Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

NLR-TP-2008-789

AUTOW

Automated Preform Fabrication by Dry Tow Placement

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Executive summary

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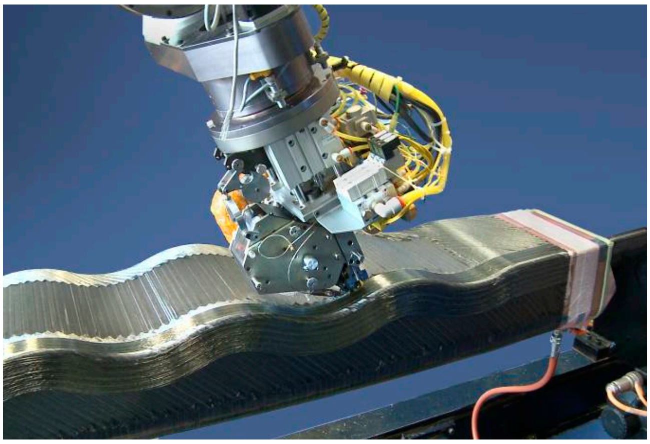

Report no.
NLR-TP-2008-789

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Report classification
UNCLASSIFIED

Date
September 2013

Knowledge area(s)
Aerospace Structures &
Manufacturing Technology

Descriptor(s)
Automated
Preform
Tow Placement
LCM
Costs

Problem area
The percentage of fiber reinforced materials (composites) in primary aircraft structures continues to grow. With this growth comes demand for continuous improvements in manufacturing technology. The most common manufacturing technology for composites used today involves manual stacking of pre-impregnated sheets of material followed by cure in an autoclave. It uses complex tooling and precludes a high level of part integration, increasing assembly effort. Combined with other advantages of AFP over hand lay-up, the capital investment of few hundred thousand to several millions Euro for AFP machinery can be more than compensated by this increase in lay-up rate.

Another novel manufacturing method, often referred to as Liquid Composite Molding (LCM). The advantages of this process are that it is possible to use cheaper materials and simpler tooling. It also enables cheaper processing and part integration, reducing assembly costs.
So far, the potential advantages of LCM could not be fully exploited, because preforming is either a manual process or else an automated process with limited scope, such as weaving or braiding. An innovative technology for the automated fabrication of complex preforms developed would overcome these problems and could enable cost savings of up to an estimated 40% in comparison with current technology, due to cheaper

This report is based on a presentation held at the SAMPE Tech, Fort Worth, Texas, October 17-20, 2011.

part manufacturing, less scrap, reduced assembly and increased accuracy. The basis of this innovation is dry tow placement using AFP technology.

Description of work

The aim of the "Automated Preform Fabrication by Dry Tow Placement – AUTOW" project was the development of manufacturing technology for automated preforming, with a parallel development of a design capability to match. The AUTOW project developed the technology by adapting existing automated deposition capability for pre-impregnated materials (prepregs) with the capability to deposit dry fiber tows, allowing the fabrication of complex preforms. These can then be injected with a cost-efficient, automated LCM process. The complexity of the challenge to develop this new technology is in the multi-disciplinary approach required to adapt, develop and explore; machine capability, material format, process window and an integrated design engineering approach.

Results and conclusions

During the AUTOW project the partners have developed Dry Fiber Placement technology which covers advanced material development by Hexcel, characterization by several partners, placement technology by adapting AFP machine and processing parameters, resin injection in a subsequent LCM-process (RTM and VARTM).

The AUTOW partners have used their aerospace expertise to determine the scope and constraints of the new fabrication capability with respect to preform shapes, fiber trajectories and processing parameters for relevant applications.

The reduction in weight and cost supported by novel design and manufacturing approaches as developed during AUTOW will further facilitate and speed up the introduction of composite lightweight structures in aerospace and other transport industries. Lightweight composite structures contribute directly to reducing fuel consumption and hence GHG emissions of aircraft and other transport vehicles, Moreover weight reduction also allows for reduced power system requirements in turn facilitating electrification.

Applicability

The AUTOW project has shown the tremendous potential of Dry Fiber Placement (DFP). During the project several AUTOW partners have started using the knowledge and experience acquired during the AUTOW project in other projects. One of these is for example the EU project ADVITAC, in which an advanced concept for a composite tailcone is being developed using DFP as one of the core technologies. Also NLR has developed and manufactured a dry preform for composite landing gear component, which was exhibited on the JEC in Paris 2011.

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Customer	European Commission
Contract number	AST5-CT-2006-030771
Owner	National Aerospace Laboratory
Division NLR	Aerospace Vehicles
Distribution	Unlimited
Classification of title	Unclassified
	September 2013

Approved by:

Author	Reviewer	Managing department
R. Klomp-de Boer	H.P.J. de Vries	H.G.S.J. Thuis
Date: 18-12-2013	Date: 18-12-2013	Date: 18-12-2013

Contents

DEVELOPMENT OF AUTOMATED DRY FIBER PLACEMENT MATERIAL, PROCESS AND DESIGN TECHNOLOGY

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ABSTRACT

With the ever increasing percentage of composites in aircraft structures aiding weight and fuel reduction, so is the level of automation expanding rapidly. One of the most notable being Automated Fiber Placement (AFP) offering high lay-up rates combined with very precise ply thickness control, in-process compaction, high consistent quality, low void content, unlimited fiber angles and low material scrap rate. Another manufacturing method being used more and more is often referred to as Liquid Composite Molding (LCM). The advantages of this process are that it is possible to use cheaper materials and simpler tooling. It also enables cheaper processing, tight tolerances, part integration, reducing assembly costs. So far, the potential advantages of LCM could not be fully exploited, because preforming is either a manual process or else an automated process with limited scope, such as weaving or braiding. The aim of the AUTOW project was combining the best of both techniques through the development of manufacturing technology for automated preforming with a matching parallel development of a design capability. The basis of this innovation is Dry Fiber Placement (DFP) using AFP technology. This paper will inform on the background objectives, the technical progress and the results achieved.

