Automated wet compression moulding of load-path optimised TFP preforms with low cycle times

J Fial*, M Harr, P Böhler and P Middendorf
Institute of Aircraft Design, University of Stuttgart, Pfaffenwaldring 31, 70569 Stuttgart, Germany
* fial@ifb.uni-stuttgart.de

Abstract. This paper describes the implementation of a wet compression moulding process using TFP preforms. The fibre paths of these preforms are derived from the actual load paths which are numerically analysed taking into account multiple loading conditions. Preforms are created using a Tajima embroidery machine. This approach allows an innovative way of textile forming in the following process step. This step is based on wet compression moulding using a flexible stamp made of silicone rubber. The wet compression moulding is implemented in the draping test rig of the Institute of Aircraft Design, University of Stuttgart. It is able to produce structures with varying thicknesses which therefore stand out for their high lightweight properties.

1. Introduction
This work presents a production process for structural carbon fibre reinforced parts. Based on tailored fibre placement (TFP) preforms, wet compression moulding is combined with a novel kind of forming process. The aim of this work consists out of three different key elements:

First of all, the goal is to create a light-weight composite structure. Thereby not only lightweight materials are used but the material layup is designed in a way that ideally suits the anisotropic material properties.

Another important point is controlling the forming behaviour of the textile during the process presented. The idea is to avoid complex draping properties and use easy to handle mechanisms instead.

The third important aspect is that the whole process of part manufacturing as well as the design shall reach a high degree of automation. The work presented is done in cooperation with industrial partners and the process is implemented using the example of an armrest designed for common aircrafts. This work is intended to serve as a pre study for a possible future series production.

1.1. Light-weight aspect of the envisaged structure
As indicated, high value is put on the light-weight character of the envisaged structure. Common industrial applications often seek to replace metal structures. Consequently, the target geometries do not always represent an ideal application for fibre reinforced materials whose anisotropy plays an important role. Therefore, the light-weight potential of the composites are rarely completely exploited [1]. Quasi isotropic textile lay-ups are one example for this subject.

The TFP process is used to meet this issue in the present work. Starting with a numerical analysis of the loading conditions of the structure, the load-paths are identified and serve as design pattern for the reinforcement yarns placed during the TFP process (see section 2.1). Variable thickness and stiffness structures are created and reinforcement material is only used where its mechanical properties are
required. This has the positive side effect of reducing any unnecessary and expensive waste to a minimum.

1.2. Avoiding complex draping mechanisms and implementation of novel forming mechanisms
During every forming process of a reinforcement textile its architecture is changed in order to adapt to the newly imposed geometry. Complex mechanisms are common and defects such as wrinkles or gaps can occur [2]. The forming process presented is based on adapting the preform properties during the TFP process: The stitching substrate and the reinforcement yarns embroidered upon it are combined in such a way that creates the simplest mechanisms possible. Those are folding for the base material and gliding in defined paths for the reinforcement yarns (cf. section 2.2.2).

1.3. Reproducible process and the test rig
The process described is built up to a large extend at the Institute of Aircraft Design (cf. section 3. ) and thought to demonstrate the feasibility in an industrial environment. The creation of the preform takes place in a Tajima embroidery machine. The wet compression moulding process is integrated into the draping test rig using low-cost tools. This allows the investigation of the most critical process steps such as textile forming and impregnation. Other important aspects like the automated handling of the preforms and the cutting of the near-net-shape structure which is generated by the wet compression moulding are not implemented and considered trivial.

2. Methodology
This section aims to explain the basic methodologies which underlie the process presented, the two main aspects being:
- The deviation of stitching paths for the creation of the TFP preforms
- The optimal use of material properties regarding forming and mechanical behaviour

2.1. Deviation of stitching paths for the creation of TFP preforms
As indicated in section 1. , carbon fibre reinforcement yarns are placed upon a glass fibre fabric base material in dedicated paths. These paths are stress related and designed in a way that a minimum amount of material has to be used.

The starting point for the creation of these stitching paths is the numerical analysis of the target structure (left side of figure 1). This method (also described in [3]) takes into account multiple load cases and is able to derive the main load paths. These load paths are in a next step identified as the area where the reinforcement yarns have to be placed and interpreted as stitching paths for the reinforcement yarns during the TFP process. Subsequently a tool automatically builds up a mesoscopic model of the preform, including stitching yarns and physical boundary conditions like friction parameters [4] (cf. centre of figure 1). The following reverse mesoscopic finite element forming simulation finds the representation of the flat preform geometry (right side of figure 1). This serves as the pattern for the embroidering of the preforms during the TFP process.

