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Final Report

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Final publishable summary report

1. Executive Summary

Through four years of intense research, the CERFAC project addressed specific issues in the improvement of fastened areas in composite structures. Many challenges in composites structures are related to critical loading near fastener areas, but these areas are too often designed based on classical methods that have been adapted to composites.

The move to composite materials offers new perspectives in terms of local reinforcement of zones and tailoring of the stiffness and strength of materials in each direction.

The 15 partners involved in CERFAC covered many of the key aspects in the design, manufacturing, testing and evaluation of composite materials and in particular composite joints. In order to maximize the impact of the project, a large panel of reinforcement solutions were studied over a range of applications categorized into “advanced joining concepts”, “butt-strap applications” and “concentrated load applications”.

As cost-efficiency is key here, evaluation of reinforcement solutions can only be done if information can be gathered on the impact of the process in terms of costs and operational efficiency. These aspects were also taken into account in the final stages of the project.

2. Project context and the main objective

The CERFAC project addresses many challenges faced in the growing use of composite structures and mainly the transfer of loads between composite parts through innovative designs for joining and assembly.

Today a rapid growth in composite applications for fuselage, wing and other structures (A380 28% and Boeing 787 50% content) has been realised due to their superior ‘specific’ mechanical properties allowing weight and associated fuel consumption and pollution reductions. However, the substitution of metals with composites has presented formidable challenges to realize lighter, stiffer and stronger, damage tolerant structures that are cost-efficient, regarding development, manufacturing, inspection, or even operating costs.

A major design problem of composite is efficient joining systems for high performance aero-structures. Due to the large number of such interfaces in aircrafts, a solution to these problems is highly promising in terms of weight and cost reductions. It can be stated that current design practices give non-optimal jointing systems that are poor in terms of weight penalties and cost efficiency. Consequently, composite designs are often rejected in favour of traditional metallic concepts.

2.1 Objectives

CERFAC’s first objective is to provide a catalogue of reinforcement solutions at the locus of fastener holes (rivet holes, bolt holes) or edges leading to lighter, stronger and more damage tolerant designs.

CERFAC’s second objective is to introduce innovative and efficient joining concepts combining some of the investigated reinforcement solutions, supporting representative target applications. This contribution would then help reducing further the number of fasteners, while increasing the load

bearing capacity and damage tolerance of the assembly. The efforts in the project are directed to allow and favor future (mid-term) introduction and exploitation of the proposed concepts by:

- Always considering other constraints such as accessibility, disassembly, repair-ability, inspect-ability, ...
- Positioning the approach in-line with current design methodologies and tools
- Accounting for current design, analysis, testing, certification rules and practice.

As the strength to cost ratio is used to classify the performance of the investigated reinforcement solutions and joining concepts, one of CERFAC's main tasks is to identify cost drivers, to predict and to verify cost for each of the latter

2.1.1 Targeted applications

The first range of target applications addresses distributed loads and shows a gradation in terms of complexity, from the optimized standard strap or splice to the advanced multi-functional profile.

As a first example of target application to be considered in CERFAC, we can mention generic straps for assembling thin walled structures (see Figure 1).

These straps (so called Butt Straps or Butt Joints) are used in many places, and therefore could be a source of overall weight loss and cost savings, accentuated by the fact that damage tolerance and load bearing capacity could be improved.

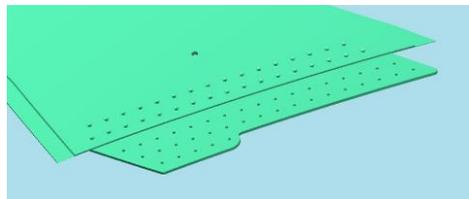


Figure 1. Example of a Butt strap connection

As a second example of target application to be considered in the CERFAC project, we can mention fuselage shells' or barrels' final assembly (see Figure 2). During assembly, splices are generally used (adding significant weight), as well as a large amount of rivets (that increase the costs)

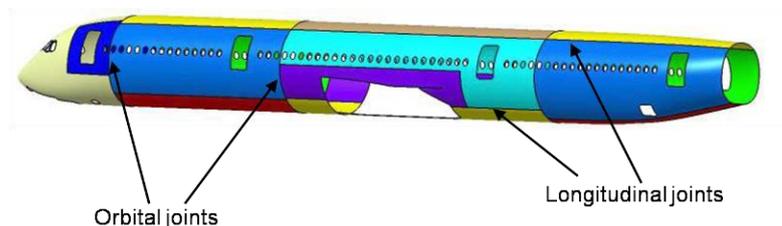


Figure 2. Illustration of longitudinal and orbital joints in final fuselage shells assembly

The third range of applications considered in CERFAC is related to the transfer of concentrated loads, through thicker laminates or thickened zones of thin walled parts, introducing a limited number of fasteners, with different configurations from local patterns of rivets (eg attachment of floor beams to frames) to connecting lugs with a single bolt (eg VTP attachment in Figure 3).



Figure 3. Example of a connection for a concentrated

2.1.2 Innovative reinforcement solutions

Fundamental understanding of the optimal fiber orientation and placement is lacking. Standard optimization tools and commonly accepted optimization approach will be followed (i.e. innovation or TRL increase does not lie in the development of a new optimization methodology). Innovation comes from the thorough understanding of optimal orientations and stacking sequence in fastener areas, with regards to the current design practice (isotropy and local thickening). In terms of new reinforcement techniques using specific manufacturing techniques the paths explored during the CERFAC project are the following ones:

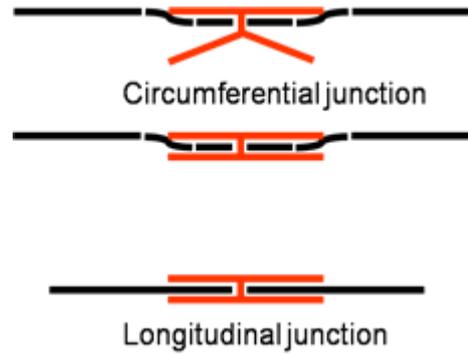
- TFP: tailored fiber placement has already been used for years and has demonstrated smooth integration in the manufacturing chain. The scientific challenge lies more in the optimal placement of tows.
- FPP: For what concerns Fibre Patch Preforms - Figure 4, the objective of CERFAC is to improve the technique already developed by EADS-IWG, and go one step closer to the target application.



Figure 4. FPP carbon fibre reinforcement rosette (EADS-IWG)

- CMP: Compression moulded patches of polymer reinforced with chopped fibres or prepreg are promising for producing stiff, strong and tough parts at low cost, as well as reinforcing add-ons. The idea of CERFAC is to explore new systems that could be compression moulded.
- HYB: Starting from the reference solution using standard laminates (stacking sequence, local thickening) and recommended joining rules, another conceptual innovation comes from the introduction of metallic foils in the lay-up. The novel idea is to introduce metallic foils in fastened areas of thin-walled structures, which would certainly result in a significantly improved strength and damage tolerance while also focusing on cost efficiency.

- GEO: Bonded / geometrically interlocked joints concepts start at a very low TRL. Thanks to this concept, the stress carried out by the rivets is reduced, some of the load being carried by the interlock, with and homogeneous stress distribution essentially ensured by the adhesive bond. The number of rivets should be lowered, the damage tolerance should be improved
- BSB: new concepts, including H-profiles, which might be assembled using preforming then B-stage bonding. Additional fasteners might or might not be necessary.
- PRO: The last step of conceptual innovation in CERFAC is the introduction of multi-functional profiles combining the stiffening and joining roles.



2.1.3 Major outputs of the project

Reinforcement solutions are developed for one or several applications. In each case the new solution will be compared to a “reference” type that is taken from the current state of the art (standard laminate solutions with local thickening from current design rules or metal hybrid solutions). Also, the possibility to include other emerging solutions is left open.

There are several major outputs planned throughout the project. The first that gathers all the results from the project is the catalogue of reinforcement solutions at the locus of fastener holes (rivet holes, bolt holes) or edges leading to lighter, stronger and more damage tolerant designs. Predictive analysis methods and optimisation techniques supported by extensive testing will enable cost and weight efficient solutions.

Secondly, the project focuses on several specific reinforcements and these will be developed throughout the project in order to achieve a higher level of maturity and hopefully allow using them in an industrial environment. The table below summarized the outputs expected for different reinforcement solutions. Concepts focus on design of the reinforcement solutions, testing and characterisation while process development will dig deeper in the fabrication of these reinforcement solutions with respect to the requirements of industrialization and integration in the manufacturing chain.

Description	Innovation type
Basic optimization of standard stacking sequences in order to improve strength. Combination of fastener area reinforcement solutions for conventional joints. Reducing the number of fasteners by reducing the stress carried by these. Reducing the assembly cost.	Concepts
Compression molded patches added on fastener holes: process set-up and patch optimization. Towards automated / cost effective process and patch, towards a reduced stress concentration.	Concepts and Process

Exploration, characterization and optimization of complete dry assembly process. Towards fastener free structures. Injection and assembly are simultaneous, thereby reducing the assembly cost.	Concepts and Process
Exploration, characterization and optimization of preforming + B-stage bonding for longitudinal joints: mechanical and chemical issues.	Concepts and Process
Design, analysis and validation of multi-functional profiles combining the stiffening and joining roles. Reducing the number of rivets by eliminating splices and reducing the stress carried by these. Reducing the assembly cost.	Concepts
Transfer of hybrid laminates technology around fastener holes to thinner structures.	Concepts
Exploration of low cost alternatives (other metallic foils than Titanium) for hybrid laminates. Underlying design, analysis, modeling, simulation and optimization activities. Reducing the cost of hybrid laminates for improving joint resistance.	Concepts
Innovative design of connecting lugs: combination of different reinforcement solutions. Minimization of the number of fasteners and of the assembly cost.	Concepts

3. Main Scientific and Technical results/foregrounds

The CERFAC project, has, over the past 4 years, explored many different applications in three categories looking at how different reinforcement solutions can improve load bearing in structural fastener regions.

Solutions must be developed keeping an industrial scale-up to mind in order not to reach optima which will then be impractical to put into place in large structures. The initial test plan and the practical implementation of several solutions were therefore heavily modified throughout the project. The scope of some activities was redefined and new solutions were also explored.

