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Dry fiber automated placement of carbon fibrous preforms

M. Belhaj ^{a,b}, M. Deleglise ^{a,b,*}, S. Comas-Cardona ^{a,b,c}, H. Demouveau ^{a,b}, C. Binetruy ^{a,b,c}, C. Duval ^d,
P. Figueiredo ^e

^aMines Douai, Department of Polymers and Composites Technology and Mechanical Engineering, 941 rue Charles Bourseul, CS 10838, F-59508 Douai, France

^bUniv. Lille Nord de France, Lille F-59000, France

^cEcole Centrale de Nantes, GeM, 1 rue de la Noë, BP 92101, 44321 Nantes Cedex 3, France

^dEADS Innovation Works, 12 rue Pasteur, BP 76, 92152 Suresnes, France

^eAerolia Etablissement de Méaulte, BP 70210, 80302 Meaulte, France

The superior material properties of carbon fiber-reinforced composites make them especially attractive for applications in aeronautics and aerospace industries. Cost reduction and time saving are continuously driving industry, leading to new industrial challenges which include manufacturing composite structures with optimal mechanical performances using the potential of advanced processes using robotics.

To produce complex part shapes, technologies implying fabric draping in a mold imply large waste amount, fabric structure variability and uncertainties concerning local fiber volume fraction amount and thus final mechanical properties. To overcome such issues and comply with cost and time efficiency, automated dry fiber placement for preform manufacturing is proposed. This approach allows to integrate many functions in a complex part thank to the ability of the robot to steer fiber tows at specific locations. The final composite part is obtained by injecting the produced preform with resin using RTM (Resin Transfer Molding) or infusion process.

The presented project aims to define the influence of the process driving parameters during fiber placement on the final preform properties range. Preforms were produced using a lab-scale automated placement demonstrator. Three preforms configurations were tested to highlight the influence of the preform structure on permeability and mechanical parameters through characterization of the compression behavior and permeability of the produced preforms. Choice of configuration will affect mechanical properties on the manufactured preforms, whereas creation of open channels to enhance the flow propagation during manufacturing does not necessarily increase the preform permeability.

1. Introduction

Composite manufacturing in the aerospace industry generally implies the use of prepregs and autoclave process [1] or infusion of non crimped fabrics, which are both semi products. In order to reduce cost, and to control the final mechanical characteristics, technologies are developed to produce preform ready to be infused, such as 3D woven structure, 3D braids or fiber placement, the main advantage being to realize a 3D structure directly from a 1D product, the row carbon fiber. Higher performance could then be reached, taking the solicitations of the final part to design the preform, without being constrained by the available 2D architecture of fiber mats.

As fiber placement, filament winding is a fabrication technique that produces components by continuous fiber (filament) application to a rotating mandrel in a geometric pattern [2]. The mandrel can be of any shape that has a body of revolution. This method can produce very large shapes, provided that the curvature is everywhere positive. It is an ideal technique to form the desired lightweight, high strength pressure vessels. Synchronized with the mandrel rotation, the head translation regulation allows controlling the angle of the winded fiber with respect to the mandrel axis, so that helical plies that are optimized to handle expected load could be laid down. However, filament winding cannot be used to produce concave surfaces since the tension in the fibers will cause them to simply bridge the concave region [3]. Robotic fiber placement is an extension of the filament winding technique. The use of a fiber-processing head in conjunction with a robot manipulator to manufacture composite parts using pre-impregnated fiber tows, which are fiber strips impregnated with a controlled amount of thermoset or thermoplastic resin, and then partially cured to give them tack quality. Robotic fiber placement offers

* Corresponding author at: Mines Douai, Department of Polymers and Composites Technology and Mechanical Engineering, 941 rue Charles Bourseul, CS 10838, F-59508 Douai, France. Tel.: +33 327712176; fax: +33 327712981.

E-mail address: mylene.deleglise@mines-douai.fr (M. Deleglise).

many important features and advantages that are not achieved with traditional fabrication techniques [4–6].