Figure 1. Derivation of the 2-dimensional stitching paths from the target structure (left). Based on a numerical analysis a mesoscopic textile model is created (middle). A reverse draping simulation creates the flat pattern for the creation of the 2-dimensional preform (right).
2.2. Optimal use of material properties regarding forming and mechanical behaviour

During the generation of the TFP based preforms, the application of different embroidery parameters can influence the preforms both in their mechanical as well as in their forming behaviour. In order to obtain optimal properties concerning these two aspects, they are analysed more detailed below.

2.2.1. Mechanical properties. The structure investigated consists out of a glass fibre fabric base material and carbon fibre reinforcement yarns. In the final structure the base material represents the geometry and is not designed to carry any loads. The reinforcement yarns on the other hand are designed to carry the stresses, incorporating different loading conditions. They are stitched according to the load-path distribution and a variable thickness structure is created. This means that there are areas of pure base material and areas with base material and one or more reinforcement yarns. The reinforcement yarns are stitched on the side of the base material which will later be on the inside of the structure. This ensures a constant quality of the visible part surface.

2.2.2. Forming properties. The cutting of the base material in areas of 2-dimensional curvatures is a way of avoiding all possible defects that can occur in a draping process (wrinkles, undulations, etc.). This is due to a local reduction of forming constraints for the textile which is formed. Regular reinforcement yarns stitched upon the base material do not influence this folding mechanisms and are formed in the exact same way.

Additional reinforcement yarns are deployed in a way that allows to directly influence the forming of the textile. These “manipulation yarns” are stitched upon the base material using two different sets of stitching parameters: Stitching with small stitching lengths and widths creates a strong bonding and prevents any relative movement. Stitching with high stitching lengths and widths and using low sewing yarn tension on the contrary means low friction which enables relative yarn movement through the stitching path. The corresponding forming mechanism is selectively manipulated yarn gliding [5].

2.2.3. Implementation. The implemented strategy is illustrated by figures 2 and 3 below. It consists of the following steps:

- Cutting of the base material (glass fibre fabric) in the edges and thereby implementation of folding instead of draping as forming mechanism.
- Stitching of the reinforcement yarns (carbon fibre tows) upon the base material along the previously deviated paths (see 2.1).
- Utilisation of some of the reinforcement yarns to span the cuts in the base material. Application of particular stitching parameters to allow local yarn gliding through the stitching for these manipulation yarns.
- Pulling of the manipulation yarns at the free ends and coeval folding of the base material. This creates the envisaged 3-dimensional geometry and closes the cuts in the final structure.

![Figure 2. Pre-cut base material with manipulated reinforcement yarn (dashed line). Arrows indicate the yarn manipulation and the closing of the cuts in the base material.](image1)

![Figure 3. Final structure represented by the folded base material and one exemplary manipulated reinforcement yarn (dashed line).](image2)
3. Implementation of the production process

The whole process consists out of the preform production via TFP, handling steps and the wet compression moulding. One key element is an especially developed multi-purpose frame which is used throughout the whole process. This frame is presented in section 3.1 whereas the embroidering and the wet compression moulding are shown in sections 3.2 and 3.3.

3.1. The multi-purpose frame

The multi-purpose frame is essential for the three main steps described above. During each step it realises different tasks and has to fulfil different requirements. This is summarised in the following table:

| Process step                  | Task                              | Requirement                                      |
|-------------------------------|-----------------------------------|--------------------------------------------------|
| TFP preform generation        | Supply of the base material       | Low thickness due to TFP stitching machine geometry |
| Handling steps                | Supply of the preform             | Light-weight design                              |
| Wet compression moulding      | Perform yarn manipulation         | Compatibility to tooling geometry                |

The requirements shown in table 1 lead to the design of the frame which can be seen in figure 4. The frame consists of three 1 to 2 mm thick sheets of aluminium and is approximately 700 mm wide and long. In the middle part, magnetic clamping is realised which holds the base material in place (dashed area). In the outer area of the frame manipulation mechanisms are integrated.