The project worked through identifying key parameters (fibre reinforcement architecture, positions and dimensions, surface treatments,...) and performance measurements (specific bearing strength, limit loads, interlaminar shear strengths,...) in low complexity test levels to perform larger test campaigns.

3.1 Butt strap applications

3.1.1 Design winglet and joint

A new reference winglet was designed by ZHAW. Its geometry is very comparable to the size and shape of an Airbus A350 winglet. The wing-winglet butt joint is representing several other areas in the design and is therefore to be considered as one of the standard joints.

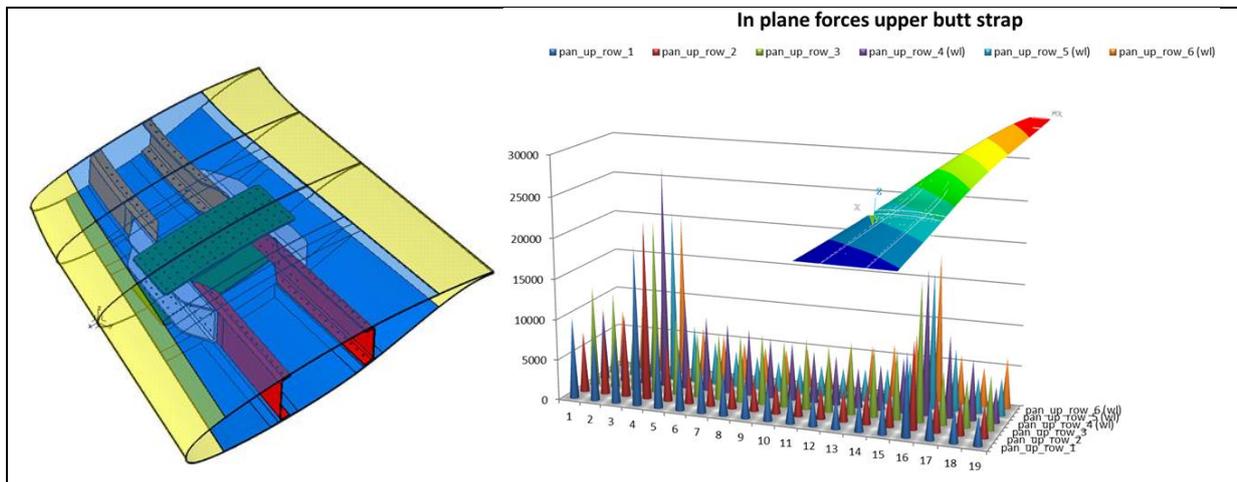


Figure 5: Wing-Winglet joint designed by ZHAW (CAD-drawing) and loads per rivet position (FEM-analysis)

3.1.2 Analysis of winglet joint

The most important load cases are defined based on an older approach in CS25 regulation. A gust envelope and a flight envelope were created during a preliminary design study for a fictive aircraft. 8 load cases are analyzed in a CFD simulation to determine the loads acting on the winglet structure. After the loads and structure are defined, the loads of each rivet can be assessed and being closer investigated for further optimization of the structure during the CERFAC project. Based on preliminary sizing, the rivet pattern (size, diameter, rivet-to-rivet distance and amount of rows) were defined in order to start with design activities.

3.1.3 Reinforcement technologies and advancements

Tailored fiber placement

The idea with fiber placement patches is the local strengthening of the laminate against bearing failure with optimised fiber architecture. The optimisation is performed with tests of different patch geometries and by simulation.

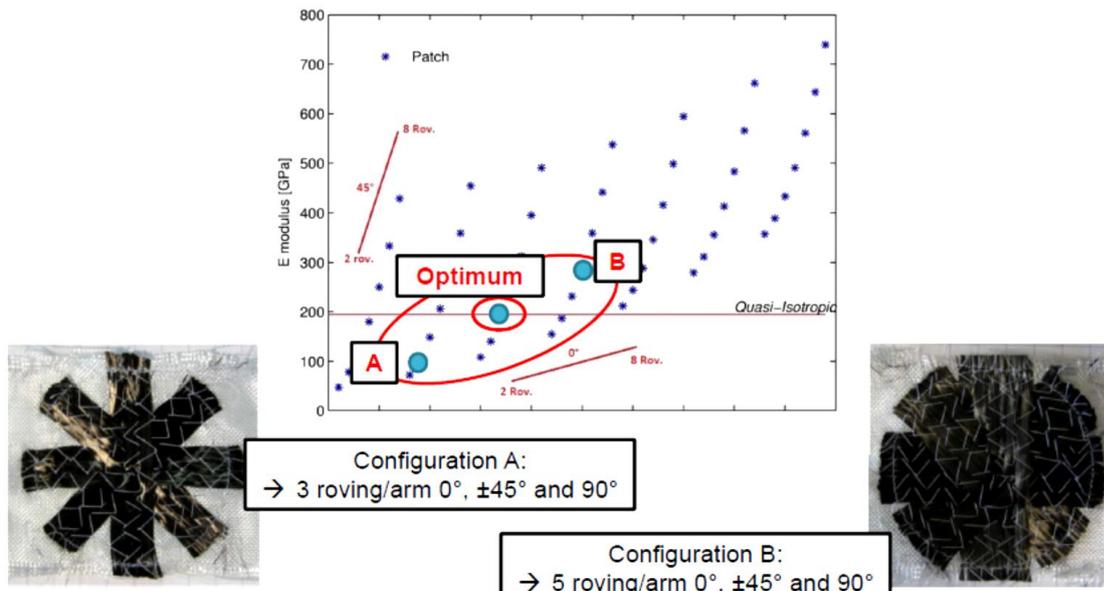


Figure 6: Optimisation of TFP patches

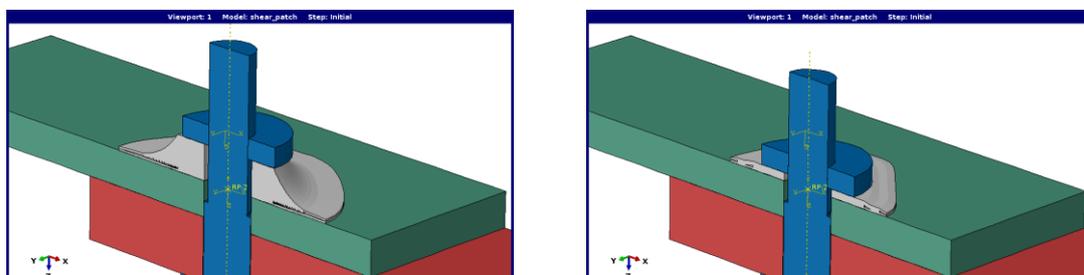
Concerning simulation work, again the modelling of crushing was extensively addressed. *Here USTUTT developed a method of how to model CPU efficiently the bearing behaviour with crushing data sets.*

The experimental work that is performed in parallel to simulation activities proves that local reinforcement by TFP with fiber content in radial direction to the bolt hole increases the load capacity of the connection most (max. increase of 31%). Basically, the bearing strength can be adjusted by the fraction of radial fibers. Nevertheless, the evaluation in WP5 showed that TFP patches are rather not to be favored concerning reinforcements in joints.

Compressed moulded patches

The influence of reinforcement patch shape on the performance of a joint was studied and developed using in-house software applied to the case of a compressed moulded patch geometry. The geometry for a single lap shear test was created and the shape of the patch was fully parametrized.

The number of plies, the drop-off ratio and the cut-out shape can be modified to generate very distinct geometries as illustrated in the figure below.



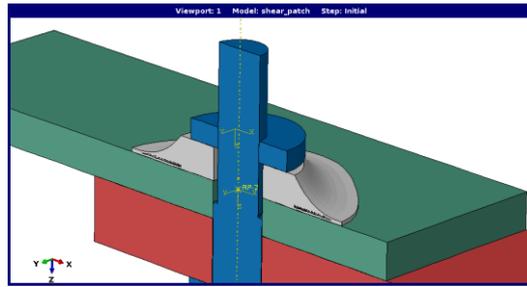


Figure 7: Patch geometries generated and studied through FEM analysis

This optimization was done first using a mixed variable space as dimensions were continuous, but thickness could only increase by steps (number of plies).

The technical outcome in terms of reinforcement is limited in this case as the specific bearing strength was not increased as with other different reinforcements, but can be used as a first benchmark or demonstrator for this type of activity.

The full through thickness analysis using a Hashin's criteria on the patch and on the base plates was performed and compared to experimental tests as shown below.

