PRODUCTION OF CONTINUOUSLY FORMED HIGH PERFORMANCE PREFORMS FOR FRPC PROFILES

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Abstract
Preforming is still based on manual or semi-automated processes. Therefore, a continuous profile preforming system was developed. Material "from the roll" can be directly utilized to form and fix the desired shape of the profile preforms. A major advantage is the reduction of preforming steps into a single process step. Different profile types e.g. T- to I-profiles can be manufactured. Fixing of the profile shape is realized with two industria stitching machines. Processing speeds up to 6 m/min were achieved. Different variants of material transportation and guidance as well as the influence of the stitch length and ply quantity on the bending stiffness of dry stitched preforms were evaluated. The main question to be addressed in this study is: What is the minimum stitching length in dependence of the textile layers in order to achieve sufficient preform stiffness for a specific aerospace grade woven textile?

1 Introduction

Main industry sectors e.g. aerospace, automotive or wind energy are interested in high-speed, low-cost, and large-volume production for the manufacture of parts made from fiber reinforced polymer composites (FRPCs). Compared to prepreg-autoclave-processes, the RTM process is an adequate manufacturing method to produce high quality FRPC parts with quantities of 20.000 and more p.a.. The idea to combine dry fiber preforms with the RTM process has existed for quite some time. It is an effective method to split up the impregnation and fiber-orientation into two individual manufacturing steps. In this way, e.g. tool-loading times could be decreased significantly [1, 2]. The change of thinking away from prepregs is strongly attributed to the rising cost of prepregs, their cost-intensive storage, and the preparation effort in connection with its manufacturing process (autoclave process) [3, 4].
Nevertheless, high costs and long cycle times still limit the use of FRPC components in serial production due to the time-consuming preforming process [5]. Too many process steps are required to fulfill the preforming effort. Generally, the preforming procedure starts with material cutting, ply orientation and stacking, as well as draping and fixing of the generated preform shape (binder activation or stitching), before the liquid composite molding (LCM) process (e.g. RTM) follows [5]. Existing strategies mainly follow the idea to automate the preforming. In this context, robotic arms are applied to reduce the manual effort and finally save time and costs [6, 7]. One of the latest approaches is the development of a continuous manufacturing method to produce curved FRPC ribs based on prepreg material utilizing the binder technology for the fixing of the preforms [8]. In this case, the processing steps are reduced and a continuous manufacturing method was developed, but processing speeds are still limited to 1 m/min due to the use of the binder technology [8]. Alternative direct

preforming methods are weaving, braiding or knitting [9, 10]. These technologies are less suitable for the mass-market [1] because of the limitations in processing speed and the restrictions in fiber-orientation. Utilizing stitching as fixing technology, both criteria, the continuous manufacturing and high production rates, can be achieved. In the past, the influence of the stitching process was widely examined and has been utilized to improve the mechanical through-thickness properties of a laminate [1, 11, 12] or to influence the permeability behavior of preforms during the RTM process [13, 14].
In order to meet the lack of a fast cost-effective preforming technology based on dry fiber structures, the idea of automatically formed and stitched 2-dimensional "endless" textile preforms arose. Hence, a continuous profile preforming system (CPPS), which offers the potential to reduce time and costs related to common preforming systems was developed (see Figure 7). Stitching technology is used to fix the previously folded shape of the preforms. Processing speeds up to 6 m/min can be achieved and preform thicknesses up to 7 mm are realizable. During the development of the CPPS several investigations were carried out to clarify transportation aspects of textiles and the resultant bending stiffness of the dry profile preforms. The stitching parameters as well as the material characteristics (fiber orientation and number of ply layers) most probably influence the resultant bending stiffness of the profile preforms. According to this criteria, different quantities of material plies were stitched together and coupon level specimens were created which vary the stitch length and the orientation of the plies. The goal was to evaluate an adequate stitching length to achieve sufficient preform stiffness utilizing a specific aerospace grade woven textile. The study showed that the resultant stiffness of the woven textile preforms is strongly influenced by the stitch length of the incorporated stitching seams. A linear stiffening behavior could be observed.