1. INTRODUCTION

The percentage of fiber reinforced materials (composites) in primary aircraft structures continues to grow. With this growth comes demand for continuous improvements in manufacturing technology. The most common manufacturing technology for composites used today involves manual stacking of pre-impregnated sheets of material followed by cure in an autoclave. It uses complex tooling and precludes a high level of part integration, increasing assembly effort. Hand lay-up of cut prepregs are labor intensive and a highly trained technician can place just about over 1kg per hour. With Automated Fiber Placement (AFP) this could be increased to 6.5 to 11kg/hour for complex tools and for simple parts even up to more than 20kg per hour [1]. The capital investment of few hundred thousand to several millions Euro for AFP machinery can be more than compensated by this increase in lay-up rate, whereas the costs of labor will only increase in future. Combined with other advantages of AFP over hand lay-up such as very precise ply thickness control, in-process compaction, high consistent quality, low void content (typically < 1%), unlimited fiber angles (tow path optimization) and low material scrap rate (5 to 20%).

Another novel manufacturing method, often referred to as Liquid Composite Molding (LCM), uses dry fabric which is pre-formed into the component shape, placed in a mold, subsequently injected with resin and cured. The advantages of this process are that it is possible to use cheaper materials and simpler tooling. It also enables cheaper processing and part integration, reducing assembly costs [2].

So far, the potential advantages of LCM could not be fully exploited, because preforming is either a manual process or else an automated process with limited scope, such as weaving or braiding. An innovative technology for the automated fabrication of complex preforms developed would overcome these problems and could enable cost savings of up to an estimated 40% in comparison with current technology, due to cheaper part manufacturing, less scrap, reduced assembly and increased accuracy. The basis of this innovation is dry tow placement using AFP technology.

The aim of the "Automated Preform Fabrication by Dry Tow Placement – AUTOW" project was the development of manufacturing technology for automated preforming, with a parallel development of a design capability to match. The AUTOW project developed the technology by adapting existing automated deposition capability for pre-impregnated materials (prepregs) with the capability to deposit dry fiber tows, allowing the fabrication of complex preforms. These can then be injected with a cost-efficient, automated LCM process. The complexity of the challenge to develop this new technology is in the multi-disciplinary approach required to adapt, develop and explore:

- Machine capability,
- Material format,
- Process window,
- An integrated design engineering approach.

Critical areas that were developed are:

- Advanced machine and materials expertise to develop a material that is compatible with the machine, will stick to the mold or substrate and allow resin injection in a subsequent LCM-process.
- Aerospace expertise to determine the scope and constraints of the new fabrication capability with respect to preform shapes, fiber trajectories and processing parameters for relevant applications.

Expertise in materials modeling, process simulation, structural analysis and optimization to obtain an integrated design engineering approach for the design of components to be made with the new fabrication capability.

A schematic overview of the project work packages (WP) and responsible work package leaders are given in figure 1. The focus of this paper will be on the work done and the results achieved in WP 1, 2, 3 and 4.

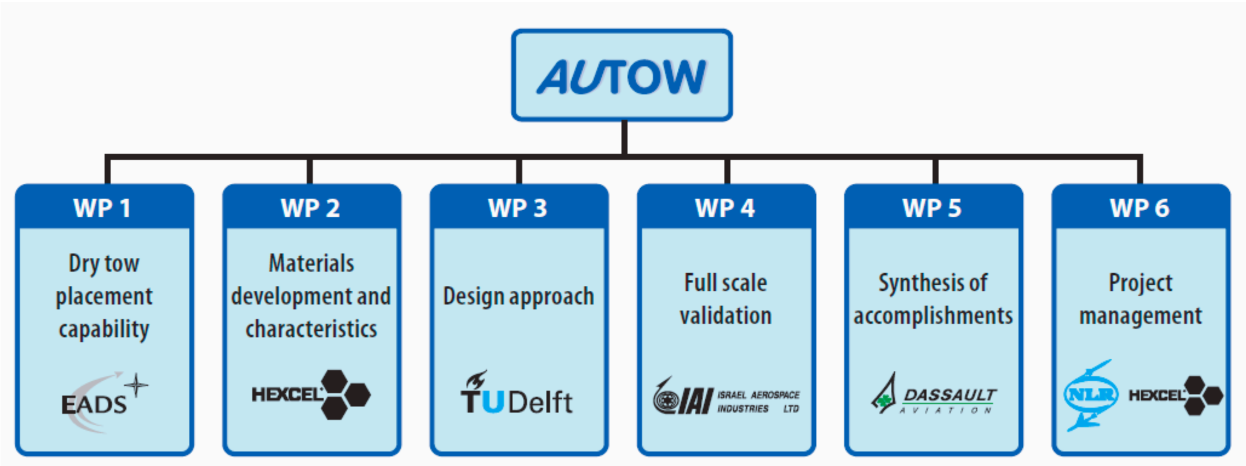

Figure 1. Organization of the AUTOW project showing the 6 Work Packages and WP leaders.

Table 1 shows all the different partners involved in the AUTOW project and the point of contact.

Table 1. AUTOW partners and Point of Contact

Short name	AUTOW partners		
	Partner	POC	Country
NLR	National Aerospace Laboratory NLR (Coordinator)	Ronald Klomp – de Boer	The Netherlands
DAV	Dassault Aviation	Mourad Chohra	France
EADS-IW	EADS Innovation Works	Catherine Duval	France
HXL	Hexcel Reinforcements	Henri Girardy	France
ONERA	Office National d'Études et de Recherches Aérospatiales	Pierre Beauchene	France
KUL	Katholieke Universiteit Leuven	Stepan Lomov	Belgium
IFB	University of Stuttgart – Institute for Aircraft Design	Klaus Drechsler	Germany
TUD	Delft University of Technology	Zafer Gürdal	The Netherlands
VZLU	Vyzkumny a zkusebni letecky ustav (Aeronautical research and test institute)	Vaclav Kafka	Czech Republic
IAI	Israel Aircraft Industries	Herman Leibovich	Israel
KSL	Keilmann Sondermaschinenbau GmbH	Guido Jaeger	Germany

2. MATERIALS AND PROCESSES DEVELOPMENT

Being the basis of the AUTOW project and the innovation, the project started with the materials and processes development. Although in the description of work and in this paper these are two different work packages, they actually very intertwined and development an iterative process.