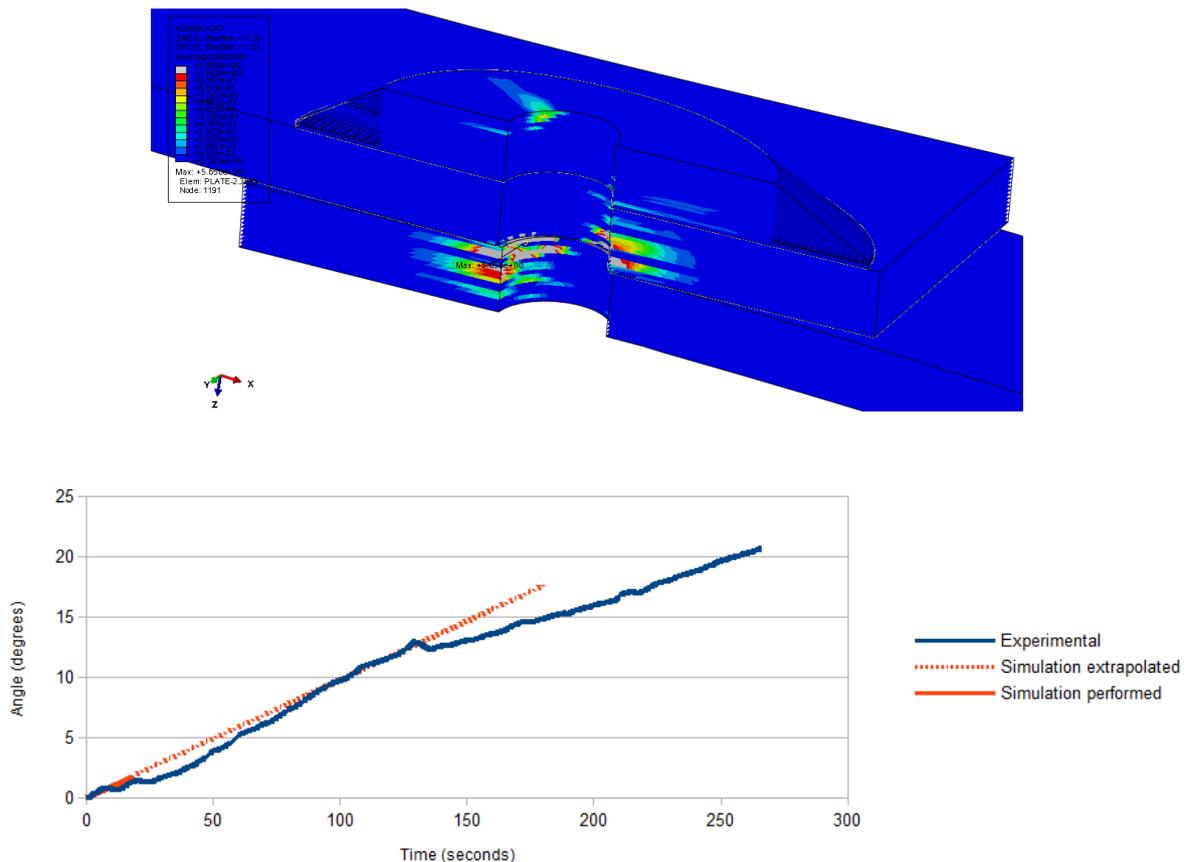


Figure 8: Stress-strain behaviour and correlation to image data from tests (bending angle of SLS specimens)

Agreement in terms of behaviour and first failure was of good quality, but progressive failure models were not included as data available was not sufficient. The interface was further studied in different

reinforcement solutions where we consider an interface between a composite panel and a metal reinforcement.

With the added complexity of the reinforcement, the interfaces can become the most critical. Estimations on the behaviour of the interface were made in design, but these could only be confirmed later in the project when tests were performed and experimental results compared to simulations. Qualitatively, the results from reinforcement solutions were good while quantitatively, we observed that first simulations were further off on the increase in bearing strength that reinforcements may bring. For the specimen illustrated below, the cohesive model initially used to estimate the strength of the interface showed underestimated values of load before failure compared to actual tests.

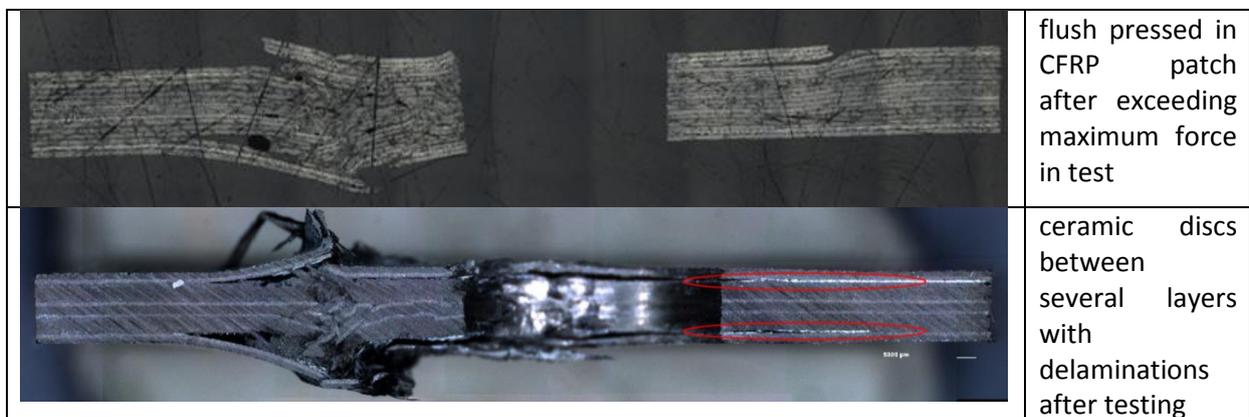
Evaluation of reinforcement methods

ZHAW mainly focused on reinforcement solutions for structures made of prepreg material. Therefore samples out of M21 UD prepreg were manufactured, machined, assembled and tested. The investigated reinforcements were:

- Increasing the fiber volume content to about 72% (flush pressed in patches)
- Increasing matrix stiffness by adding ceramic particles (powder and very thin discs)

It was shown that the ceramic powder had no significant influence on bearing strength. The ceramic discs led to delaminations at lower loads than without.

Further investigations were only made with flush pressed in patches with the M21 UD Prepreg material.



Testing

Testing was done according ASTM standards. We mainly performed single lap tension tests as this configuration is the most common one in an aircraft. It is also the most complex load case regarding out-of-plane-stress and bolt tilting. Therefore these results can be seen as conservative for double lap configurations.

For most of our tests protruding bolts were used due to the much lower price and easier procurement. Nevertheless it was shown with our c-level-tests that the 2% offset bearing strength with protruding bolts is about 30% higher than with countersunk ones.

Tests with the flush pressed in patches showed an increase of 2% offset bearing strength of about 8%, but the distance between the fasteners can be decreased from 5xd to 4xd without decreasing the load transmission capability.

Cost and weight analysis

ZHAW developed the spread sheet for the cost and weight analysis to be used for comparison within the butt strap application. Cost and weight analysis shows that the reinforcement solutions developed at ZHAW are suitable for lighter structures with moderate increase of costs.

3.2 Advanced joints applications

3.2.1 H-Junctions

The main objective of Airbus Group Innovation in CERFAC project was to evaluate the capability to use the mid cure technology to assemble composite sub element for aircraft composite fuselage application. The concept is presented Figure 9.

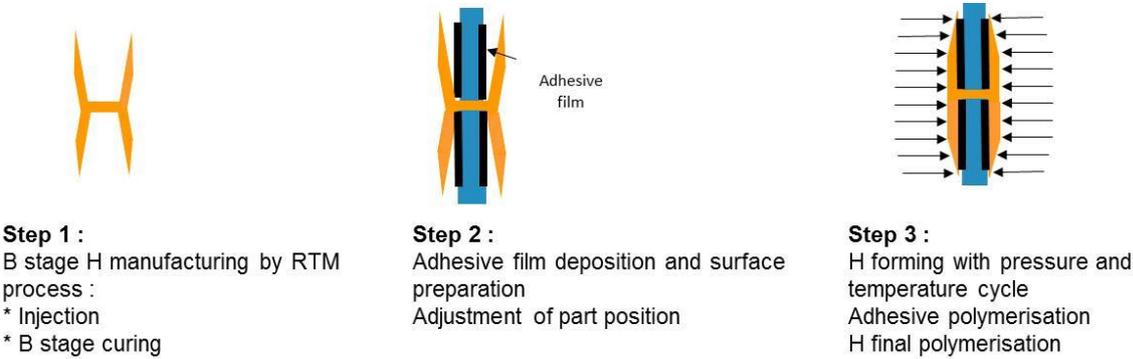


Figure 9 : Concept studied in CERFAC project by Airbus Group Innovation for composite part assembly with mid cure technology.

The studied materials for the composite elements were RTM6 epoxy resin from Hexcel and preforms for H elements. Two types of preforms have been evaluated. 3D preforms from Biteam and NCF preforms from USTUTT.

To propose adapted mid cure cycle, the polymerization kinetic of the RTM6 resin has been characterized for mid cure cycle utilization with DSC and rheological studies. The evolution of the conversion ratio with the curing temperature and time is presented Figure 10.

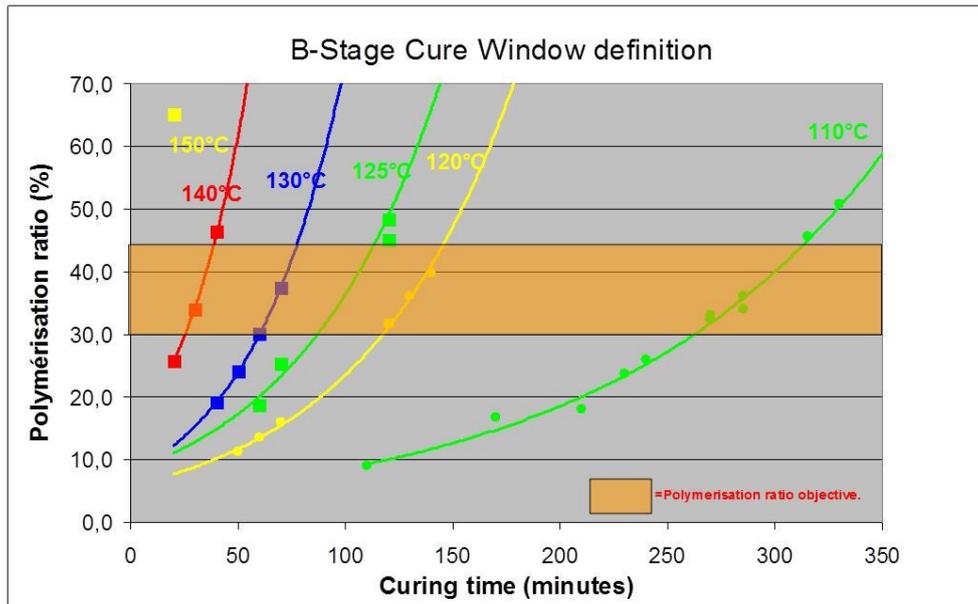


Figure 10 : Evolution of RTM6 polymerization ratio with curing time for different curing temperatures.

H elements have been manufactured with different preforms produced by Biteam with 3D weaving technology and by USTUTT with NCF materials. These H elements have all the same H geometry. The epoxy resin used to inject the H elements was RTM6 from Hexcel. Curing cycles have been determined with different conversion ratio for the H elements and for the flat laminates used with the H elements. The different configurations tested are presented Figure 11. Different samples for tensile, shear and four points bending have been manufactured. The mechanical tests have been performed by VZLU.

