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Digital element simulation of aligned tows during compaction validated by computed tomography (CT)

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Abstract

Meso-scale geometrical changes during transverse compression of aligned tows have a significant influence on resin permeability during infusion as well as on the mechanical properties of the resulting polymer composites. These geometrical changes need to be captured at each and every stage of composite manufacturing and realistic geometrical models verified by accurate experimental data are needed to simulate the changes during forming to predict the mechanical properties of the composite laminates. In the present work, the aligned fibre tows in a dry plain woven glass fabric are simulated by digital element method. A meso-scale compaction study of the tow geometrical changes has been conducted by 3D X-ray computed tomography (CT) under compression loading. The evolution of meso-scale geometrical features such as tow area, thickness, width and waviness has been quantified using high quality CT images. The realistic tow geometrical data by digital element simulation under different compaction levels has been validated by experimental data obtained by CT.

Keywords: compaction, tow geometry, woven textile, digital element, computed tomography (CT)

1. Introduction

Recent accelerated growth in the use of advanced composites is sustainable only through continuous development of advanced manufacturing techniques matched by improved design and simulation tools. Prepreg hand lay-up techniques developed primarily for high-value markets such as military airframes and Formula 1 cars are being gradually replaced by automated tape-laying and tow-placement techniques. Further expansion to cost-sensitive
high-volume markets, such as passenger car industry, will only be feasible through a significant reduction in manufacturing and product development costs. Liquid resin infusion technologies in conjunction with dry fibre preforming have been widely recognised as a way forward for achieving the next level of affordable composites manufacturing. Dry textile preforms have meso-scale features due to the interlacement of tows that affect the ease of resin infiltration and the final properties of the manufactured composite. These meso-scale geometrical features need to be captured as a function of external loading and realistic geometrical models verified by accurate experimental data are needed to simulate the changes during forming and to predict the mechanical properties of the composite laminates.

For composites manufacturing, a number of different techniques are employed. These manufacturing processes involve compaction of the dry preform to a certain level of pressure which changes the tow geometry of the preform affecting the fibre volume fraction and the resin permeability. Based upon these facts, the compaction process is taken as an important parameter of the manufacturing process (Robitaille and Gauvin, 1998). Extensive research has been done on the compaction behaviour of textiles (Chen and Chou, 1999; Chen et al., 2001; Chen et al., 2006; De Jong et al., 1986; Gutowski and Dillon, 1992; Latil et al., 2011; Nguyen et al., 2013; Pearce and Summerscales, 1995). Van Wyk (1946) was probably the first to treat the fibres under compression as a system of bending units. Moustaghfir et al. (2013) studied the compression behaviour of textile rovings by using finite element and experimental methods. Pearce and Summerscales (1995) performed experimental work on the compressibility of the reinforcement fabric under loading and relaxing cycles, and attributed the loading cycle response to a power-law relationship. A typical pressure-thickness curve was proposed by Hu and Newton (1997) and Matsudaira and Qin (1995). The curve can be divided into three regimes; namely two linear stages separated by an exponential
stage. Matsudaira and Qin (1995) attributed the first stage to the bending of the fibres, the second to friction between the fibres, and the third part to the lateral compressional modulus of the fibres themselves.