![Figure 4. Multi-purpose frame with embroidered preform. Part of the yarns are connected with the manipulation mechanisms.](image)

The manipulation mechanisms consist of slides which are inserted between the top and bottom aluminium sheets of the frame. At one end of a slide, the manipulation yarn is wound around and at the other side springs are attached (see figure 5). This applies a constant force upon the yarn and a passive and therefore failure tolerant yarn manipulation during the wet compression moulding process is guaranteed.
3.2. **Embroidering process: Yarn deposition in manipulation mechanism**

This section is dedicated to emphasise particular characteristics of the embroidering process of the manipulation yarns. Basic explanations on the TFP process itself are set aside.

As explained above, different stitching widths are used to create areas with high yarn fixation and areas where yarn gliding is enabled. Locally, the sewing yarn is cut, in order to create yarn paths that span the cuts in the base material (cf. figure 2). This is also done when depositing the manipulation yarn into the manipulation mechanism. In this region, the needle is in the topmost position and the fibre placement follows automatically the path indicated by the dashed line in figure 6. No further manual interference is necessary.

![Manipulation mechanism consisting of slides applied with spring forces.](image1)

**Figure 5.** Manipulation mechanism consisting of slides applied with spring forces.

3.3. **Wet compression moulding**

The wet compression moulding takes place in the test setup shown in figure 7. This figure shows the draping test rig of the Institute of Aircraft Design that has been equipped with the necessary tooling and a material infeed system for the frame (including the preform). Subsequently, details on the process steps as well as on the stamp configuration are given in sections 3.3.1 and 3.3.2.

![Embroidering process with yarn deposition in manipulation mechanism.](image2)

**Figure 6.** Embroidering process with yarn deposition in manipulation mechanism.

![Test set-up for the wet compression moulding: On the left-hand side, the frame is placed upon the material infeed system which will transport the frame in and outside the tooling (right-hand side).](image3)

**Figure 7.** Test set-up for the wet compression moulding:
3.3.1. Process steps during wet compression moulding. Once the frame is put on the infeed system, epoxy resin is manually applied upon the preform. The centre part of the lower tooling (cf. figure 8) is heated and the frames slides into the tooling. Centring pins ensure a reproducible relative positioning of the tool and the frame.

Proper sealing allows to depress the whole cavity. Inside the tooling a stamp is pushed down and promotes the folding of the preform. As described in section 2.2.3, the manipulation yarns are pulled simultaneously and the final part geometry with closed cuts is created. After curing, the cavity can be opened and the frame together with the near-net-shape structure slides out of the tooling.

3.3.2. Stamp configuration and preform compression. As indicated in figure 8, the stamp is built up of different materials. The centre material is stiff and allows the introduction of the necessary compression forces. The outside is covered with a flexible coating made of silicone rubber.

The flexible coating enables the stamp to adapt to the varying thickness of the preform. It pushes into regions of pure base material and also allows the compaction of areas with one or more layers of reinforcement yarns. Due to a hydrostatic-like pressure which builds up during compression, this effect can also be seen on the side walls of the preform. The goal is to thereby reach a constant fibre volume ratio throughout the whole structure.

4. Process evaluation

As stated in section 1, this process is thought to demonstrate the feasibility of the different techniques involved. Therefore, the means implemented, like e.g. the tooling, are low-cost and the wet compression moulding is not to be directly compared to a process used in industry. For these reasons, in this process evaluation the qualitative influence of different varied parameters is presented in this section.

There are a number of parameters which have an impact on the properties of the final structure. These parameters are set during different process steps which is shown in the following table:

| Process step                          | Process parameter                                |
|---------------------------------------|--------------------------------------------------|
| TFP preform generation                | Stitching parameters like e.g. stitching length   |
|                                       | Number of reinforcement layers                   |
| Wet compression moulding preparation  | Resin distribution on preform                    |
|                                       | Temperature of the tooling                       |
| Wet compression moulding process      | Stamp material                                   |
|                                       | Stamp pressure and blank holder forces           |
|                                       | Sealing and cavity depression                    |

During the realisation of the process, the parameters shown in table 2 are studied. For some of them it is possible to quickly find an optimum which is shown in section 4.1. Others have to be investigated more carefully which is argued in 4.2.
4.1. Basic process parameters

The first basic parameters investigated are those set by the embroidery machine during the stitching in the region where the gliding of the manipulation yarn is necessary. The general idea is that the friction on the manipulation yarn has to be as low as possible. This is accomplished by a low sewing thread tension as well as high stitching lengths and widths. These parameters directly influence the capability of successfully closing the cuts during the forming of the TFP textile. This is shown in the following 2 figures:

**Figure 9.** Effect of tight stitching pattern (left) on the gliding behaviour of manipulation yarns (right): Ideal yarn paths cannot be accomplished.