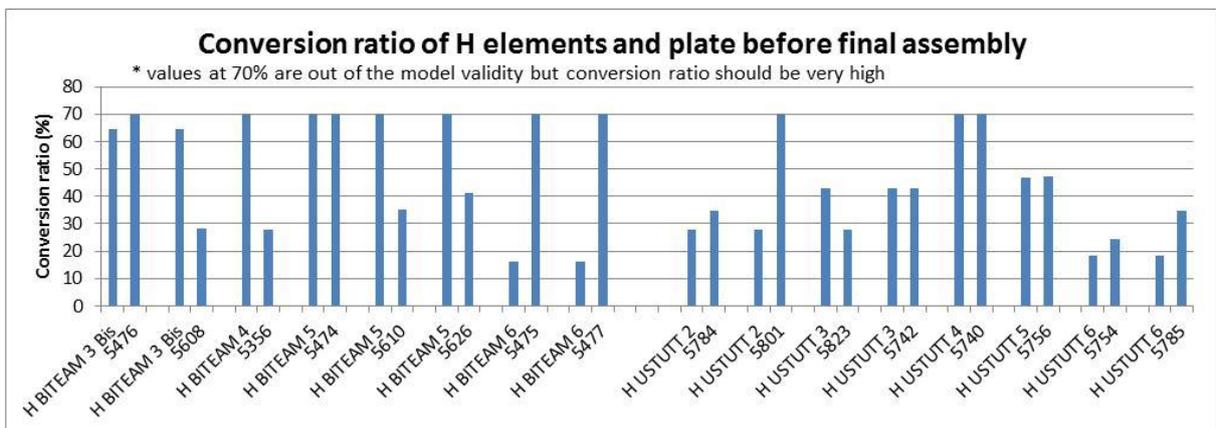


Figure 11 : Configuration of curing ratio used for the manufacturing of the assembled H elements with flat laminates.

Results obtained

Airbus Group Innovation has produced different samples for G1c and Double Lap Shear tests to evaluate the final properties of assembled mid cured laminates with and without the presence of an adhesive film between the two mid cured assembled laminates. A final curing cycle is used to cure the adhesive film and to complete the conversion ratio of the laminates. The mechanical tests have been done by VZLU. On Figure 12, an example of results obtained with G1c tests is presented. It is possible to make an assembly of two mid cured laminates without addition of adhesive film only if conversion ratio of the laminates is below 20%. In case of addition of an adhesive film, the G1c values increase with the reduction of the conversion ratio of the laminates.

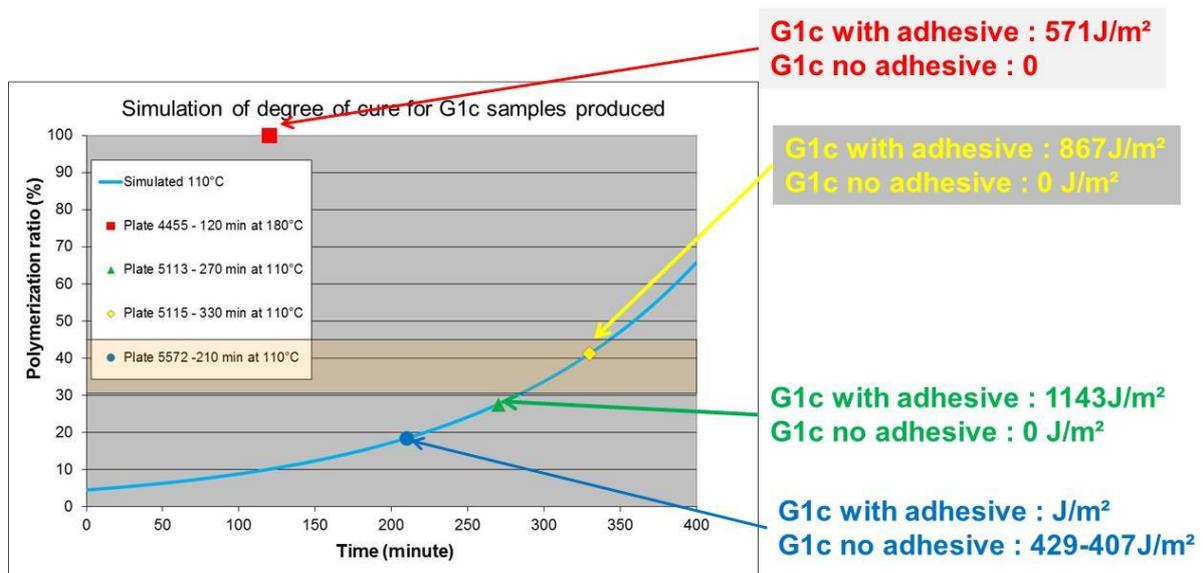


Figure 12 : G1c properties of mid cured assembled laminates with different conversion ratio with and without the addition of an adhesive film. After assembly of the laminates the final curing cycle give a conversion ratio closed to 100%.

3.2.2 Reversible bonding

Reversible adhesive bonding technology based on resistive heating of thermoplastic material was developed. By applying an electric current to a thin resistive mesh embedded in a thermoplastic film, the film is molten and an adhesively bonded joint can be formed. If the joint needs to be disassembled, current can be applied again to the mesh, heating the film and releasing the joint.

Phenoxy thermoplastic adhesive was selected as bonding material for use in a reversible bonded joint. The phenoxy material is supplied by InChem as thin foils of 21 μm thickness.

Methods to efficiently manufacture a phenoxy film with embedded resistive heating wires were investigated. It appeared that the integration of a thin stainless steel mesh with wire diameter of 0.03 mm gave good results. Manufacturing trials included methods to embed the mesh into the film using vacuum and oven heating and methods to attach power connections to the mesh. The final adhesive film that was used within the project was composed out of 8 layers of the phenoxy film with the heater mesh in the centre. One problem encountered was the proper connection of power leads to the wire mesh. The best solution for this problem was to braze copper wires to the mesh.

Obtaining an even heat distribution also proved difficult, deformation of the mesh and discontinuities must be avoided to get a good result.

Different mechanical tests were carried out to evaluate the mechanical properties of the joint. Static lap-joint, flatwise tensile thick adherend and peel tests were carried out.



Figure 13: Stainless steel mesh embedded in phenoxy

Static and fatigue testing on hybrid lap joints was carried out to investigate the effect of the application of fasteners on the adhesive joint. These thin fasteners (2 mm) were assembled into an oversized hole (2.5 mm) in order to limit the peel stresses. Delamination growth was measured during testing using ultrasonic inspection. Strain gauges were used to attempt to correlate damage growth to deformation of the sample by measuring the strain at the opposite side of the delamination area.

The average static apparent shear stress without bolts was 9.6 MPa, with bolts it was 19.1 MPa.



Figure 14: Hybrid bolted joint



Figure 15: Failed joint

Bolts have an influence in reducing the peel stress in the adhesive layer. Fatigue strength is roughly twice as high when using bolts up to 2×10^5 cycles.

The manual probe used had a diameter of 6 mm and proved to have insufficient accuracy when measuring damage disbond length.

Strain development can be measured qualitatively using strain gauges, but after damage has grown past the strain gauge area, direct monitoring is no longer possible.

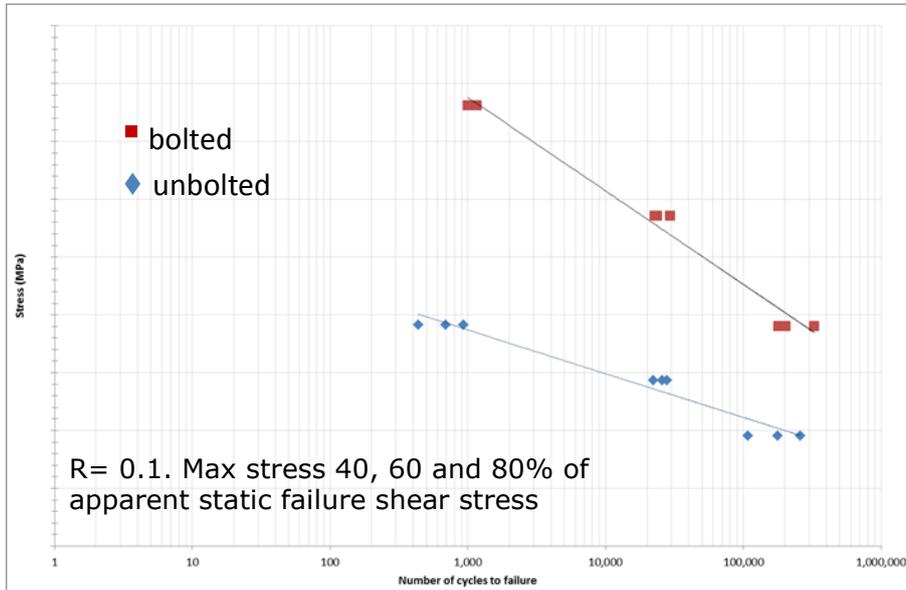


Figure 16: Fatigue test results for bolted and unbolted joints

A hybrid joint (see Figure 17 and Figure 18) was manufactured and thermal measurements were carried out. CENAERO carried out thermal simulations on this joint.

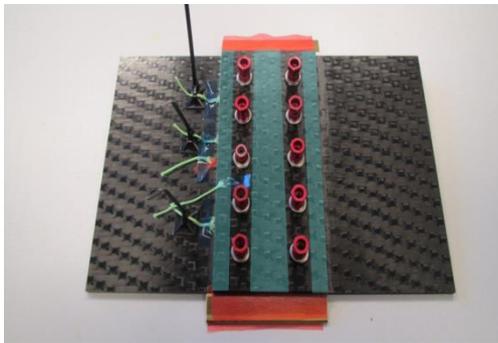


Figure 17: Hybrid joint for thermal analysis

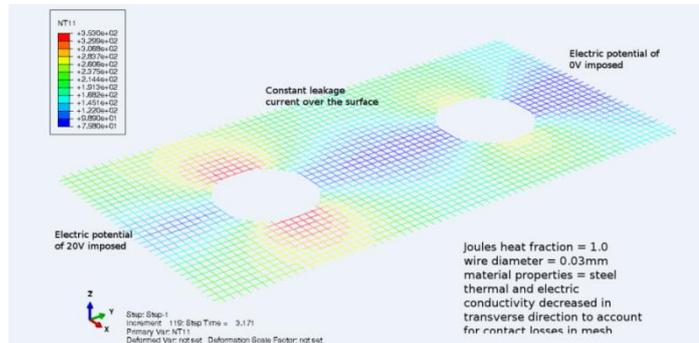


Figure 18: Thermal analysis results

Compared to the actual measurements the calculated temperatures were lower possibly caused by a more uniform distribution of the heat into the heater mesh.

