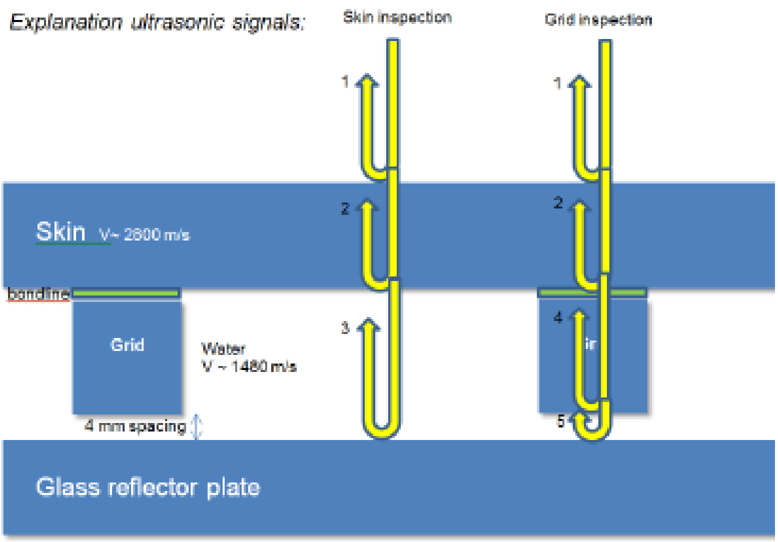


Figure 36: Schematic view of the interaction of the sound beam at the skin and skin/grid configuration

Results from the test, correlation & validation sub-project

Coupon, structural detail and panel testing

The overall objective of this WP was to define and organise coupon, structural details and panel level testing in order to coordinate test requirements with respect to the test pyramid. Tests were conducted in order to achieve measurements of required material properties for validation of multi-scale analysis and debonding analysis approaches.

The thermal conductivity characterisation test campaign has substantial beneficial results. First of all, it has provided a wide range of results for IMA/M21E and T800/M21 laminates widely used for aeronautic structures. Moreover, it has explored variations of thermo-physical properties of parameters such as fibres, resin, lay-up, and grade. Tests were performed on load control fier lay-up coupons and panels (49 NLR).

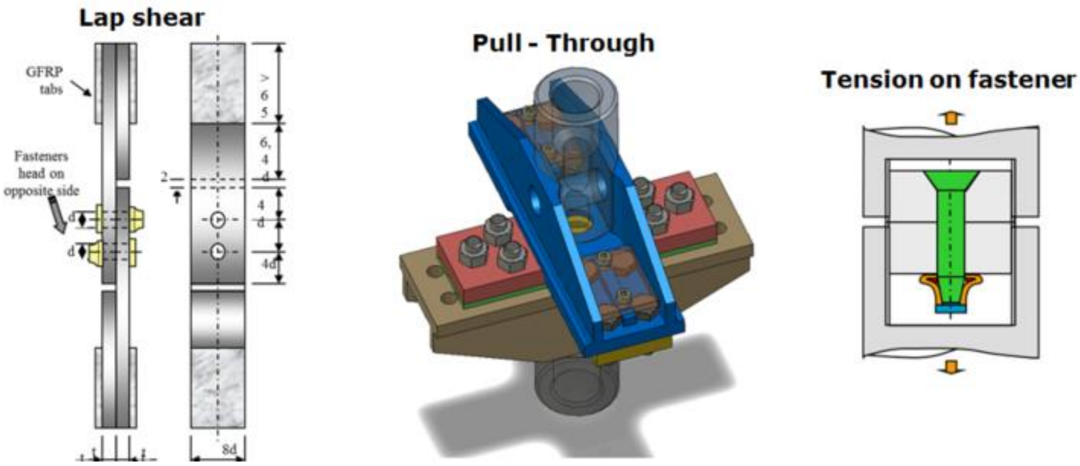
Figure 37: Determination of (TPF) material properties; IMA/M21E (NDA)

The main conclusions of the study are that thermo-physical data do not significantly depend on composite grade. Moreover, composite staking sequence strongly influence in-plane thermal conductivity whereas it has no effect on the transverse one. Finally it was seen that IMA/M21E composite is more insulating than T800/M21. A part of this result is due to the resin properties. In fact, M21E is more insulating than M21. To obtain these results, the hot wire measurement method has been used after being validated. Compared to guarded hot plate method, this device has the advantage to measure two thermal conductivity in one experiment : *kxx* and *kzz*.

Several types of validation tests were also performed by several partnbers (46 SICOMP, 14 CEAT, 17 AGI-F, 26 IMPERIAL, 34 LATECOERE, 52 TUHH and 57 ULIM), see also image below:

- Low velocity impact tests have been carried out on composite plates with and without compressive in-plane pre-load. It could be observed that the pre-load has significant effect on peak force, impact duration and energy absorption as well as delamination size. Further, for high pre-loads a change of failure mode could be observed.
- Mechanical tests were run on coupons and structural details representative of the composite door structure designed by Latecoere. The goal of these tests was to evaluate the influence of sewing (carbon and Kevlar) on laminate basic static properties (tension, compression) and interlaminates fracture energies (G1C and G2C) as well as to validate stiffeners outer flange strength, inner flange compression after impact, I-beam inner cap in compression after impact and finally the stop load transfer between carbon fiber inserts and I-beam web.
- Results shows that sewing introduces a decrease in in-plane properties of composite material but it allows in the same time a huge increase in out-of plane properties.

- Tests run on stiffeners and beams allow validating the design of the door since complete appeared far from ultimate load limit and that no detrimental growth appears after BVID.
- The influence of voids in CFRP laminates on modulus and strength under compression as well as on delamination growth was investigated by TUHH. The defects resulting from the decreasing autoclave pressure occur between in the fibre layers and in resin rich areas between the plies. It could be observed that voids have a significant influence on the compressive strength and crack propagation but not on the compressive modulus.



