FACTORS OF PROCESS ROBUSTNESS IN MULTILAYER PREFORMING OF CARBON FIBRE REINFORCEMENTS

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Abstract
Draping of complex geometries with textile reinforcements can lead to forming defects. While wrinkling has been a broadly studied object of research, the emergence of in-plane defects can be regarded as an interaction of the fabric's structural integrity, process conditions and the forming geometry. These influencing factors are characterized by conducting friction evaluations, pull-out tests and thickening analysis of the reinforcement, respectively. A basis for the simulative implementation of a forming failure criterion is hereby given.

1. Introduction

Until the year 2025 between 65-90 million cars will be produced annually [1]. By then, over 2 billion cars will be on global roads leading to significant emissions if no adequate measures are taken. Reducing the weight of automobiles by utilizing high performance materials such carbon-reinforced composites will result in lower emissions. A broader application of carbon reinforced materials is hindered by the high costs of raw materials and the challenging automated production of complex automotive geometries.

Unlike aerospace structures automotive parts are small sectioned, usually double curved due to stringent design and packaging requirements and characterized by small radii and sharp edges. These factors limit the application of fast and cheap press-forming operations for the manufacturing of *preforms* in the Resin-Transfer Moulding (RTM) process, in which the dry fabric is formed first and subsequently infiltrated by the liquid resin.

The geometrical complexity not only limits the load carrying capabilities of the composite material from a structural perspective, but also leads to higher risks of forming failures during preforming, which further decrease the mechanical performance of the material and implicate difficulties for following infiltration processes.

2. State-of-the-art

To counteract the higher complexity different measures are taken to allow the application of mould forming processes. Numerous material characterisation tests, draping experiments and simulative models were developed [2] to describe the forming behaviour of various reinforcements. Forming manipulation by means of rollers [3], springs [4], draw beads or blank holders [5-7] have been developed for dry and preimpregnated fabrics. These measures are all characterised by initiation of tensile forces on the outer boundaries. Local binder application [8] and stitching [9] have been investigated to extend the known influence of the textile architecture [10] on the forming behaviour. Weave patterns can also be varied locally [11] to adjust the forming behaviour to the geometry.

Besides the limited formability of single plies failures can also result from interactions of the plies during forming, when the fabrics are in contact with each other or with the tool. Due to the inhomogeneous structure, friction will occur on the micro level (between filaments and between tows [12]) and on the macro level (between the adjacent plies) both leading to defects. The coupling of these scales has been investigated in detail by Cornelissen et al. [13]. The influence of the meso structure of woven fabrics was examined by Allaoui [14] and it was found that the fabric's architecture is reflected in the friction response and that shocks occur from yarn-yarn contacts.

Vanclooster [15] derived forming limit diagrams for multilayer thermoplastic composites and concluded that the amount of interlayer softened matrix dominates the onset of wrinkling and that relative orientation of woven plies dominates the size of wrinkles. Nevertheless, the transfer of these findings to dry fabric is limited, since the matrix acts as a lubricant during forming of thermoplastic sheets. Allaoui et al. [7] formed two layers of a dry carbon fabric and stated that forming failures occured in the same areas as in single ply forming. However, the extent of affected areas increased. Frictional shocks are believed to be the basis for the failure mechanisms. In [5, 6] in-plane forming failures are reported to occur on a hemisphere geometry, when two plies of woven fabrics were formed with blank holders to suppress wrinkles. Fibre distortions were more intensive with increasing relative orientation of plies and were occurring only in the unsheared regions, when the fabric was formed in the cold state. Divergent local forming mechanisms and relative displacements were stated as reasons for the damage.

3. Objectives of Research

Due to the changing configuration of the fabric throughout forming and the numerous possible constellations of fabric stacking, this paper aims at extending the understanding of damage propagation in composite forming from a small scale. A systematic approach is presented to deepen the comprehension of textile and process-induced factors. Experiments are carried out to assess the influence of different factors.

4. Experimental Method

4.1. Material specification

Areal weight	329.3 g/mm²	± 1.9 g/mm²
Tow width weft	4.94 mm	± 0.18 mm
Initial tow spacing weft	0 mm	
Tow width warp	4.11 mm	± 0.02 mm
Initial tow spacing warp	0.78 mm	± 0.18 mm

Table 1. Specifications of Hexcel T700-12K plain woven fabric

A plain weave T700-12K carbon fibre fabric provided by Hexcel was used for the experiments. The fabric was examined by microscopy and the results of visual measurements are given in Table 1. The fabric is not fully balanced as it can be seen from the different roving widths and spacings in both axes of the fabric. The material is the same as reported in [5, 6] to allow comparison of the results.