2.1 Dry tow placement capability

The objectives of WP1 were to develop fabrication capabilities to deposit dry carbon fibers on a defined laying-up tool by automated tow placement and obtaining process windows for the new preforming method by fabricating generic preforms. To achieve these objectives a number of issues needed to be dealt with. Current AFP machines can place preimpregnated fiber reinforced thermoset and / or thermoplastic tape, making depositing dry fiber material a real novelty and challenge. The AFP machines used within the consortium were not laid out for placing dry tows and needed to be modified. This implied the specification, conception, design, fabrication, assembly and instrumentation of the adaptations to the machines.

EADS-IW, DAV and NLR worked in parallel on their AFP machines experimenting with the dry fiber tows supplied by Hexcel. In order to deposit the dry fiber tows successfully on the tooling, they first need to the guided thru the AFP machine and head appropriately. The partners involved have successfully developed and implemented machine modifications to enable this and overcome problems encountered such as fraying at the compaction roller and fraying and winding of the tows around the pinch rollers. But also tuning the flow of the gas torch to prevent the fibers from being blown apart was investigated.

Once the machines were properly adapted to placing dry tows, which happened in close co-operation with WP2 materials development and characterization, the work started on investigating the process windows for the new capability. This implied the identification of configurations of interest, and the specification of the features to be investigated, such as fiber trajectories-steering radius, minimum access areas, and limits for concave and convex curvatures, as well as the development of innovative lay-up tooling. Only very few parts of an aircraft are flat, therefore a number of generic geometries were created to investigate the processability of the dry fiber tows for real structural parts. Basically these generic preforms cover typical design features such as inner radii, outer radii and slopes. These tools were developed by NLR, EADS-IW and Dassault in close cooperation with KSL. Figure 2 shows examples of dry fiber placement trials on two of the generic preform tools.

Figure 2. Dry fiber placing trials on outer and inner radii generic tool at EADS-IW / Dassault respectively NLR location

Manufacturing trials on these generic preform tools revealed the processing window within which an acceptable preform can be manufactured. Outside this processing window defects start to occur such as wrinkling and shifting on concave surfaces and fiber bridging in concave sections. The process window was mainly geometrically defined, resulting in e.g. minimum radii for inner and outer contours. One of the attractive features of AFP is the ability of fiber steering. This allows for variable stiffness design and optimizing fiber paths as discussed in the next chapter, but also following variable part contours such as in the flange of a sine wave rib as described in chapter 4. The limitations of fiber steering and minimum radii were also investigated for the dry fiber tow configuration. The design of sine wave eventually complied with the minimum steering radius achieved in the AUTOW project and could be manufactured accordingly. The development of the dry fiber placement capability was an iterative process of dry fiber tow placement trials and AFP machine and processing modifications. The resulting processing window formed an essential input for the design and manufacture of the full scale validation part and the analysis and simulation tool development.

2.2 Materials development and characterization

The objectives of WP2 were to develop one or more material configurations, consisting of dry tow material suited for AFP and LCM processing. In doing so the material properties and process parameters also needed to be determined by fabricating and testing specimens. During the AUTOW project Hexcel was able to develop and manufacture a dry tow fiber configuration. The dry fiber is based on the fiber HexTow® IMA 12K and combined with HexFlow® RTM6 resin for injection, both well-known high performance composite constituents. The performance and processing requirements were discussed with EADS-IW, DAV and NLR. These partners in turn investigated these dry fiber tows on the compatibility with the machine and the tackiness. A range of process parameters such as torch temperature, compaction roller pressure, speed, etc. were investigated along with machine modifications in WP1. This resulted in successfully depositing dry fiber tows onto a flat mandrel and injecting this dry preform using Resin Transfer Molding (RTM). Figure 3 shows the NDI results using C-scan revealing a good quality laminate which was confirmed by microscopic pictures taken from cross sections of the test laminates.

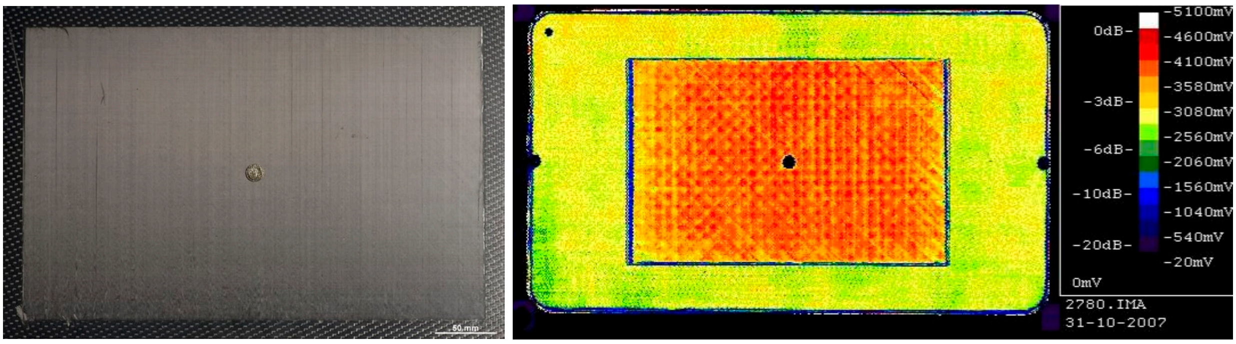

Figure 3. Injected preform using Resin Transfer Molding [RTM] and C-scan revealing good quality laminate (inner square is the test panel)

This was only the first phase of the material development. Next the architecture and mechanical properties of preforms and cured composite laminates had to be determined. These provide crucial input for design and simulation. The laminates are made using LCM which involves injecting a resin through the dry preform. To be able to understand and predict the flow the permeability of the dry preforms must be determined. ONERA was responsible for determining and modeling the permeability characteristics of the dry tow fiber preforms. ONERA developed and improved their permeability measurement setup enabling detailed measurement of the permeability and flow front. Both air and silicon oil was used as test media. Here it should be noted that generally LCM uses dry fiber preforms consisting of woven fabrics and the behavior of dry tow fiber preforms before AUTOW was rather unknown. The tested dry tow fiber preforms addressed manufacturing tolerances by investigating the effect of gaps between and overlaps of the tows. The research at ONERA showed that the dry tow fiber preforms show different permeability characteristics than conventional dry fabric preforms, but the behavior can be predicted and successful injection using either vacuum assisted infusion or RTM is possible.