All tests to failure on single-bolt, single-lap joint coupons have been carried out by partner 57 ULIM and strength and stiffness data are now available for the various joint configurations. A preliminary test has been carried out on a six-bolt, single-lap MAAXIMUS joint. It was found that an approximation of the load distribution could be obtained using three-dimensional digital image correlation (3-D DIC) and that failure of multi-bolt joints under laminate E configuration is dictated initially by bearing failure, while final catastrophic failure of the joint occurred due to failure at the bolt threads.
Quasi-static material identification tests were performed providing a full suite of test data from both basic material identification tests and tests to calibrate advanced model features. Good repeatability and minimal bending effects have been observed in all samples to date (save small bending problems in zero degree compression tests). Preliminary testing of impact/indentation samples has been carried out to validate the procedures used and the impact tower manufactured at (57) ULIM. Good repeatability was obtained in repeated tests on impact samples using a compression after impact (CAI) rig in terms of load-displacement response and the test series is 35% complete. The resin system Epsilon, from Henkel company, featuring new resin chemical (benzoxazine) was tested with success. The manufacturing of the flat panel through RTM process did not present any problem. Concerning the mechanical performance of the material, it can be said that the benzoxazine resin is similar to classical epoxy systems (in terms of Tg, Modulus, Tensile, FHC and CAI performances, which were the tests conducted by 13 DASSAV). A great advantage of this new resin is its good performance in Hot/Wet conditions, with a high knock-down factor between 0.85 and 0.91, better than most of the epoxies. An interesting industrial process feature must be added to this good mechanical behaviour: the Epsilon resin system can be transported and stored at roomtemperature, in comparison with -18°C freezers needed by epoxy systems. This study concluded that Epsilon resin system is an interesting candidate for future RTM process developments.

With regards to heat tests performed by 14 CEAT and 40 ONERA, an infrared thermography system has been installed on CEAT burnthrough test bench. The first experiments on metallic plates have been realized for the characterisation of the heat flux generated by the flame impingement. The temperature measurements have been post-processed by an inverse heat conduction method to obtain the heat flux distribution.

Then, ten composite plates were submitted to fire impingement. Thermocouples measurements by CEAT have been analysed and compared to IR measurements. They show the different phenomena that appear: heat conduction through the material, resin pyrolysis, delamination. It is important to note that the resistance of a composite sample depends of the thermal condition on its rear face. If it is insulated then its temperature will increase more rapidly and it may be subject to burnthrough, while it may resist if its rear face is free to exchange heat with the environment.

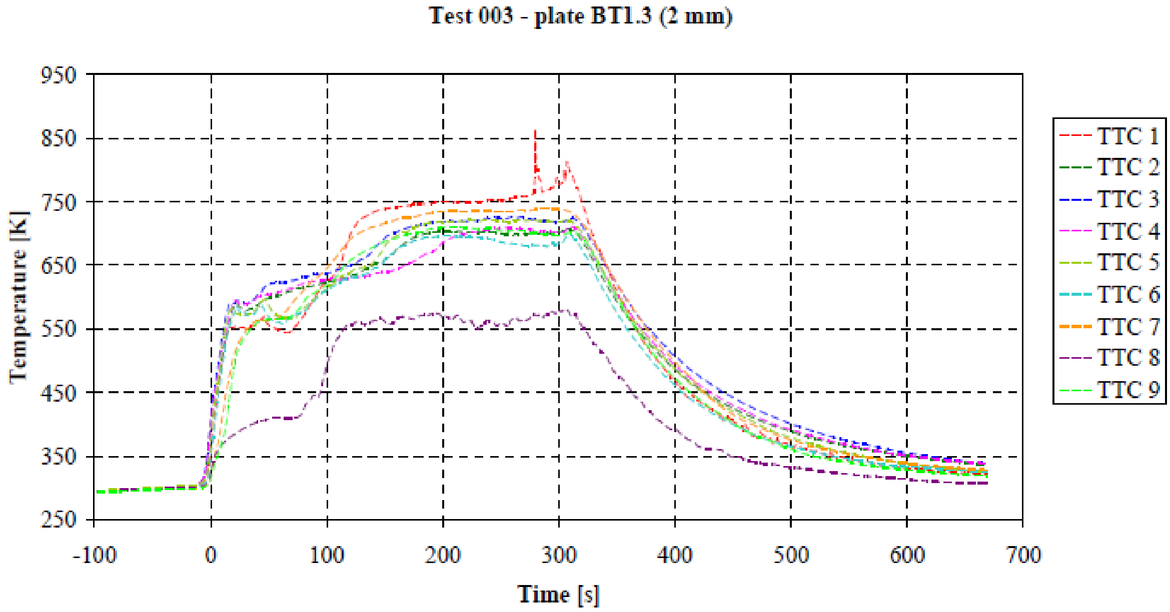


Figure 38: Test 003 thermocouples measurements

Figure 39: Test 003 photo during test (left=265 s, right=280 s)