4.2. Systematisation and approach

Three factors describe textile forming operations:

- Forming *geometry* (curvature, radii, edges, size …),
- *Reinforcement* characteristics (materials, architecture, lay-up, binder …), and
- *Process-induced parameters* (blank holder forces, tooling).

This systematic is shown in Figure 1. Some of the factors can have interactions, for example depending on the given forming geometry and the stacking sequence of the reinforcements relative displacement can occur because of different local forming modes, while this displacement can be manipulated to some extend by segmented blank holders as well [5, 6].

In general in-plane damage will occur when the fabrics structural integrity is lower than the acting local forces on the fabric. While the integrity might change because of shearing and the initiated membrane tensions, the counteracting forces on the fabric's surface are dependent on the friction coefficient of the respective constellation, the acting normal forces and geometrical factors from the tooling's geometry and/or the opposing fabrics topology.

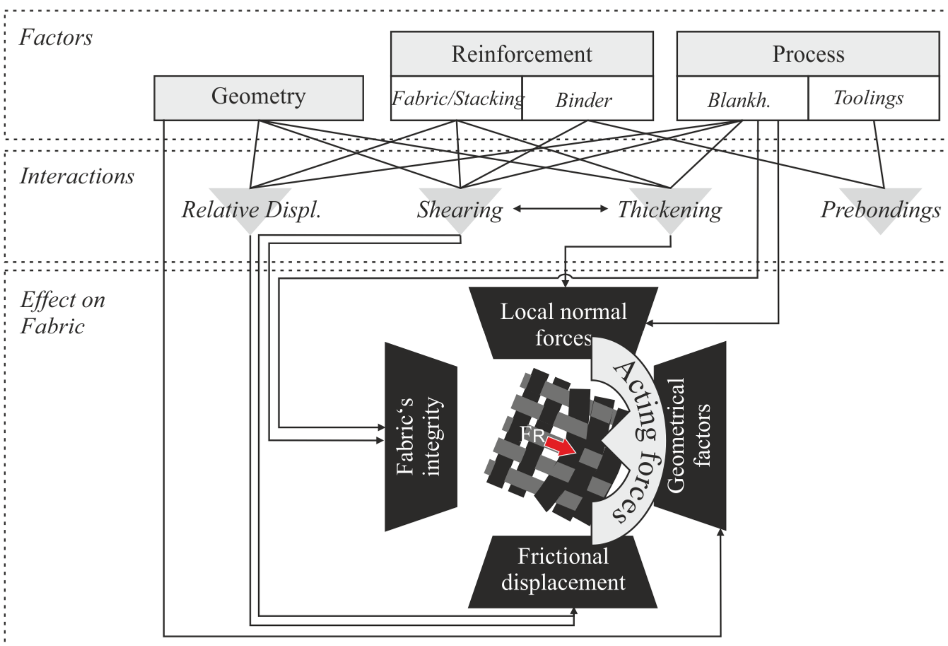

Figure 1. Factors leading to interaction based in-plane damage of fabrics

The fabrics changing integrity and the ability to withstand the acting forces is characterized here by fibre pull-out tests under shearing with different amplitudes of membrane tension. This set-up represents the initiated tensions by blank holders in industrial processes.

Evaluation of friction coefficients under four relative orientations (0°, 22.5°, 45°, 67.5°) and between an unsheared ply and a sheared ply with four shear angles (0°, 15°, 30°, 45°) were carried out to evaluate both the effect of material stacking and the change of the fabric's constellation throughout forming on the friction interaction of opposing plies. Geometrical factors are left to be investigated in future works.

4.3. Characterisation tools

To characterise the interactions a novel set-up was designed (Figure 2). The testing bed is framed by needle rows to place the fabric samples after preparation without misalignments of the fibres and to fix the sheared fabrics under the given orientation.