As discussed earlier, the transverse compaction of the fabrics change the geometry and packing fraction of the tows. In order to predict the mechanical properties of the composites, realistic geometrical models verified by accurate tow geometrical data are required to simulate the changes during forming. Idealised tow geometry may not be sufficient for the verification of textile models due to variation in tow geometries (Desplentere et al., 2005). Several researchers have paid attention to obtain actual tow geometry by using cross-sectional images of laminated composites (Kruckenb erg et al., 2008; Potluri et al., 2006; Potluri et al., 2002; Saunders et al., 1998, 1999). Recently, computed tomography (CT) has been employed to capture the meso-scale tow geometry of textile composites (Barburski et al., 2015; Naouar et al., 2015; Naouar et al., 2014; Pazmino et al.). Models have been developed to represent textile geometry by several researchers (Durville, 2010; Green et al., 2014; Lomov et al., 2001a; Lomov et al., 2001b; Lomov et al., 2007; Mahadik and Hallett, 2010; Miao et al., 2008; Verpoest and Lomov, 2005; Wang and Sun, 2001; Zhou et al., 2004). For example, Wang and Sun (2001) introduced the concept of digital elements to simulate the textile processes and micro geometry of textile fabrics. Zhou et al. (2004) further developed the concept of multi-chain digital elements to simulate the textile tow morphology. In this concept, fabric was taken as an assembly of yarns and each yarn was considered as assembly of macro fibres. Thousands of micro-fibres have been replaced by a few macro-fibres with equivalent cross-sectional area. In this new approach, the fibres were modelled as a frictionless pin-connected rod element chain called as digital chain. On reaching the length of these rod elements to zero, the digital element becomes a fully flexible
one dimension entity with circular cross section. Yarns were modelled as assembly of digital chains. Similar to the concept of Wang and Sun (2001), the contact between digital chains was modelled by contact elements. The geometry of woven and braided fabrics was simulated by this process. This new concept of multi chain digital element was more realistic as each fibre was modelled as a flexible one dimensional physical entity whereas in previous model of Wang and Sun (2001), each yarn was modelled as one dimensional physical entity. An improved digital element approach was introduced by Miao et al. (2008). They used the static relaxation algorithms to simulate the fabric micro geometry. The concept of multi chain digital element was further researched by various researchers (Green et al., 2014; Huang et al., 2013; Iarve et al., 2009; Mahadik and Hallett, 2010). Multi-chain digital elements have the great potential to predict realistic tow geometry in interlaced textile architectures without the necessity to measure meso-scale constitutive properties of each dry fabric. Non-idealised tow geometry as well as inter-tow and intra-tow pore geometries under a variety of individual or coupled-loading conditions, compression, shear, bending and biaxial tension may be predicted with digital element models. However, there has been limited experimental validation of these sub-tow digital element models. For example, a) it is not clear how (many) macro-fibres would realistically represent thousands of micro-fibres in the relaxed state as well as under significant loading (during preforming, infusion and consolidation processes). This work is part of a collaborative effort between Manchester University and AFRL to capture 3D tow-geometry in a dry fabric under compression loading (quasi-static) in-order to validate and subsequently improve the digital element models.

Transverse compression may be investigated on a single layer or multi-layer stacks. Nesting and ply-shifting dominate the deformation of multi-layer stacks (Saunders et al. 1998).
paper is based on single-layer compression in order to capture subtle tow-geometry changes. Deformation processes in multi-layer stacks will be presented in a future publication.

Nomenclature

a  Tow width
b  Tow thickness
P  tow spacing/ original tow length without crimp
L  cramped length
θ  tow crimp angle (degree)
C%  tow crimp percentage

2. Material and mechanical testing

The material under observations was E-glass plain woven fabric having a warp density of 4.8/cm and a weft density of 4.4/cm. The warp and the weft counts were 600 Tex. The specific gravity of the fibres was 2.60 g/cm³ and the areal weight of the fabric was 620 g/m².

2.1 Mechanical testing

An Instron 5569 machine was used for the mechanical testing of the single layer fabric samples with a small capacity load cell (5kN). The surface areas of the top and bottom plates were 15 cm². The fabric samples were cut into 5x5 cm pieces. As the fabric thickness is small in comparison to the machine stroke, the accuracy with which the compression strain is measured becomes important. In order to minimise errors, machine compliance as a function of the applied load was measured and accounted for in the fabric strain calculations. For the mechanical testing of the fabric samples, a quasi-static test method was employed to maintain constant thickness at constant pressures. During the static test method, a cross-head speed of 1 mm/min was used. The cross head was moved to the desired load and then held for five
minutes. The hold time was chosen because the fibres tend to relax during compression due to the visco-elastic nature of the fibres which results in a decrease in fabric thickness with time. This five minute period was considered to be adequate for these types of loadings (Kim et al., 1991; Kruckenberg et al., 2008). The final thickness attained at each pressure level was recorded and used to calibrate the compression rig for the meso-structure analysis.

