INTERNAL GEOMETRY OF STRUCTURALLY STITCHED NCF PREFORMS

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Abstract

Internal geometry of a textile reinforcement is an important factor of the reinforcement performance during the composite manufacturing and service life. In this article, generalized geometrical models of structural stitching loops are presented for the sewing, tufting, and dual-needle stitching methods. The term 'structural' presumes here that the stitching yarn does not only consolidate the plies (as the non-structural one does) but forms also a through-the-thickness (3D) reinforcement. The models account for the general features of the yarn loop geometry and are believed to allow for enough precise modelling on the meso-scale (textile unit cell) level. The modelling approach is validated with experimental data.

1 Introduction

Combining different plies in one preform, through-the-thickness stitching is known as an effective way to improve the lay-up of textile or fibrous plies. Also, if the stitching is 'structural', i.e. produced using a relatively thick and firm yarn and thus forms a transversal reinforcement, a considerable improvement can be achieved in the interlaminar fracture toughness, in-plane shear, and out-of-plane strength. These advantages induce a widespread use of the stitched preforms, especially in the aerospace industry, where the need for superior damage resistance and tolerance of composite parts has a gained momentum.

In the industry, a preform is often composed of several layers of a non-structurally stitched (knitted) non-crimp-fabric (NCF) material; then, the preform is stitched structurally to improve the final lay-up and interlaminar properties, Fig.1. It appears, therefore, that such a preform has a complex hierarchical structure that should be taken into account in analytical or finite-element (FE) models of the unit cell permeability, effective properties, and damage mechanics. However, a wide set of possible parameters (stitching method and speed, distance between stitches or seams, dimension of the needle, properties of the preform and yarn, yarn tension, etc.) imply certain difficulties for a general investigation. The task of the geometrical modelling thus becomes sophisticated and case-dependent. A number of studies have addressed the irregularity of the knitting pattern, geometry of the stitching yarn, or openings in/between the stitched plies. However, the studies dealt with non-structural stitching, which is not similar to the structural one either in the yarn thickness or in the stitching method.

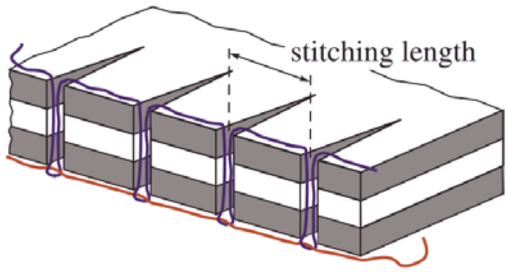

Fig. 1. Sewing scheme of structural stitching

The present paper aims at the geometrical characterization of the yarn loop and resin-rich zones (so called 'openings') in structurally stitched preforms. The objects of study are several basic types of the stitching (sewing, tufting, and dual-needle techniques) applied for a pile of multi-layer multi-axial carbon-fibre NCF layers. Experimental data are presented and discussed.

2 Experimental

2.1 Positions of stitching sites

As it is usually programmed for the stitching robot, the seams should be straight and parallel. However, an irregularity of the stitch placement is observed in reality. The main reason of this effect can be that, even if the preform boundary is clamped while stitching, its interior had some compliance. Then, the yarn is brought into the plies with a certain force and tension. As a result, after removal of the clamp, the preform deforms, and the piercing pattern thus distorts, even it was perfect at first.

The available experimental data, [1], reveal a considerable deviation from the preset stitching length, up to 20%. Typical photos of the stitched preform surfaces are shown in Fig.2.

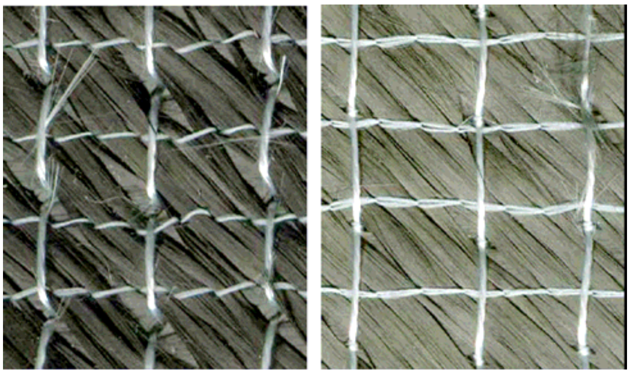

Fig. 2. Face (left) and back (right) surfaces of the stitched NCF preform. Sewing method, glass yarn.