Pre-impregnated fibers, Thermoplastic powdered fiber or dry fiber placement are in parallel development [7] and consist in placing a fiber tow directly or after a premium treatment on a mold to create a preform. Those technologies allow exploiting the anisotropy of composites. This challenge needs to orientate the continuous fiber in multiple directions to give desired strengths. Dry fiber placement also requires the use of a tackifier agent between the fiber layers, although the quantity used can be reduced to a minimum as long as the preform shape can be maintained prior to injection. The challenge proposed here is to develop an instrumented dry fiber placement tool that could monitor the fiber placement process and to determine useful criteria that could help decide of the validity of a preform or not for manufacturing and/or for mechanical performance of the final composite. Similar investigations are conducted to develop a visual control of fiber placement during manufacturing of 2D fiber-reinforced polymer structures, using a camera and a laser light section sensor to track inclusion and fiber displacement or misplacement [8,9]. This system has the advantage of being a precise way for on-line surface quality control of the preform, but requires either to install devices in the placement head environment or a second step in the part manufacturing dedicated to inspection. On another hand, this technique may not be applicable for structures of several layers that show little contrast, or complex parts that show zones that cannot be lighted properly. It is also a local inspection, as the effect of the default observed in one ply cannot be evaluated at the preform level.

The work presented here aims towards the understanding of the placement mechanisms during dry fiber placement. In order to do so, the influence of different preform patterns (or final architecture of the microstructure) on macroscopic properties of the final preform part in terms of permeability or mechanical characteristics is studied. According to the pattern followed, (gaps or overlapping of fibers tows) the final reachable thickness or fiber volume fraction can differ. On the other hand, the preform permeability is also a parameter of importance as it directs the processability of the preform during the injection process. Excess of fibers should enhance mechanical properties while decreasing the permeability (thus the processability) of the preform.

On another hand, the mechanical history of the first deposited ply may differ from the last one, as the first ply will be compressed several times while the last one will be compressed only once.

The obtained preform may be non homogeneous through the thickness direction, as fibrous preforms show a viscoelastic behavior [10,11].

2. Fiber placement device

As part of the overall objective, this approach proposes a new technology for manufacturing preforms for structural composites by automated dry fiber placement. An automated dry fiber placement device for preform manufacturing is proposed (Fig. 2). The features include cutting and restarting of the fiber tows, debulking and consolidation of the material in situ, precise control of fiber placement angles when required for a high degree of repeatability.

This approach allows integrating many functions in a complex part thanks to the ability of the robot to place fiber tows at specific locations. Furthermore, the use of a robot manipulator increases the flexibility of the fiber placement process.

Fig. 1 shows the set-up of the lab-scale automated placement demonstrator fiber placement system. An automatized head is gripped onto a six axes robot arm. In addition a 7th external axe drives a rotating table. The four dry carbon fibers coil are stored

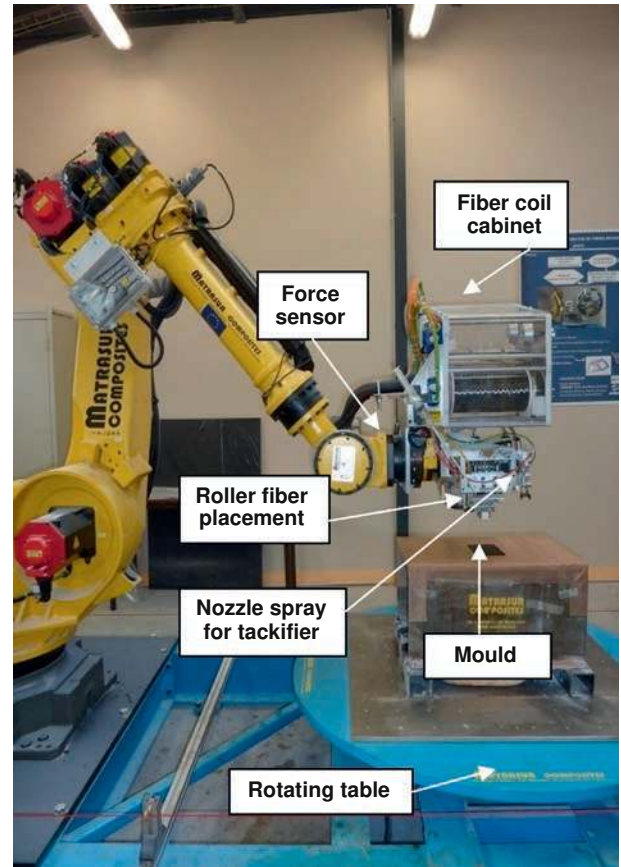


Fig. 1. Experimental robotic dry fiber placement system.

in a fiber coil cabinet. The cabinet is a closed chamber that protects from dust and humidity variation. The dry tows are fed through a series of guiding system and tensioners before entering below the fiber placement roller that lays and presses the tows on the mold. The tows are cut and engaged under the placement roller automatically when required. Furthermore, a nozzle sprays an adhesive solution between layers to give them cohesion. The programming methods of the robot use off-line analytic method. An external software calculates theoretical coordinates of points to reach, to respect specifics distances between the tows, cutting and advancement of the fibers. Only the origin position has to be taught manually. A specific internal on-line program calculates the other positions to generate trajectories with respect to the placement scheme. Each layer is oriented in different directions according to the defined stacking sequence. Spacing between the fiber tows is also taken into account by the software.

