NEW APPROACHES IN TEXTILE AND IMPREGNATION TECHNOLOGIES FOR THE COST EFFECTIVE MANUFACTURING OF CFRP AEROSPACE COMPONENTS

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Abstract

During the past years, several textile technologies, such as robot-assisted braiding, weft knitting and textile fibre placement, have been developed and optimized for application in composite structures. In combination with new stitching technologies, these basic fabrics can be combined automatically to complex, 3D reinforced preforms. It has been demonstrated that this approach – combined with adequate infiltration techniques – has a high potential for the cost-effective manufacturing of high-performance composite structures with superior damage tolerance and structural integrity.

The paper describes the basic textile technologies, the influence of stitching on the mechanical properties, the application to a very challenging fuselage part (Eurofighter wing attachment box) and an advanced non-autoclave infiltration process.

1 Introduction

The high potential of composite materials for realizing high-performance, light-weight structures for aerospace applications is well known. Today the research and development activities focus on further improvements of mechanical performance, such as damage tolerance and cost-effective manufacturing methods. Textile preforming technology in combination with advanced impregnation techniques offer a high potential to reach these goals.

Basic textiles like woven and non-crimp fabrics, tubular braids and unidirectional fabrics, as well as near net shaped sub-preforms such as fibre placement structures and complex three-dimensional braids manufactured by overbraiding mandrels, have been developed during the past years. The next step is the combination of these textile structures to highly integrated fibre preforms.

Different stitching techniques have been developed by the EADS Corporate Research Centre at Ottobrunn (Munich, Germany) together with several partners:

- conventional lock-stitch machines for perform stabilization, for attaching stiffeners to flat panels or for fast through-the-thickness reinforcement of wide areas;
- three different robot-guided, single-side stitching heads for sewing large preforms on spatial, curved contours;
- robot-guided lock-stitch head.

The single-side stitching heads do not need access to the rear side of the preform. Therefore the seam length is practically unlimited. With linear units, the robot can access even a whole airplane wing or fuselage section.

Stitching preforms can be divided into two main applications:

- preform mounting and stabilization for handling and storage;
- improvement of structural performance.

For preform mounting, the problem seems rather simple. Stitching must only prevent the sub-preforms from relative movement. In detail, the problem is much trickier: Stitching with unsuitable parameters can easily destroy material properties due to fibre misalignment and resin enrichment in the seam.

In order to improve structural performance, special sewing yarns with high stiffness and strength must be used. Today only threads of aramide, glass and carbon meet the requirements. The available stitching heads are able to work with all of them after intensive optimization of yarns and equipment.

Parameters like stitching density, seam position and penetration angle greatly influence the material properties.

The paper will discuss the results of first investigations on the different stitching techniques and will present various examples of complex preforms manufactured by integrating basic textiles.

In addition adequate resin infiltration processes are required to impregnate these net-shape performs. Here a high potential for cutting cost was identified in non-autoclave techniques.

2 Preforming versus prepreg lay-up

For many years, prepregs have been successfully applied for high-performance aerospace structures. All the processes are well known, and the in-plane material properties of carbon tape laminates are unbeatable. Nevertheless, prepreg laminates are very expensive and not useful for mass production, due to a high amount of hands-on effort.

Preforming with dry fibres offers a great potential for automation and, as a result of decreasing fibre damage and improved fibre alignment, the properties of these new materials are no longer far away from those of a prepreg.

Additionally, the possibility of realizing a 3D fibre reinforcement allows significant improvements to out-of-plane properties.

3 Manufacturing of sub-preforms

3.1 Basic (low-cost) textiles

Compared to woven fabrics, which have been available for many years, carbon-fibre non-crimp fabrics (NCF) are relatively new and still undergoing continuous improvement. Due to the straight fibres, NCF laminates reach about 98% of prepreg laminate properties. NCFs are available in many stacking sequences, different area weights and fibre types. One advantageous feature of the NCF process is the incorporation of layers with diagonal fibre orientation.

Woven fabrics, and especially NCFs, are frequently used for preforming plane or slightly curved sub-preforms. But also complex three-dimensional shapes are feasible by means of folding. Such structures are normally stabilized by plain lock-stitch sewing or binders.

