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КЭ-МОДЕЛИРОВАНИЕ СЛОИСТОГО КОМПОЗИТА СО СТРУКТУРНОЙ ПРОШИВКОЙ

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FE MODELLING OF A STRUCTURALLY STITCHED MULTILAYER COMPOSITE

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С помощью МКЭ, на примере типичного слоистого углеродно-волокнутого композита, исследовано влияние различных детализаций структурной (т.е. сравнительно толстой углеродной нитью) прошивки в поперечном направлении. Расчёт показывает существенное увеличение поперечной жёсткости при прошивке. Побочным эффектом, однако, является заметная концентрация напряжений.

Finite-element models are presented for a typical structurally stitched carbon-fibre composite. The term 'structural' means that the stitching yarn is thick enough to form a through-the-thickness reinforcement. The influences of different model features are revealed. The stitching, on the one hand, is shown to increase the stiffness, especially its out-plane component. On the other hand, it creates prominent stress-strain concentrators.

1. Introduction. Structural (i.e. with a thick and strong yarn) stitching is used to ease the lay-up process as well as to improve the delamination resistance and out-of-plane stiffness of a textile composite; a similar idea is so called z-pinning. On the other hand, the advantages are accompanied by a significant distortion of initial fabric structure [1,2]. As indicated by earlier studies [3], this usually decreases (even slightly) stiffness and strength under in-plane tension or bending, although some improvements can sometimes be observed. The interlaminar fracture toughness is improved considerably, that naturally happens for high stitch densities. Limited data are obtained for the out-of-plane stiffness.

Since a theoretical approach is very limited in this case, the subject is usually addressed experimentally or using an FE analysis. The known FE research is broad for 'pure' NCF preforms, [4,5], less studies deal with z-pinned preforms, [6,7], and only a few articles address structurally stitched ones [8,9].

The present study focuses on a typical carbon-fibre non-crimp fabric (NCF) preform, unstitched or structurally stitched. It continues the previous work by the authors [9,10] and aims to explore a typical influence of several modeling features on the stiffness response and strain distribution. The results are validated with experimental data reported in [2].

Table 1. Measured dimensions of the surface 'openings' and stitching yarn, mm.

composite	length	width	yarn width	loop height	loop width
unstitched	4.1±0.9	0.4±0.1	--	--	--
stitched	6.2±1.0	0.9±0.2	1.0±0.2	1.4±0.2	1.8±0.2

2. Materials. 0/90° and ±45° Saertex NCFs having the areal weights of 556 and 540 g/m² are used. Zero is the machine direction of production of NCF, or that of the non-structural stitching. The areal weight of ±45° and 90° plies is 267 g/m², while 0° ply weights 283 g/m². Tenax HTS5631 fiber bundles are knit together with a thermoplastic yarn (7.4 tex, 2.6×5 mm pattern, 6 g/m²). The lay-up is [45/-45/0/90/45/-45]_s, resulting in a 4.2 mm thickness in the dry state.

For the structural stitching (tufting), 1K Tenax HTA 5241 carbon rowing is employed with a 5×5 mm piercing pattern. The machine direction coincides with 0° direction of the preform, Fig.1. During the knitting and tufting, fiber-free 'openings' appear; they are oriented along the global fibre orientation in a ply. More details on the geometrical characterization are reported in [2].

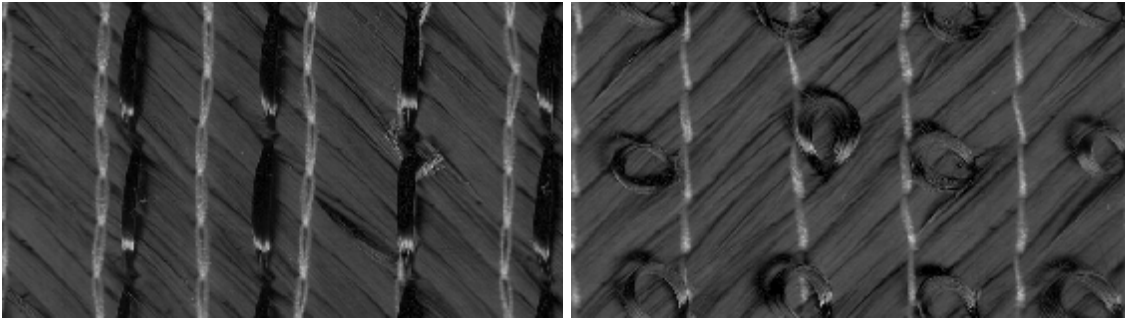


Fig.1. Face side (left) and backside (right) of a stitched preform.