The permeability investigation formed part of a test matrix involving determination of preform properties, material architecture, mechanical performance and cure characteristics. A commonly used test method providing information on the cured laminate quality and mechanical performance is the short beam interlaminar shear strength (ILSS) test. A range of dry fiber material configurations were tested, revealing the best version. As the coupons showed an actually rather ductile behavior, which can be considered advantageous, it is recommended to use for example ASTM D 3846 instead of the standard ILSS method. An important mechanical property in the design of robust aerospace composite structures is the compression strength after impact (CAI). Coupons were manufactured and conditioned and were impacted with an energy level of 35J. Subsequent NDI revealed that the delamination and damaged area was sufficiently small so as not to be influenced by the supporting structure and allowed testing the coupons to their ultimate compression strength impact. Also the tension and compression modulus were determined and combined with strength data provided input for the design of the full scale validation part.

3. ANALYSIS AND SIMULATION

The objectives of WP3 were:

- To support fabrication with a design capability
- To develop integrated design engineering approach for dry tow placement:
    - Optimize designs for compatibility with manufacturing constraints, as well as design requirements.
    - Make use of new capabilities, notably fiber steering, to improve performance.

The partners in this WP under leadership of TUDelft, were KULeuven, ONERA, IFB and Dassault. This work package set out to support a new fabrication capability with the development of an integrated design engineering approach. For this purpose, it was envisaged to use both commercially available models and software and tools developed in other EU-projects. The interaction between the different modules had to be established, with a structure optimization module guiding the design process. This approach is needed to efficiently adapt a design to comply with manufacturing constraints, while still satisfying the design requirements, and optimizing fiber paths.

In AUTOW all design aspects are linked. For example the stacking sequence required for optimal mechanical performance will also have an effect on the permeability. To ensure this optimal lay-up can also be injected, the permeability characteristics need to be simulated as well.

For this purpose ONERA developed a set of generic preforms and worked on predictive models of fibrous materials (preforms) permeability both analytical as well as 3D FE.

To better understand and hereby being able to predict static and cyclic, dynamic behavior of composites, composites can basically be investigated at three levels. Starting at the highest, the macro level in relation to composites denotes the gross properties of a composite as a structural element but does not consider the individual properties or identity of the constituents. This is the level at which the mechanical properties of the designed composite laminate, consisting of several plies, are used. The micro level denotes the properties of the constituents, i.e., matrix and reinforcement and interface only, as well as their effects on the composite properties [3]. The third meso level forms the important transition area from the separate constituent materials fiber and resin to the reinforcement architecture. The ultimate strain at failure in epoxy-based carbon fiber reinforced composites under tensile loading in the fiber direction is typically 1.3-1.8%. However, typically the allowable strains used in designing composite parts are only 1/5 of the strain-to-failure. If it would be possible to increase this to 1/3, then less heavy parts could be made that in turn would lead to reductions in fuel consumption and Greenhouse Gas (GHG) emission. Reducing and eventually eliminating this performance gap, requires detailed insight in damage initiation and growth which starts at the micro level. The damage initiation threshold depends on material properties of the matrix but is also sensitive to the meso- and micro-scale geometry of the reinforcement architecture, including non-uniformity of the fiber distribution, the presence of resin rich zones, etc. These microstructural features of the material are closely related to the production method. If the latter can improve microstructure of the composite, the damage resistance of the composite and the final part made of this composite can also be significantly optimized. The KULeuven was responsible for investigating this for the dry fiber tow material. For this various experimental methods were applied such as tensile testing accompanied by acoustic emission (AE) and full-field strain mapping measurements; characterization of damage patterns and failure mechanisms using X-ray radiography and scanning electron microscopy. The ultimate goal is to relate damage in the material at different loading levels to microstructural features of the material and defects of production. KULeuven has published work related to AUTOW in [4].

As mentioned one of the most promising advantages of automated fiber placement machines is fiber steering. Previous research, e.g. [5] and [6], has shown that buckling loads of composite panels can be improved significantly by allowing the laminate stiffness to vary locally. This variable stiffness approach results in improvement of buckling performance in excess of 100% compared to quasi-isotropic laminates [0, ±45, 90 deg orientation]. The TUDelft was responsible for developing a design optimization method for steered composites structures. In doing so they developed a two step approach. In general the structural response, so the deflections and strains due to loading, can be computed using equivalent stiffness values determined using e.g. Classical Laminate Theory (CLT). This approach therefore starts at the macro level, because in terms of structural design and optimization, it is neither realistic nor necessary to model each tow, as an equivalent stiffness distribution is sufficient. Lamination parameters uniquely define the laminate's stiffness properties and hence allow an arbitrary stiffness distribution to be modeled with the minimum number of design variables. The solution of the continuous optimization provides the designer with a conceptual stiffness distribution best matching the desired performance constraints. This conceptual stiffness distribution can be translated into actual fiber paths and stacking sequences while applying manufacturing constraints such as minimum steering radii. Using a Genetic Algorithm (GA) to obtain an initial fiber angle distribution and Cellular Automata (CA) to enforce manufacturing constraints, the true fiber architecture can be determined (see figure 4). Using design sensitivities the optimum lay-up can be retrieved [7]. On the subject of variable stiffness and optimization a number of technical papers have been published [7] – [9].

