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MITIGATION AGAINST FORMING DEFECTS BY LOCAL MODIFICATION OF DRY PREFORMS

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Abstract

The advantages of continuous reinforcements are known – the continuity in material provides efficient load paths, avoids triggering delaminations at ply drops sites, and makes the ply deposition easier. However, the continuity of reinforcement causes difficulty in forming or draping of preforms. Some geometries may be simply not formable, i.e. it is not possible to comply material with a tool without excessive shearing and causing critical defects – wrinkles, folds, and fabric distortions. The paper discusses feasibility of a new approach to defect mitigation in forming: local modifications of textile preforms. The local deformability of preforms and the resistance of preforms to shearing is enhanced by printing liquid resin into preform and its subsequent thermal treatment. Modification of fabrics leads to the redistribution of shear angles and suppression of wrinkling. The position and distribution of patches with modified deformability were derived through numerical simulations. Manufacturing trials with the position of patches dictated by the simulations successfully confirmed the possibility of defect mitigation.

1. Introduction

Defect mitigation is central to forming of continuous textile reinforcements. A wide range of methods have been established to prevent wrinkling and to control the shear angle distribution. The two main strategies are constraining fabrics outside the forming domain and local modifications of preform in critical locations. The fabric constraining is implemented using various blank holders [1], tensioning elements, or flexible tracking devices [2]. The preform modification can be realized through stitching [3], tufting [4], activation of yarns commingled with thermoplastic fibres [5], and varying weave patterns [6]. The local modification of preforms may present a particular interest when complex constraints of the fabric are either difficult or time-consuming and, hence, costly in implementation and challenging for automation. The local treatment of preforms, on the other hand, may be significantly intrusive to preform architecture and, consequently, to the material properties of the cured composite part. For instance, tufting or stitching cause local distortions of fibres and has an impact on the in-plane properties of composite components.

This study explores yet another possibility of local modification of the fabric behaviour: local deposition of liquid resin into dry preform and thermal treatment. The approach is similar in scope to Liquid Resin Print [7, 8] and, as opposed to the more traditional approaches, has a minimum impact on the internal architecture of the reinforcements. The main idea is to apply local infusions of the reactive resin in the potential locations of excessive shearing, activate partial cure in the injected resin to change material deformability, and remap the shear to produce a more effective drape.

Establishing parameters for local property modification is not a trivial task. Multiple parameters are involved including locations, density of stabilizing elements, area covered, etc. The role of numerical simulations in this process is essential. There exists a wealth of numerical modelling techniques that can be used for this purpose. Overviews of modelling techniques for forming can be found in [9] and [10]. In this paper the applicability of two approaches is tested. At the design stage, a simple representation of the fabric is used. Inspired by the paper of Skordos et al [11], a fabric is approximated by a pin-jointed network of beams representing yarns and diagonal trusses representing the shear response. At the analysis stage, a continuous hypo-elastic model [12, 13] is applied to explore the details of the forming process and confirm experimental findings.

The test case, chosen for this study, is a non-structural component with exaggerated geometry. Kinematic drape simulations suggest that this component is not formable: independently of drape starting point and initial fabric orientation the shear angle in some locations approaches 90°. This does not however mean that the component cannot be formed in principle – it means that it is not possible to align fabric reinforcement with the geodesic lines and hence, an additional material treatment is needed. The challenge set by this study is to explore feasibility of making such component formable by applying stabilising elements through liquid injected resin.

2. Design of forming process

2.1. Component geometry

The case study considers a thin-wall doubly symmetric component (Fig.1) tapered towards the centre with characteristic dimensions of ~230 mm in length, 30-50 mm in width, and ~25 mm of maximum height (at A-A′). The process considered for manufacturing of this component is liquid resin infusion of a dry biaxal preform. The essential driver for the choice of processing technique is to minimize a manual interference such as sequential draping operations. Hence, the infusion must be preceded by forming and consolidation of the fabric. Forming of this component requires deep drawing and combines features which are known to cause defects: double curvature, taper, convex/concave corners.