2 Manufacturing concept, material and testing methods

2.1 Concept of profile preform generation

At the IVW, a preforming concept to realize continuously formed and fixed T- / I-profiles has been developed. The preforming system is divided into four main sections: the material supply, the folding, the fixing and the cutting unit. All of the sections are variable and independently movable with respect to each other. To realize the profile preforms with the appreciated stacking sequence sixteen material supply rolls can be utilized for the material feeding. The fiber structures (from the roll) are transported with a conveyor belt through a roller system to the folding unit. The transport support rollers are placed behind the conveyor and at the end of the CPPS as pullers. The material package will be folded, while passing through a five-stage folding unit made of curved sheets, and afterwards guided by transport support sheets across the fixing unit. The fixation of the preform is realized by the use of connected pillar stitching machines. Reaching the end of the system, the "endless" profile preform will be trimmed and cut to the appropriate lengths by a cutting unit.

2.2 Concept review

Initial folding tests showed that two-part preforms (see Figure 1) are more adequate for this process in comparison to one-part preforms. With this design configuration it is possible to avoid unwanted off-set of borders of the individual material layers to each other during the profile generation of the T- or I-preforms. The first part of the preform get as often folded to right as to the left. This procedure enormously reduces the material preparation effort. A five-stage folding unit was developed to fulfil a save guidance of incoming flat material and to fold the appreciated profile shape which can be seen in Figure 1.

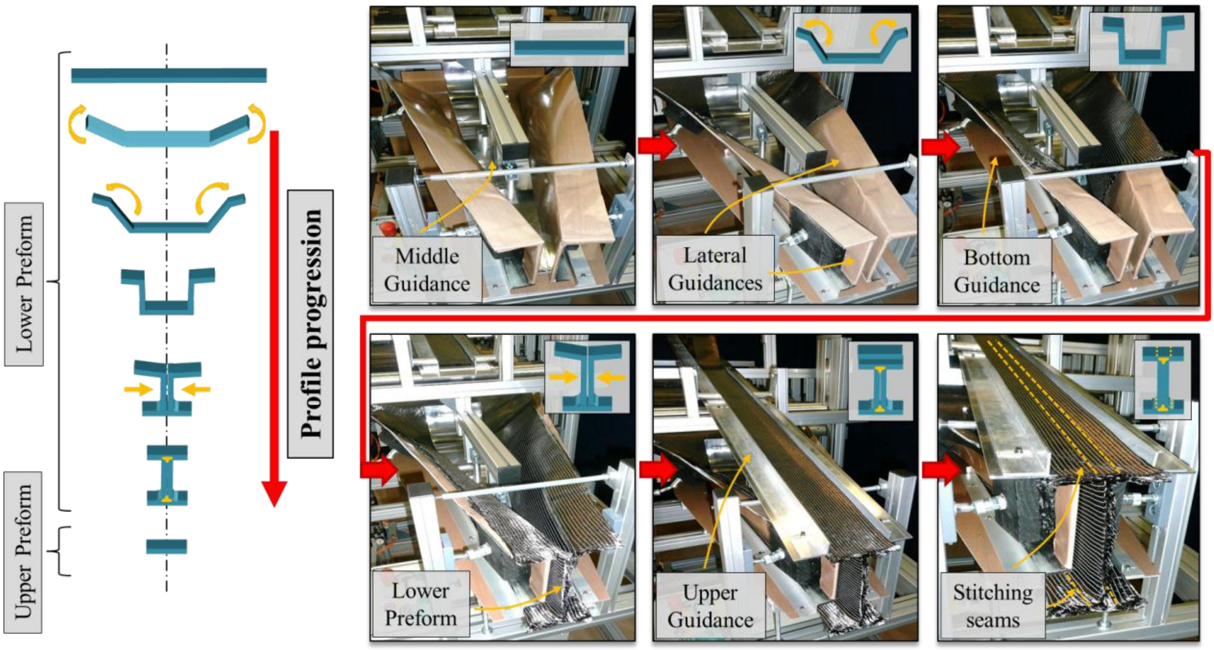

Figure 1. Schematic progression of the material folding process of I-profiles (left); profile generation utilizing the five-stage folding unit (right).