Unidirectional woven fabrics with carbon fibre warp yarns and a weft insertion of thin polyester or glass and tubular braids are additional low-cost components of the preformer's construction kit.

3.2 Net shape fibre structures

3.2.1 Three-dimensional braids and fabrics

3D braids are produced with a new generation of braiding machines (see below). These braiders allow continuous production of goods with inherent through-the-thickness reinforcement and even variable cross sections. Typical applications are filler noodles without straight fibres and smaller frame profiles.

Further textiles with inherent through-the-thickness reinforcement are 3D weaves. The through-the-thickness fibre fraction can be very high and oriented in a 90° or 45° direction to the surface, depending on the requirements.

3.2.2 Overbraiding

A very cost-efficient production method for net shape preforms is overbraiding contoured mandrels. The speed of braiding and the high number of simultaneous processed yarns are one reason, the other is the potential to create a highly or even fully automated process.

Mandrels can be either removable or light-weight to stay in the part. Lost mandrels usually were made of foam. But thin-walled PET hollow bodies (comparable to disposable water bottles) have been tested successfully, too.

There are many ways of designing removable cores. In some situations, the mandrel can be simply dismounted or an expandable structure will be shrunk after braiding. More complex geometries are possible with soluble (salt, sand-binder compounds, aquacore™), meltable materials (high-performance waxes, low-melt metals) or granulate-filled contoured bags. Removable mandrels allow not only hollow fibre preforms. Many different geometries have already been realized with a subsequent folding process (see below).

3.2.3 Tailored fibre placement

Tailored fibre placement (TFP) utilizes more or less conventional embroidery machine hardware to stitch a carbon roving to a thin substrate. This allows fibre orientations that are exactly adapted to the load path. So, in theory, it is possible to have maximum utilization of the fibre together with a minimum of structural weight.

TFPs have been applied very successfully to the reinforcement of holes and load introductions, and recently also to big complex structures like robot arms and I-shaped beams.

One stitching head can handle only one roving at a time. But embroidery machines are equipped with up to twelve (usually eight) stitching heads. In addition, the process is fully automated and therefore very cost-effective.

4 Preform integration by stitching

4.1 Characteristics of stitch-bonded preforms

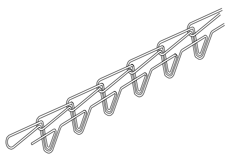
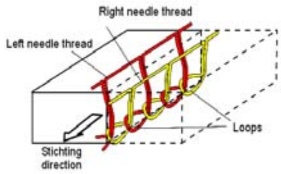
When stitching dry fabrics, fibre damage is negligible compared to the effect of fibre displacement by the thread, which results in a reduction of in-plane properties, depending on the stitching technique itself and on the parameters applied. Current fundamental investigations at EADS focus on the optimisation of stitching preforms with respect to improved damage tolerance, minimized reduction of in-plane properties, and automated preform attachment processes. Therefore stitching parameters such as sewing thread properties (i.e. stiffness, strength and interfacial properties), stitching density and pattern have to be considered as well as automation concepts for fabric cutting, handling and positioning to develop flexible preform manufacturing processes with high productivity and a uniform quality level.

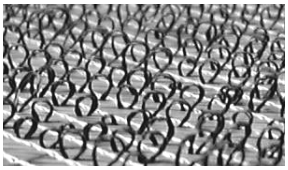
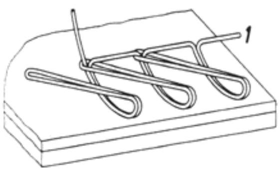
4.2 Stitching techniques

Conventional sewing techniques like lock stitch and chain stitch need access to both sides of the material. So they are restricted to flat preforms and limited size.

In close co-operation, the partners ALTIN, ITA, KSL and EADS have developed four different single-side sewing heads. Three of them are available at the EADS lab in Ottobrunn on two different robot systems (see below), and the set is completed by a robot-mountable lock-stitch head.

The available single-side heads are very different as regards the stitching mechanism. Therefore the sewing thread path and angle within the preform are also characteristic, as well as the resulting seam properties. See the following table for stitch types and main characteristics.