2.2 Openings in plies

During the stitching process (both for the initial non-structural and subsequent structural stitchings), the initial fibre placement is distorted in the plies due to a penetration by the needle and insertion of the yarn. As a result, fiber-free 'openings' are formed around the trough-the-thickness yarn path, Fig. 2. The openings are naturally oriented along the global fibre orientation in a ply. If they are long enough, and the global fibre orientation coincides with the lines connecting the stitching sites (particularly, with the machine or cross direction), then the openings can congregate to form continuous 'channels'.

The experimental results, [1,2], reveal that the ratio between the average length and width of the openings increases with the stitching length. For a virgin NCF, the ratio can be much higher than after the structural stitching. It can be related to a higher yarn tension and, therefore, compaction of the fibre tows during the non-structural stitching. Then, a new 'structural' opening can not spread far sideways, since it is locked in the compacted zones between the non-structural stitching sites.

It is also observed that the openings can occupy a large portion of the dry preform surface, [1]. Thus, the average fibre volume fraction (v_f) is increased in the same extend.

In order to investigate the composite internal structure after the Resin Transfer Molding (RTM), the cross-sections were inspected using an optical microscope, [2]. Typical micrographs of the structural stitching sites are shown in Figs. 3 and 4. Large and nonuniform deformation of the fibrous plies is seen, especially nearby the yarn loop; this effect is attributed to a severe perforation with a relatively thick stitching needle. A stepped variation of the opening width, Fig. 3, is obviously due to a different density and global fibre orientation in the plies that results in their varied response to the action of the stitching needle.

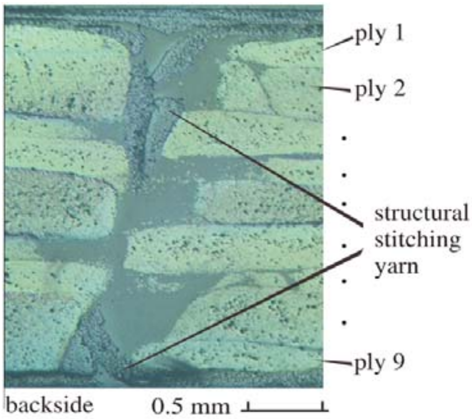

Fig. 3. Micrograph of out-of-plane section cut through a stitching site (tufting method)

The openings are larger in the surface plies, Fig.3; this evident fact is due to the geometry of the yarn loop, which bends at the face and backside and, therefore, pushes away the surface fibres bundles more than the inner ply bundles.

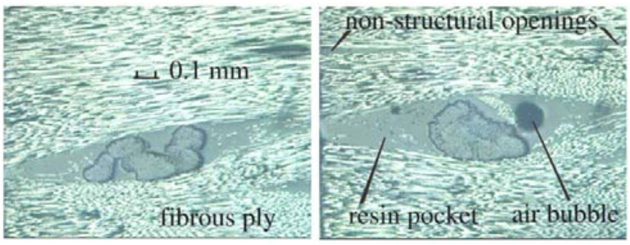

Fig. 4. Typical in-plane micrographs of the inner openings and yarn cross-sections

The overall preform compression during the RTM explains also a considerable reduction of the on-surface opening width in comparison with the dry preform, [2]. This effect should be related to the considerable densification of the fibrous plies in the RTM process.

2.3 Gaps between NCF layers

When laying up a NCFs preform, the non-structural stitching yarn (rather, its paths occurred at the fabric surface) prevents a perfect nesting of the layers. As a result, numerous narrow 'gaps' are created between the NCF layers with certain periodicity [2]. A micrograph of a typical gap near a stitching site is shown in Fig.5.