2.2 Tomography and compression rig

A compression rig, shown in Fig. 1, was developed to compress the dry preforms for CT. The rig comprises two clear polycarbonate plates 60 x 35 x 12 mm in length, width and thickness, respectively. Two side screws were used to compress the plates from both sides, and two thickness gauges were placed on either side to maintain uniformity on both sides. The edge to edge distance of the two side screws was 40 mm. The sample size of the dry fabric compressed between the two plates was 40 x 35 mm. At each pressure level, a slip gauge of known thickness was placed between the two plates on each side (Fig. 1).

![Diagram](image)

**Fig. 1.** Plain woven fabric compacted between two clear polycarbonate plates for CT scan

Once mounted on the x-ray scanner (Fig. 2), the side screws were tightened to compress the fabric preform to the desired pressure. From the pressure - thickness curve, the thickness value against desired pressure was taken and the slip gauge of thickness corresponding to that pressure was put on both sides of the plates.
The CT method involves collecting a large set of radiographs (projections) of the sample as it is rotated through 360°. Together with a small number of calibration images, these images are reconstructed into a 3D volume, which represents the attenuation through the sample. A Nikon Metris 225/320 kV Custom Bay system was used for scanning. The system was equipped with a 225 kV static multi-metal anode source with a minimum focal spot size of 3 µm and a Perkin Elmer 2000x2000 pixels 16-bit amorphous silicon flat panel detector. The current and voltage were adjusted to 115 µA and 85 kV, respectively. The entire volume of fibre preform was scanned. The data acquisition was carried out with an exposure time of 1000 ms, the number of projections was set to 3142 and the number of frames per projections was 1, resulting in an acquisition time of 53 minutes. The 3D data set was reconstructed with a voxel size of 13.2 µm. Image analysis was performed using software Avizo 8. In order to remove the noise from the data a non-local mean filter was employed. For segmentation of individual tows, the tows were first selected manually with the help of the lasso tool at different slices, the selection of slices was repeated after every 3~5 slices and then by using
the interpolation between these slices, the volume of interest was created. Finally with the help of Generate Surface function, the 3D surface of the tows was generated.

3. Virtual Textile Morphology Suite (VTMS)

The following section is a basic description of the mathematic behind VTMS. It is followed with a specific description of the compaction simulation.

3.1 Multi-Chain Digital Element for Textile Tow Morphology

The multi-chain digital element method was employed in the present study to obtain realistic textile tow morphology (Zhou et al., 2004). In this method, a tow is represented as a number of macro filaments where each macro filament is treated as a digital chain. A digital chain consists of many rod-elements, known as digital elements (Fig.3) (Zhou et al., 2004). The rod elements in the digital chains are connected by rotational nodes which make it possible to represent a 1D flexible physical entity with a fixed cross-section, such as a fiber.

![Diagram of digital chains](image)

**Fig. 3.** Schematic of a single digital chain (a) and two digital chains (b) interacting through a contact element

When a digital chain approaches another digital chain, contact between two digital chains can be represented by contact between nodes from two neighboring chains as shown in Fig. 3. If the distance between two nodes is smaller than the defined diameter of the digital chain, a contact element is added between them. When contact occurs between two nodes, one of two kinds of physical conditions would exist: sticking or sliding, which is governed by the normal...
force between nodes and the defined friction coefficients (Mollenhauer et al., 2014; Zhou et al., 2004).