ALTIN	**ITA**
stitch type:	
chain stitch	multi-thread chain stitch
	
characteristics:	
• sewing needle at 45°, 90° hook needle	• two sewing needles at 45°
• thread chain on upper side	• thread chain on rear side
highlights:	
• simultaneous reinforcement at 90° and 45°	• ± 45° threads for shear reinforcement in one path

KSL tufting	**KSL blind stitch**
stitch type:	
unchained open yarn loops	chain stitch
	
characteristics:	
• open loops	• curved needle R=25mm
• loops may end within material or penetrate through	• thread chain on upper side
highlights:	
• material thickness up to 40mm	• no needle puncturing ⇒ sewing in the mould possible
• processing of thick yarns	

4.3 Stitching yarns

Sewing yarn selection depends mainly on the purpose of the seam. For preform assembly without the need for structural improvement, polyester yarns, for example, are sufficient. These yarns should be of very low yield to prevent fibre misalignment as far as possible.

Threads for structural seams have to meet other criteria. Their main function is to carry and distribute out of plane and/or shear stress. It is obvious that they must be thicker, but many other properties must fit into the total system. The most important point is the yarn modulus in combination with the resin interface. Carbon sewing threads are the first choice, because the stiffness should be as high as possible, combined with high ultimate strength. But in general, glass or aramide yarns show also sufficiently good performance.

5 Textile machines at the lab of EADS Germany

5.1 Robot-assisted tubular braiding and overbraiding

Tubular braiding is well established in the industrial production of high-performance fibre braids. EADS has designed a braiding machine, where the braiding yarns can be placed on mandrels that are handled by an industrial robot. The braiding process is fully controlled by the robot programme.

Fibre orientation and coverage ratio depend on several parameters:

- mandrel diameter;
- yarn lay-up width;
- mandrel speed and position;
- braider speed.

All speed and position parameters are completely controlled by the robot programme to ensure correct fibre orientation. This allows a variation of yarn angles between 10 and 80 degrees. Angle variations caused by core diameter variations can be absorbed in a wide range.

The thickness of the preform is in principle unlimited and can be varied over the length of the profile, because the robot allows multiple overbraiding of the core over the full length or in sections.

In addition to the braiding yarns, a set of fibres in longitudinal direction can be integrated over the whole circumference or only locally in order to improve the mechanical performance.

Figure 1. Robot-assisted braiding machine.

5.2 3D braiding machine

The EADS research lab worked jointly with the company Herzog (Oldenburg) and the ITA (Aachen) on a new braiding technology to generate complex profiles with a real 3D fibre architecture. To realize these preforms, the bobbins are moved by horn gears along tracks which are individually selectable by pneumatic switches. This device permits generating nearly any shape of cross section and also a multitude of fibre orientations within the braids, and even continuous changes in the profile cross section.

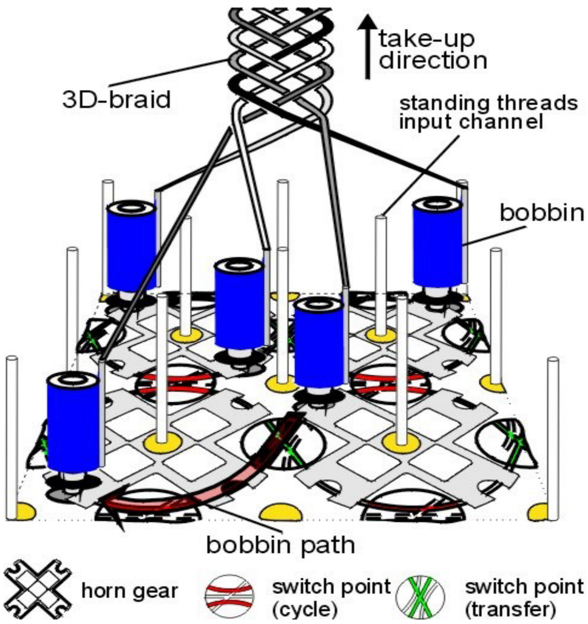


Figure 2a. Principle of 3D braiding.