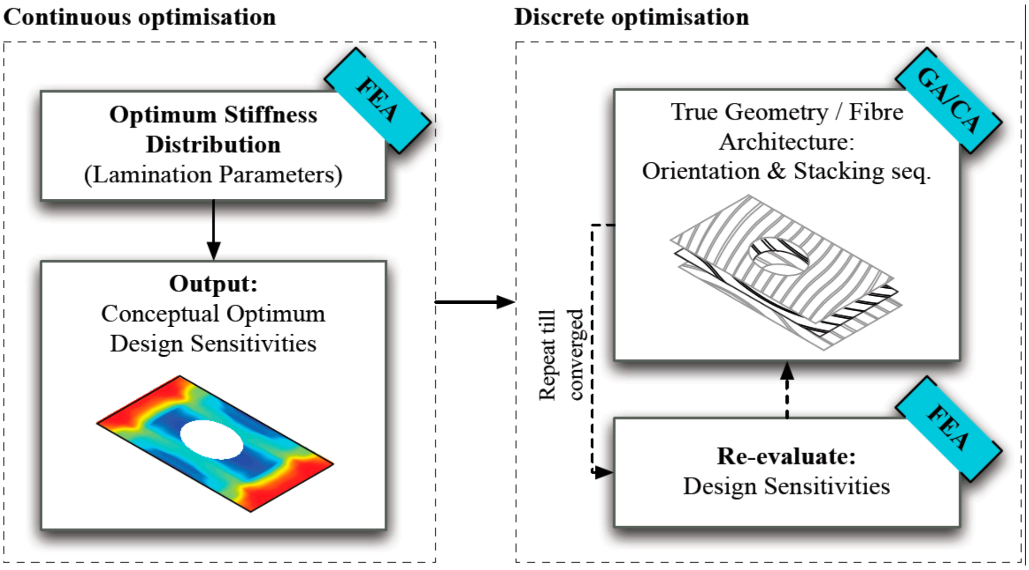

Figure 4. Overview of the proposed optimization process (FEA: Finite Element Analysis, GA: Genetic Algorithm, CA: Cellular Automata) [7]

The independent modules and methods developed by ONERA, KULeuven and TUDelft needed to be integrated. To fully exploit the potential of the scientific research and results, these academic methods preferably need to be embedded in engineering tools and software commonly used by aerospace engineers. This will greatly facilitate implementation and acceptance of the novel approach of variable stiffness and fiber steering. IFB was responsible for connecting these separate modules. With CATIA being a mainstay in the aerospace industry this was the most logical choice of the CAD/CAE software to be used. For the FEA step several standard software tools were investigated. During the project it became clear that MSC Nastran as finite element (FE) solver was the right selection as the familiarization and the integration during the project showed. With Nastran it is possible to compute the necessary sensitivities for the optimization process. IFB developed three different software modules in Visual Basic code which is supported from CATIA V5. The first module CATNAS connects the CATIA design to Nastran and the TUDelft optimizing module. The second module CATVIS is necessary for the visualization of the calculated fiber orientation for each element in CATIA V5. By visualization of the fiber orientation by a line over the actual part geometry it is possible for the designer to look at the fiber orientation optimization result. The designer will be able to connect the result to a global fiber layout which can be manufactured afterwards on the AFP machine. Finally the program CATADC links the tow path generation in CATIA V5 with the machine software named Fiber Placement Manager (FPM).

To test and demonstrate the potential of the integrated design approach and optimization tools in WP3 an alternative design of a beam with a flat web was created using the above described approach, whereas in WP4 the more conventional lay-up orientations [0, ±45, 90] and engineering tools were used to design, manufacture and test a sine wave beam. The first challenge for TUDelft and IFB was to develop an equivalent but geometrically less complex flat-rib. The reason for this was that by reducing geometric complexity, tooling and manufacturing could be reduced while fiber steering could be used to compensate for the resulting loss of buckling resistance. To meet all design and manufacturing requirements as used for the sine wave rib by IAI in WP4, the optimum flat-rib was found to be 15% heavier than the sine-wave rib. However, this design has the benefit of using considerably less complex manufacturing tooling. Additionally, it should be noted that only a reduced area of the web was designed using fiber steering and further weight reduction is possible if the entire rib were to be designed using the variable stiffness approach allowing thickness variation. Also the variable stiffness design improves the buckling load factor by more than 50% compared to a quasi-isotropic lay-up for the flat rib web area showing the added value of variable stiffness design. In a final step it was demonstrated how fiber paths can be generated from the obtained fiber angle design. These fiber paths can be used as input for the tow-placement machine.

Although the variable stiffness approach in combination with fiber steering has been mainly investigated for buckling optimization, the same methodology can also be used for optimizing the composite structure strength wise. For this purpose the TUDelft and Dassault developed a conventional and variable stiffness design of a tension test panel representing a fuselage panel with window cut-out. Ideally a laminate is created with a variable stiffness (VS) resulting in a strain distribution with each location in the panel being equally critical. The stress concentration normally found at the holes' edge and causing initial failure can hereby be avoided. The effect is illustrated below in figure 5 as the failure index distribution. Note that the values of the failure index are normalized such that a critical value of 1 is reached for the baseline quasi-isotropic plate. The research on optimizing in terms of the failure index was presented in another paper [10].

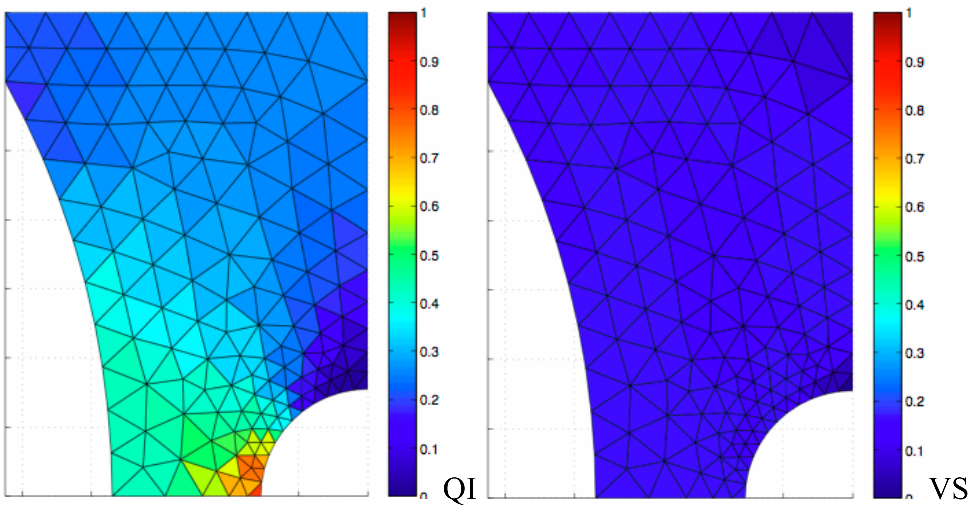

Figure 5. Failure index distribution for the quasi-isotropic (QI) plate and the optimal variable stiffness (VS) plate (quarter of model shown)