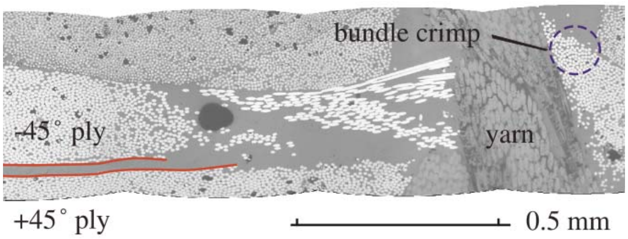

Fig. 5. Typical micrograph of section cut through a stitching site. The gap between two neighbouring NCF layers is marked with red lines (left)

The nesting can cause a significant statistical distribution of the fabric or composite properties (permeability, overall density, etc.), both at different positions within a sample and between different samples in a set of otherwise identical parts. This plays an important role in determining permeability of the laminated preform and mechanical properties of the composite.

2.4 Fibre distribution in plies

Even in a virgin NCF, the fibre placement is not perfect in the plies, since they are manufactured of thick fibrous tows spread as uniformly and unidirectionally as possible. Then, the needles of a knitting device penetrate the plies to keep them together. This process increases the non-uniformity creating openings and zones of affected fibre content. While stitching structurally, the fibres are also pushed aside the needle and then do not recover the original positions due to the friction and inserted yarn. A breakage and vertical movement (crimpling) of some fibres can also be induced with a relatively thick needle or rough yarn, Figs. 4 and 5. During the RTM, the fibre distribution is changed again.

Figure 6 shows a typical microscope image of the fibre placement near a stitch site. It is clearly seen that the local fibre fraction is decreased towards the stitching yarn. Statistical data, [2], illustrates that a prominent (10% in this case) decrease of ν_f can appear sideways the stitch channel; this observation is in contrast with the obvious assumption that the fibres should be densified close to the yarn. Analogously to the inner openings, this effect is attributed to a perforation with the thick tufting needle disturbing the tows severely. Also, since the yarn diameter is less than the needle thickness, a gap is usually formed between the yarn and the fibrous plies. Then, some fibres move into the gap thus decreasing the content at their initial positions. However, the distortion is confined within a small region (≈ 0.5 mm wide for the studied case).

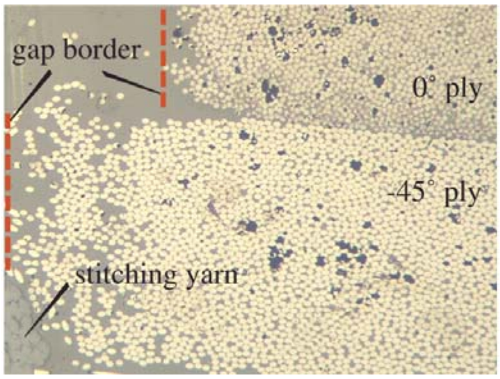

Fig. 6. Micrograph showing distribution of the local fibrous content near a stitch site

2.5 Fibre distribution in yarns

It is a well-known fact that the multifilament yarns have a non-uniform fibre distribution in the cross-section. The fibre content is usually decreased towards the yarn edge; however, the maximum of ν_f can be observed somewhere in between the centre and the edge, [3]. If the yarn is composed of several strands twisted together and/or compressed non-symmetrically, the fibre distribution is much more complex, [2]. Figures 7 and 4 reveal randomized shapes and positions of the strands; very often, there is no a distinct boundary between them. A decrease of the fibre content is often observed towards the yarn edge; although, the magnitude of this drop varies in different directions.