Figure 2b. EADS 3D braider prototype.

The cross section of the braided profile on the existing prototype machine (with 10 by 10 horn gears) is limited to approximately 400 square millimetres, according to the number of bobbins and the thickness of the fibres, because the preform is generated in a single step. In the meantime, an industrial braider with a 12 by 12 horn gear array is available which allows cross sections up to about 600 square millimeters.

5.3 NC gantry sewing machine

A multi-purpose sewing machine with a stitching area of 1m by 1.7m with two different sewing heads comprised the start of automated stitch bonding activities at EADS. One sewing head (DA 767 lock stitch) was designed for tests on heavy textiles up to 18mm thickness and for plain preform assembly. Due to several modifications this device enables the processing of carbon fibre threads with a speed of 1500 stitches per minute.

A second zigzag stitch head was equipped with a roving feed system for TFP. To enable the sewing head being aligned with the direction of the seam, it was mounted on a rotation axis.

A special programme interface permits sewing-path generation on a CAD system. The CAD-drawn seam positions can be converted directly into a sewing programme.

Figure 3. NC-controlled gantry sewing machine.

5.4 Robot-guided single-side sewing machines

There are basically two main advantages of robot-assisted, single-side sewing:

- Single-side sewing is not limited in preform size;
- Robot-guided sewing heads can produce spatial curved seams on complex shaped preforms.

Figure 4. Blind stitch sewing head on industrial robot.

Of course, compared with a gantry system, an industrial robot is not always the best solution for single-side sewing. But it offers very high flexibility and easy programming.

6 Properties of stitched composites

6.1 Seams for preform assembly

The only function of seams for preform assembly is to prevent relative movement of preform layers or subpreforms. But the essential fact is that the seams must not disturb the textile structure or decrease the material's in-plane properties. In reality, a minimum degradation of about 2% in static compression strength is the best achievable value, though reductions of about 70% have been observed, too. Stitch type, needle and yarn thickness, yarn tension and therefore fibre undulation are the most critical parameters.

6.2 Seams for structural improvement

EADS has performed investigations on sewn Compression After Impact (CAI) specimens. As the ultrasonic C-scans demonstrate, the delamination area decreases significantly with a higher stitch density. The compression strength after impact rises from 172 MPa to 312 MPa (80%). Though without impact, compression strength drops from 477 MPa to 386 MPa (19%).

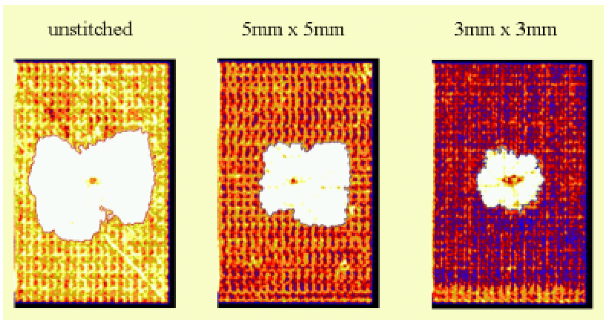


Figure 5. C-scans of CAI specimens.

A similar result was achieved on stitched plain laminates in a front crash test. The energy absorption was enhanced from 17 kJ/kg to 46 kJ/kg (+170%).

Tests on T-pull specimens also show promising results. The ultimate load could be increased by 74%.

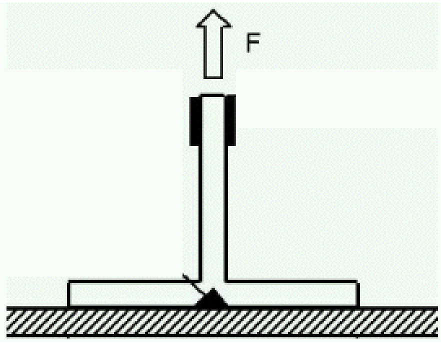


Figure 6. T-pull specimen.

As mentioned above, yarns for through-the-thickness reinforcement must bear loads in the cured structure. Therefore they may not fall below a certain thickness. Out-of-plane improvement and in-plane degradation have to be balanced in line with the needs of the individual product.