3.2.3 Integrated profiles

A T-connection is a standard element in most frameworks. In the chosen use case of a helicopter subfloor group, main loads on the connection are shear and bending loads. Current state of the art in helicopter design is a Double-L design made from prepreg, riveted after cure of the sub-components.

An innovative solution is proposed to improve weight, cost and performance using the 3D-weaving technology with project partner BITEAM. This innovative approach has been compared to a more conservative preform-LCM approach.

These solutions have been designed, simulated, manufactured, tested and cost assessed within CERFAC

i. Design, Sizing and Modelling

For the general Specimen Layout a NASTRAN model was used with shell elements for the lamina and solid elements for the adhesive layers. It showed a very good performance with a calculation time < 5 minutes and a good possibility to judge fiber failure behaviour. However ILS failure at joints and between plies cannot be predicted reliable with the solid elements and especially the gussets behaviour is not predictable.

For detailed investigation of the final Layout an ABAQUS Model has been used. Every layer was modeled with a single solid element. For judging delamination and bonded joint failure, cohesive surface behavior was used, the calculation time was approximately 8hours. The critical spots for interlaminar failure could be predicted very well, however the failure theory is still based on some assumptions and therefore test result still differs from calculation.

Assumption had to be made because in many cases material parameters and analysis procedures (e.g. out of plane properties and fracture toughness) are not available. These parameters are investigated in the frame of follow-up projects including an extensive testing campaign to evaluate missing material properties. These tests are subsequently simulated to obtain an analysis procedure for interlaminar failure.

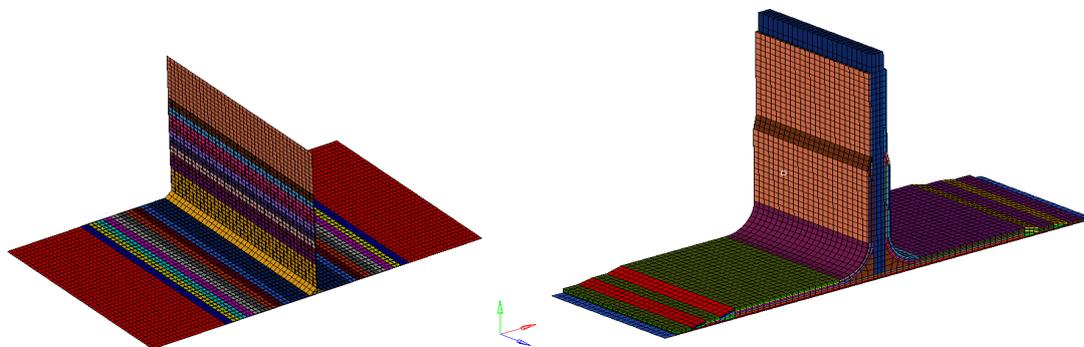


Figure 19: Left: NASTRAN model; right: ABAQUS model

ii. Manufacture of Shear and Bending Specimen

In the following sequence the performing and infiltration of the T-specimen for bending and shear tests is shown.

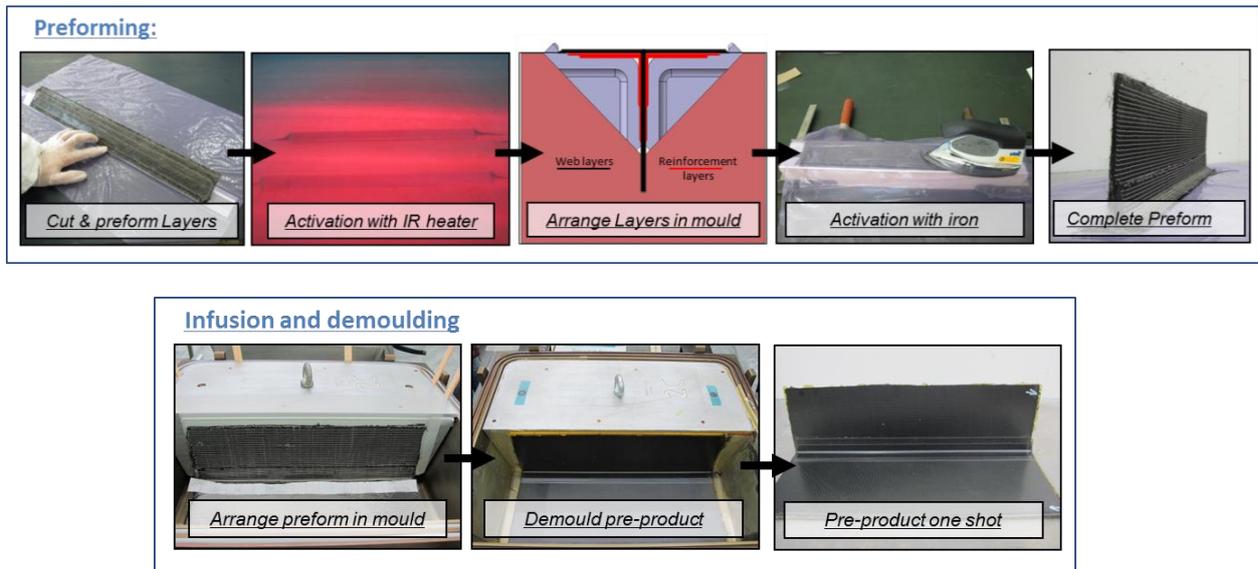


Figure 20: Manufacturing process chain

The final part showed satisfying quality. The gusset area has been identified as critical (braided preform “noodles” have been used). The fillers get deformed during molding which leads to undulation and resin rich areas in the final composite. Stabilisation of the fillers through thermoplastic binder

iii. Testing

Testing activities focussed on comprehensive shear and bending test campaigns. Results show a ~18% higher bending strength of the NCF based profiles and ~8% higher shear strength of the NCF based profiles.

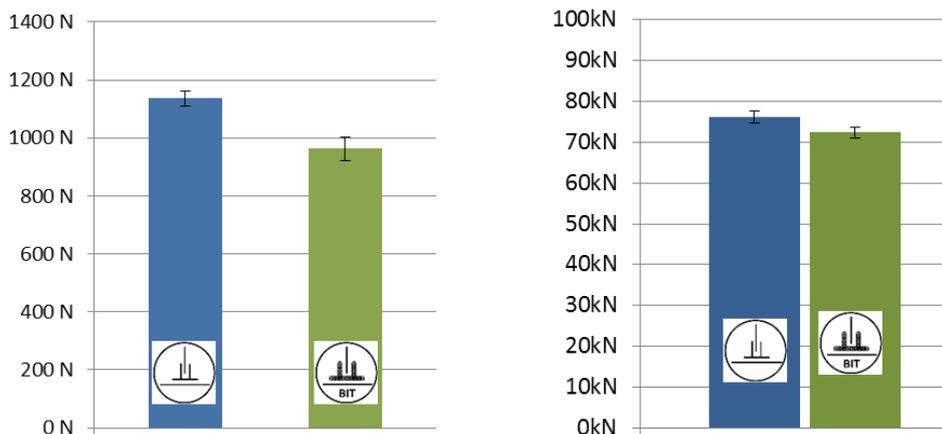


Figure 21: Left: Bending strength NCF profiles (left, blue column) and 3D woven profiles (right, green column); Right: Shear strength NCF profiles (left, blue column) and 3D woven profiles (right, green column)

iv. Assessment

The costs of the designs have been assessed. No serial price is available yet for the 3D woven profiles. However a realistic price has been assumed with BITEAM. The following graph shows the comparison of cost fractions between the 3D woven and the NCF based solution. Significant

manufacturing costs can be saved using the 3D woven profile which compensates for the increased material costs for the end user.

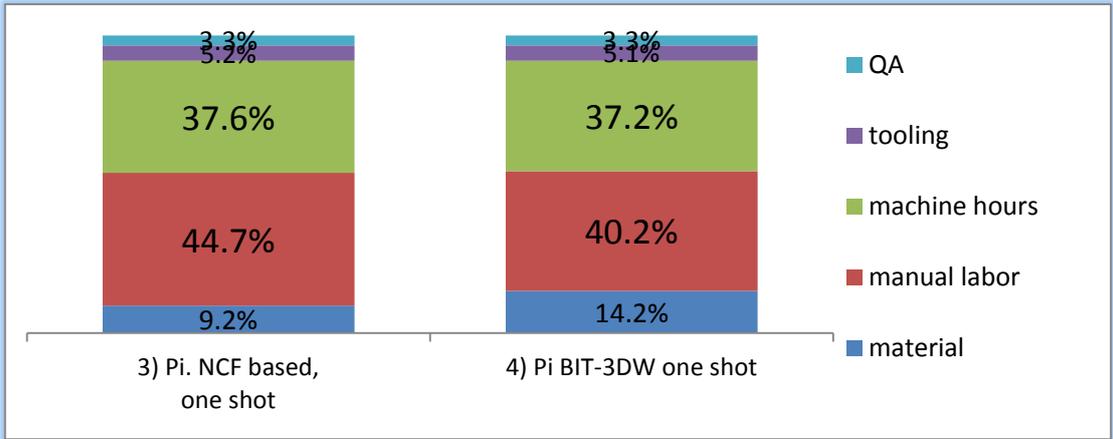


Figure 22: Cost fractions for NCF design vs. 3D woven design

As a conclusion it can be said, that the Pi-design for T-joints could be simulated and the potential of the 3DW technology could be confirmed. For its realization, however use cases for this technology must be chosen according to the specific mechanical potential of the technology (e.g. out-of-plane strength) to compensate the increased material cost for the end-user.