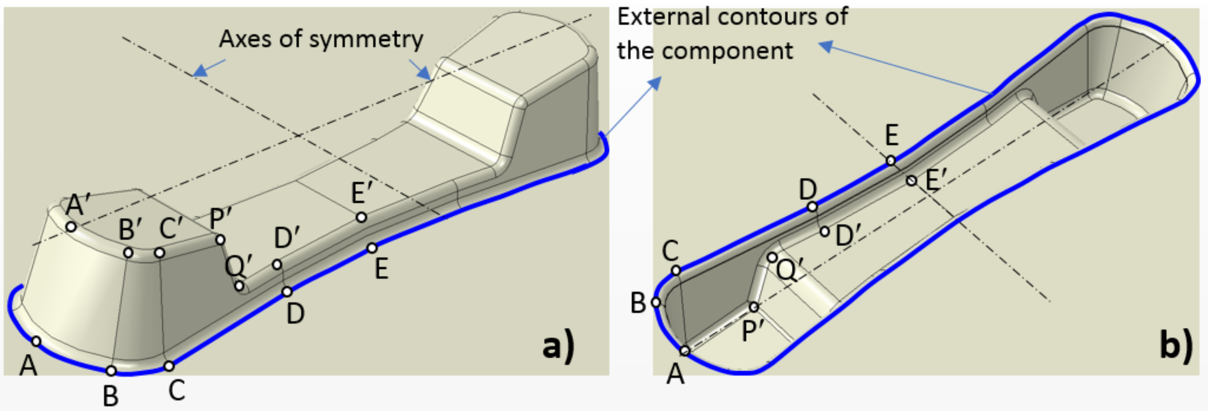


Figure 1. Geometry of the a) male and b) female moulds of the component.

Kinematic simulations of fabric aligned with the component symmetry axes show excessive shearing at the regions of B-B′-C′-C and along the concave corner P′Q′D′ (Fig. 1)– well above the locking angle, *i.e*. when the lateral interaction of sheared yarns causes out of plane buckling of fabric. As shown below, full forming simulations predict similar issues. Hence, the process requires essential interference in redistribution of the shear angle to mitigate against occurrence of critical defects.

2.2. Choice of stabilisation zones

Local preform treatment was used to improve formability of the material. The main idea was to change material properties in critical locations where shear deformation was high and shear bands were narrow. Increased materials resistance in selected regions was expected to delocalize fabric deformation, redistribute the shear angle over a larger area, minimise the magnitude of shearing in the regions of interest, and hence reduce the probability of defect occurrence.

In the instances when geometry is complex and contains multiple critical regions, choosing the positioning of the stabilising elements in a right place is important. Stabilising material in one location may lead to a defect in a different location. The size and shape of stabilising elements also play role. Hence, forming simulations are essential in designing a stabilisation map.

In the current work, the fabric was approximated by a network of orthogonally pin-jointed beams which is equivalent to kinematic modelling since the elements can rotate around the pins and the network shows no resistance to shearing. To include material resistance in the model, diagonal truss elements were added and connected to beams at the pin-joints as suggested in [11]. For design purposes knowing the actual material properties was not considered critical. It was considered important to set the sufficient contrast in properties – higher stiffness of the beams compared to trusses (1 MPa vs 0.05 MPa) prevented the fabric from tensile deformations along the yarns, while the response of trusses was tuned to capture actual physical behaviour of the preform in shear. The grid size of 3.3 mm was found suitable for the purpose of computationally-efficient yet mesh-independent analysis.

The modelling was conducted in Abaqus Explicit 6.16. In the dynamic forming simulations, the network of 1D elements was placed between the matching male and female moulds discretised with solid 10-node tetrahedral C3D10M elements with approximate linear size of 7.5 mm – Fig. 2. The mould included flat area outside the component contour of 375*375 mm in-plane dimensions. Coulomb friction model with penalty algorithm was set to model contact between the fabric and the mould. A small coefficient of friction (10^{-6}) was added to stabilize the numerical solution. A higher shear resistance of material in stabilised regions was set compared to the behaviour of fabric in other areas. Hence, the truss elements were set to behave linear elastically and stiffness of truss elements in the stabilised patches was scaled up by an order of magnitude to achieve a notable contrast in their stiffness.