7 Exemplary applications

7.1 Textile frames

One focal point at EADS was to develop concepts for stiffened shells. J- and T-stiffeners may be made of braided preforms as well as of non-crimp fabrics. A textile J-shaped fuselage frame has shown a reduction of effort by more than 80% in contrast to the prepreg component, due to a high degree of automation. In addition, there is a dramatic reduction of pre-cuts. For the prepreg frame, about 300 individual pre-cuts are necessary. The textile version consists of only 36 pieces of NCF, unidirectional woven fabrics and a 3D braided filler noodle.

A second, even more cost-effective approach is the overbraiding of a curved mandrel. The braiding yarn lay-up was controlled so that the fibres are at an angle of ±45° in the later web of the profile. Longitudinal inlay yarns were provided in the later foot and flange section. They lay straight in the braid and already in their correct length, which differs in the foot and the flange.

Figure 7. Braiding of a curved J-frame.

After braiding two plies, the textile must be fixed before removing the mandrel. This was done with a resin-compatible powder binder. Single-side sewing can improve the stability and fix a filler noodle, if needed.

Figure 8 shows the principle of the folding process. Sections marked in blue are ±45° only, red areas also contain straight 0° fibres.

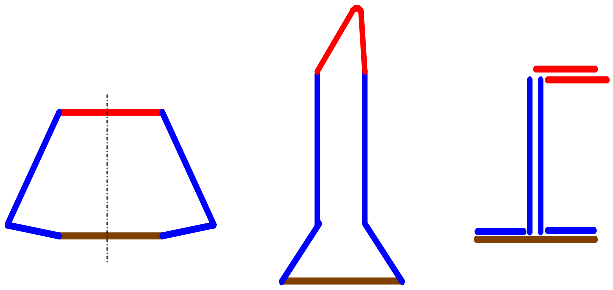


Figure 8. Folding principle of the braided J-frame.

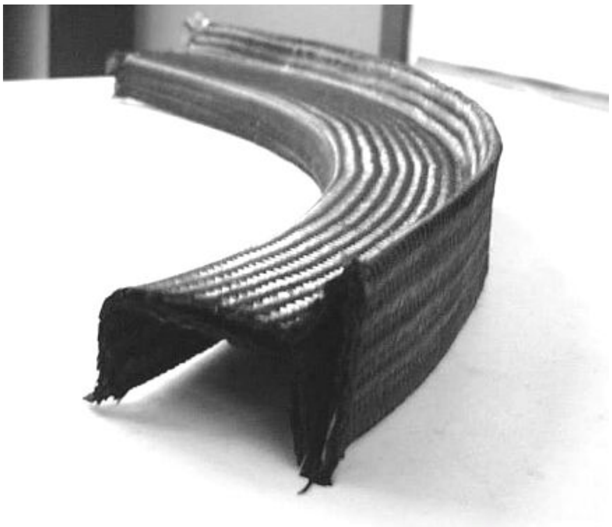


Figure 9. Braided J-frame after folding

7.2 Stiffened shells

Up to now, the most challenging part realized by stitching at EADS-CRC is the so-called Wing Attachment Box (WAB). The WAB is part of the EFA fuselage side skin. Today this part is manufactured as a 100% prepreg structure. A textile version of the WAB should demonstrate that highly complex preforms can be manufactured using the new concepts and techniques.

The WAB has an NCF skin and eight NCF J-frames. The overall dimensions of the part are 2.3m x 1.8m x 1.1m. Four of the J-frames are full-size (1.8m x 1.1m), the others are cut out for manholes.

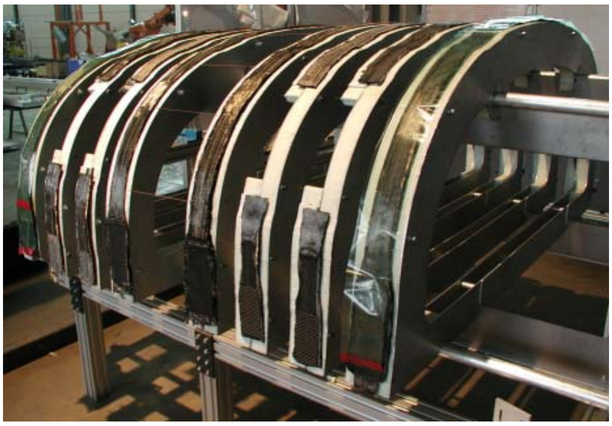


Figure 10. Sewing fixture with J-frames.