The work performed on advanced joints through the manufacturing and machining of reinforcement profiles on composite specimens

The 3D woven braided profiles proved to be an important time saver in the setup of the preform in the mould. Only 6 plies were replaced out of the 12 and the shape of the profile was quite simple, but we could estimate the time gained during setup to be 0.5 hours over a total of 4 hours (or 7 hours taking into account infusion). Replacing completely the NCF plies could double this gain in time and reduce the amount of people required during setup.

Maturity of the technology has to evolve though in order to produce more complex shapes, balance between tailored/standardized reinforcement paths and uniformity in the geometry of the preforms.

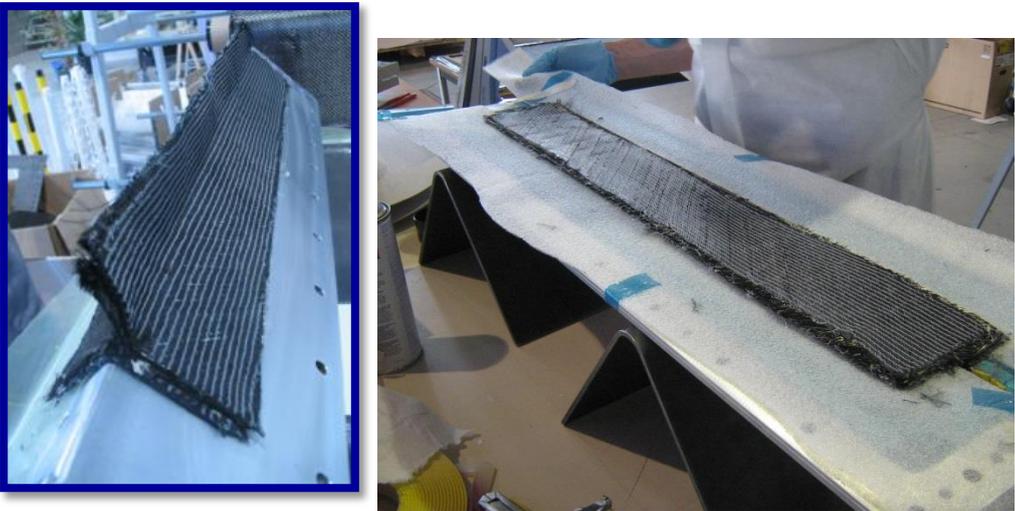


Figure 23: Preform installation in mould

3.2.4 Finite element analysis

Progressive damage modeling of hybrid Ti/CFRP bolted joints

An efficient progressive damage model for simulating the mechanical performance of hybrid Ti/CFRP bolted joints has been developed. Figure 24a shows the flowchart of the model while Figure 24b shows the FE mesh of the joint.

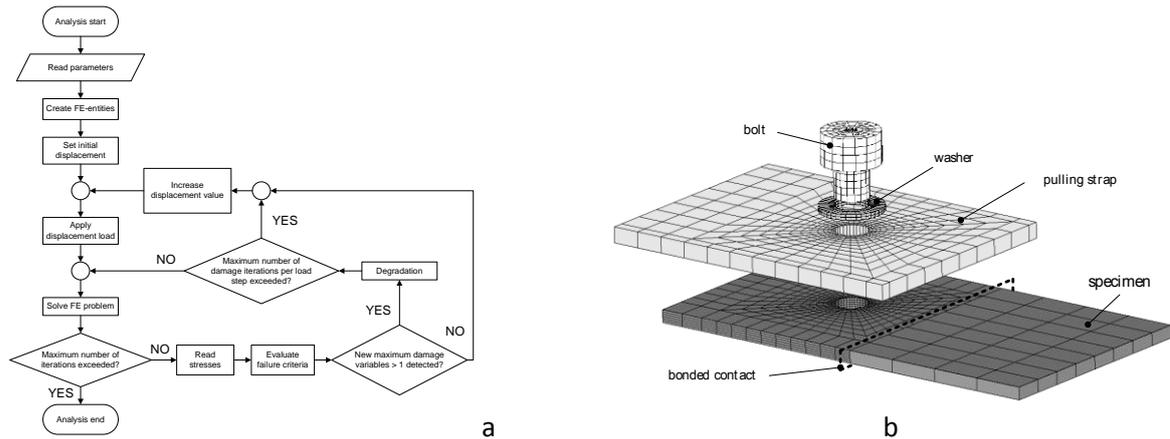


Figure 24: a. Flowchart of the progressive damage modeling methodology, b. FE mesh of the hybrid Ti/CFRP bolted joint.

Numerical characterization of woven fabric composites

A methodology was developed for the numerical characterization of plain weave composite materials. The methodology is described by means of the flowchart shown in Figure 25. The methodology was applied in the non-crimp fabric and 3D woven fully interlaced composites. FE meshes of the representative volume elements (RVEs) of the two materials are shown in Figure 26. The results from the numerical characterization are in the form of stress-strain curves of the materials at different material directions under different loading conditions.

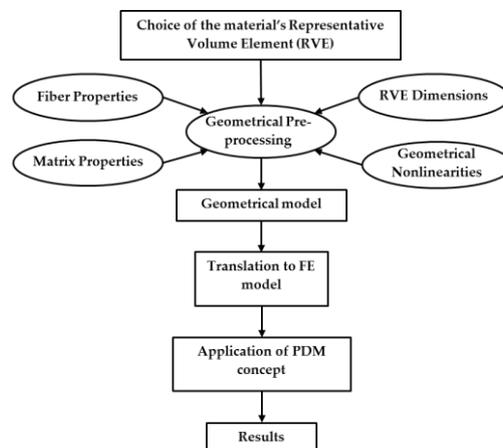


Figure 25: Flowchart of the numerical characterization methodology.

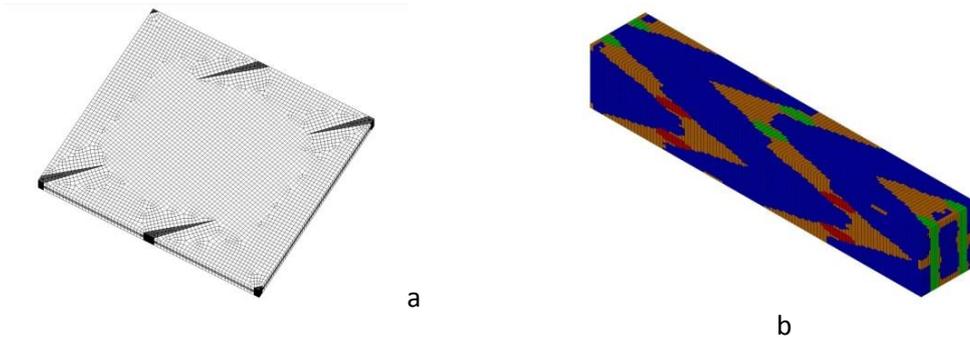


Figure 26: a. FE mesh of the NCF RVE, b. FE mesh of the RVE of the 3D woven material.

Optimization of the H- and Pi-shaped bonded joints

In the frame of CERFAC, a numerical methodology was developed for optimizing the geometry of composite structural parts without increasing the weight was developed. The methodology is described by means of the flowchart in Figure 27. The methodology was based on the progressive damage modeling technique and uses as input the data derived from numerical characterization of woven fabric composites module.

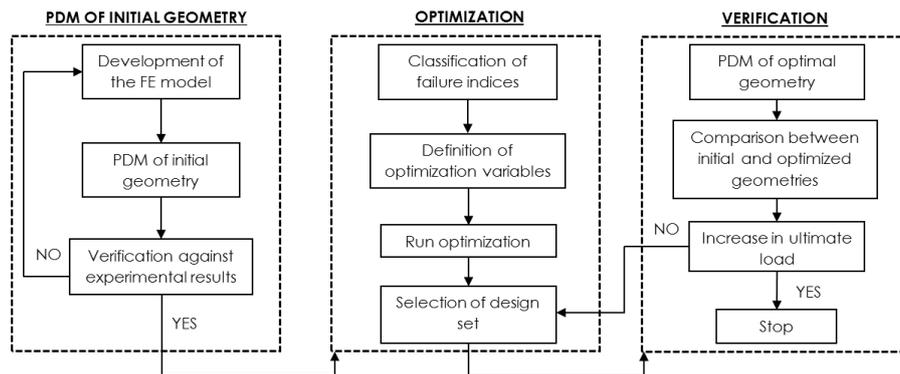


Figure 27: Flowchart of the optimization methodology.

The optimization methodology has been applied to bonded joints realized using H-shaped joining elements made from NCF and 3D woven material. The FE meshes of the joints are shown in the figure below.

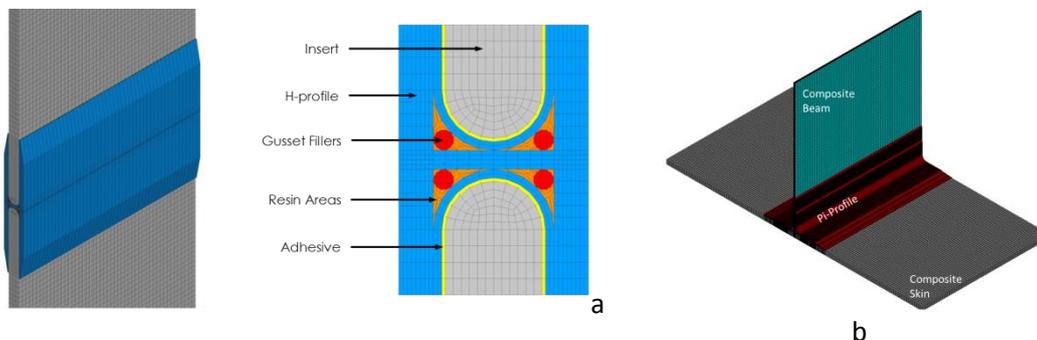


Figure 28: a. FE mesh of the H-shaped joint, b. FE mesh of the Pi-shaped joint.

The optimization results for the H-shaped joint are illustrated in Figure 29 in the form of force-displacement curves. For the NCF joint, optimization led to an increase in the ultimate load and displacement at failure by 6.3% and 9%, respectively, and to a decrease of weight by 4%. For the 3D woven joint, optimization led to an increase in the ultimate load and displacement at failure by 8.1% and 5.3%, respectively, and to a decrease of weight by 6.7%.