Additionally, a vacuum bag or hard mold may be simulated using the multi-chain digital element method. To achieve this, a network of rod elements is connected via nodes. The stiffness of the vacuum bag is controlled by the stiffness of the rods. A hard mold is enabled by fully constraining the nodes. Fig. 4 shows examples of application of the multi-chain digital element method (Mollenhauer et al., 2014).

**Fig. 4.** (a) A single tow represented by multiple digital chains that has been compressed across its middle. (b) 2-D woven fabric generated by multi-chain digital element model (c) A simple plain weave compacted by a digital chain vacuum bag.

### 3.2 Plain Weave Compaction

The local tow geometry of a plain weave dry fabric preform at various levels of compaction was simulated using the software code Virtual Textile Morphology Suite (VTMS). The input parameters for simulation of the compaction sequence were chosen to match the dry cloth examined in the X-ray CT experiment. In this case, a virtual preform was created in VTMS that had 4 warp tows and 4 weft tows. Warp and weft tow spacing was defined to be 2.08mm and 2.27mm, respectively. Each tow was modeled using 49 circular filaments of 0.079mm diameter in order to match the cross-sectional area of fibers in each tow of the experimental specimen. Axial rod element lengths are user-defined and in this work were set to 1/2 the filament diameter. Generally speaking, the larger the number of filaments in a tow, the better
able VTMS is able to capture tow cross-sectional and axial deformations during compaction. The benefits decrease nonlinearly as filament number increases, however. With increasing number of filaments, the filament diameter reduces, thus increasing the number of elements. The number of filaments, 49, chosen in this work was determined to be a good blend of fidelity and computational efficiency considering the available computational resources.

A simulation of compaction in VTMS begins by applying a slight initial tension to each tow. The tension is allowed to reach an equilibrium state during a “relaxation” cycle. Boundary conditions, filament stiffness, tow tension, and interactions with molds govern how the relaxation proceeds. In this work, the ends of each tow were restricted from movement in their respective directions and out-of-plane during the relaxation event. That is, filaments on a warp tow were allowed to move only transversely to the warp direction in the plane of the fabric. A similar boundary condition was used for weft tows. Additionally, due to an observed difference in crimp between warp and weft tows, weft tension was adjusted to be a factor of 1.5 higher than warp tension. All filaments had the same stiffness. Two rigid molds were defined that had dimensions of 9.0mm in the warp direction and 8.3mm in the weft direction, leaving 0.4mm of fiber preform overhanging each direction. The molds were positioned initially above and below the preform. The 0.4mm preform overhang allows the mold to compress the preform without interfering with the tow end constraints.

Once the initial model was defined, pressure was applied to the molds and a converged relaxation step was obtained. In this manner, the preform was compacted. Pressure was increased incrementally in order to obtain a converged solution with an average thickness matching the 10 kPa, the 50 kPa, and the 100 kPa experimentally observed levels of compaction.
VTMS in the current form has not incorporate frictional effects in the simulation. Rather, the aim was to simulate the qualitative trends observed in the experiment correctly with as simplistic of a model possible. With this in mind, tow stiffness and tension properties within VTMS are essentially only important in a relative sense if friction is not present. Therefore, the applied pressure is not necessarily directly comparable to the values applied in the experiment. However, the relative values of each level should reflect increasing relative levels associated with the experimental observations. In the experimental effort, 10KPa, 50KPa, and 100KPa were applied, resulting in ratios of 5 and 10 when the higher 2 levels are compared with the lowest level. In the VTMS simulations, these ratios were 5.6 and 8.5. The lower relative pressure ratio at the highest applied pressure is almost certainly due to the lack of fiber entanglement represented in the simulation as well as slight adhesion effects between fibers due to sizing and/or static electricity. Entanglement and filament adhesion would require additional pressure (as observed in experiment) to achieve a specified fabric thickness.