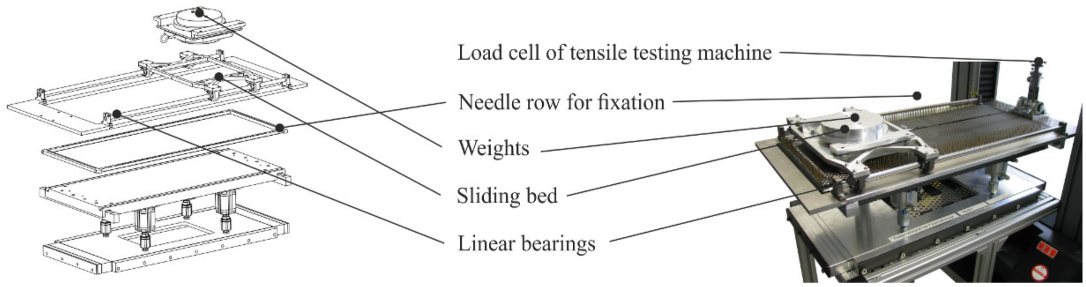

Figure 2. Characterization set-up for friction evaluation

As the measured forces for fibre pull-out tests are influenced by the boundary conditions it was decided to use a picture frame tester with controllable membrane tensions and adjustable shear angle [5, 6] as a test fixture. The rovings were pulled out in the normal direction. The pulled roving was left in an overlength condition, such that the contact area did not change throughout testing (Figure 3).

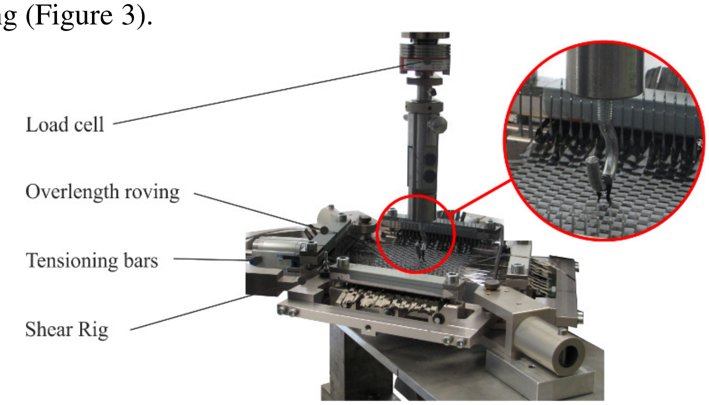

Figure 3. Characterization set-up for fibre pull-out tests (15° of shear shown here)

5. Results

5.1. Friction characteristics

The results of the unsheared plies under different relative orientations are shown in Figure 4. Obviously tool-ply friction is almost insensitive to the fabrics configuration as the flat metal surface offers no counterpart for topological locking with the fabric's architecture. Friction coefficients vary from 0.23 to 0.27 with small deviations. Ply-ply friction shows a decrease of friction coefficients with higher relative orientation followed by an increase to 0.35 for a relative orientation of 67.5°.