The lower part of the incoming preform material will be continuously guided by the use of the bottom, two lateral and the middle guidance sheets. The upper preform part will be led to the previously folded lower part utilizing a slide as top guidance. Both parts complete the I-profile and can be transferred for final fixing. A prototype of the folding unit was built to prove the concept. As shown in Figure 1, it is possible to fold continuously several plies of material "from the roll" (woven and/or NCF) into the I-profile under low tensile forces. In case of T-profiles, the lower flange will be cancelled by only changing the middle guidance. Processable heights of 150 mm should be achievable for the profile preforms. For this reason, pillar stitching machines were chosen in order to complete the upper stitching seams, placed at the junctions of the flanges and the web (see Figure 1). This machine type offers the possibility to stitch the previously folded preform without bending. Common flat industrial stitching machines are not suitable for this process due to the maximum lifting (needle) restriction of 7 mm. The pre-tests showed that it is possible to stitch the folded woven textile with industrial stitching machines by adding a feeding wheel and roller presser transportation.

2.3 Material and Test methods:

The material used in this research was a standard textile from Hexcel, the G0986. It is a twill 2x2 woven carbon fiber (HTA 5131 6K) fabric with a nominal weight of 300 g/m² containing 2.5 wt.-% epoxy powder on both sides. The textile characteristics are 3.5 yarns/cm, weight distribution is 50 % in the warp and weft directions and the total thickness is 0.29 mm.

Bending stiffness tests referring to DIN 53362 were carried out to determine the basic resistance of single plies of the G0986 against deformation [15]. Therefore, the cantilever test set-up consisting of a horizontal platform with the length of the sample (25 mm * 250 mm) on which the sample was moved horizontally from left to right within 10 s until it passed for the first time the angle of 41.30° was used (see Figure 2). The length of overhang l_o was recorded with a scale, which was placed on top of the sample, and utilzed for Equation 1

$$G = \frac{F_1}{b} * \left(\frac{l_o}{2}\right)^3 \quad (1)$$

where F_1 is the weight force and b is the width of the sample to determine the bending stiffness G [mN*cm] [15]. The fiber orientations of the preform samples are [0°/90°] and [±45°] in testing direction.

In the next step, the preform stability was investigated according to the incorporation of stitching seams. The cutting of the samples was performed in single layers to avoid fiber joints between the layers due to the thermoplastic binder and the cutting edge itself. The stitching was performed with a PFAFF 3574 industrial stitching apparatus fitted with a 120 CL needle for technical textiles. The dry samples 25 mm * 250 mm were stitched with one straight line along the length, positioned in the middle (see Figure 3). The modified lockstitch, which forms the loop at the bottom of the stitched sample instead of its center, was choosen as the stitch type. This arrangement has been investigated in the past and the results showed advantages in terms of packing of the complete lay-up between upper and lower thread, much less restrictions on type of thread and also improvements of mechanical properties e.g. crush energy absorption or compression after impact strength have been demonstrated [11, 16, 17]. The stitching thread was a 224*3 dtex polyester Saba C 50 with a tenacity of 3091 cN from AMANN Ackermann. The alterable stitching parameters varied from 2 mm to 5.5 mm stitch length. The thickness of the preforms varies between 2 to 10 plies. The vertical drop along the length of the stitched samples was chosen to describe the stiffeness of the $[0°/90°]_x$ preforms and the bending stiffness G could be utilized to characterize the $[\pm45°]_x$.

3 Results and discussion

The length of overhang is the key parameter to determine the bending stiffness G of the dry samples. A large difference in the length of overhang could be measured. 18.2 mm for the [0°/90°] samples and 10.2 mm for the [±45°] samples (see Figure 2). Hence, the fiber orientation strongly effects this parameter. Regarding the different types of samples, the fiber lengths of the [0°/90°] samples are 250 mm compared to 35.4 mm of the [±45°] samples.