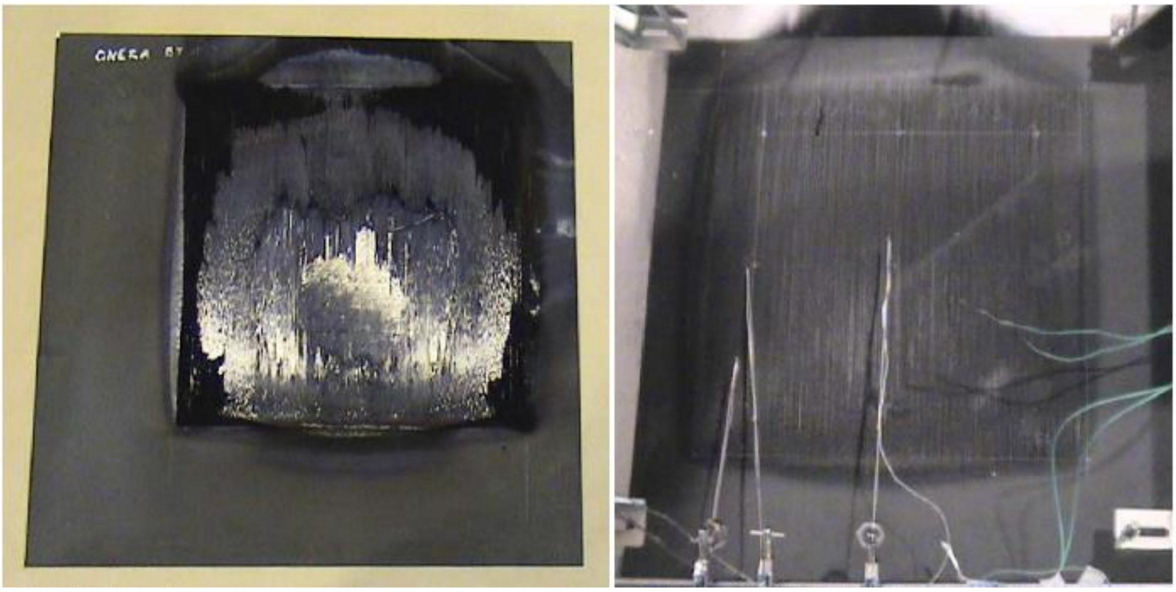


Figure 40: Test 003 photo after test (left=front face, right=rear face)

Test-Analysis environment

This activity was focused on the development of dedicated tools to increase the efficiency of test-analysis correlation (test preparation, test monitoring, test interpretation and model validation). A test-analysis correlation environment for both static and dynamic analysis was defined All activities that need to be performed, from the model assembly within a CAD environment to the updating of numerical models using experimental data, were studied. After the final development phase, the full-scale system was analysed. Similar procedures can also be applied in earlier phases.

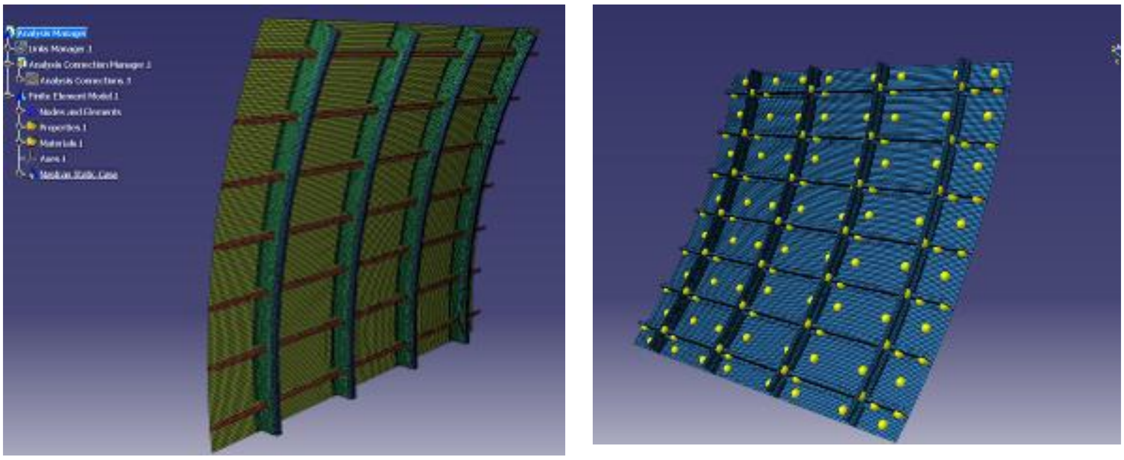


Figure 41: Aircraft composite fuselage panel model (left) and sensors locations(right).

Coupons, structural details and panels test results analysis

This activity focused on the validation of either advanced models, analytical or numerical methods (incl. multi scale), numerical chain by correlation with material or structural test results analysis. This permitted justification procedures based on each scale from coupons to aircraft components to be established which permitted the structural design robustness by numerical analyses to be assessed. Key results include the validation of simulation methods for impact vulnerability.

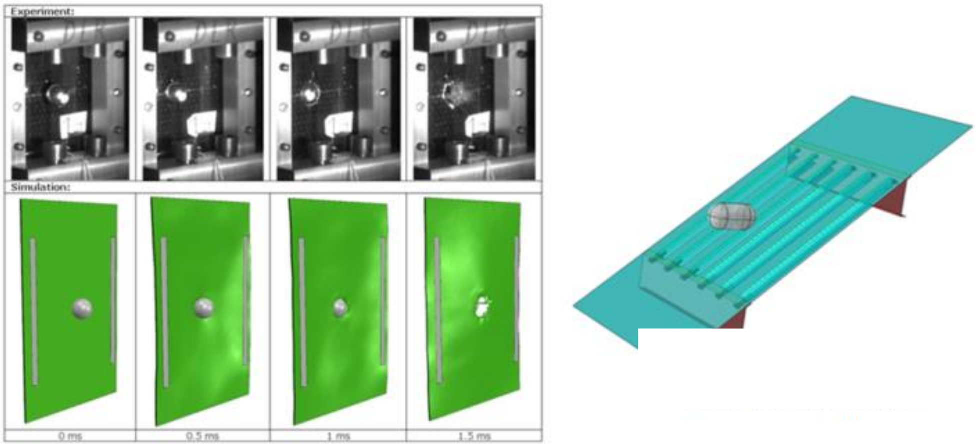


Figure 42: Bird strike model

Also, buckling on a variety of different panels were performed with comparisons being made between simulation and test results being assessed in different loading configurations.