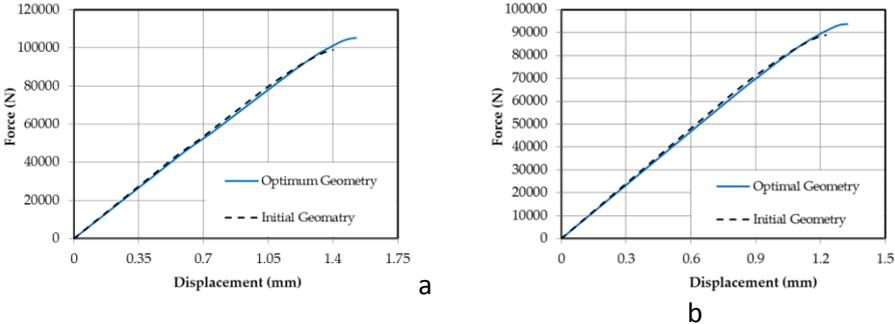


Figure 29: Force-displacement curves of initial and optimum geometries: a. NCF H-shaped joint, 3D woven H-shaped joint.

3.3 Concentrated loads applications

3.3.1 Fiber patch preforming

The first investigated solution is to use the Fiber-Patch-Preforming technology as a cost and weight efficient solution to reinforce locally composite laminates. The process automatically lays short band of spread tows of any orientation and therefore enables to manufacture specific reinforcement designed to improve the bearing performances, and with a reduced added weight. Such optimised “star” shaped reinforcement can be fully automatically manufactured with the process, and is then manually positioned onto to the base laminate surface, as depicted herunder, prior to its cure cycle.

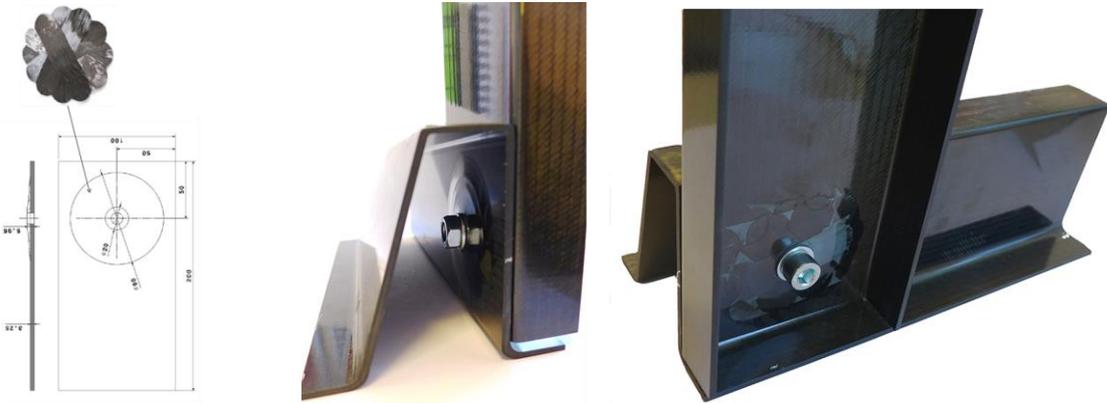


Figure 30: Schematic representation of laminate reinforced with a Patch placement add-on (left) Manufactured demonstrator of the floor frame/beam connection with a patch add-on reinforcement (Right)

Based on the assessment performed, the use of add-on reinforcement using the patch placement technologies seems to be an efficient reinforcement solution for this application. The optimised star shape reinforcements based on narrow band of spread-tow material led to an improvement of the overall laminate bearing strength up to 19% compared to a standard reinforcement solution. The weight of the joint area could be reduced by 14%, especially because the reinforcement is very local and its size is much smaller than a standard pad-up. The manufacturing cost for the elements and their assembly can be reduced by 11%. This is due to the fact that the reinforcement manufacturing is fully automated, and that placing it as an add-on to the laminate surface, simplifies and reduces the manufacturing cost of the sub-elements.

3.3.2 Thin ply reinforcements

The second reinforcement solution is the Interleaving of thin plies in laminates at reinforcement areas and enforcement of higher FVC as a cost & weight efficient design solution.

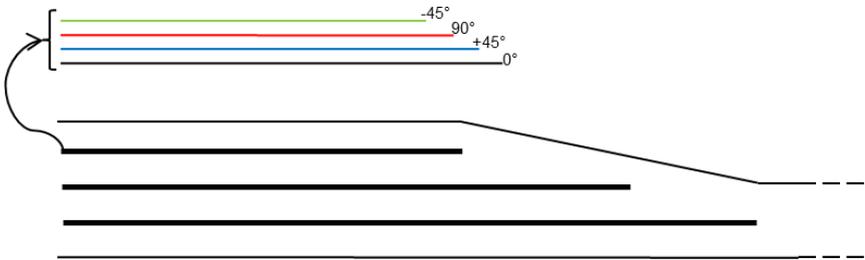
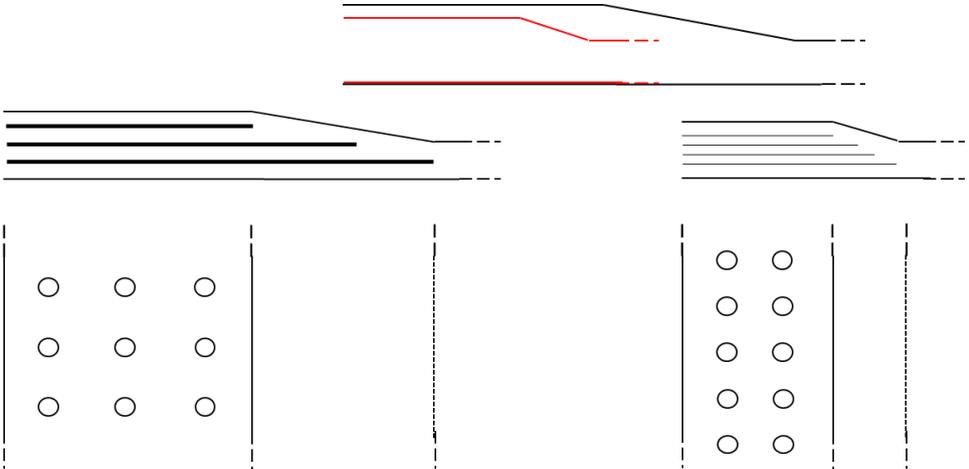


Figure 31: Illustration of local reinforcement of a laminate with pre-manufactured QI laminates

Laminates based on spread-tow thin plies have better bearing strength because of the great in-plane homogeneity of each spread-tow layer and the improved out-of-plane homogeneity. The use of thin plies, reducing the stress peaks at drop-off areas enables to reduce the chamfer area. Also the increase of FVC enables to increase the bolt density and reduce the joining area. Use of thin plies would also enable increase the design freedom in terms of reinforcement thickness, typically with pad-up increments of ca. 0.3mm instead of ca 0,75mm (using plies of ca 75gsm instead of 190gsm). Enforcing a higher FVC also results in further increase of bearing strength. Therefore it would be possible to reduce the reinforcement thickness t_R . This reinforcement technique proved to be an efficient solution for performance increase and weight reduction.



3.3.3 Braiding and tailored fiber placement reinforcements

The work of the University of Stuttgart is experimental and numerical investigation of the performance of textile reinforced CFRP joints. As technologies, braiding and tailored fibre placement (TFP) were chosen, which are applied in CL and BS application. In the following part, for each technology, the results concerning mechanical performance and advances in numerical simulations are presented.

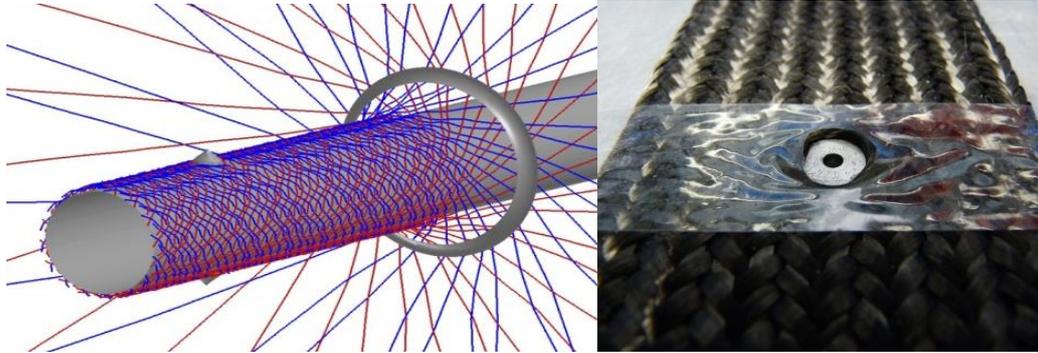


Figure 32: Braiding simulation of integrated holes

For any exact calculation of the material properties at the joint, the fibre architecture (fibre angle, undulation, fibre thickness and width) is needed. The only way of calculating the real local material properties is to know the exact fibre architecture at every place of the component. To get this information a braiding simulation is performed. A hole is created as soon as the yarns get in contact with the pin and lay down next to it.

The braiding simulation is able to give the fibre architecture represented by bar-elements. For the calculation of the material properties this architecture is necessary because of its very high influence to the material behaviour. A Matlab tool is developed to calculate the material properties using this fibre architecture as a basis.