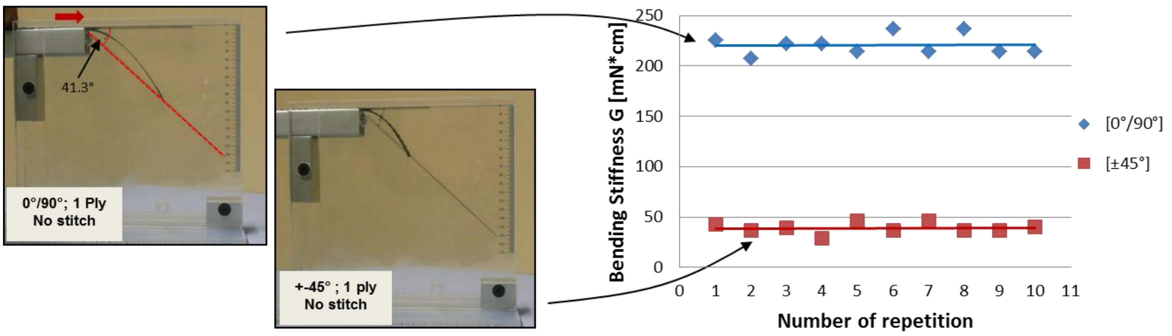

Figure 2: Cantilever test set up to determine bending stiffness G of the G0986 fabric in [0°/90°] and [±45°] fiber orientation (left); overview of determined bending stiffness G of [0°/90°] and [±45°] single plies.

The resultant bending stiffness G of the dry G0986 single layers was 221.5 mN*cm for the [0°/90°] plies and 39.1 mN*cm for the [±45°] plies. Regarding the test series of one sample type, variations in the bending stiffness were observed. This appearance is most probably linked to the presence of the binder on the G0986 surfaces.

Figure 3 displays the stiffening behavior of the dry stitched preforms. A single stitching seam in the middle if the specimen was applied by decreasing the stitch length from 5.5 mm to 2 mm. The stacking sequence was a mix of six [±45°] and four [0°/90°] orientated plies. The vertical drop of the [0°/90°/±45°/0°/90°/±45°/±45°/±45°/±45°/0°/90°/±45°/0°/90°] samples was measurable and utilzed to describe the influence of the stitch length on the stiffening of the preforms.

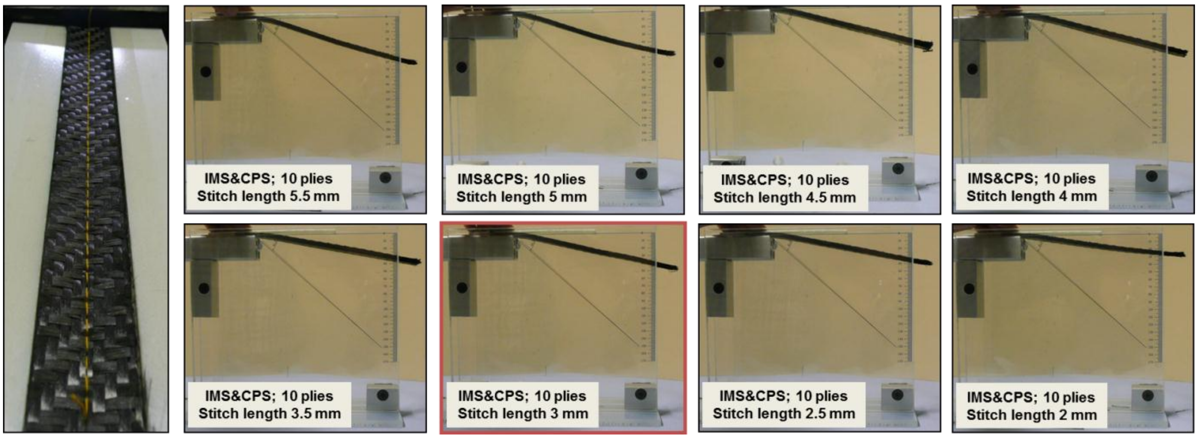

Figure 3: Cantilever test set up to determine the influence of stitch length on preform stability; 10 plies G0986 per sample stitched (stitch length 3 mm) in the middle position along the length of the sample (left); stitch lengths varied between 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5 mm to observe its influence on the stiffness of the [0°/90°/±45°/0°/90°/±45°/±45°/±45°/±45°/0°/90°/±45°/0°/90°] preforms (right).