Taking into account the manufacturing constraints such as a minimum fiber steering radius, the optimal variable stiffness distribution can be translated to a fiber angle distribution. An example is shown in figure 6.

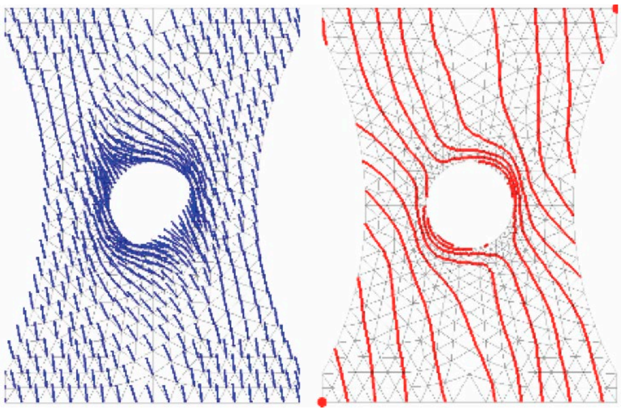

Figure 6. Two ways of representing fiber angle distribution for one ply

Several designs were generated and compared to the baseline constant stiffness layup, which was a quasi-isotropic lay-up. Applying a variable stiffness design for a number of plies allows theoretically predicted panel strength to improve by 50 to 90% for readily manufacturable designs. However, due the tight project timeline only parallel-path designs could be considered for manufacturing, as building the shifted fiber path designs would have required significant modifications to the machine software for production. Dassault manufactured and tested both the baseline and optimal parallel-path variable stiffness panel (same materials and equal thickness) successfully with the steered configuration achieving over 50% higher ultimate load. Comparing the failure strains at the hole edge of both panels it was found that these are comparable. The fabricated steered panel was found to have a 5% higher fiber volume fraction. The fibers of the optimal parallel-path design were aligned primarily along the primary load direction; hence the majority of the improvement in strength was concluded to be attributed to the fiber alignment, which can also be achieved without steering. The agreement between predicted load carrying capability and test results was excellent. Based on the predictions for the shifted-path steered design, it is possible to obtain up to 35% further increase of load carrying capability. The tested parallel-path steered design was, therefore, not well suited to demonstrating the potential of fiber steering. Further research will consider building and testing the shifted-path to fully understand and exploit the potential of variable stiffness and fiber steering.

4. FULL SCALE VALIDATION

In WP4 the objective was to validate the new technology, by performing the complete cycle of design, analysis, fabrication and testing for a representative component – a component which is generic, but “full-scale” and sufficiently detailed to illustrate the new automated dry fiber placement capability. Changing to AFP offers advantages, but there are some hurdles to overcome before it can be successfully integrated. Besides the investment cost, there is a learning curve. Designers will have to learn to design composite structures that work and integrate or in other words are compatible with AFP software, requiring engineers to learn the fundamentals of automated fiber placement and how it works with the design, while machine operators must be trained to use the new equipment [1]. In WP4 this learning curve is part of the validation of the new technology.

WP4 started out by performing a trade-off study versus traditional technology for five structural components to qualify the new capability. To focus this trade-off study, five components were already defined in the Description of Work each of which are envisaged suitable candidates to be fabricated with the new technology, and incorporate features which are specifically achievable with dry tow placement. These components are: a center wing box fitting, a sine-wave beam with access hole, an angled wing panel, a landing gear component and a lattice wing nose rib. All partners evaluated these components on several issues such as manufacturing (AFP, LCM), design and optimization, testing using their expertise. After a joint meeting and evaluation, the sine wave beam was selected as the full scale validation part.

4.1 Design

IAI designed and stressed a concept composite sine-wave rib with a central hole being representative for a rib of a business jet wing, with a machined aluminum rib as benchmark. Figure 7 shows the sine wave rib location and FEM model from IAI. This concept design provided a good starting point for discussions on manufacturability and design/stress. One of the major issues is the definition of the fiber orientation. What is defined in the Patran-Nastran model certainly does not always match with what can be programmed in FPM and can be placed using the AFP machine. For example very basically the partners need to agree on the definition of 0deg orientation in the rib flange. Also the wave length and depth are partly determined by the capabilities of the AFP machine and need to be considered in the design. The central hole was later deleted to allow a design fully critical on buckling and not failure around the edge of the hole. At that stage this allowed WP3 to try and develop an alternative design of the rib with a flat web and using variable stiffness through fiber steering and comparison between these two concepts. IAI further detailed the design supported by NLR, DAV and EADS-IW, on topics related to tow placement requirements and limitations. For the design several load cases were represented through a Nastran/Patran FEM model, such as continuous up gust, pratt up gust, crushing loads and fuel tank pressure. An example is shown in figure 7.