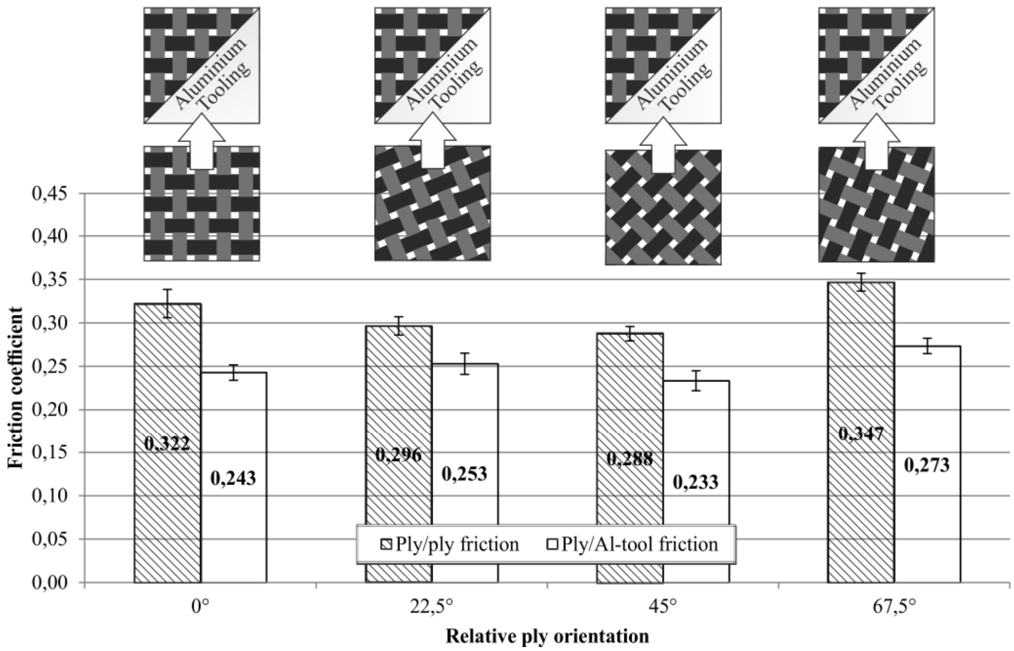

Figure 4. Friction coefficients under different angles of relative orientation

Higher variations of friction coefficients were measured for fabrics under shear (Figure 5), when the unsheared fabric moves relatively to the shear angle's bisector. The highest friction coefficient (0.41) was determined at 15° of shear. No increasing or decreasing trend is observed with increasing shear angles. Nevertheless, ply/tool friction is also insensitive to changing fabric configurations here.