The vertical drop of the [0°/90°/±45°/0°/90°/±45°/±45°/±45°/±45°/0°/90°/±45°/0°/90°] preforms decreased from 54 mm to 30 mm by reducing the stitch length from 5.5 mm to 2 mm (see Figure 4). Regarding the $[0°/90°]_{10}$ series (10 stitched plies per sample), the general stiffening effect was higher with a minimum drop of 24 mm (2 mm stitch length) compared to the [0°/90°/±45°/0°/90°/±45°/±45°/±45°/±45°/0°/90°/±45°/0°/90°] lay-up. By increasing the stitch length to 5.5 mm the maximum drop amounts to 34 mm, which is stiffer compared to the mixed series. This behavior is related to the ±45° orientated plies, which lower the stiffening intensity due to their lower basic bending stiffness.

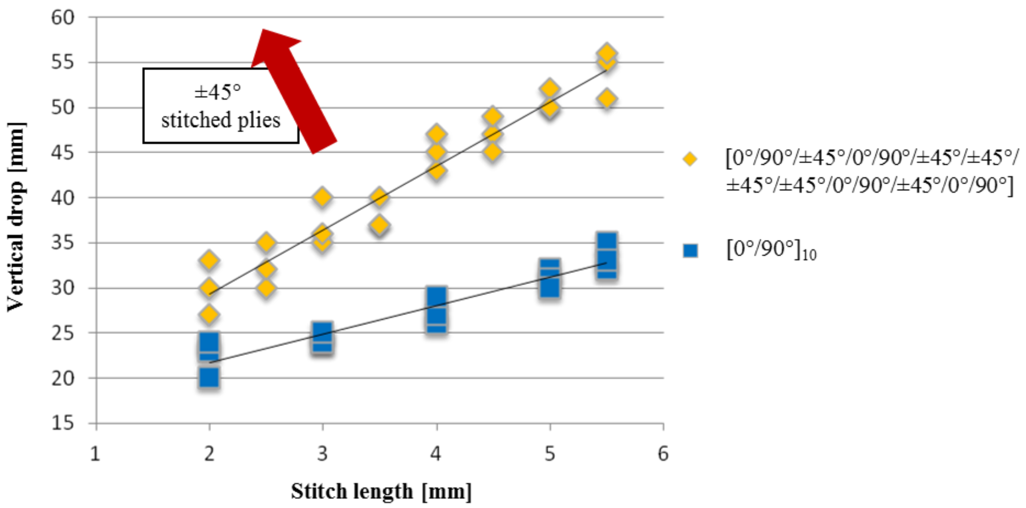

Figure 4. Influence of stitch length on bending behavior of dry preforms; fiber orientation of the samples were $[0°/90°]_{10}$ and [0°/90°/±45°/0°/90°/±45°/±45°/±45°/±45°/0°/90°/±45°/0°/90°]; stitch length varied from 2 to 5.5 mm.

For the $[±45°]_{10}$ samples, the bending stiffness could be determined similar to the tests of the single plies. It was not possible to determine the vertical drop of this series as displayed in Figure 4. The bending stiffness G increased from 70.2 mN*cm (5 mm), over 78.3 mN*cm (4 mm) and 86.6 mN*cm (3 mm), to 92.5 mN*cm utilizing a stitch length of 2 mm. Hence, a controlled reinforcement of the G0986 material could be achieved with a linear correlation to the stitch length. Furthermore, the higher the amount of 0° orientated fibers in stitching direction the higher is the general stiffening effect on the preform.

Also the ply quantity has an remarkable effect on the stability of the preforms. Figure 5 displays a section of the stiffening change of the [±45°] and the [0°/90°] samples. The stitch length of 3 mm was kept constant, while the ply quantity varied from 2 to 10 plies.