Composite plates (stitched and non-stitched) are produced by means of Vacuum Assisted Process technology, using HexFlow RTM-6 epoxy resin. The average thickness is 3.3 mm that gives the fibre volume fraction (V_f) of 55%.

Several pieces are inspected with a microscope for the dimensions of openings, Table 1. Taking an average rhomboid 6.2×0.9 mm 'structural' opening, it can be estimated that the openings occupy about 11% of the total volume, and local V_f after the stitching is thus about 67%. If a single 4.1×0.4 mm 'non-structural' opening is also included, this increases the local V_f by another 3%.

The material properties – Young's modulus, E, Poisson's ratio, ν, etc. – of the main constituents are listed in Table 2.

Table 2. Properties of the composite constituents (longitudinal / transversal)

	fibre Ø, µm	twist, t/m	density, g/sm ³	lin.dens,tex	E, GPa	ν
ply	7	0	1.77	--	240/14	.27/.028
stitch	7	S15	1.76	67	238/14	.23/.014
resin	--	--	1.14	--	2.9	0.38

3. Modelling assumptions. When modelling, such complex structure as a textile composite is inevitably simplified [11,12]; there is no possibility to account for all randomized real features. This brings up a question about the degree of idealization; e.g., in the present case: to model or not to model the 'openings' and the stitching yarn. The following assumptions are accepted here:

a) the non-structural knitting yarn is disregarded, since its mechanical properties are very close to those of the cured resin.

b) the structural stitching loop is presented as a through-the-thickness 'pin' having a cylindrical cross-section and ultimately packed until $V_f=91\%$ (to reduce its radius). The test data reveal that the cross-sectional shape and fibre distribution inside a yarn can be much randomized. Also, the cross-sections of two neighboring yarns (as well as their strands, if any) often interpenetrate each other. Here, an idealized case is studied, when two yarns are modelled as a single one having elliptic cross-section and uniform V_f distribution.

c) this 'pin' is positioned vertically. In reality, it can be inclined due to specifics of stitching, while draping, during compression in the mould, etc. This can play a role for the out-of-plane stiffness but is difficult to be measured. Also, the yarn twist is not accounted for in the homogenized stiffness.

d) the openings are diamond-shaped or continuous (channel-like) in the plane and perfectly oriented along the global fibre orientation in the ply. Their width is equal in all the layers; this is a simplification, since real openings may have different widths in different plies, especially in the surface ones [1,9].

e) a local fibre re-orientation sideways the openings and a local fibre densification between them are not modeled. If an opening is introduced in the ply, its V_f is increased uniformly, according to the changed volume.

f) the plies are not nested. Thus the composite is a stack of flat plies which have equal uniform thickness, and their bounding boxes do not intersect. In reality the plies can heavily be nested and even deplaned by the out-of-plane compression when consolidating the laminate in the mould [2,9].

4. FE modelling. A parametric model of a 5×5 mm unit cell is built with standard Ansys tools, using the data given in Tables 1 and 2. The macros creates

a) unit cell consisting of a number of homogenized (by Chamis' formulae) plies, with the local co-ordinate systems defined according to the lay-up.

b) rhomb-like (in $\pm 45^\circ$ plies, $V_f=60\%$) or continuous channel-like (in 0° and 90° ones, $V_f=64\%$) openings having the properties of isotropic matrix material.

c) structural stitching as a cylindrical homogenized (also by Chamis' formulae, at $V_f=0.91\%$) z-pin inserted at the centre of the model.