During simulated compaction, it became clear that the VTMS software was predicting higher average tow fiber volume fractions than were observed in the experimental study. This resulted in tow boundaries that incorporated significantly smaller cross-sectional area than observed. As a remedy to this problem, each filament diameter was increased to obtain a better prediction of tow cross-sectional area, equivalent to considering each macro-filament with internal porosity reflecting the micro-filament bundle that it replaces. This results in a filament area in a simulated tow cross-section approximately 1.4 times higher than the fiber area in an experimental tow cross-section (equivalent to considering intra-bundle volume fraction of 0.71). Approaches to allow VTMS to predict more realistic local tow fiber volume fractions are being examined. Fiber migration will be incorporated in future models.
4. Macroscopic deformations

The thickness results for the single layer dry fabric at different pressures are shown in Fig. 5. Two curves were recorded for each loading, one represents the thickness immediately after the load is applied, the other after 5 minutes of holding at that loading point.

![Graph showing pressure-thickness response](image)

**Fig. 5.** Pressure - thickness response for a single layer fabric immediately after the load has been applied and after 5 minutes of hold

The thickness decay while holding the pressure constant for duration of 5 minutes is considered due to relaxation/rearrangement of fibres as already discussed in the literature. So the thickness reduction in the first curve can be attributed due to compaction effect and the thickness reduction in the second curve can be attributed to the viscoelastic effect. Significant compaction occurs over time at constant load, the change having stabilised after 5 minutes. It is clear from Fig. 5 that the displacement has essentially plateaued within 5 minutes of loading. Unsurprisingly, the change of thickness was least during the final stages of compaction; this reflects the fact that as the fibres become more packed at higher pressure, there is little room for the fibre movement or slippage and hence insignificant viscous effect was observed.
5. Tow geometry by computed tomography (CT) and digital element analysis

Single layer dry fabric compressed between polycarbonate plates was scanned by CT for its tow geometry analysis at different pressures. The parameters describing the tow geometry are illustrated in Fig. 6. Tow geometry parameters were measured by using ImageJ software according to Fig. 6.

![Diagram of tow geometry parameters](image)

**Fig. 6.** Definition of the tow geometry parameters used to quantify the fabric

For tow crimp percentage, the original length $P$ and crimped length $L$ was measured (Fig.6) and by using equation 1, the crimp percentages of warp and weft tows were calculated.

$$C = \frac{(L - P)}{P} \times 100$$

(1)

Tow angle was measured along the central line of the tow as described in Fig.6. The tow widths were calculated by measuring edge to edge distance of the tow as shown in Fig.6. Tow geometrical parameters were calculated at different points along the tow length for all the tows and the values were averaged out for all the data points.

Fig. 7 represents the 3D structure of the fabric sample with dimensions 10 mm x 9.8 mm x 0.83mm, segmented using Avizo 8 on the basis of simple thresholding and the simulated 3D image created by digital element simulation.
Fig. 7. 3D view of the dry preform (a) segmented CT image, (b) simulated by digital element

The experimental CT and simulated tows at various compaction pressures are shown in Fig.8. For simulated tow, the preforms were trimmed to dimensions of 9.15mm in warp, and 8.25 in weft in order to remove the boundary regions and improve visibility.

Fig.8. Cross sectional view of the preform as a function of pressure at the centre of the tow intersections of the (a) warp tows and (b) weft tows both simulated (right) and CT images (left)
Black horizontal lines in these images are the locations of the compaction mold surfaces. Various tow geometry parameters of the warp and the weft tows were calculated at different pressure levels both by CT and digital element simulation (Fig.10-12 & 14-15).