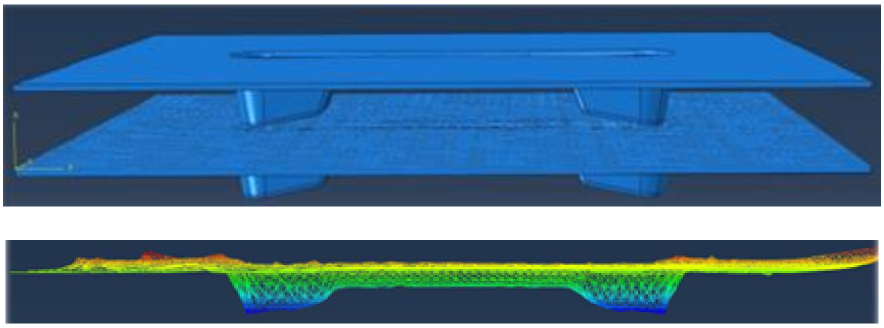
a)
b)


Figure 2. Forming simulations at the design stage: a) matching moulds with flat fabric in between, b) side view of the deformed fabric.

In the initial design stage, four major zones were selected as candidates for stabilisation – Fig.3a. Zones 1 and 4 were the areas of potentially highest shear concentration in concave and convex corners, whereas zones 2 and 3 bridge them. This gave 16 possible combination ranging from no zones stabilised (reference case) to all zones stabilised. The most successful combination was deemed to be the one where maximum shear angle within the contour of the component is minimal. Not all the simulations out of 16 could be brought to successful completion and some of the simulations were aborted before the moulds were in full contact. Hence, for fair comparison, all the forming simulations were stopped at 15 mm upper mould displacement out of 25 mm required for complete closure – at this deformation the results for all the runs could be successfully derived.

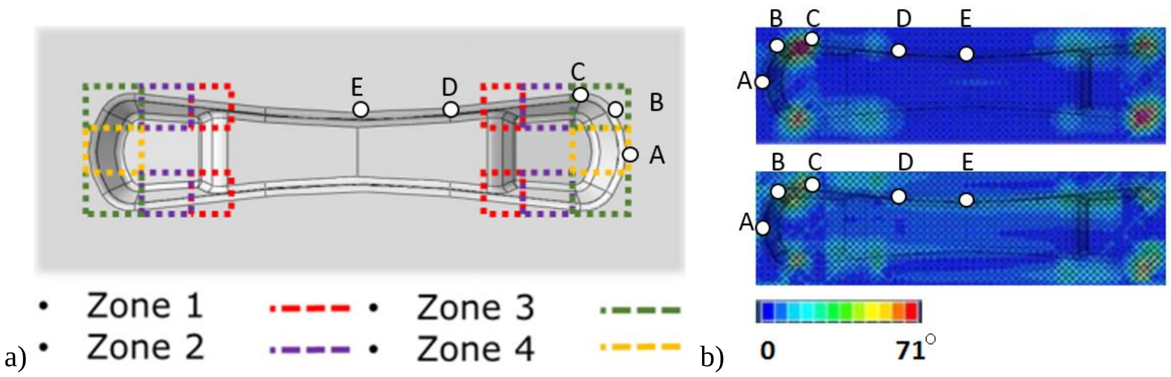


Figure 3. a) Definition of zones for introducing stabilising elements, b) Comparison of shear maps in reference (non-stabilised) and stabilised configurations (zones 3, 4).

The simulations showed that the most promising patch configuration was to place stiffer material in zones 3 and 4 – Fig. 3b. Stabilisation considerably redistributed the deformations and reduced the intensity of the shear from 71° to 58° in the critical location. The simulations also showed that the shear deformation spreaded outwards from the contour of components, i.e. to the areas which were to be trimmed after the component was infused and cured.