Skin and frames have been stitch-bonded with two different sewing systems, the KSL blind stitch and the ALTIN OSS RN810 system.

Due to the seam geometry, four blind stitch seams have been applied on a frame. With the ALTIN chain stitch, two seams were sufficient.

Figure 11. First blind stitch seam after skin lay-up

The sewing fixture was designed as a light-weight structure. Its main components are the profile fixtures, which are manufactured from an aluminium-foam sandwich. The fixtures are cut in a laser cutter with very low tolerance to guarantee the correct shape of the final preform. The frame fixtures fit into slots of a comb-like device for accurate positioning one to another.

After sewing, the sewing fixture can be turned upside down together with the preform and placed in a female mould. Then the sewing fixture is dismounted and the resin injection can be prepared.

8 Non-autoclave impregnation

EADS-CRC, Ottobrunn in collaboration with the Military Aircraft Department of EADS in Augsburg have developed a cost-effective non-autoclave manufacturing technology for complex high-performance CFRP structures.

The operating principle of this advanced resin infusion technique for textile preforms (called VAP – Vacuum Assisted Process) is the advantageous use of a microporous membrane to separate air and resin. Consequently it is sufficient to apply vacuum and temperature to obtain a laminate quality – concerning void content and fibre volume fraction – which meets the requirements of the aircraft industry.

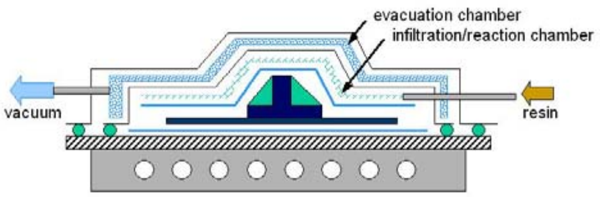


Figure 12. Principle of VAP

The capability of VAP has been shown with several manufacturing demonstrations e.g. a rear pressure bulkhead for the Airbus A320, a lower wing skin panel (12m x 2.5m; ca. 400kg) and the wing attachment box mentioned above.

Figure 12. Impregnated fuselage side skin demonstrator

7 Conclusions

It has been demonstrated that the application of advanced textile preform techniques – in combination with adequate resin infiltration processes – offer a high potential for significant cost savings in the manufacture of high-performance composite structures. In contrast to prepreg manufacturing the use of textile fabrics in combination with a non-autoclave infiltration process like VAP makes CFRP structures affordable or even cheaper compared to aluminium components.

However, much work still remains to be performed jointly between textile machinery and preform manufacturers and end users. It is expected that advanced textile composite materials may help to meet not only the cost-efficiency demands of the aircraft industry. These developments even look promising for some spin-offs for the automotive industry and other sectors of the transportation industry.

References

[1] Schneider M, Wulfhorst B. Bedeutung der Flechttechnologie für die Konstruktion von Faser-verbundwerkstoffen. *Proc 35. Internationale Chemie-faser-tagung*, Dornbirn, 25.-27. 9. 1996

[2] Rattay F (ALTIN GmbH, Germany), Geßler A (DaimlerChrysler AG, Germany), Pickett A (ESI GmbH, Germany), Gliesche K, Grube J (IPF Dresden, Germany), Wulfhorst B, Laourine E (ITA, Germany), Keilmann R (KSL GmbH, Germany). Single innovative textile preform integration technique for fiber reinforced plastics. *Proc* Materialica, Munich, 2000

[3] Brandt J, Drechsler K, Geßler A (EADS Deutschland GmbH, CRC Germany). Comparison of Various Braiding Technologies for Composite Materials in Aerospace Applications. *Proc ACE Conference2001*, Seattle, paper no. 2001-01-2626