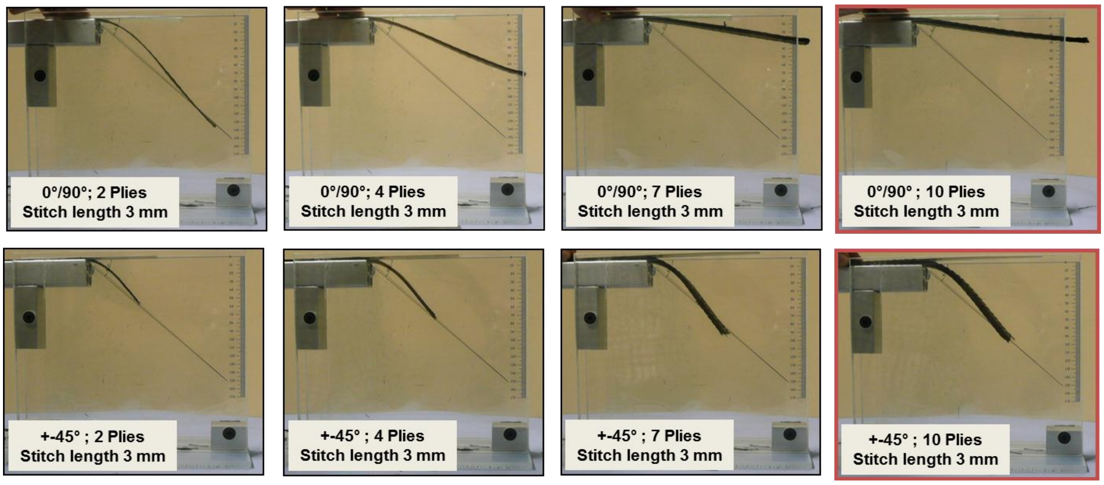

Figure 5. Stiffening change of stitched G0986 samples utilizing a stitch length of 3 mm; $[\pm45°]_x$ and $[0°/90°]_x$ samples were stitched containing different ply quantities x = 2, 4, 7 and 10 (left to right).

The change in the resultant stiffness of the preform can be clearly seen in both cases. The vertical drop of the [0°/90°] samples enormously decreases from 2 to 10 plies as well as the length of overhang of the [±45°] increases. Figure 6 gives a detailed overview of the bending stiffness G of the $[\pm45°]_x$ samples and the vertical drop of the $[0°/90°]_x$ samples in correspondence with different stitch lengths (2, 3, 4, 5 mm) and ply quantities (3-10).

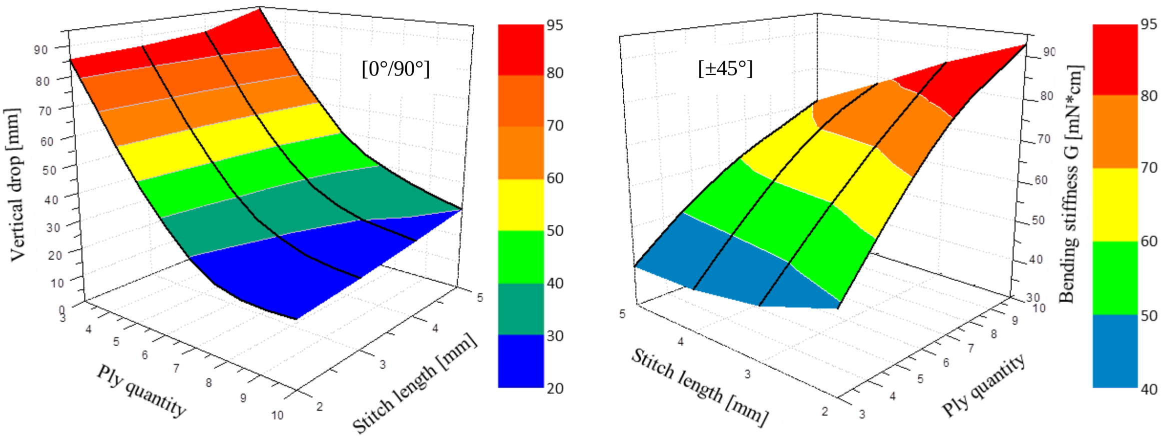

Figure 6: Influence of stitch length (2, 3, 4 and 5 mm) and ply amount (from 3-10) on the vertical drop of the [0°/90°] preforms (left) and bending stiffness G of the [±45°] preforms (right).

The maximum vertical drop of 94.3 mm was measured for the 3 ply and 5mm stitch length samples. The minimum of 22.3 mm could be achieved by the 10 ply and 2mm sample. A correlation between vertical drop (reinforcement) and ply quantity could be established for the [0°/90°] stripes. The minimum bending stiffness G of the [±45°] samples show 40.2 mN*cm (3 plies, 5 mm stitch length) and the maximum of 92.5 mN*cm could be observed by 10 plies utilizing 2 mm as stitch length. The stiffening effect on all types of preforms could be further increased by decreasing the stitch length. For all series of the same stitch length (black lines Figure 6) the stiffening effect due to the increasing ply amount from 3 to 7 plies is more pronounced compared to 7 to 10.