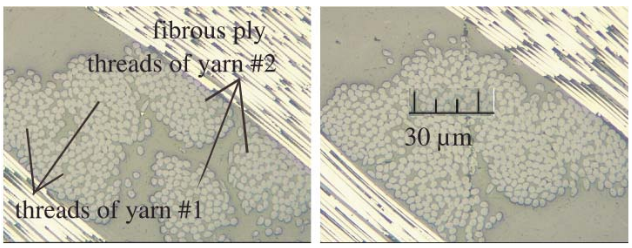

Fig. 7. Micrographs of the fibre distribution over the yarn cross-section

3 Modelling

3.1 Structure of the stitched laminate model

The modelling approach follows the generalised description of the internal structure of a textile reinforcement implemented in WiseTex software package [4]. Thus, the models of stitching are integrated with existing mechanical models of the relaxed and deformed state of 2D and 3D woven, 2- and 3-axial braided, weft-knitted, and non-crimp warp-knit stitched fabrics, and laminates built on their base. The models are implemented in StitchTex software, which is a stand-alone application based on WiseTex approach to the textile description. Also, this allows for an easy use of the existing software solutions for modelling of a resin flow through the reinforcement, micro-mechanical calculations of the composite properties, micro-macro analysis of a composite part, FE models, and virtual reality visualisation, [4].

The structurally stitched laminate is modelled as a combination of a) stitching yarn loop and b) laminate. Three following textile objects are employed according to the used WiseTex approach:

- yarn object;
- structural stitching loop (can be considered as General Fabric WiseTex object);
- laminate object.

Details of these basic objects are shortly listed in Table 1. As can be seen, superior level objects use inferior objects (loop uses the yarn data, yarn uses the fibre data, etc.). Also, objects hold not only the data (geometry, properties) but also the behaviour.

Table 1. Data structure of a stitched laminate

Object	Properties
Yarn(s)	Mono- or multifilament, twisted or not twisted, optionally with non-uniform fibre distribution over the cross-section. The cross-section are idealized as circular. This cross-section shape and its dimension are constant along the yarn path. See [5] for details.
Yarn loop(s)	Point curve objects created according to the prescribed stitching method, stitching length, distance between seams, etc. The cross-sections are defined according to the tangent vector and yarn diameter. See details below.
Laminate	Consists of several equal layers (optionally nested). A layer can be rotated, reflected, and shifted in the plane. In its turn, each layer consists of one or several plies. Within one layer, the plies can have different thickness, orientation, and material properties, and are knitted together with a thin yarn (NCF with so called 'non-structural' stitching). In its turn, a ply can consist of fibres (unidirectional fibre mat) or yarns (textile fabric). See [5] for details. Includes 'openings' according to the yarn loop placement (for structural and/or non-structural stitching).

3.2 Stitching loop: assumptions

The experimental data discussed above reveal a number of micro-level phenomena (local v_f distribution, etc.). It is obvious that these features can be neglected when considering the meso-scale problem. This simplification will lead to physically sound and computationally feasible models sufficient for a correct estimation of the homogenized properties (stiffness, permeability, etc.). Therefore, several simplifying assumptions are accepted

- yarn is modelled as consisting of a single strand (in reality, it can be composed of several twisted strands);
- circular cross-sectional shape is preserved along the yarn path. Local deformation of the stitching yarn (compression, flattening) is thus not considered;
- elastic yarn bending is assumed in some cases; in other cases, the yarn bent shape is defined reasoning from purely geometric considerations;
- loop shape allows some mismatch for the tangent vectors at junctions of its different geometrical parts. In other words, the spatial rotation of the yarn path is not always smooth.

In the strict sense, first two assumptions can provoke an incorrect estimation for the permeability but no better solution can be done due to a strong randomization of the strand positions and shapes along a yarn path. For the out-of-plane stiffness and in-plane shear stiffness, varying cross-sections would have a negligible small influence.

Several assumptions are also accepted for the meso-level geometry

- piercing pattern is considered to be regular (constant stitching length and distance between seams). This is a reasonable simplification for a well-controlled robot process, although some irregular scatter is observed in reality;
- seams are straight (no zig-zag offset of the piercing pattern) and parallel. No initial shift is assumed between the seams (i.e., a rectangular piercing pattern is produced);
- transition of the stitching yarn between the preform faces is either straight or helical (spiral built around an imaginary straight line). In reality, the yarn path can often be inclined by a certain angle due to the movement of the stitching head, local deformation of the preform during the piercing, draping operations, compression during RTM, etc. This should play an important role for the estimation of the out-of-plane stiffness of the composite but is

difficult to be modelled without an unnecessary complication of the models.