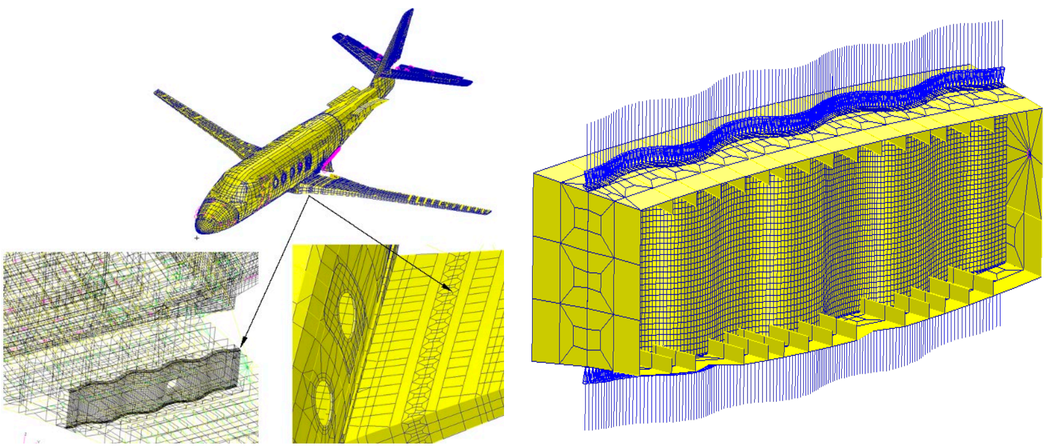

Figure 7. Sine wave rib location, overall FEM model and detail of rib with crushing loads from IAI

The resulting sine wave rib design and example of programmed 45 deg ply are shown in Figure 8. The rib consists of a central web area with a thickness of nearly 2mm surrounded by almost twice as thick a laminate extending into the ribflanges. The general dimensions of the rib are 1370mm length and approximate height of 400mm.

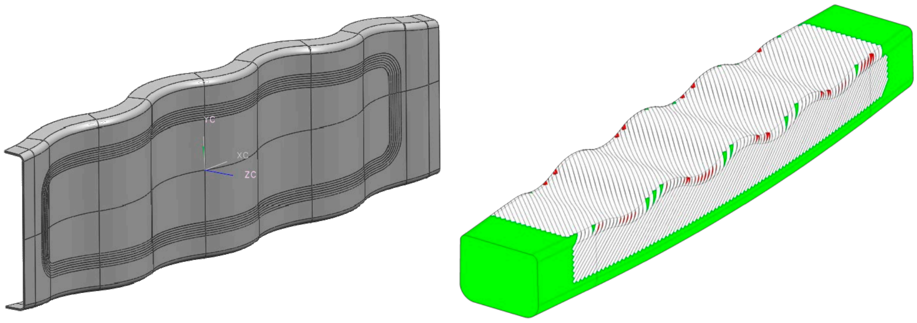

Figure 8. Final design of sine wave rib full scale validation article and example of 45 deg ply programmed on AFP tool

As there were some concerns on the structural performance of the flange to web corner area under tensile loading, radius fillers (throat washer) were designed for the full scale test article. Compared to the original I-shape aluminum rib the weight was reduced by 10%, taking into account the aluminum radius fillers. The weight would be further reduced by 25% if these were eliminated.

4.2 Manufacture

As IAI designed the rib in close cooperation with NLR, DAV and EADS-IW, NLR could translate the design into a program for AFP manufacture of the dry preform without undue delay and major difficulties. Parallel to this KSL developed the sine wave tooling supported by NLR, DAV and EADS-IW. Figure 9 shows the manufacture of the sine wave dry preform using the AFP machine at NLR. Here it is of interest to note that manual lay-up of sine wave ribs is complex and time consuming, requiring a trained technician two days for the rib size considered. With further AFP process and machine improvements the preform can be made in a matter of hours or less.

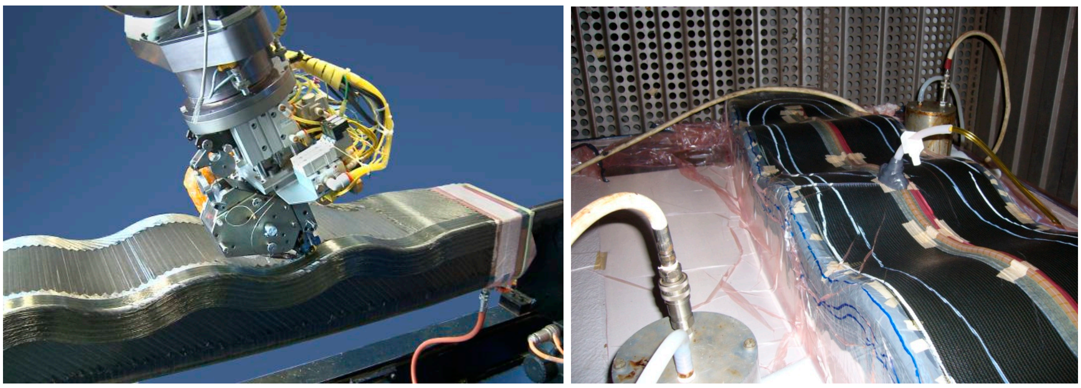

Figure 9. Manufacture of sine wave dry preform with AFP at NLR showing fiber steering in the ribflange and resin vacuum infusion of the preform at IAI

The dry preform was shipped to IAI. IAI developed the metal tooling and used resin vacuum infusion for injecting the dry preform with HexFlow ® RTM6 resin. Resin vacuum infusion involves a single sided tool, with the dry preform covered by auxiliary materials and a vacuum bag. The resin is drawn through the dry preform using vacuum only. ONERA supported IAI in simulating the resin flow during resin infusion. Combined with IAI’s extensive knowledge and experience infusion and curing of the sine wave ribs proved to be feasible.

Three dry preforms were manufactured and vacuum infused. In general it can be concluded that even though the sine wave rib is a challenging shape to manufacture, good laminate quality can be manufactured especially for less complicated geometries such as skin and fuselage panels. Further machining of the cured sine wave rib revealed no problems and two vacuum infused ribs were shipped to VZLU for testing.

4.3 Testing

IAI in close cooperation with VZLU setup the test plan and performed the static analysis of the sine wave rib in the test configuration. Two vacuum infused ribs were shipped to VZLU. One rib was provided with front and rear brackets and upper and lower skin sections to represent the location in the wingbox. From the other rib four sections were cut for tensile and compression testing with and without the radius filler. Figure 10 shows the full scale test setup of the sine wave rib at VZLU. The rib was tested by global bending to ultimate values of load, which it withstood successfully.