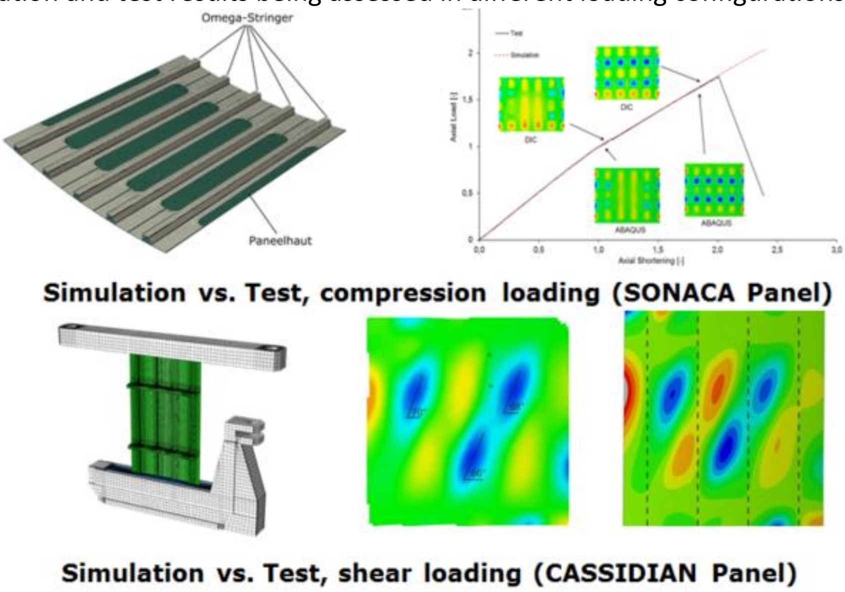


Figure 43: Panel buckling (15 DLR-FA)

Finally, partner 57 ULIM achieved validation of their thermal modelling methods (see below).

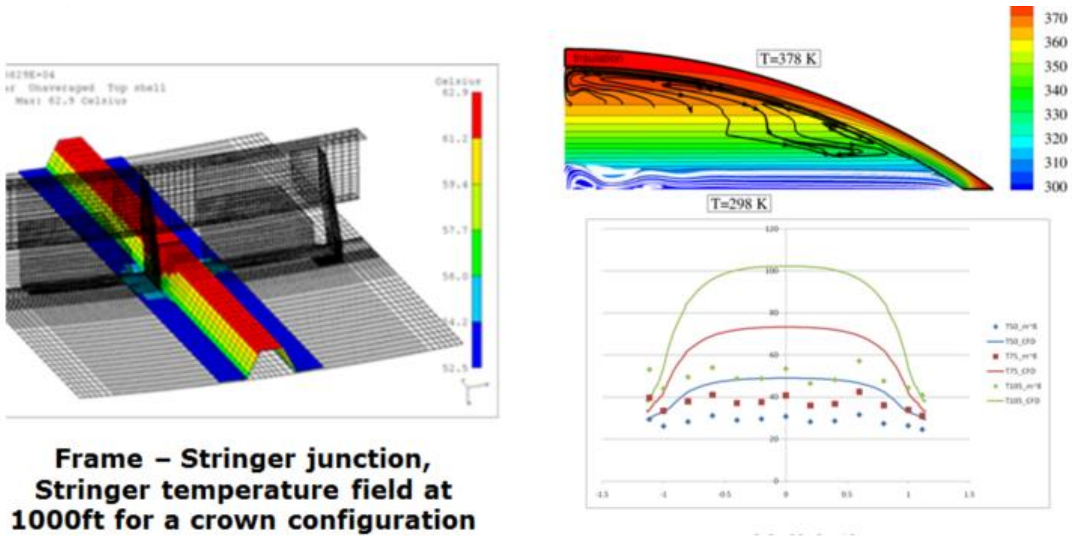


Figure 44: Validation of ULIM (partner 57) thermal modelling methods

Test of sub-components

Panels (with Z section frames from 63 ALA and 20 FACC C-section) where tested by partners 63 ALA and 25 IMA with bending testing being applied from zero load to failure load with the frame inner chord being in compression or tension. The test data was compared with analytic simulation leading to good predictions with only a 14% difference in the predicted failure load.