3. Manufacturing trials

3.1. Patch Stabilisation

Material selected for the experiments was 2/2 biaxial twill E-glass fabric with areal density of 280 g/m^2 and yarn spacing of 1.25 mm. Permanent ink grid was print-painted on the fabric surface to ease tracking of deformations. Prior to forming fast-curing resin (Huntsman Araldite LY 3585 epoxy resin and Aradur 3475 amine hardener) was injected into the pre-defined zones of laid flat fabric with a silicone sheet underneath to allow the tapered 21G needle to penetrate the needle tip through the fabric. This resin allowed a comfortable ~30 min pot-life while able reach fast gelling once heated. Fabric was then thermally treated to raise the viscosity of the injected resin while avoiding full vitrification – Fig. 4. Thermal history was adjusted to achieve low (~10%, 70°C for 2 minutes) and high (~30%, 70°C for 4 minutes) degrees of cure (DoC) with the gel point of the system estimated to be between 40% and 50% DoC. Heating was applied using the heat plates installed on a tensile machine thus insuring that the heat plates could be brought in contact with the fabric but without applying consolidating pressure. For reference configuration a spray binder was deposited on the fabric surface uniformly over the entire area to retain the forming deformations.

Manufacturing trials were conducted by placing the fabric between two matching Acrylonitrile Styrene Acrylate moulds printed using Fused Deposition Modelling (FDM) technology at GKN Aerospace with 0.1 mm resolution. Constant pressure equivalent to 6 kg weight was applied to close the moulds. After the forming process was completed, the male mould was removed, and the fabric was examined. Because of binder or resin applied the deformation in critical locations was retained after the opening of the mould.

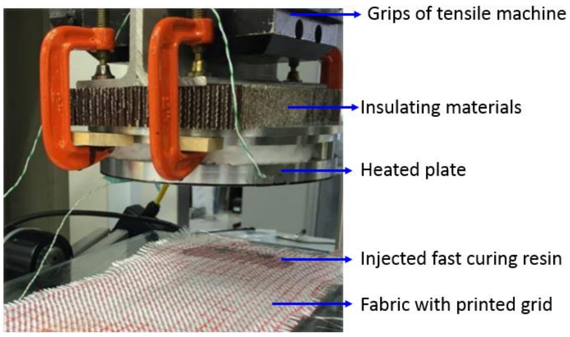
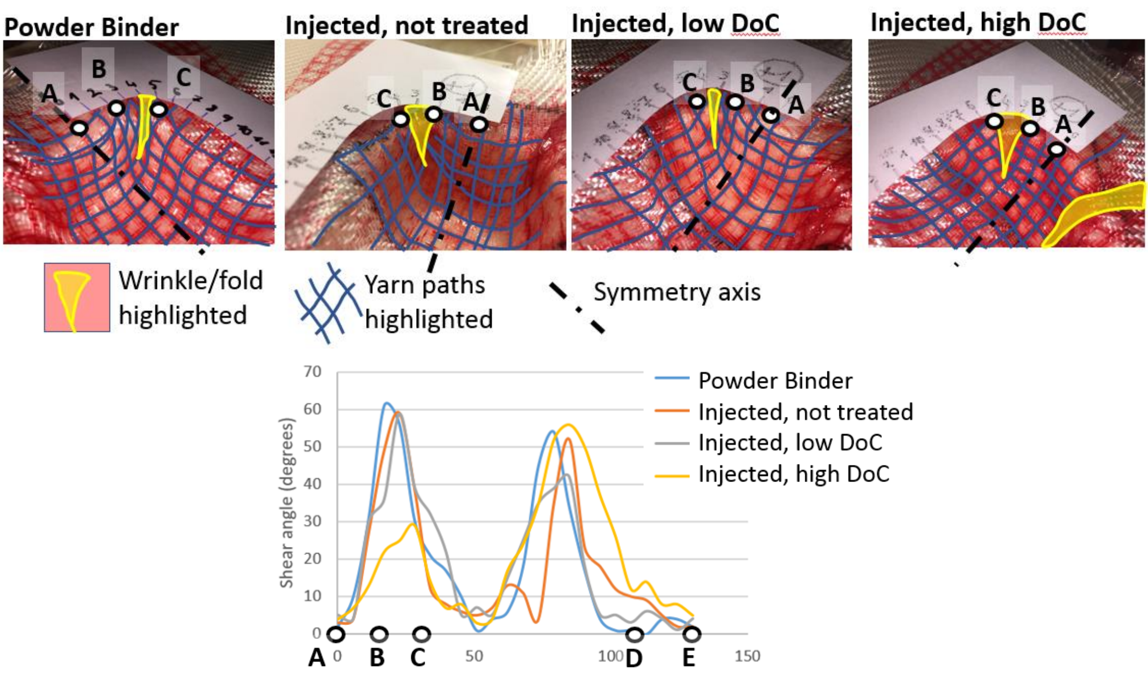