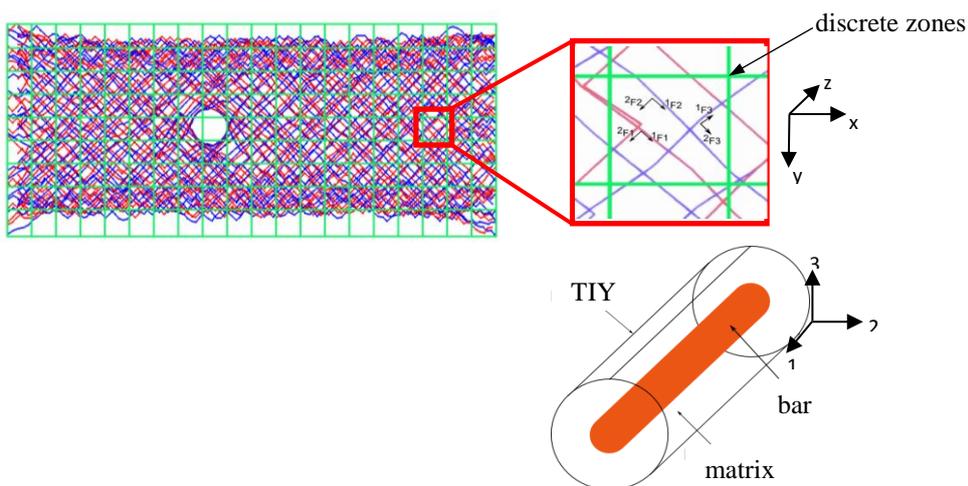


Figure 33: Discrete elements with bar elements

In order to be able to predict progressive damage behaviour, a methodology known from classical crash simulation is used to represent the crushing-like bearing effect in the joint area (see Deliverable 2.3)

Both methodologies are developed in CERFAC. The simulations have been validated by test, either for mechanical performance or validation of the process simulation. The quality and accuracy of the process simulation is acceptable, while the mechanical performance is rather bad with this technology.

4. Potential impact

The design of composite fastener joints is quite a specific task and can be done to a certain detail on small specimen sizes. The challenge remains on how to be able to scale up design taking into account specific reinforcements. The detailed analysis will help in defining new allowables specific to a reinforcement that may increase the post-processing time of an analysis, but leave the same level of complexity for the model size and analysis time.

This scale up should be performed on promising solutions in order to push towards further standardization and implementation in industrial environments.

As each type of reinforcement solution or application is at a technology readiness level varying from 3 to 5, different types of conclusions on outcome for each technology can be drawn. We summarize these in this section.

4.1 Butt strap reinforcements

Potential for weight reduction is more distinct than potential cost savings. Nevertheless, the construction of the joining area is much easier because the patches are flush pressed in the base laminate and there is no ramp up that must be considered.

In future it should be possible to integrate the flush patches in a high automated layup process which leads to an increase of cost efficiency.

The weight reduction of the joint may possibly lead to a moderate saving of fuel consumption.

The dissemination activities of the University of Applied Sciences (ZHAW) are concentrated numerous semester and bachelor thesis for a lot of students. DLR, FHNW, University of Stuttgart and Sabca will each lead potential follow up activities on the respective reinforcement solutions reviewed during the project.

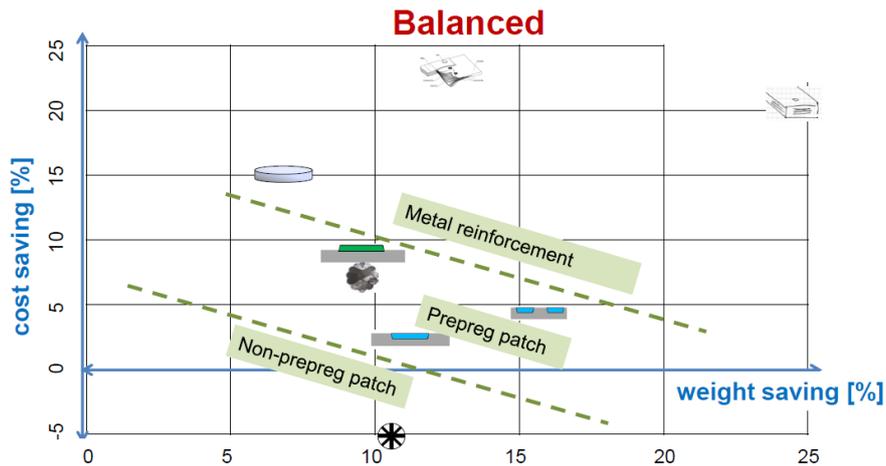


Figure 34: Cost-weight saving analysis of reinforcement solutions on butt strap application demonstrator

Impact of weight and cost savings estimated at the end of the project show the gain expected on a demonstrator scale application. Different solutions bring new possibilities, but also new challenges that have to be addressed and solved to push towards a deployment at an industrial scale.

4.2 Advanced joints

The potential impact of the work performed is the cost reduction of composite parts assembly due to the one shot process assembly to replace a time consuming process involving part assembly with bolts and screws. This assembly process is also weight reduction efficiency with elimination of metallic bolts and screws. The final benefits with a global structural weight decrease are for the airliners an increase of the payload or a reduction of the operating cost. At the end it should be a global benefit for the end user. The weight reduction is also at the origin of pollution reduction. For an equivalent payload mass, the global weight of the aircraft will be reduced and so CO₂ and NO_x emission will be also reduced.

The technical and economic potential of innovative H, Pi, or complex-joint technologies has been demonstrated and can be provided to engineering functions during the development phase of future aircrafts and helicopters. Its actual use in the serial product depends on more factors like the specific design and part numbers of the helicopter, the planned numbers of the helicopter and, above all, on serial prices for 3D woven structures. Furthermore there is currently no satisfying calculation approach for 3D Woven profiles, which is mandatory for primary structure.

New ways of modelling have been investigated and assessed. Open points concerning modelling techniques and calculation methods have been identified. Relevant issues have been identified and are already incorporated in on-going research projects.

Significant development effort has been put into the shear test together with project partner VZLU. These findings and the rig design, that eliminates unwanted peeling effects, will be considered in future material characterisation studies.

With use of the 3D weaving technology from BITEAM, AHD would further diversify its supply chain and support supplier's competition.

Reversible bonding as studied in this project is a viable option for joining parts. A major advantage is the possibility to quickly reverse the process and disassemble a structure. The potential impact in the area of recycling can be significant, as it can reduce dismantling time and even make re-use of parts that previously may have been scrapped possible.

This technology is not limited to aerospace, but can be employed in a large variety of areas where structures are bonded, e.g. construction, wind energy, automotive, boatbuilding, just to name a few.

The results obtained for reversible bonding in this project are being exploited further in another FP7 project " Boltless Assembling of Primary Aerospace Composite Structures (BOPACS)

4.3 Concentrated loads

Due to rather bad mechanical performance of the textile reinforcements compared to other solutions, the exploitation of the braiding and tailored fiber placement technology itself for this purpose is limited. But the exploitation of the developed simulation methods is encouraging. Besides aerospace industry, the car industry is interested in CPU efficient modelling of joints. One can think of transferring the methodologies to this industry. It is e.g. possible in Stuttgart due to the research campus ARENA2036 (<http://www.arena2036.de>) in which the institute is leading the research topics in simulation.

Concerning scientific dissemination, USTUTT had 2 presentations at conferences and two PhD theses that could be finished, one of them already published, thanks to CERFAC project.

Laminates require local thickening in order to withstand the load introduced through fasteners in joining areas. Widely present in aircraft structures, these pad-ups and associated fasteners add significant weight to the overall structure. The manufacturing of such reinforcements is also generally expensive. Indeed the state-of-the-art production processes, for instance AFP, are well appropriate to manufacture large laminates but not for small reinforcements. The resulting slow lay-up of these areas limits the global production rate of the facilities and can lead to overall slow productivity and high NRC when parallel production systems are required. The developed solutions for improving the joint efficiency in terms of design & manufacturing are therefore required and could lead to significant overall cost and weight savings. Some solutions will be assessed for existing products and could be implemented if proven successful and robust.

4.4 General conclusions

The impact of the CERFAC project is widespread for all structural composite applications. Although the most common situations are probably found in aerospace domains, civil engineering, nautical, transportation and sports industries can gain from the research that was carried on throughout the project.

Today the aerospace industry as a whole faces a mutation from traditional aluminium structures to carbon fibre reinforced plastic structures for many parts. This strong move was initiated by Boeing and the launch of the 787 with a CFRP wing and CFRP fuselage (in-line with latest increases of the use of composites in the Airbus A380 and A400M programs). If the European reaction was skeptical at the beginning, it is today clear for everybody that a new orientation was given to the aerospace industry and that a point of no return was reached when Airbus announced that the next generation aircraft A350 will also feature CFRP wing and fuselage.

Many European aerospace industries not only develop and produce component for Airbus but also for Embraer, Bombardier, Dassault or even Boeing in a globalised market. To keep their competitiveness on this market, the European industry is now deploying the industrial capacity to supply state of the art composite structures.

Massive insertion of composites is thus one of the solutions to meet the top-level objectives of the Vision 2020 of the European aeronautics majors which is implemented by the strategic research agenda of the Advisory Council for Aeronautics Research in Europe (ACARE). In terms of structures, the statement "...towards a more affordable, safer, cleaner and quieter aircraft..." can be reformulated as:

- Towards structures with a reduced development cost, manufacturing cost and life cycle cost, that will make future aircraft and air-traffic more affordable
- Towards lighter structures (optimized design, better confidence in the capacity to sustain significant damage – i.e. damage tolerance) that will help decreasing the fuel consumption
- Towards high-performance structures (new materials, optimized design, in-situ monitoring, ...) with improved quality and reliability for a safer aircraft.
- Towards more automated manufacturing routes and net-shaped products for manufacturing cost-efficiency and reproducibility
- Towards the inclusion of strong environmental constraints in the early design phase
- Towards a reduced time-to-market that will allow for rapid insertion of more affordable, cleaner, high quality products

The six items listed here above give very clear objectives to today's structure designers and engineers. CERFAC has advanced mainly on the 3 first points, keeping the next three in close consideration for further activities. Concurrent objectives have to be achieved (e.g. minimum weight, maximum performance, minimum cost), which have a particular meaning in terms of joining of structures, at the locus of fastener areas.

CERFAC addressed the specific issues of cost-efficiency, performance and reliability of joints, trying to implement the afore-mentioned solutions. CERFAC is in-line with some of the global strategic objectives and brings knowledge, techniques and methodologies that will help the European Aeronautics Sector meeting them in the near future as well as other promising sectors for the european industry.

5. Project internet site

The description of the project, the consortium involved and further details can be found at the following webpage:

<http://cerfac.cenaero.be>