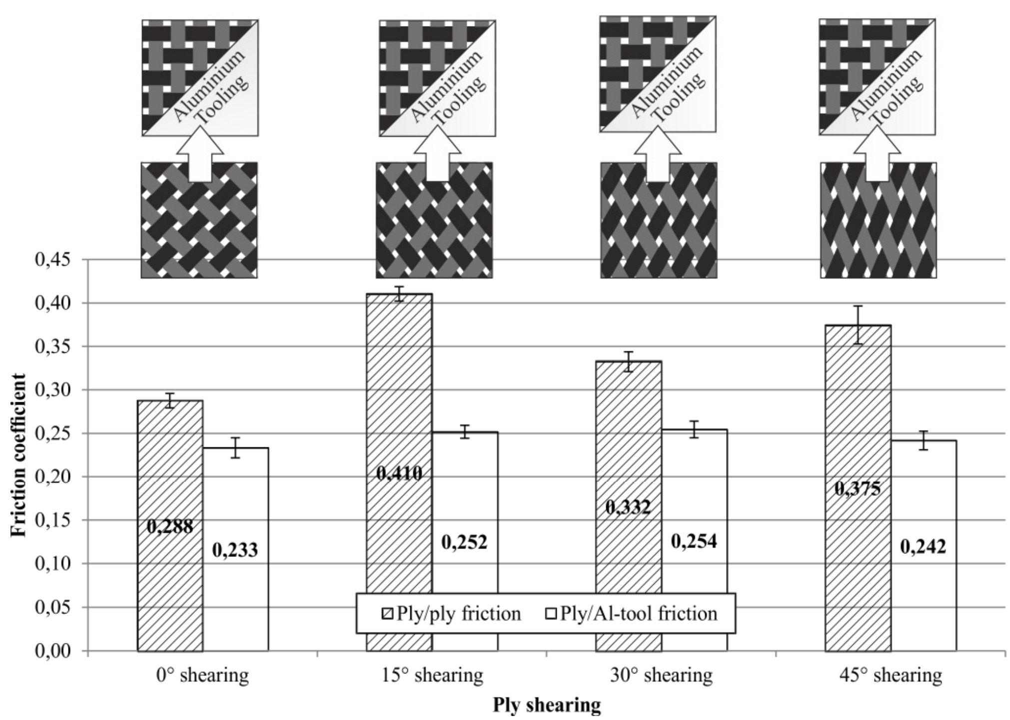

Figure 5. Friction coefficients of sheared fabric

5.2. Pull-out forces

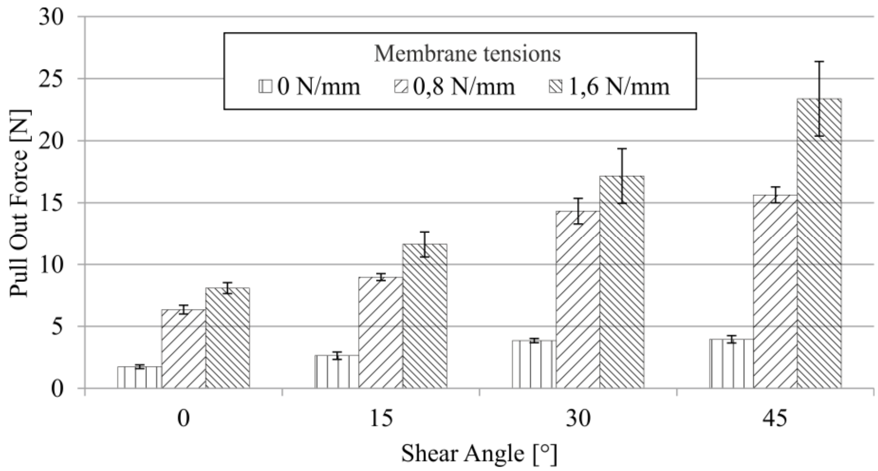

Figure 6. Pull-out forces under shear and membrane tension

With increasing shear angle the forces for fibre pull-out are higher as Figure 6 shows. Due to the higher normal pressure at the interlacing points of the fabric, membrane tensions increase the friction at the crossing points and, thus, higher forces are necessary for moving the fabrics out of their initial position. Both factors, shear and membrane tensions, fix the rovings in position. Therefore, a general increase of the fabrics structural integrity can be concluded from the experimental results.

5.3. Thickening

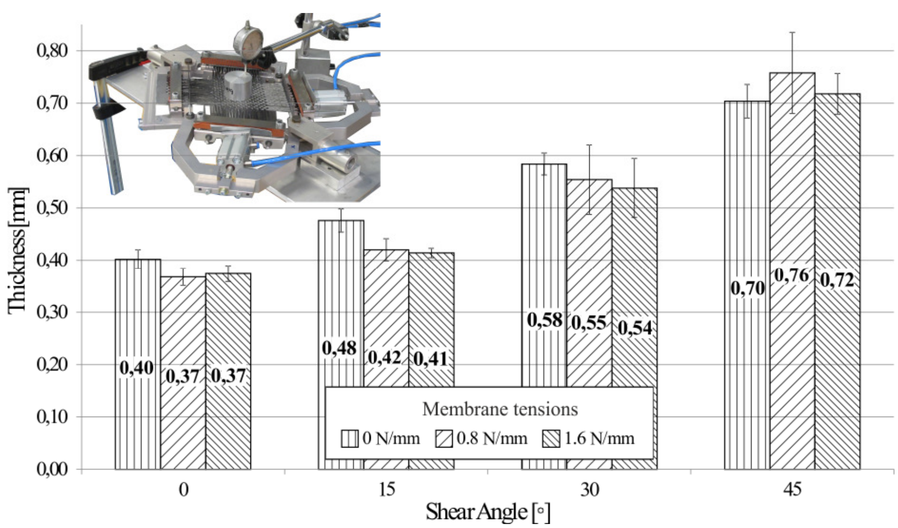

Figure 7. Thickening of the fabric under shear and membrane tension

Higher shear angles result in a thickening of the fabric between 0.4 mm and ~0.7 mm. Deviations increase with higher shear angles leading to higher standard deviations. Membrane tensions lead to a limited decrimping of the fabric and hereby reduce the fabrics measured thickness. Due to the higher standard deviations this effect is not statistical valid for shear angles over 30°.

6. Conclusions

Variance of friction coefficients of ply-ply interactions are stronger influenced by in-plane shearing of the plies than by the relative orientation of unsheared plies towards each other. Blocking of rovings as reported by Allaoui et al. [7] was confirmed, allthough the effect is decreasing with higher ply orientations as no face-to-face blocking of the rovings is given. Experiments with a relative orientation of 67.5° show the influence of unbalanced woven fabrics, when compared to the 22.5° series. The fabric's structural integrity, which was measured by fibre pull-out tests, increases with higher shear angles and higher membrane tensions.

The results confirm earlier multilayer draping experiments [5,6], which showed that in-plane damage is most likely to occur where sheared regions are in contact with unsheared areas of adjacent plies moving relatively to the shear angle's bisector. At this configuration contact forces are highest while the structural integrity of the fabric is lower on the unsheared fabric, where defects are occurring while the sheared areas remained undamaged. Moreover, shearing will lead to thickening and thereby increase the normal forces on the sheared areas locally (especially under blank holders) and hereby increase risk of damaging the fabrics.