Figure 4. a) Definition of zones for introducing stabilising elements, b) Comparison of shear maps in reference (non-stabilised) and stabilised configurations (zones 3, 4).

In the first set of trials, four configurations were tried:

a) Fabric with spray binder applied uniformly over the entire area
b) Fabric with zones 3-4 injected using liquid resin and formed straight after the injection is applied
c) Fabric with zones 3-4 injected using liquid resin and resin is thermally conditioned to reach 10% degree of cure prior to forming
d) Fabric with zones 3-4 injected using liquid resin and resin is thermally conditioned to reach 30% degree of cure prior to forming

a)



b)

Figure 5. a) Deformation of the formed fabric with different patch treatments, b) Shear angle along the edge A-B-C-D-E (see Fig. 1 for references).

The results revealed a clear pattern of fabric behaviour – Fig. 5a. A pronounced wrinkle formation occurred as expected in the reference (binder-stabilised) configurations. Injecting resin with no thermal-treatment or inducing low DoC did not significantly affect the deformation map. On the other hand, high DoC of stabilising resin, and hence stiffer material locally, did have a considerable impact on the shear map. The shear angle was significantly reduced in the area of interest – from 60° to 30° maximum – Fig. 5b. Interestingly, this did not allow to eliminate the defects: instead of localised wrinkle a significant folding of fabric was observed in the same location.

This experiment clearly showed that the local shear of the fabric alone could not be used to flag the likelihood of defect occurrence. Indeed, bending stiffness is known to play a considerable role in the shape of wrinkles [10]. Resin injected in the form of a patch not only ramped up the local shear resistance but also significantly increased the bending rigidity of the patch making it more prone to folding. Hence, the challenge associated with local stabilisation was to prevent shearing while minimising the interference with the natural response of fabric in bending. Such treatment is described in the next paragraph.

3.2. Line stabilisation

To comply with the requirements of both a higher shear resistance and low bending rigidity, the patch configuration was replaced by the deposition of narrow bands of the resin at 45° to the direction of yarns. To minimise the effect of resin spreading due to the capillary forces, a fine powder was added to the injected liquid resin making it substantially more viscous.

The resin was deposited on a flat preform along the lines that upon forming should coincide with B-B′ and C′-C (Fig. 1). These lines form the contours of the region where wrinkles/folds form. The shape and position of patch regions constrained the shear deformation of preform yet allowed a relatively high flexibility in bending due to the difference between the fibre and line patch directions. In the same way in the previous paragraph, the region was thermally conditioned. The results of these trials are shown in Fig. 6.