In principle, the first two simplifications (straight seams and rectangular piercing pattern) can be excluded from the model without considerable computation efforts.

3.3 Stitching loop: sewing

This method is also known as double locked stitching (DLS) and employs two yarns. In StitchTex, it is assumed that both yarns are equal. The face yarn is lead through the laminate and twined with the second yarn at the backside. In a particular case, if both yarns experience equal tension, they are interlocked somewhere at the preform midplane, Fig.8. The opposite case (so-called modified plain DLS) occurs when the back yarn tension is high enough to keep it almost straight as shown in Figs.9 and 10.

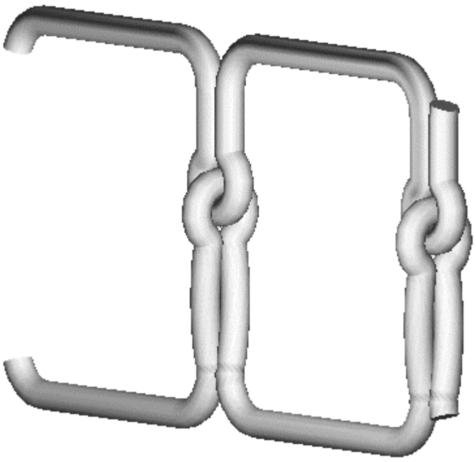

Fig. 8. General case of DLS stitching loop

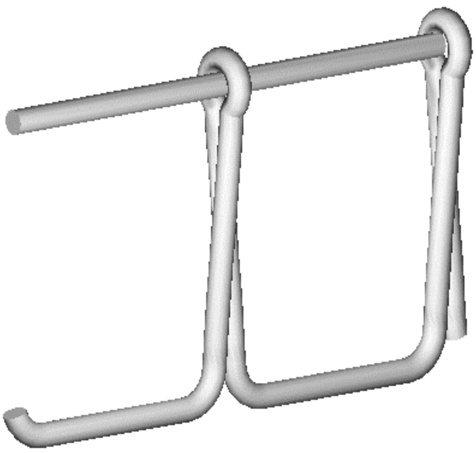

Fig. 9. DLS stitching loop with straight backside yarn (before sinking)

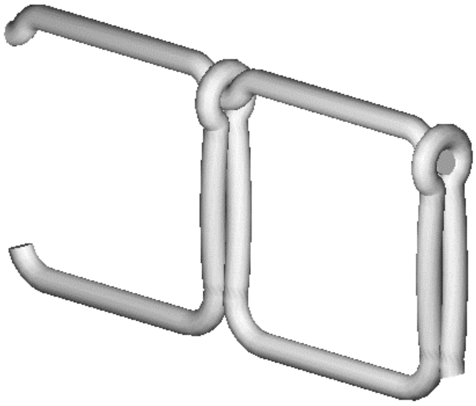

Fig. 10. DLS stitching loop with straight backside yarn (after sinking)

3.4 Stitching loop: tufting

Tufting is the simplest one-side stitching technique. A single hollow needle brings the yarn into the preform, forms a loop at the reversal point, and then goes back; the yarn stays inside the preform due to friction. Subject to the adjustable perforation depth, the backside loop can be hidden inside the preform ('short' loop), Fig.11, or can protrude over the backside, Figs.12 and 13.