4 Case of Application: Continuous Profile Preforming System (CPPS)

The CPPS was build up according to the previously modeled design specifications. As mentioned before it is divided into four sections: material conveyor, folding, stitching and cutting unit (see Figure 7).

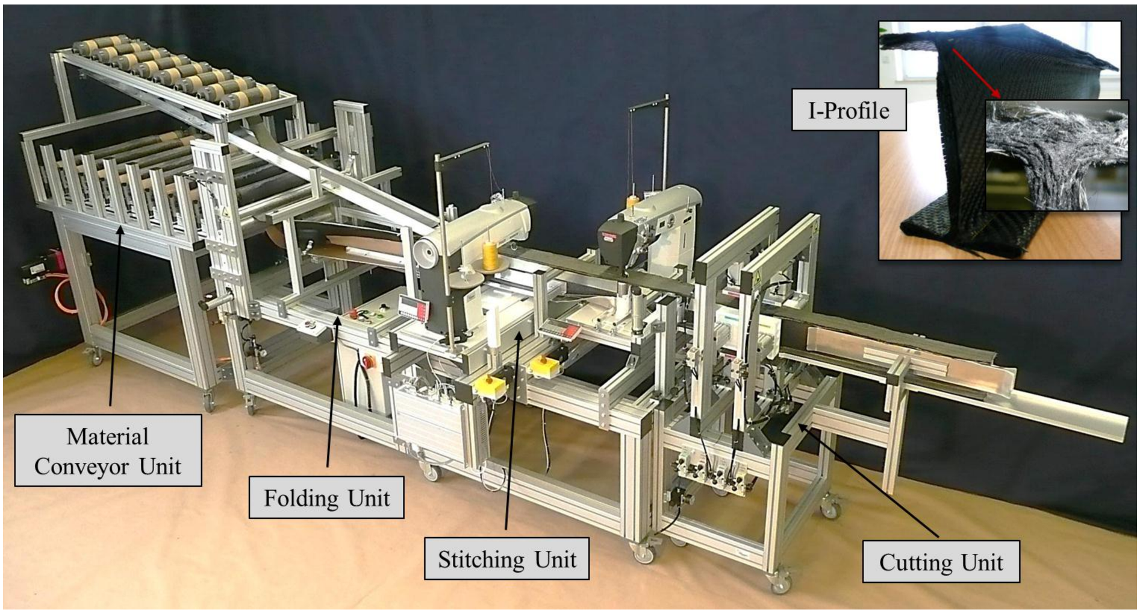

Figure 7. Continuous Profile Preforming System (CPPS) containing material conveyor, folding, stitching and cutting unit; I-profile preform manufactured by the CPPS (upper right image).

The dimension of the CPPS is 5600 mm * 1500 mm * 1900 mm. Two PFAFF 2571-810/011 ME PREMIUM pillar stitching machines are fitted to realize the fixing of the profile preforms. 3500 stitches/min are possible to achieve a theoretical production rate of 10 m/min. A LabView master program was programmed to connect the basic signals from the multiphase motors of the pillar stitching machines as point of reference with the conveyor belt and the two pullers. The cutting unit and the transportation rollers are controlled by a pneumatic system. The clamping jaws, to fix the dry preform all-around, are self-built as well as material transport support sheets of the entire system.
T-profiles can be manufactured in one pass (single step). For the I-profiles, four stitching machines are required to fulfil the preforming in one single step. Therefore, after the material has passed for the first time the two stitching machines and the upper fixing seams are completed, the preform will be cut into the desired length, turned, and guided a second time through the stitching machines to realize the stitching seams of the second flange.

5 Conclusions

A continuous profile preforming system was developed and built to ensure a fast and cost-effective preforming based on the stitching technology. The study showed that the resultant stiffness of the woven textile preforms (coupon level) is strongly influenced by the stitch length of the incorporated stitching seams. A linear stiffening behavior could be observed. Also higher ply quantities results in higher stiffness. For the purpose of the CPPS a stitch length of 3 mm was chosen due to the sufficient basic stiffening effect on the preform.

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