**Fig.9.** Tow area (a) warp tows, (b) weft tows

**Fig.10.** Tow thickness (a) warp tows, (b) weft tows

The range of pressures studied varied from 10 kPa to 100 kPa to investigate the behaviour of the geometrical changes for vacuum infusion process. During the tow analysis of the compressed dry fabric preform by CT, it was observed at an initial pressure of 10 kPa that the shape of the warp tows was elliptical and the weft tows was lenticular (Fig.8). At this initial pressure level of 10 kPa, warp tows area was slightly bigger than the weft tow area while thickness of weft tow was higher than the warp tows (Fig.9-10). Tow width was larger.
in warp tows than weft tows (Fig. 11). Weft tows spacing was higher than warp tows due to the fact that weft tow density was less than the warp tows (Fig. 12).

**Fig. 11.** Tow width (a) warp tows, (b) weft tows

**Fig. 12.** Tow spacing (a) warp tows, (b) weft tows

Both warp and weft tows were segmented separately and extracted from tomographs (Fig. 13). The warp tow was highly crimped and it was following the sinusoidal path, whereas the weft tow was with very low crimp. Due to higher warp tow crimp percentage, the crimp angle was also higher in the warp tows than the weft tows (Fig. 14-15). The simulated images of the tows predicted the similar geometry for the warp and weft tows at this initial pressure level.
On increasing pressure level from 10 kPa to 50 kPa, the tow area and thickness decreased for both warp and weft tows (Fig.9-10), the simulated images also showed the same trend for tow area and tow thickness and there was good agreement between the experimental and simulated values.

![3D reconstruction of the warp and weft tows](image)

**Fig.13.** 3D reconstruction of the warp and weft tows

The tow widths remained unchanged in experimental results but small increase in tow widths for both warp and weft tows was observed for simulated results by digital element analysis.

![Tow crimp %](image)

**Fig.14.** Tow crimp % (a) warp tows, (b) weft tows

Similar trend for simulated tows under compaction was observed by Green et al. (2014) and Mahadik and Hallett (2010) and they defined this phenomenon by the fact that the actual tows consists of several thousand fibres which resist to spreading due to frictional forces between the fibres and also the individual fibres entanglement stop tow spreading while in
case of digital element model a tow is combination of very small number of digital elements and they have very less resistance to tow spreading. No change in tow spacing was recorded at this pressure level by experimental and simulated results.

Fig.15. Tow crimp angle (a) warp tows, (b) weft tows

As the pressure increased to 100 kPa, again a decrease in tow area and thickness of warp and weft tows was recorded by experimental and simulated results. Similar to the previous pressure level of 50 kPa, the experimental results did not display any significant change in tow widths while again a small increase in tow widths for both warp and weft tows was recorded for simulated results obtained by digital element analysis. No change in tow spacing was observed for both experimental and simulated images even at this pressure level. It is worth mentioning that the tow cross-sectional geometry does not remain constant along the tow length. Transverse compaction of the tow was higher at the cross-over points in comparison to in-between tows. For example, at 10kPa, the warp tow cross-sectional area at cross-overs was 0.46 mm$^2$ and at in between the tows is 0.49; corresponding tow thicknesses were 0.31mm & 0.33mm respectively. There is no appreciable change in two widths. At 100kPa, tow cross-sectional area and tow thickness at tow cross-overs were 0.43 mm$^2$ & 0.30 mm compared to in-between tows where they were 0.47mm$^2$ & 0.36 mm respectively.
As already described that the warp tow crimp percentage was higher than weft tows and tow crimp angle was also higher for warp tows at initial pressure level of 10 kPa (Fig. 14-15). In the first step of compression the crimp percentage of the warp tows reduced as the pressure increased from 10 kPa to 50 kPa; by contrast, the crimp percentage of the weft tows increased (Fig.14). Crimp angle also behaved in a similar manner where warp crimp angle decreased and weft crimp angle increased on application of pressure (Fig.15). Both experimental and simulated results presented the similar behaviour for tow crimp at this pressure level. It should be noted that the tow crimp reduces the compressive strength of the laminates (Yang et al., 2000) and the magnitude of the crimp angle is important in predicting the in-plane compressive strength of the composite. The phenomenon of crimp interchange behaviour may be attributed to the balancing of the warp and the weft tows in which the crimp in one tow increases and the other tow decreases to reach the balancing position under transverse compaction. This balancing of crimp was discussed in detail by Potluri and Sagar (2008) and Lomov and Verpoest (2000). This crimp interchange is an important phenomenon which effect the laminate tensile moduli (Potluri et al., 2006). When the pressure was increased from 50 kPa to 100 kPa, the same phenomenon of crimp balancing continued in which the crimp percentage and the crimp angle decreased in the warp tows and increased in the weft tows (Fig.14-15). The simulated results also depicted the same trend of crimp interchange. Standard deviation of the tow geometrical parameters, due to the flexible nature of fibre assemblies, is higher than the local deformations due to compression. However, the measurement accuracy has been improved by statistically averaging at a large number of points (64).