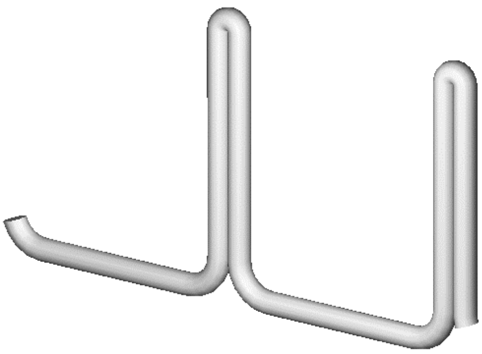

Fig. 11. 'Short' tufting loop

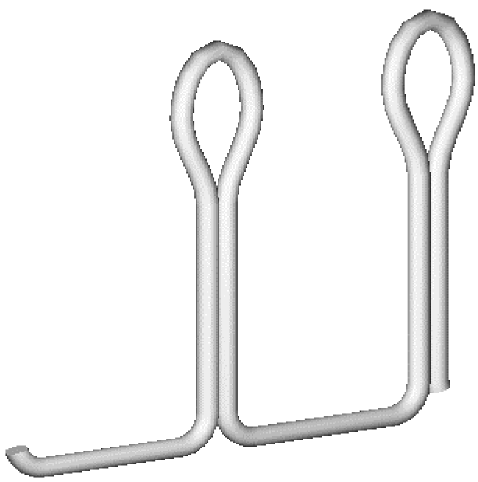

Fig. 12. Tufting loop before sinking

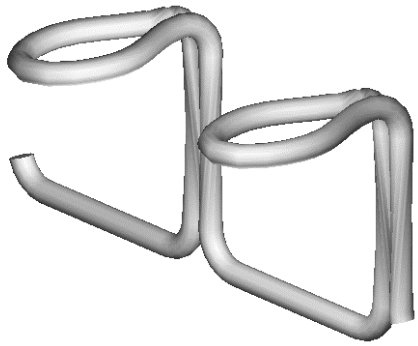

Fig. 13. Tufting loop after sinking

3.5 Stitching loop: dual-needle

In this process, the first needle leads the yarn through the preform. This movement causes a loop at the backside that is quite similar to the tufting loop. The second needle perforates the preform also, takes the loop, and pulls it back to the front side. Then, the grabber holds the loop, while the second needle stitches again through it till the backside thus causing a locked stitch. In practice, a few combinations of the infeed angles are mostly used: 45°-45°, 90°-90°, 45°-90°, and 90°-45° for the first or second needle, respectively. The second case (with 2 right angles) is shown in Fig.14.

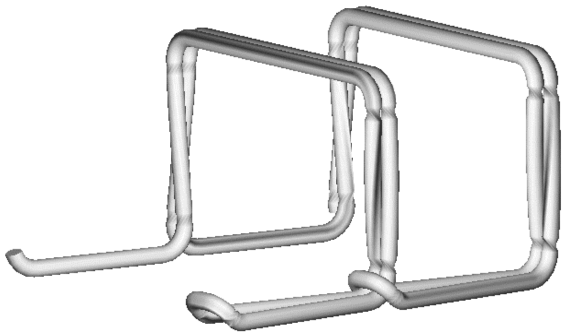

Fig. 14. Dual-needle stitching loop

3.6 Openings in the plies: assumptions

Only uni-directional fibrous plies are considered in WiseTex approach. The fibre distribution can either be even in the ply volume (excluding fiber-free 'openings') or have a defined disturbance sideways the openings (optionally). The model of the internal geometry of a structurally stitched preform presumes the following:

- preform is a flat stack of NCF or textile layers, each layer has uniform thickness;
- structural stitching pattern is defined by the stitching loop data;
- no openings exist in a preform composed of textile layers; the yarns volumes intersect with the textile yarns without their splitting. This is non-realistic simplification accepted due to impossibility to 'split' the WiseTex yarn object.

Several assumptions are also accepted for NCF fibrous plies:

- non-structural stitching (knitting) pattern is characterised by a regular warp-knit coding;
- prior to the first stitching (it can be non-structural or structural), the fibres are straight, parallel, and uniformly distributed in each ply;
- stitching distorts this distribution by introducing 'openings' (fibre-free zones). After a stitching, the local fibre orientation is always disturbed near the openings if compare with the global fibre orientation in the ply;