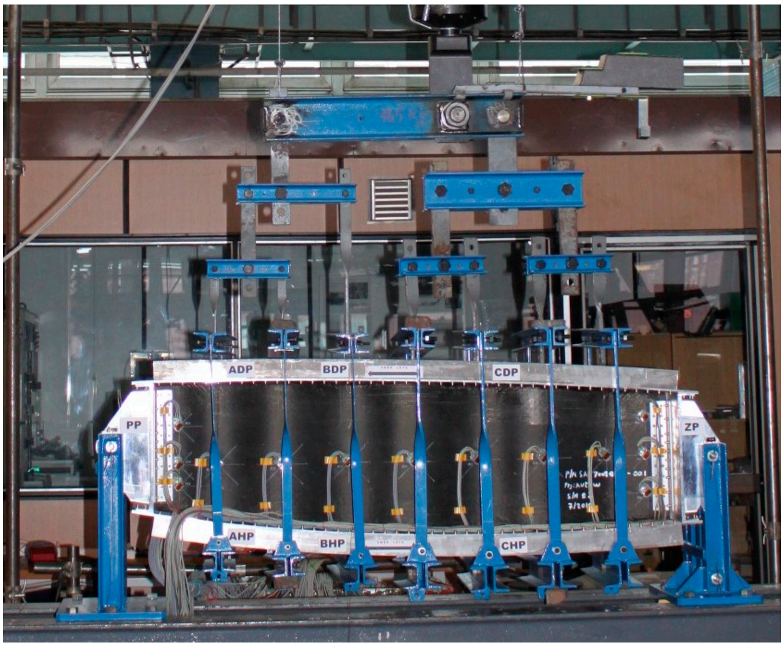

Figure 10. Full scale testing of sine wave rib at VZLU

The test rib segments with radius filler are shown in figure 11. The test rib segments without radius filler are basically the same and tested in a similar way. Special guide was designed to eliminate transversal forces on load cell and actuator.

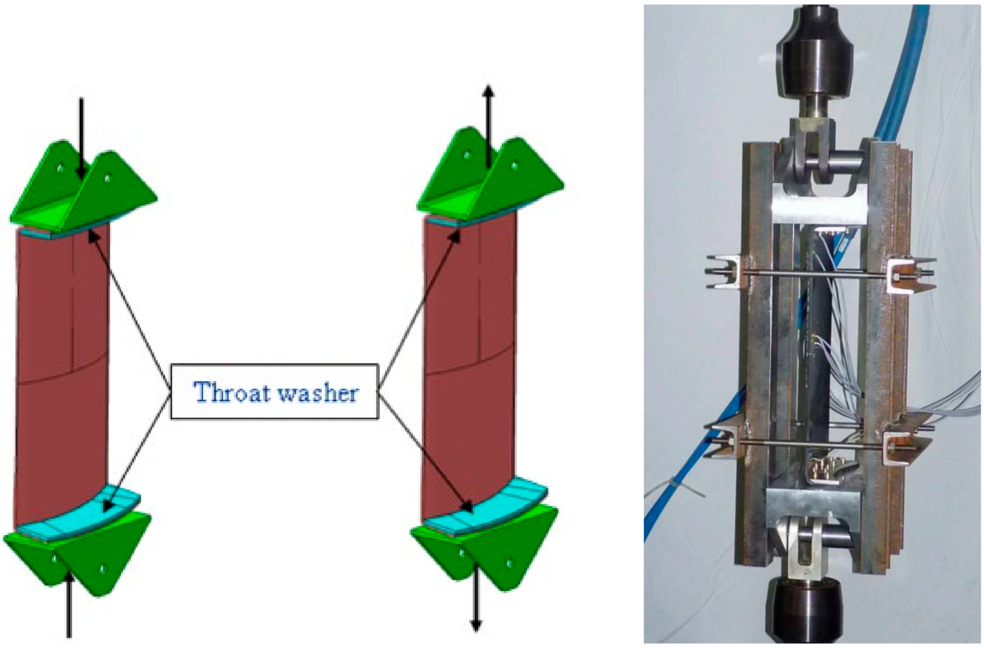

Figure 11. Test segments with radius fillers (throat washer)

Although the strengthening influence of the radius fillers was obvious, rib segments both with and without radius fillers withstood the ultimate tension and compression loads. In case future cyclic behavior shows similar acceptable structural response, this can further simplify the design and reduce the weight of the composite rib.

5. CONCLUSIONS

Whereas for large aircraft manufacturers like Airbus and Boeing it almost seems default to use composites and a high level of automated fabrication with e.g. AFP, it is also lucrative for the small aircraft industry [11] and the transport industry in general. Both weight and cost reduction can be achieved using automated composite manufacturing like AFP. Further material cost reduction are achieved through use of dry fibers instead of more expensive prepregs, in combination with LCM instead of costly autoclave curing. The reduction in weight and cost supported by novel design and manufacturing approaches as described in this paper will further facilitate and speed up the introduction of composite lightweight structures in aerospace and other transport industries. Lightweight composite structures contribute directly to reducing fuel consumption and hence GHG emissions of aircraft and other transport vehicles, Moreover weight reduction also allows for reduced power system requirements in turn facilitating electrification.

The AUTOW project has shown the tremendous potential of Dry Fiber Placement (DFP). During the project several AUTOW partners have started using the knowledge and experience acquired during the AUTOW project in other projects. One of these is for example the EU project ADVITAC, in which an advanced concept for a composite tailcone is being developed using DFP as one of the core technologies. Also NLR has developed and manufactured a dry preform for composite landing gear component, which was exhibited on the JEC in Paris 2011.

6. ACKNOWLEDGMENT

Instrumental to the success of this project was the team effort and great technical pleasure shown by all partners involved. Although there was no room for mentioning all the authors, they made this project and paper possible, for which I as coordinator heartily thank them. The AUTOW project was co-funded by the EU as part of the European Union's 6th Framework Programme.

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