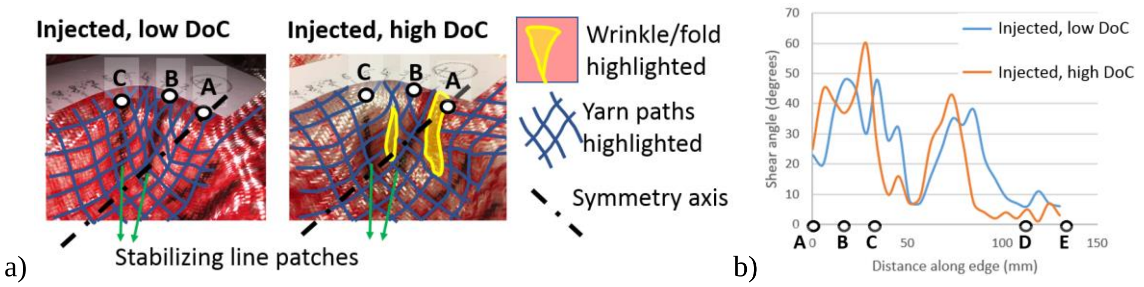


Figure 6. a) Deformation of the formed fabric with different line treatments, b) Shear angle along the edge A-B-C-D-E (see Fig. 1 for references).

Line patching and conditioning resin to low DoC allowed to achieve both – decrease the shear intensity and fully eliminate the wrinkle occurrence – Fig. 6. Even though the maximum shear angle was relatively high – up to 50°, material fully complied to the mould and no out of plane deformation could be observed. On the other hand, further treatment of the resin led to reoccurrence of the defects and, in addition, new defect formed at the axis of component symmetry (point A). This shows that a fine balance between the shear and bending stiffness needs to be satisfied to achieve a defect free component.

4. Continuous modelling of patching

To verify the findings and confirm the potential of line-stabilisation, additional numerical simulations were conducted. This time a different approach was needed to make sure that a convergence of the numerical process can be achieved at the full mould closure and assign more realistic material properties. Following Thompson et al [13], a continuous shell representation of fabric, was adopted. This hypo-elastic model, initially suggested by Khan et al [14], captures fibre reorientation in biaxial fabric. An important further development includes superposition of shell and membrane elements to correctly represent both the high in-plane tensile stiffness and low out of plane bending stiffness characteristic for woven materials. The model is implemented in Abaqus sub-routine VUMAT. Like the discrete simulations, the shear stiffness of the material points along the line patches was artificially increased. At these regions a linear shear response, approximately equal to that experienced at the fabric locking angle, was prescribed.

The results of simulations are shown on Fig 7. In agreement with the manufacturing trials, the model predicted decrease in local shear in the critical locations, substantial suppression of wrinkles and the formation of large fold outside the contour of the component. The model did not consider the actual material properties and hence, more work needs to be done to understand the fine balance between shear and bending stiffness as observed in manufacturing trials. Nevertheless, these simulations confirm the potential of local preform treatment.