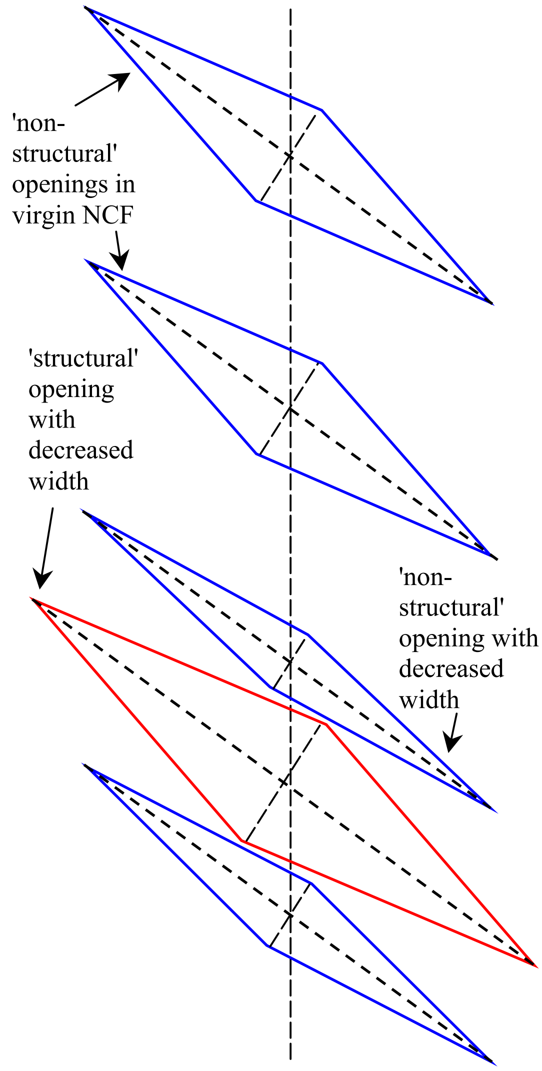

Fig. 15. Openings in a fibrous ply

- if NCF layers are stitched, the fiber-free zones caused by the stitching (both structural or non-structural) are diamond-shaped and symmetric. In reality, their shape is more complex, [1], but this is difficult to be accounted for. In particular cases, continuous channels can form in the ply;
- the width of an 'opening' is assumed to be either equal to the diameter of the stitching yarn in the inner plies or user-defined for both surface plies. As for the 'opening' length, it can either be user-defined or is calculated automatically using a simple analytical estimation;
- if the centre of a new 'structural' opening appears inside old 'non-structural' opening, the latter is absorbed by the former;
- if the long diagonals of 'structural' and 'non-structural' openings lie in one line and overlap, then one larger opening or continuous channel is formed in their place;
- if the areas of two 'structural' and 'non-structural' openings overlap and two previous conditions are not fulfilled, their widths are reduced to avoid the overlap and to provide some minimal thickness of the separating fibre streak, Fig.15.

In general, these assumptions describe the actual behaviour observed in the NCF preforms, [1].

4 Conclusions

The main results can be outlined as

- the general conclusion from the available experimental data is that a non-negligible variability exists in the micro- and meso-level geometry of a stitched preform. The parameters like a stitching density, thickness of a needle, penetration angle, etc. greatly influence the local geometry and, therefore, composite properties;
- since the unit cell of a preform (e.g., non-structural knitting pattern in an NCF) and unit cell of a structural stitching (piercing pattern) are not equal and are shifted in the general case, then the unit cell approach can not be used for the final (structurally stitched) preform;
- generalized geometrical models of structural stitching loops are presented for the sewing, tufting, and dual-needle stitching methods. The models are integrated with WiseTex textile modelling approach. This allows using a unified description of the meso-scale geometry of a textile reinforcement;
- the models can further be used for: a) geometrical visualisation, b) calculation of the overall fabric parameters (areal weight, fibre volume fraction) and local data (fibre volume fraction and orientation at a point), c) draping deformability estimations (using FEA or approximate analytical methods), d) estimation of the homogenized stiffness constants (TexComp software, voxel transformation in to an FE model), e) estimation of the permeability parameters (FlowTex software), g) creation of a general-purpose FE model (deformability, permeability, homogenized stiffness, damage onset and development, etc.);
- the proposed meso-level models disregard a number of the micro-level factors, which can nevertheless be important for an FE modelling of a local damage onset and propagation criteria. The micromechanics of damage would require a model with much more detailed description of the micro-level geometry (including its strong randomization).

5 Acknowledgements

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