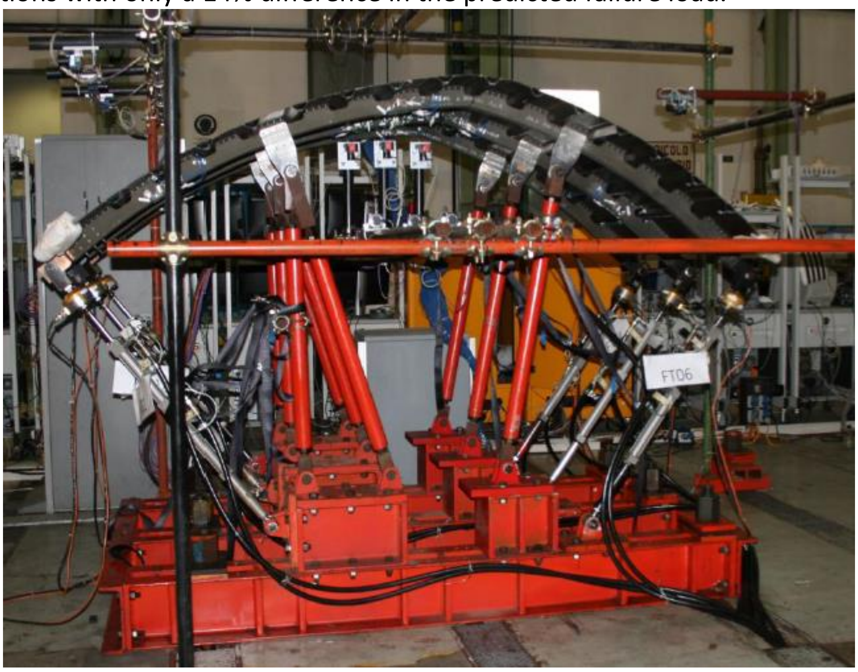


Figure 45: Panel bending testing at partners 63 ALA and 25 IMA

Similiarly, test were performed on a one frame bay of window belt in which an RTM winbdow frame from partner 56 TAI was co-bonded on a skin panel and successfully tested by partner 25 IMA. The purpose of the tests were to verify the stress analysis results of the most critical load case and to confirm the ability to predict the expected failure load capability and to assess capabilities and limitations for prediction of post-buckling behaviour and final rupture.

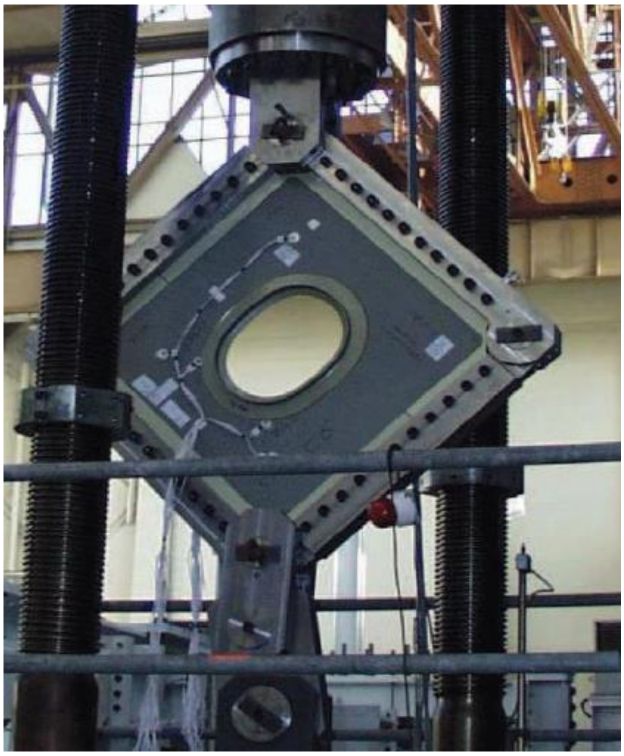
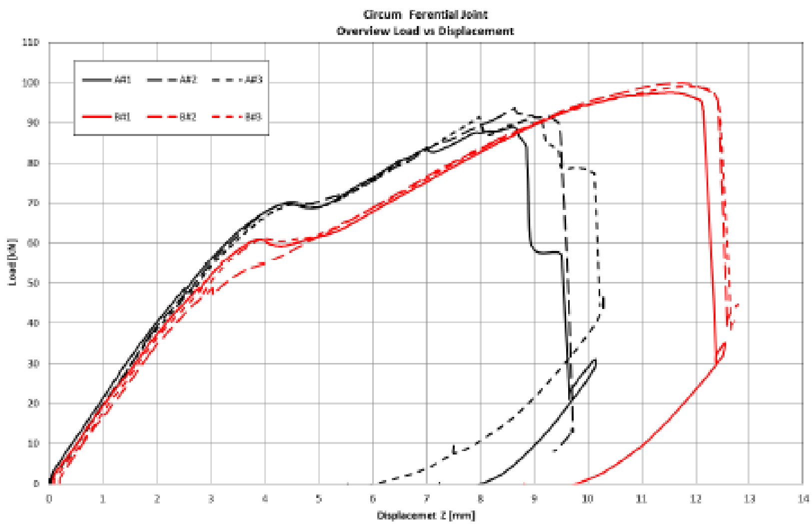


Figure 46: RTM window frame (56 TAI) co-bonded on a skin panel for testing at partner (25) IMA

Test of the circumferential junction



Six flat CFRP panels were delivered in two configurations. All panels consisted of a CFRP outer skin with 2 CFRP stringers. In the centre of the skin was a circumferential junction

in two different design solutions (3 specimens of each). They were tested with a tension load sequence up to rupture. The test batch consisted of two groups of different junction designs (A and B) with 3 panels each (1 to 3). All panels were loaded up to limit load (LL) and ultimate load (UL) and passed >3 sec this load levels. No damage was detected during visual inspection after limit load. The average rupture load for series A was 91.4 kN and series B 98.8 kN.

Analysis of components and Sub-component tests

A CFRP stiffened fuselage panel was modelled using SIMULPAC on top of the Finite Element software Abaqus. The results were compared to test results of pure compression and combined shear and compression load cases. Good strain gauge correlation between tests and FE analyses has been found up to buckling onset. Imperfection sensitivity analyses have shown that the FE results heavily depend on the imperfection shape. Detailed information on the panel's imperfection shape is needed for the FE analyses to obtain buckling patterns comparable to the tests.