**Figure 10.** Effect of lose stitching pattern (left) on the gliding behaviour of manipulation yarns (right): Yarn paths correspond to the intended pattern.

Another basic parameter set concerns the implementation of blankholders. They are put in place on every side of the rectangular mould in order to give the textile a certain resistance when being formed into the cavity. The main thing to consider is having a constant blankholder force distribution on every side. This guarantees a symmetric forming result and moderate pressure is sufficient.

4.2. Process parameters with more complex influence on the result

The first parameters which are considered more complex are the type of resin and the corresponding forming temperature. These aspects directly influence the process cycle time and are important for the implementation of the process. Two types of epoxy resins are investigated and provided by the industrial partner Sika. As the target application is to be installed inside an aircraft cabin, also fire, smoke and toxicity related issues are taken into account. Various different parameter sets are studied and finally a forming temperature of 80°C in combination with the resin system Sika Epolam 2500 [6] shows a promising cycle time of 5min.

The application of the resin on the preform is equally important for the process quality. As indicated in section 3.3.1, this is done manually and directly influences the local impregnation level of the final structure. Epolam 2500 shows good results once the resin is distributed homogeneously amongst the whole preform surface. This is due to the characteristic short resin flow path of compression wet moulding which is mainly in thickness direction. The resin application as well as the corresponding local impregnation is shown in figure 11 below. In the centre picture there is also an example of an unsuccessful impregnation.

**Figure 11.** Impact of the resin distribution on local textile impregnation. An uneven distribution (left) leads to poor impregnation results (middle). A more homogeneous resin application leads to better results without local dry spots (right).
Another set of parameters investigated in this part of the work is the number of reinforcement yarn layers and the material of the flexible stamp coating. As the preform possesses areas without any reinforcement yarns, the number of embroidered layers defines the local change in thickness of the structure. In order to avoid areas of pure resin, the flexible stamp has to be soft enough to mould every detail of the preform. Accordingly, the bigger the difference in preform thickness, the softer the stamp has to be. At a maximum number of 3 layers, a silicone rubber shore hardness of 0 respectively 20 is tested for the coating of the stamp. The results are shown in the figure below:

![Figure 12](image)

The analysis of entirely embroidered areas of the final part also shows, that a fibre volume ratio of 58% is possible on the side wall of the structure. This indicates that the hydrostatic-like pressure created by the stamp material is successful.

Finally, the last parameters mentioned in table 2 - cavity pressure and sealing strategy - have to be taken into account. The sealing of the tooling needs special attention as during the process the cavity is depressed in order to reduce the void content in the part. The fact that the frame is put between the two moulds demands a double sealing towards the upper as well as the lower mould. Additionally, the stamp is controlled by actuators which are fed through the upper mould. In this region, special sealing is also essential. These precautions lead to a good result concerning the void content on the part surface which can be seen in figure 12 on the right.

However, the maximum part quality achievable with this process is limited as during these investigations a low-cost tooling is used. Additionally, it has to be mentioned that this analysis shall be used just for a first impression. A more differentiated examination, like a photomicrography analysis of the part, is necessary in order to get more reliable results.

5. Results and outlook

The positive result of this work is the successful implementation of a novel kind of production process for TFP based composite structures. It is shown, that direct yarn manipulation can be implemented in an automated forming process and thereby significantly reduce issues regarding draping defects. In connection with a silicone rubber based stamp, good part quality with varying thicknesses can be reached in a wet compression moulding process.

The process time for the wet compression moulding – including textile forming – is 5min. As other process steps are easy to perform in parallel, this is considered as the most important time factor.

For the resulting structure (see figure 13) the initial weight is reduced significantly. With two layers of embroidered reinforcement yarns, its weight is about 66g. Also, local fibre volume ratios in the side wall areas of the structure are verified to reach 58%. It has to be mentioned that the evaluation regarding mechanical performance is still ongoing. First testing results are promising but final conclusions cannot be made at this point.
If this feasibility study is to be further examined for industrial applications, several details have to be looked into in detail. Some of those details are e.g.:

- Proper metal tooling design for wet compression moulding. In this context, sealing techniques are of high importance. In [7] possible solutions are presented.
- Investigation of the fatigue behaviour of the silicone rubber material in context with high forming temperatures and contact with epoxy resin.
- Automation of manual tasks such as resin application.
- Inspection of current mechanical solutions (e.g. yarn manipulation mechanism) in regard to process robustness.

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