These components are shown in Fig.2. For a comparison, an 'unstitched' model is studied also, when the ply properties are assigned to the openings and stitching, and the average V_f is calculated for the whole model volume. Another comparative model contains openings but without the stitching yarn (in this case its volume is modelled as having the matrix properties).

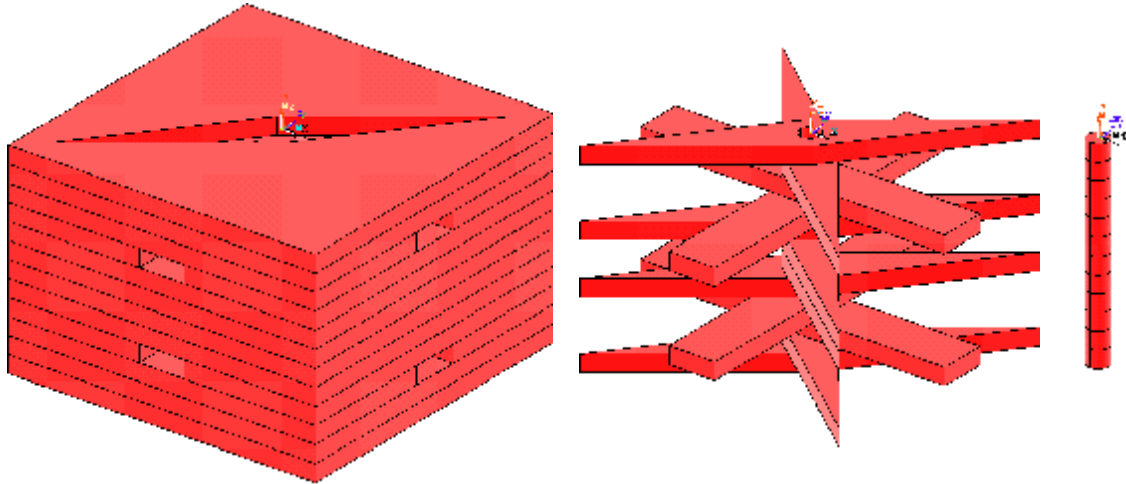


Fig.2. FE model components (plies, 'openings', and stitching).

The last but not the least problem is how to build volumes for the plies. The simplest way is to create one opening in each ply and then glue the volumes to achieve the mesh connectivity at the interfaces of the plies. This results in a relatively small number of volumes (40 in the present case) but they are hardly collated into components (plies, openings, yarn – see Fig.2), since VGLUE command causes unpredictable re-numbering of the volumes. Also, in a general case, this does not produce identical meshes at the opposite sides of the unit cell, to pose the periodic boundary conditions in their exact formulation (although this is still possible but in an approximate way). Only tetrahedral mesh is available in this case. Typical patterns of volumes are shown in Fig.3(a,b).

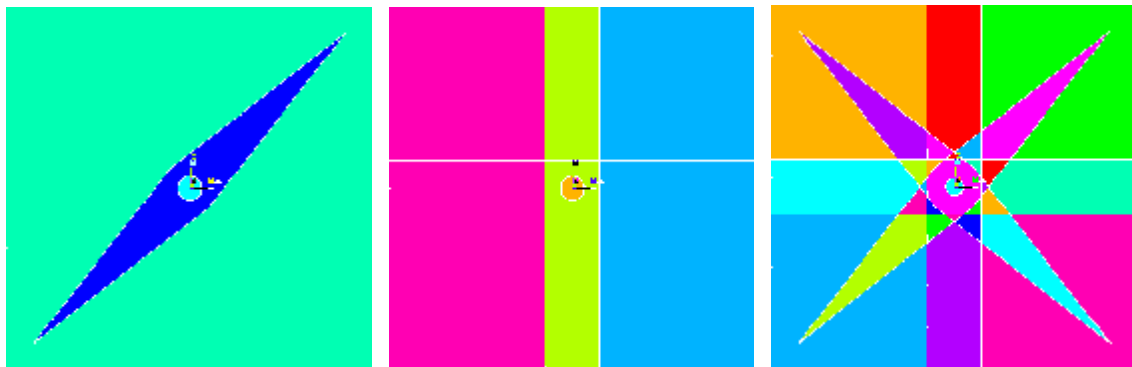


Fig.3. Variants of the volume partitioning in the FE model.