Results from the full scale demonstrator sub-project

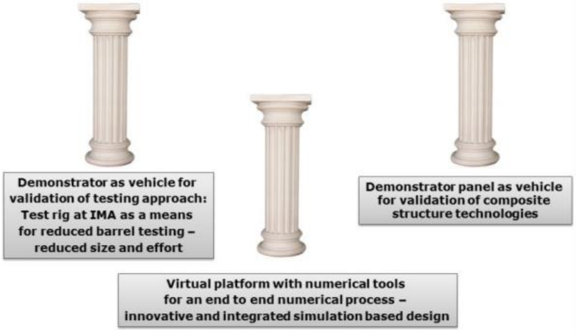


Figure 47: MAAXIMUS Phase II or SP7 and its three pillars

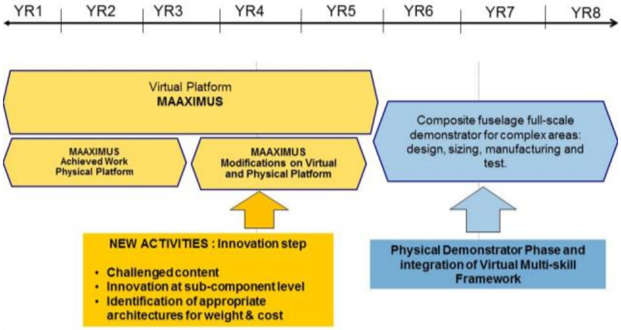


Figure 48: MAAXIMUS time plan for all eight project years

Major results can be summarized as follows:

- Definition of the test scenarios and testing: Interface loads are the driving factors in sizing PAX Door and PAX Door surround structures. The developed method led to a significantly reduced test preparation effort and to more detailed information about the PAX Door – Fuselage interface. The impact of modifications in the PAX Door or fuselage design was determined more precisely and subsequently, the validation of FE models was significantly improved. Static and dynamic tests have been performed, which show very good results with good correlation with numerical predictions.
- <u>New test method is available for door and door surround panel testing: The test method is able to fulfil requirements of TRL 6 in the research and development process of complex fuselage structures.</u>
- Manufacturing at suppliers for tools and parts as well as the re-scheduled overall manufacturing and assembly were successfully finalised with a reduced time delay. The Full Scale Demonstrator and its components were successfully manufactured and delivered for testing.
- Optimisation of Virtual Barrel and Full-Scale Demonstrator: PAX Door interface modelling has been harmonized between PAX Door DFE model and barrel model (19 AIRBUS HELI). Besides serving as prerequisite for the validation activities in WP7.8. "Validation and Correlation", AI-D can use the improved model for their sizing activities.
- The down-selection of technologies produced a list of promising technologies to the MAAXIMUS full scale demonstrator, which will be also useful and beneficial for future application in aircraft programs.

The <u>integration of the VP and PP based on dedicated use-cases within the MAAXIMUS demonstrator</u> was another major focus of technical activities. Major results can be summarized as follows:

- Optimized PAX Door DFE model and barrel model modelling serves as prerequisite for the validation activities in WP 7.8. "Validation and Correlation" where door stop loads are used to validate the virtual tools with the test results.
- The key Hub C use case "C1 - Close loop between design and analysis" (12 DS) was able to gather the following metrics for all stages of the tests pyramid:

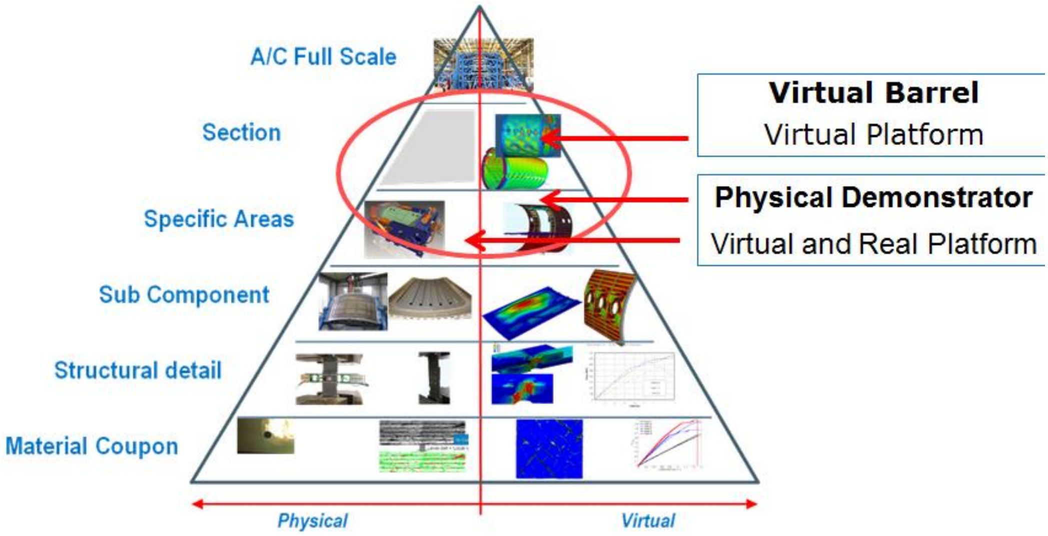


Figure 49: MAAXIMUS metrics as per use case "C1 - Close loop between design and analysis" and their interrelation with VP and PP

- Clearly, the Virtual Platform capabilities, enhanced throughout MAAXIMUS, have demonstrated beyond state-of-the-art performances, on industrial standard IT hardware. Such a breakthrough will definitely be utilized by the aerospace industry, with extension possible to other industries (i.e. transportation, shipbuilding, industrial equipment in particular) for complete design cycles. Such initiatives, in particular with Airbus entities, were already started during MAAXIMUS project.
- Main objective for partner (18) ESI within MAAXIMUS Phase II was to demonstrate capability of its infusion simulation prototype and to validate it at coupon level in collaboration with partner (17) AGI-F. Final Virtual Platform Methods results are beyond expectation, indeed, full infusion simulation at industrial level (i.e. full C74 frame meshed with more than 500 thousands elements) taking into coupling between solid mechanics (i.e. mechanical behavior of preform) and fluid mechanics (i.e. resin flow within preform) was never performed before and was not planned to be possible within MAAXIMUS time frame.
- A highlight of the AI-UK work in the field of Virtual Platform Methods was the construction of a non-linear finite element simulation that was full dependent upon geometric features for its definition without the need for any form of bespoke script creation. Updating of the geometric data was cascaded to the finite element model without further user intervention.