Therefore, to suppress damage several measures can be taken:

- Decrease of normal forces by blank holders if allowable for wrinkle suppression.
- Change of part's geometry to prevent membrane tension initiation from geometrical factors if possible from design aspects.
- Decrease of relative orientation of plies towards each other or rearrangement of stacking sequence if acceptable from a structural point of view.
- Decoupling of the interactions between fabrics with the insertion of a metal interlayer in the blank holder area, which can be removed after draping easily when divided into subsegments.

Due to the large number of influencing factors a sound description of fabric contact in macro-scale simulative models remains challenging. Artificial neural networks might help to increase prediction quality but would increase already high calculation time for contact conditions in draping simulation. Nevertheless, a qualitative criterion for damage occurring during draping taking into account the given aspects is realizable to overcome shortcomings of macroscopic simulative models and to allow a process robustness prediction.

It should be kept in mind, that special care was taken during the studies to ensure comparable sample conditions, for example by positioning plies towards each other with opposed rovings lying above each other. Large scatter was observed when this routine was not followed. Nevertheless, this should not be regarded as an experimental set-back, but as an allegory for the difficulty of deriving homogenized data from an inhomogeneous material.

References

[1] R. Kalmbach, W. Bernhart, P. G. Kleimann, M. Hoffmann. Automotive landscape 2025 – opportunities and challenges ahead. Roland Berger, Munich, 2011.

[2] T. Gereke, O. Döbrich, M. Hübner, C. Cherif. Experimental and computational composite textile reinforcement forming. A review. *Compos Part A-Appl S.*, 46:1-10, 2013.

[3] U. Breuer, M. Neitzel, V. Ketzer. Ketzer. Deep drawing of fabric-reinforced thermoplastics: Wrinkle formation and their reduction, *Poly Comp*, 17:643-647, 1996
[4] H. Lengsfeld, C. Lübbering. Verfahren und Vorrichtung zur Bereitstellung eines trockenen Vorformlings, patent DE1020040970A1, 2012
[5] F. Nosrat Nezami, T. Gereke, C. Cherif. Manipulating fabric shear deformation by means of membrane tensioning – from picture frame tests to generic geometries, In *SETEC 13*, 11-12th September 2013.
[6] F. Nosrat Nezami T. Gereke, C. Cherif. Automated preforming of woven fabrics with segmented blank holders: a multi scale experimental approach, In *TexComp-11*, 16-20th September 2013, Leuven.
[7] S. Allaoui, G. Hivet, C. Cellard. Effect of inter-ply sliding on the appearance of defects for multi-layered composite shaping. In 19th International conference on composite materials, 894-902, 2013.
[8] L. Girdauskaite. *Local structure fixation in the composite manufacturing chain*. Dissertation TU Dresden, TUDpress, Dresden, Germany, 2011.
[9] P. Mitschang. *Prozessentwicklung und ganzheitliches Leichbaukonzept zur durchgängigen, abfallfreien Preform-RTM Fertigung*. Institut für Verbundwerkstoffe GmbH, Kaiserslautern, 2004.
[10] C. Cherif. *Textile Werkstoffe für den Leichtbau: Techniken – Verfahren – Materialien – Eigenschaften*. Springer, Heidelberg, 2011.
[11] M. Hübner, O. Diestel, C. Seenewald, T. Gereke, C. Cherif. Simulation of the Drapability of Textile Semi-Finished Products with Gradient-Drapability Characteristics by Varying the Fabric Weave. *Fibres & Textiles in Eastern Europe*. 20: 88-93, 2012.
[12] L. Liu, J. Chen, B. Zhu, T. Yu, X. Tao, J. Cao. The yarn-to-yarn friction of woven fabrics.In *Proceeding of the 9th Esaform conference*, pages 1-4, 2006.
[13] B. Cornelissen, U. Sachs, B. Rietmann, R. Akkerman. Dry friction characterization of carbon fibre tow and satin weave fabric for composite applications. *Compos Part A-Appl S.*, 56:127-135, 2014
[14] S. Allaoui, G. Hivet, A. Wendling, P. Ouagne, D. Soulat. Influence of the dry woven fabrics meso-structure on fabric/fabric contact behavior. Journal of Composite Materials, 46(6) 627-639, 2012.
[15] K. Vanclooster. *Forming of multilayered fabric reinforced thermoplastic composites*. PhD Thesis, Katholieke Universiteit Leuven, 2009.