A force sensor is positioned between the 6th axis of the robot arm and the fiber processing head to control layers compaction force during manufacturing process. The roller is mounted on an actuator to provide compliance on the vertical axis. Constant compaction pressure or constant azimuthal position of the robot arm can thus be applied during fiber placement.

A minimum pressure is to be applied to insure adhesion of the fiber tow on the substrate. Below this pressure, the fiber tow glides but does not stick.

3. Preforms description

The first step pursued in this development is to obtain preforms with different types of pattern in terms of fiber tow spacing, number of layer and orientation of each layer being the same for the

different produced preforms. The preforms will be plane plates of $200 \times 300 \text{ mm}^2$ according to the placement table capacity and will thus be composed of 8 plies which stacking sequence is defined as $[90,45,0,-45]_s$ to obtain a quasi ISO structure representative of the aeronautics structures generally followed and to obtain a thickness of at least 2 mm to comply with standard requirements. A 12 K high resistance carbon fiber tow is used.

The research program focuses on three patterns with different morphologies representing configurations that could be observed on industrially manufactured preform, implying local displacement of a fiber tow, either overlapping the neighboring tow or creating a gap. The maximum displacement observed is in the order of 2 mm. The studied morphologies are shown in Fig. 2. The nominal preform is manufactured with no spacing between the fibers. The robot will then translate of the width of the dry fiber tow as defined by the guiding system. An overlap pattern will reduce this displacement of 2 mm every five placed fiber tows. On the contrary, an opened pattern will include a spacing of 2 mm every five fiber tows. Change in fiber volume fraction and thus on the mechanical behavior of the preform under compaction is expected [10,12,13]. Characterizations of the preforms are conducted under static and cycled compressive tests. Preforms permeability are also studied.

4. Mechanical behavior of the fibrous preform

The objective is to compare the mechanical compaction response of each preform pattern. In a first step, maximum fiber volume fraction that could be reached on each preform type is determined and then mechanical tests are conducted [7] Each test is conducted on a Zwick compression test unit, mounted with two flat platens.

The load applied on each preform type and the fiber volume fraction derived from the preform thickness is monitored during the loading phase, as presented in Fig. 3. The preforms are loaded at a compression speed of 0.5 mm/min until reaching 90 kN. For a given load, the fiber volume fraction is lower for the samples with an opened pattern (65%) and higher for the samples presenting an overlapping pattern (72%), the nominal pattern having a fiber volume fraction of 69%. On the contrary, the minimum thickness that can be reached with the overlapping sample (1.22 mm) is higher than the one with the open pattern (1.10 mm). The generated preform are thus very different from one another, which shows that to manufacture a preform using fiber placement, the definition of the placement pattern is a compromise between the composite desired final thickness and final fiber volume fraction.

Eight successive compressive loading and unloading cycles were performed on $60 \times 60 \text{ mm}^2$ overlapping, opened and nominal samples. The number of cycles correspond to the number of solicitations the first places ply would see during the considered manufacturing process. In order to reduce viscoelastic effects, tests were conducted at a low speed during loading and unloading

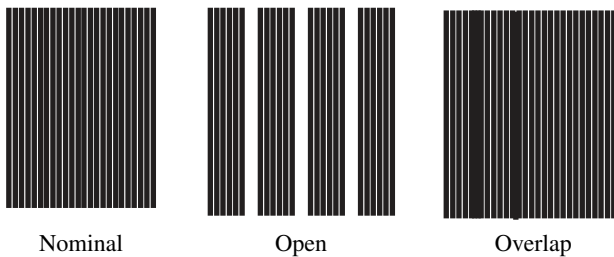


Fig. 2. Produced preforms patterns.