The challenging project objectives regarding weight savings, manufacturing and assembly R/C reduction, section FAL time reduction, cost and overall time reduction in development, manufacturing, simulation and validation were widely achieved. MAAXIMUS technical activities led to numerous excellent results of high importance which is also reflected by the achievement of all Phase II milestones.

1.4 Potential Impact

1.4.1 Wider Societal Implications

See tables in chapter 3

1.4.2 Main Dissemination Activities

MAAXIMUS research results were published in peer-reviewed scientific journals and widely presented at national and international conferences (details can be found in chapter 2.1 of this report). The project's main results and their potential applications were presented at the final public MAAXIMUS workshop at IMA, Dresden, Germany, 27-29 September 2016. Beyond project duration, the MAAXIMUS website (www.maaximus.eu) presents the "MAAXIMUS" concepts, realization methods and major results.

1.4.3 Exploitation of "MAAXIMUS" Results

In Airbus Structural analysis community, the most practically useful work from MAAXIMSU Phase I was the implemented solid-like-shell element. In subsequent work internal work, after Phase I finished, i.e. from 2012 through 2014, this element has been tested and further developed internally.

-Tests involved behaviour of composite angles (tested by ONERA), which requires curved geometries.
-Improvements included;
-procedure for letting solid like shell element be used in a curved geometry (thus fully utilizing its capability to cover large surfaces of thin thickness materials)
    -procedures for orienting the element in arbitrary planes in space
    -including this element in the Airbus internal fast test panel modelling tool SIMULPAC (Within phase I in D3.11.9, and used in D6.2.3))

-The element was furthermore tested in stacked manners, to get experience of this way of working
    In connection with this, the question of damage quickly came back, since damage is what composites do, once you test them to their limit!
    -In order to utilize the solid like shell elements capability for a full 3D material (not done in the official Phase I) an internal work took place to implement an arbitrary 3D material model inside the solid like shell element. This would normally be a gigantic task, However, the ABAQUS user material interface proved possible to be implemented "inside" the element, (by subroutine call at proper place). Thus a combination of 3D damage models and solid like shell was successful, and Airbus should be one of the first in the world to have this very powerful combination! First tests of its behaviour have started and look promising.

The selection of adequate numerical technologies and the definition of an integrated design process contribute to the satisfaction of HLOs: FEMIX automates the creation of GFEM in a parametric context and PRESTO performs sizing. Together these both tools enable months of lead time reduction in structural sizing and design, considering also that the generation of detailed geometry can be automated from adequate design rules managed by MAAXIMUS Virtual Platform (3D experience).

Modelling of real damage behaviour of laminated composite structures:

-Progress by improved physical-geometrical modelling:

- modelling of laminate by solid-like-shell (performed in MAAXIMUS Phase I)

Efficiency: Since the weak link in composites most often is in the out of plane direction, (applies to both cracks and delamination) it can never be hoped to closely resemble the real conditions by using only an in-plane element! But this is what most engineers do today! Airframe computations involving composites are still today often using various classical shell elements, i.e. that have a geometry only in the in-plane directions. Their thickness is only defined as a factor! When 3D elements are used it has most often been "Solid" elements (also named "brick" elements) which do fully take all dimensions into account, but their aspect ratio of max 3 to 1 or at the most 4 to 1, hinders their size to be large in plane. Since a composite is thin, there needs to be very many elements over the plane, and this gets numerically expensive!
Therefore a new element type, the solid like shell, the basics of which were researched prior to the beginning of MAAXIMUS, was taken as a basis in Phase I and a working implementation was produced by ALE in close cooperation with Airbus. For the first time known this type of element was then tested on airframe type composites as used in civil aviation. The results were promising. In the first place one element over the thickness was used, which is the simplest way of use, including the different plies within the element, but here severe ply damages should ideally not occur. Good behaviour versus ABAQUS standard elements proved to exist with less numerical effort possible. (Sources: Task 3.18.10, D 3.2.6; paper Peter Linde on Final MAAXIMUS Review!

- 3D material; the solid-like shell implemented in Phase I by ALE proves to have a functioning material tensor, that has capability for full 3D material models, (at the same time as permitting large aspects ratios, well over 4 to 1, as discussed above). This is important since the out-of-plane direction is included here, and can be nonlinear (and by that display: damage!). No such development were existing at Airbus previously. In Phase I Prof. Joris Remmers of the TUE gave further proof of this capability (Source; D3.11.7). Airbus has obtained the ALE implementation and worked with it. It has been used, at Airbus in Hamburg, Filton and Toulouse, since 2012.