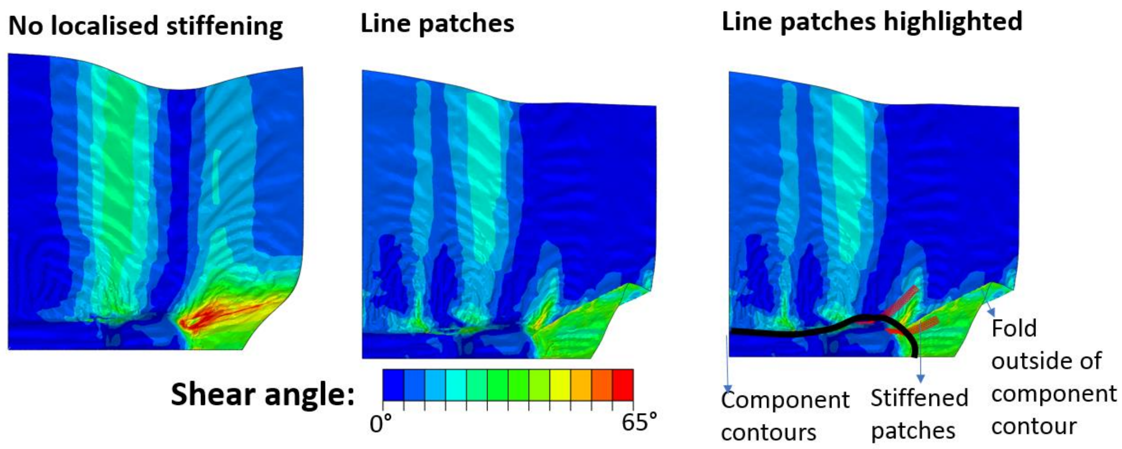


Figure 7. Forming simulations with and without stabilising patches

5. Conclusions

The current study suggested a method which adds to the palette of instruments available for improving forming of continuously reinforced composites. Compared to other methods it has several promising advantages including non-interference with reinforcement geometry, flexibility and simplicity in implementation. The use of liquid resin as stabilisation mechanism allowed to achieve fine tuning of preform properties required to achieve a defectless component. At the same time this method requires sophisticated modelling tools and extensive characterisation of resin and fabric to find optimum position for stabilisation, shape of patches, and the thermal treatment of injected resin.

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References

1 Nezami N.F., Gereke T., Cherif C. Active forming manipulation of composite reinforcement for the suppression of forming defects, Composites Part A, 99 (2017) 94-101.

2 Breuer U., Neitzel M. Deep drawing of fabric-reinforced thermoplastics: wrinkle formation and their reduction, Polym Compos, 17 (1996): 643-7.

3 Molnar P., Ogale A., Lahr R., Mitchang P. Influence of drapability by using stitching technology to reduce fabric deformation and shear during thermoforming, Compos Sci Technol, 2007, 67 (15-16): 3386-93.

4 Liu L., Zhang T., Wang P., Legrand X., Soulat D. Influence of the tufting yarns on formability of tufted 3-Dimensional composite reinforcement, Composites Part A, 78 (2015): 403-411.

5 Dobrich O., Gereke T., Cherif C. Drape simulations: Textile material model for correct property reproduction to improve the preform development process of fiber-reinforced structures, Proceedings of the 12th International LS-Dyna conference, Deraborn, June 3-5, 2012

6 Hubner M., Diestel O., Sennewald C., Gereke T., Cherif C. Simulation if the drapability of textile semi-finished products with gradient-drapability characteristics by varying the fabric weave, Fibres Text East Eur 2012, 20(2): 88-93.

7 Ivanov D. S., White J. A. P., Hendry W., Mahadik Y., Minett V., Patel H., Ward C. Stabilizing textile preforms by means of liquid resin print: a feasibility study, Advanced Manufacturing: Polym & Compos Sci, 2014, 1, 26-35.

8 Ivanov D.S., Le Cahain Y. M., Arafati S., Dattin A., Ivanov S.G., Aniskevich A. Novel method for functionalising and patterning textile composites: liquid resin print, Comp A 84 (2016) 175–185.

9 Gereke T., Dobrich O., Hubner M., Cheriff C., Experimental and computational composite textile reinforcement forming: A review, Composites: Part A 46 (2013), 1-10

10 Boisse P., Colmars J., Hamila N., Steer Q. Bending and wrinkling of composite fiber preforms and prepregs. A review and new developments in the draping simulations, Composites Part B 141 (2018), 234-249.

11 Skordos A. A., Monroy Aceves C., Sutcliffe M.P.F., A simplified rate dependent model of forming and wrinkling of pre-impregnated woven composites, Comp A, 38(5): 1318–1330, 2007.

12 Thompson A., El Said B., Such M., Belnoue J.P-H., Hallett S.R. Discrete modelling of non-crimp fabric multi-layer preforming processes, Proceedings of TexComp-12 Conference, Rayleigh, USA, 26-29 May.

13 Thompson A., Belnoue J.P-H., Hallett S.R. Numerical modelling of defect generation during preforming of multiple layers of 3D woven fabrics, Proceedings of ECCM17 conference, Munich, Germany, 26-30th 2016.

14 Khan M.A., Mabrouki T., Vidal-Salle E., Boisse P. Numerical and experimental analyses of woven composite reinforcement forming using a hypoelastic behaviour. Application to the double dome benchmark. Journal of Materials Processing Technology, 210(2010): 378-388.