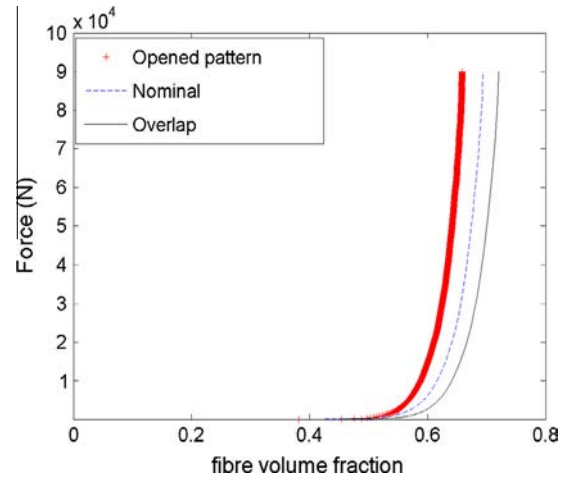


Fig. 3. Fiber volume fraction evolution versus compression load for nominal, overlapping and opened pattern samples.

stages (0.5 mm/min) [11]. The compression load was defined according to the manufacturing device use and derived from the contact surface with the fiber preform and the applied load during manufacturing. The testing load is thus set to 19,850 N. The test then represents the load applied on the actual preform during laying-up of future plies. The studied mechanical characteristics are the plastic deformation ε_p representing the overall plasticity developing during the successive cycles [10], and for each cycle, the total $\varepsilon_{t-cycle}$, plastic $\varepsilon_{p-cycle}$ and elastic $\varepsilon_{e-cycle}$ deformation respectively expressed as:

$$\varepsilon_{p-cycle} = \frac{h_i - h_{i+1}}{h_i} \quad (1)$$

$$\varepsilon_p = \frac{h_0 - h_i}{h_0} \quad (2)$$

$$\varepsilon_{t-cycle} = \frac{h_i - H_i}{h_i} \quad (3)$$

$$\varepsilon_{e-cycle} = \varepsilon_{t-cycle} - \varepsilon_{p-cycle} \quad (4)$$

with h_0 the sample initial thickness, h_i the preform thickness unloaded down to 10 N at each compression cycle and H_i the preform thickness loaded to 19,850 N, i being an integer referring to the cycle and being comprised between 0 and 7. Results are shown in Fig. 4.

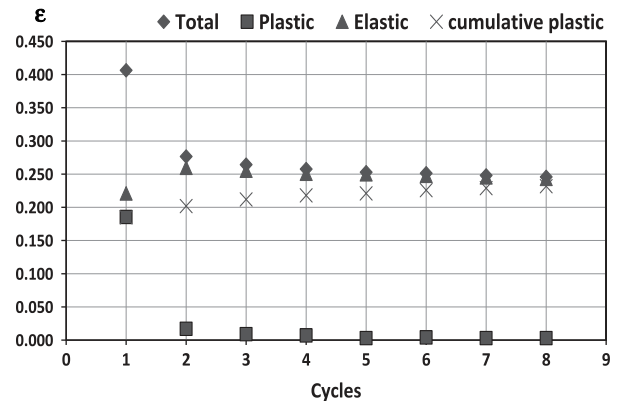


Fig. 4. Deformation evolutions for nominal samples developed at each loading/unloading cycle.

During loading and unloading cycles, plastic deformation $\varepsilon_{p-cycle}$ is almost fully generated during the first loading cycle. Then in the following cycles, the plasticity developed per cycle remains small. Successive loading cycles stabilize fiber architecture and after the fifth cycle, the preform thickness will thus remain unchanged. The same conclusions were drawn from characterization conducted on samples with the open and overlap pattern. The cycled compressive tests showed that most of the plasticity is stored in the last placed layer.

5. Influence of patterns on plasticity evolution

Comparison between obtained levels of plasticity of the different samples was conducted. According to Fig. 5, opened preforms exhibit a higher plastic deformation, due to the gap left between fibers. Fiber arrangement thus occurs at each compression cycle, leading to a higher plasticity of the preform.

The two other preforms, nominal and with overlaps, present a similar plastic deformation even if the plasticity developed on the preform with overlaps is slightly higher (7% more) than the nominal preform. New fiber arrangements are expected for the preforms with an open pattern, as fibers have more room to slide. If we consider that the first plies laid on the mold were already loaded and loaded several times during the fiber placement process, the 7% plasticity difference between the different tested architecture is non negligible. This difference is actually generated during the first loading cycle, the plasticity generated during the following loading and unloading cycle being the same for the three tested preforms. Compressive property of a preform manufactured using dry fiber placement can thus evolve in the thickness direction. The first placed plies are more compacted than the last ones, however the density variation is very low as most of the plastic deformation is generated after one compressive cycle, meaning after the next roller passing. Plasticity developed during compression of the fiber bed is thus directly linked to the fiber volume fraction of the considered preform. Overlapping pattern which induces a higher fiber volume fraction will present a compacted architecture that does not allow numerous fiber movements during loading. On the contrary, a lower fiber volume fraction, such as for the open pattern sample, leaves relative freedom of displacement and re-organization of the fibers that may slide to fill the areas with lower fiber density. After re-arrangement of the fibers, fiber movements are more and more limited, inducing a reduced plasticity during the other loadings. Those results are encouraging for the on-line control of fiber placement by monitoring the mechanical behavior of the preform under local compression. Gaps between fi-