Airbus did some first comparisons within Phase I; D 3.2.7, D 3.2.11

Theorethical derivations, were carried out of Solid like shell elements by USTUTT, and included here element formulations, element parameters, some basic element tests (patch tests etc). This work forms a good complement to the implementation work done by ALE, and the Airbus internal evaluation, further adaption and exploitation. All partners interacted with P. Linde as central focal point during Phase I. Source; D3.11.2, D3.11.3

-Progress by multi-scale damage modelling

Commonly in engineering practice, one handles composite materials as if they were a "smeared" material on the "meso level" consisting of an artificial material (Involving some combination of fibres, matrix, and possibly the bond between them), and then in the best case separate failure criteria for "fibre failure" and "matrix failure" are introduced. This might work in several cases. ALE in Phase I implemented a "multi scale" damage model into ABAQUS. The multi scale model carries over strain data down to the "micro level" in which the behaviour of a single fibre is studied. Down on this level somewhat simpler failure models can be sued, than if one smears them on the meso level as is customary. ALE has implemented the transfer from meso to micro scale, damage modelling on the micro scale, and transfer back up to the meso scale in a reliable manner, and verified their model in some examples. Their work made up one, of several, interesting contributions within Phase I, concerning composite failure models. Sources: D3.2.6

The current certification process of commercial aircraft does not allow significant PAX Door product improvements after type certification. In contrast, the test method developed in MAAXIMUS could be an enabler for iterative product improvements before and after type certification that will lead to an earlier implementation of new technologies in order to reduce the environmental impact of aircrafts.

1.5 The MAAXIMUS Consortium

Aircraft manufacturers, material behaviour specialists, software developers, computational mechanics experts and test centres from industry and academia

More Affordable Aircraft structure through eXtended, Integrated, and Mature nUmerical Sizing

Figure 50: The"MAAXIMUS Consortium at the Kick-Off in 2008 and at the Final Meeting in 2016

Each of the 57 involved organisations from 18 countries has been carefully selected to bring particular expertise or facilities to the Consortium. The combination of such experience and know-how ensures proper capitalisation of results from past and current national and international projects (see Table 1).

Table 1: List of „MAAXIMUS" consortium partners

Partner	Short Name	#
Airbus Operations GmbH (DE)	AI-D	1
Dassault Systèmes Simulia Ltd (UK)	ABQ*	2
Advanced Lightweight Engineering BV (NL)	ALE	3
Airbus Operations SAS (FR)	AIRBUS OPERA-TIONS	4
Airbus Operations S.L. (E)	AI-E	5
Airbus Operations Limited (UK)	AI-UK	6
ARTTIC SA (FR)	ARTTIC	8
Centre de Recherche en Aéronautique ASBL (B)	CENAERO	9
Centro Italiano Ricerche Aerospaziali SCPA (IT)	CIRA	10
Constructions Industrielles de la Mediterrannée (FR)	CNIM*	11
Dassault Systèmes SA (FR)	DS	12
ISIGHT Software SARL (FR)	ENGI-NEOUS*	
Dassault Aviation SA (FR)	DASSAV	13

Partner	Short Name	#
Centre d'Essais Aeronautique de Toulouse (FR)	CEAT	14*
Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)	DLR	15
Airbus Defence and Space GmbH (DE)	AIRBUS DS-D	16
Airbus Group SAS (FR)	AGI-F	17
ESI Group S.A. (FR)	ESI	18
Airbus Helicopters Deutschland GmbH (DE)	AIRBUS HELI	19
Fischer Advanced Composite Components AG (A)	FACC	20
Fundación de la Ingeniería Civil de Galicia (E)	FICG	21
IMA Materialforschung und Anwendungs-technik GmbH (DE)	IMA	25

Partner	# Short Name	
Imperial College of Science, Technology and Medicine (UK)	IMPERIAL	26
Integrated Aerospace Sciences Corporation O.E. (GR)	INASCO	27
University of Stuttgart (DE)	USTUTT	28
Institut National des Sciences Appliquées de Lyon (FR)	INSA	29
Instituto Superior Técnico (E)	IST	30
Israel Aerospace Limited (IL)	IAI	32
National Institute of Aviation Technology (RU)	NIAT	33
Latécoère (FR)	LATECOERE	34
Gottfried Wilhelm Leibniz Universität Hannover (DE)	LUH	35
Latécoère Czech Republic S.R.O. (CZ)	LLV	36
Siemens Industry Software NV (B)	LMS	37
École Normale Supérieure de Cachan (FR)	ENSC	38
MSC.Software Limited (UK)	MSC	39
Office National d'Études et de Recherches Aérospatiales (FR)	ONERA	40
Politecnico di Milano (IT)	POLIMI	41
Qinetiq Limited (UK)	QINETIQ*	42
Rheinisch-Westfälische Technische Hochschule Aachen (DE)	RWTH	43
Samtech S.A. (FR)	SAMTECH	44
Short Brothers plc (UK)	BOMBARDIER	45
Swerea SICOMP AB (SE)	SICOMP	46
SOGETI High Tech GmbH (Capgemini) (FR)	SOGETI	47
Société Nationale de Construction Aérospatiale SA (B)	SONACA	48
Stichting Nationaal Lucht - En Ruimtevaart-laboratorium (NL)	NLR	49
Eidgenössische Technische Hochschule Zürich (ETH)	ETH	50
Technische Universität Carlo-Wilhelmina zu Braunschweig (DE)	TUBS	51

Partner	# Short Name	
Technische Universität Hamburg-Harburg (DE)	TUHH	52
Eindhoven University of Technology (NL)	TUE	53
Technology Partners Foundation (PL)	TPF	54
The Swedish Defence Research Agency (SE)	FOI	55
TUSAŞ -Türk Havacılık ve Uzay Sanayii A.Ş. (TR)	TAI	56
University of Limerick (IRE)	ULIM	57
University of Patras (GR)	LTSM-UP	58
Fundación Imdea Materiales (E)	IMDEA Materials	59
Fundación Tecnalia Research & Innovation (E)	TECNA	60
	FATRONIK *	
Dassault Systèmes UK Ltd (UK)	DS-UK	61
Ministére de la Défense (FR)	MIN-D	62
Finmeccanica S.p.A. (IT)	ALA	63

* Terminated partner / Transfer of rights and obligations to another partner