An alternative is to create projections of all the openings as areas, make partition, and then extrude the areas ply-by-ply (taking areas of the previous ply as the pattern). This creates identical meshes at the opposite unit cell sides but results in a large number of volumes (360 in the present case). Many of these volumes are small and can badly be shaped in a general case, causing too fine and sharp mesh. A typical pattern of volumes is shown in Fig.3(c). On the other

hand, this way allows for hexagonal elements, and thus it is possible to create a simplified model with only one element per the thickness of each layer.

5. Results and discussion. This short paper focuses on the elastic properties only. First the homogenized compliance matrices are calculated, under the periodic boundary conditions. Then the Young's moduli are assessed, Table 3.

Table 3. Stiffness under MD (0°), CD (90°), BD (45°), and transversal (z) loading.

	E_0	E_{90}	E_{45}	E_z
test data, unstitched [2]	39.3 ± 2.5	41.4 ± 1.6	--	--
test data, stitched [2]	38.9 ± 1.7	40.1 ± 2.1	--	--
classical laminate theory	39.9	39.9	57.6	7.0
FEA, uniform plies	38.8	38.8	57.0	7.8
FEA, opening, no yarn	38.8	38.9	55.6	8.0
FEA, opening + yarn	38.9	38.9	55.7	8.8

The FE results agree well with the experimental data for the in-plane tension. They show that the influence of stitching is very minor. However, introduction of the stitching yarn improves the transversal stiffness by 10%.

Figure 4 shows typical stress distributions under in-plane shearing. It is seen that there is a strong stress concentration near the opening; thus, they can trigger earlier damage. Nevertheless, for the present case the acoustic emission indicates a lower crack development in the tufted specimens [2].

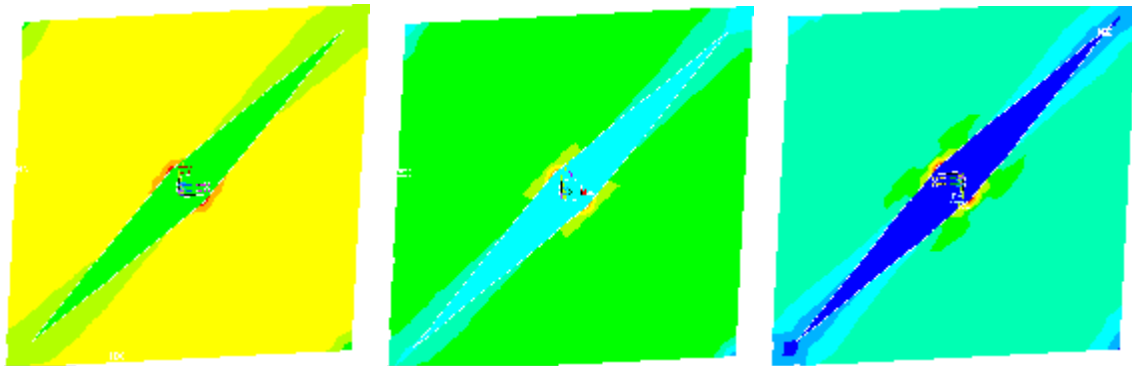


Fig.4. Normal, shear, and von Mises stresses in the surface ply. Shear loading.

6. Conclusions. This paper deals with the meso-level FE modeling of a structurally stitched NCF preform. The influence of modelling features on the homogenized stiffness and stress distribution is addressed. The main results are

a) the structural stitching produces a negligible influence on the in-plane stiffness components; this corresponds to the most of earlier results [3].

b) the stitching significantly improves the transversal stiffness. To account for this, a simple 'pin-like' model is sufficient, instead of a detailed modelling of the yarn loop shape. The openings can also be omitted in this case.

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