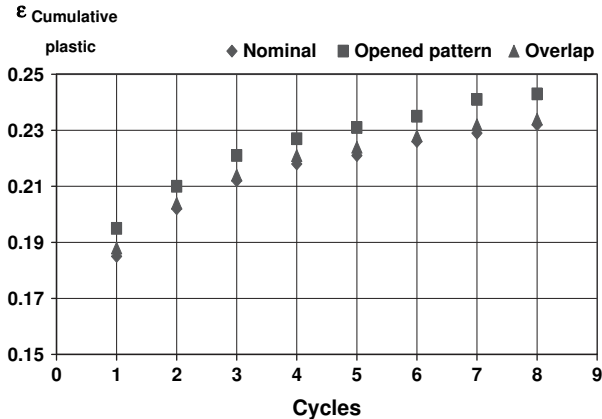


Fig. 5. Plastic deformation of nominal, opened and overlapping pattern preforms with respect to the loading cycle number.

ber tows overlapping can be detected through the plasticity development, as shown in Fig. 5, as the plasticity for the opened pattern preform is more important than the two others preform types. Opened pattern on the other hand would be detected through the shifting of the compaction curve towards higher fiber volume fractions, as presented in Fig. 3. Change in the preform compaction response could attest for the presence of a different pattern or a placement problem. It would then be possible to define the process tolerance with respect to the future use and associated performance of the final composite part to be produced.

6. Preforms permeability

Permeability of a preform describes the capability of a porous or fibrous material to let a fluid flows through it. The permeability test consists in generating a stationary unidirectional flow in a plane rectangular mold. Fluid is injected at a constant pressure and flow rate is measured when the stationary flow is established. Permeability of the preform is then calculated using Darcy's law expressed for a 1D flow, knowing the fluid viscosity:

$$\frac{Q}{A} = -\frac{K \Delta P}{\mu L} \quad (5)$$

where Q is the measured flow rate, A the cross sectional area, ΔP the pressure difference applied, L the preform length and K is the preform permeability.

Preforms permeability was characterized for a given fiber volume fraction and under infusion condition (under a 0.9 bar vacuum pressure) on preforms 100 mm wide and 150 mm long for each preform pattern. Pressure sensors to determine with precision the pressure drop are placed at the mold inlet and outlet. Flow rate is defined by measuring the weight of fluid coming out of the mold with time. Experiments were conducted using water. In order to check the validity of Darcy's law under those conditions, Reynolds number was determined:

$$Re = \frac{\rho v d}{\mu} \quad (6)$$

where ρ is water density, d the distance between fibers evaluated to be 8 μm , μ water viscosity around 1×10^{-3} Pa s, and v is the fluid interstitial velocity evaluated to be 6.6×10^{-4} m s^{-1} during the permeability test. Following those assumptions, Reynolds number is calculated to be 5.3×10^{-3} , so much lower than 1, justifying the use of Darcy's law.

The experiments parameters and the main results are expressed for the different studied preforms in Table 1. Nominal and open pattern preforms have similar permeability values for a given fiber volume fraction. However, the overlap preform shows lower permeability values. The channels generated during fiber placement of the open pattern preform do not help the fluid flow through the preform. The only channels that help the fluid flow are the one oriented directly in the flow direction. As the preform stacking sequence [0,90,+45,-45]₈ on eight plies only generate two plies with those kind of channels, associated with the fact that fibers can slide and fill partly the generated channels during compaction of the preform during closing of the mold, no significant improvement can be obtained regarding the permeability value. The overlap pattern preform presents a more homogeneous architecture generating high resistance to flow in the eight plies constituting the preform. The obtained permeability is thus higher than for the other preforms, but are consistent with values obtained on multidirectional preforms.

Table 1
Perform characteristics and corresponding permeability.