In addition to tow geometry parameters, inter-tow and intra-tow porosities were also investigated as a function of transverse compression load (Figure 16 & 17). It has been
observed that VTMS under-predicts intra-tow porosities and over-predicts inter-tow porosities in comparison to experimental values.

![Fig.16. Inter-tow porosity (a) warp tows, (b) weft tows](image1)

![Fig.17. Intra-tow porosity (a) warp tows, (b) weft tows](image2)

However the rate of change in porosity with compression was similar. Possible reason for the under-prediction of intra-tow porosity was due to the idealization of marco fibre bundles. In the VTMS, all the macro fibres remain parallel to each other where as in real tows, there is a fibre migration resulting in increased porosities. Proportion of inter-tow and intra-tow porosities is important for the rein infusion process.

In this study of tow geometry by CT and digital element method, the experimental and simulated results were in close agreement. The simulated results captured the similar trends
of the tow geometrical changes as studied by experimental results except that there was discrepancy in simulated and experimental results in tow widths behaviour over increase in compaction pressures. The simulated results were showing slight increase in tow widths over increasing pressure levels whereas no significant change in tow widths was observed in experimental results. This needs further investigation with improved digital element simulations that account for realistic frictional contact between the macro-fibres that represent frictional contact between several thousand micro-filaments in a real tow.

6. Conclusions

In this study, compression behaviour of aligned interlaced tows was performed with digital element methods using the software code Virtual Textile Morphology Suite (VTMS) developed by AFRL. Experimental study of the aligned tows was performed under compressive loading by computed tomography (CT). A detailed tow geometrical analysis was conducted for simulated images by digital element analysis and experimental images by CT covering a pressure range up to 1 bar being representative of vacuum infusion process. It was observed that tow cross-sectional area and tow thickness decreased under this pressure range. Tow spacing remained unchanged. The experimental and simulated results were in close agreement regarding changes in tow area, thickness and tow spacing. The simulated results showed a slight increase in tow widths on application of pressure in contrast to experimental results where no significant change in tow widths was observed on application of pressure up to 1 bar. This trend was attributed to the absence of frictional forces between the modelled macro-fibres compared to thousands of micro-fibres in actual tows making the simulated tows easier to deform under compaction. In case of tow crimp, the un-deformed fabric exhibited higher warp crimp than weft crimp. On application of pressures, there was a decrease in warp crimp with a corresponding increase in weft crimp. This phenomenon of crimp interchange was attributed to the balancing of tows under transverse compaction. The
tow crimp angle also presented the same trend as tow crimp. Both simulated and experimental results were in good agreement regarding tow crimp percentage and crimp angle. In addition to tow geometrical parameters, inter-tow and intra-tow porosities were also investigated for both experimental and simulated images. It was observed that VTMS under-predicted intra-tow porosities and over-predicted inter-tow porosities in comparison to experimental values. However the rate of change in porosity with compression was similar. In future, this work will be extended to complex loading, compression-shear, compression-inplane tension etc. as well as shifting and nesting effects in multilayer fabrics.

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