	Nominal preform		With open pattern		With overlap pattern	
	$V_f = 54\%$	Under vacuum	$V_f = 54\%$	Under vacuum	$V_f = 54\%$	Under vacuum
Thickness (mm)	1.5	1.8	1.4	1.7	1.6	1.9
Permeability K (m^2)	1.44×10^{-12}	5.15×10^{-12}	1.49×10^{-12}	5.21×10^{-12}	1.06×10^{-12}	3.15×10^{-12}
Fiber volume fraction V_f (%)	54	45	54	44	54	46.5

7. Conclusion

The mechanical study that is presented here is encouraging for the development of a fiber placement tool with on-line control based on mechanical parameter. The contact device that applies the carbon fibers to the preform mold can act as an instrumented platen of a compression test setup. The three tested preforms (nominal, overlapping and opened patterns) exhibit three different mechanical responses, especially in term of plasticity; the three different patterns thus have different mechanical signatures. As the placement device developed is equipped with a pressure sensor and that the main loading applied on the substrate during placement is transverse compression, the compaction tests presented here could be integrated in the placement software for control of the gaps left between fiber tows, and indirectly on the final fiber volume fraction or thickness of the preform. The mechanical signature of each preform type could then be compared to a mechanical response during placement to identify the placement quality.

The acceptance of a defect can also be evaluated: the new laid down fibers on the substrate might compensate the defect, the preform quality could then be acceptable, whereas optical inspection cannot monitor the entire history of placement, making the decision to discard a preform more difficult. The permeability test conducted showed that it is not possible to differentiate preforms, as the expected benefits of open channels introduced in the preform cannot be obtained.

In a future step, a protocol to be conducted for on-line characterization of the preform will be established, including the possible control actions that need to be determined. The governing parameters seem to be the plasticity coefficient as well as the maximum reached fiber volume fraction. The definition of an accurate model would require an extensive experimental program, involving study of different placement pattern and different fiber grade, sizing and yarn size. The placement process could also be optimized in terms of definition of the yarn path according to the part final solicitation, the fiber placement process being a mean to reinforce a structure in a precised area.

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References

- [1] Loos AC, Sturges RH, Viehland D. Non-autoclave processing and manufacturing of large reusable aerospace structures. Research Proposal for NCAM Louisiana Partnership University of New Orleans Research Technology Foundation; 2001.
- [2] Carrino L, Polini W, Sorrentino L. Method to evaluate winding trajectories in robotized filament winding. *J Compos Mater* 2004;38(1):41–56.
- [3] Wei-Ching S, Susan CM, Kim AS. Modeling and control of the in situ thermoplastic composite tape-laying process. *J Dynamique Syst Meas Contr* 1998;120:507–15.
- [4] Rudd CD, Turner MR, Long AC, Middleton V. Tow placement studies for liquid composite moulding. *Compos A Appl Sci Manuf* 1999;30:1105–21.
- [5] Ahrens M, Vishal M, Parfrey K. Robot-based thermoplastic fiber placement process. *Ind Robot* 1998;25(5):326–30.
- [6] Zehnder N, Ermanni P. Optimizing the shape and placement of patches of reinforcement fibers. *Compos Struct* 2007;77:1–9.
- [7] Shirinzadeh B, Alici G, Foong CW, Cassidy G. Fabrication process of open surfaces by robotic fiber placement. *Robotics and computer-integrated manufacturing*, Monash University 2004;20:17–28.
- [8] Miene A, Göttinger M. Digital image analysis for quality assurance in the preforming and draping process. In: CFK valley stade convention, June 13–14, Stade, Germany; 2007.
- [9] Miene A, Hermann AS, Göttinger M. Quality assurance by digital image analysis for the preforming and draping process of dry carbon fiber material. In: SAMPE Europe conference, April 1–3, Paris, France; 2008.
- [10] Comas-Cardona S, Le Grogneq P, Binetruy C, Krawczak P. Unidirectional compression of fiber reinforcements. Part 1: A non-linear elastic-plastic behavior. *Compos Sci Technol* 2007;67(3–4):507–14.
- [11] Bickerton S, Buntain MJ, Somashekar AA. The viscoelastic compression behavior of liquid composite molding preforms. *Compos A Appl Sci Manuf* 2003;34(5):431–44.
- [12] Vinçon I, Allix O, Sigety P, Auvray MH. Compressive performance. *Compos Sci Technol* 1998;58:1649–58.
- [13] Saunders RA, Lekakou C, Bader MG. Compression in the processing of polymer composites. A mechanical and microstructural study for different glass fabrics and resins. *Compos Technol* 1999;59:983–93.