# NUMERICAL STUDY OF THE RELATIONSHIP BETWEEN TRANSVERSE MATRIX CRACK DENSITY AND APPARENT STIFFNESS OF TEXTILE REINFORCED COMPOSITES

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## Abstract

*A new computational chain is used for the numerical analysis of transverse cracking in textile composites. The method relies on the solution of a boundary value problem on the unit cell representative of the architecture of the composite by the finite element method. Automated crack insertion is possible which allows the analysis of the loss of stiffness and of the evolution of the strain energy release rate due to an increase of the crack density. Preliminary results are presented on a fictitious composite unit cell.*

## 1 Introduction

### *1.1 Transverse (micro-)cracks in laminates*

The first damage mechanisms to occur in composite materials under monotoneous or cyclic loading (provided a tensile deformation mode is present) are generally matrix cracking and fibre/matrix interface debonding transversely to the ‘principal’ loading direction. This early damage accumulation can be directly or indirectly detected using various techniques (optical microscopy on the edges of samples, acoustic emission, X-ray radiography, micro-computed X-ray tomography, …) and quantified. Usually, the number of cracks or the total crack length per sample unit width is reported as a function of the macroscopic strain or of the number of load or (hygro)thermal cycles.

Depending on the stacking sequence and on the stress transfer to the examined ply, this early fatigue damage mechanism is generally shown to saturate at a given value, corresponding to a state where the strain energy release rate drops below the resistance to micro-cracking of this specific ply material. Some authors report that this value is consistent with the interlaminar mode I fracture toughness ([1,4]).

Again, depending on the stacking sequence, thickness and architecture (including the balanced / un-balanced character) of the plies, the transverse cracking scenario will somewhat differ in cracking rates and saturation values. Moreover, edge effects can be observed with a strong competition between transverse crack initiation and propagation (along the yarns or fibres) (see for instance [6]).

In 'perfect' cross-ply laminates made of UD plies, the occurrence of cracks is controlled by a statistical distribution of local strength, also associated with variations of the micro-geometry. In other circumstances, any local meso-heterogeneity will promote transverse cracking by introducing defects or acting as a stress-riser (stitches, tracers, …). For instance, transverse damage in NCFs can be trigerred by the 'stitches'. In most biaxial weaves, transverse cracking will most probably occur at tow ends, or in resin rich regions. Several transverse cracks can sometimes be observed in a single yarn. This must obviously be nuanced by the variability of the local architecture.

The apparent properties of the laminate are affected by the presence of those micro-cracks. Notably, a reduction of the Young's modulus in the main loading direction is generally observed, while the residual strength after fatigue can also be affected by transverse cracking. Therefore, it is of utmost importance to predict the resistance of the material to micro-cracking, and to determine the effect of the crack density on the mechanical properties and the saturation crack density.

A large research effort has already been dedicated to the modeling of damage in composites in order to predict the in-service response, including damage tolerance. Among these efforts, a class of models is dedicated to the description the stress-strain state of cross-ply laminates with transverse cracks (and for some of them local delamination). Shear lag type models and related approximations ([1-6]) are used to determine the stress and stress fields in the plies and readily compute the strain energy release rate and the elastic properties of laminates with transverse cracks, under static and cyclic mechanical or thermal loads. In this frame, the so-called 'finite fracture mechanics', initiated by Hashin [5], has been used for instance by Nairn [1,3,4] to reverse engineer some intrinsic resistance to micro-cracking for cross-ply laminates made of UD-plies. With another approach, essentially based upon the experimental identification of a damage evolution law, Talreja and coworkers (e.g. [7]) have derived the relationship between crack density and stiffness for a range of composites.

This contribution presents an application of the 'finite fracture mechanics' concepts to the transverse cracking of composites with woven reinforcement based upon a fine discretization of the geometry of the representative unit cell and the use of the finite element method to solve the boundary value problem. A CAD/CAE chain has been developed for that purpose. The evolution of the apparent elastic properties and of the strain energy release as a function of the transverse cracks density is illustrated here for a fictitious plain weave reinforcement.

## 2 Description of the computational chain

A new computational chain has been developed based upon the following software:

- TexGen [10,11] for the geometrical modeling of the reinforcement;
- Gmsh [12] for the handling of the geometrical model and the automated meshing;
- Abaqus [13] for the solution of the boundary value problem by the finite element method.

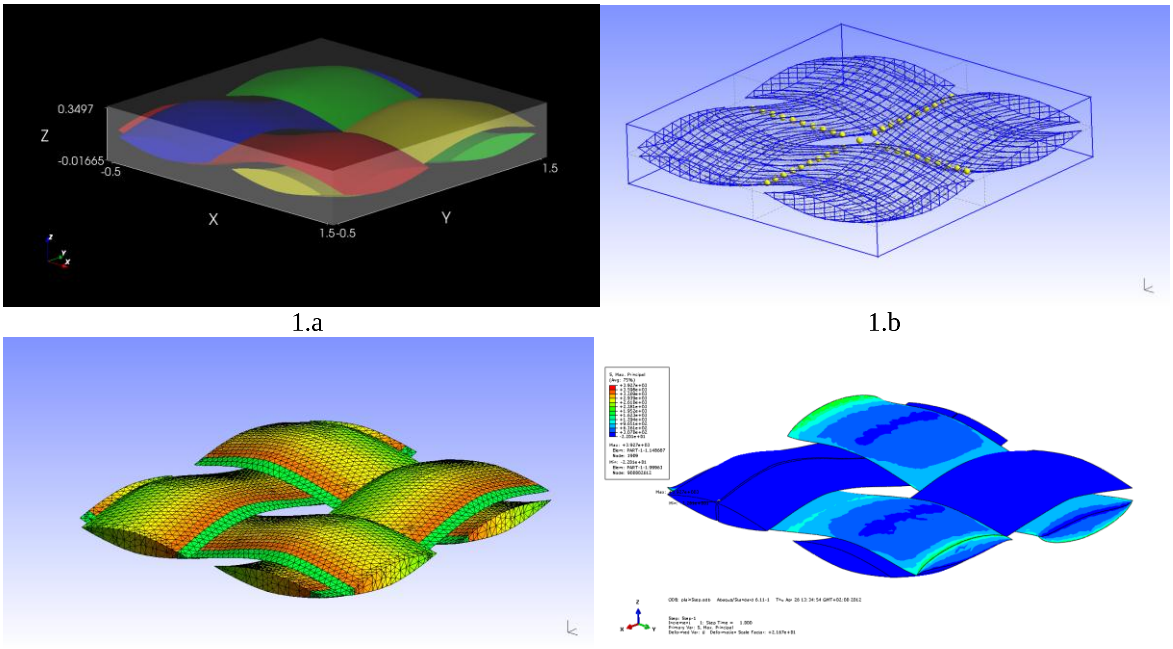
Besides, parameterized Python routines have been written in order to

- generate and export geometries to Gmsh;
- generate the material orientations in the yarns;
- generate transverse cracks in the yarns by node duplication;
- generate boundary conditions, including periodic BCs;
- export Gmsh meshes and write Abaqus input files;
- perform homogenization of the stress and strain fields per phase on the unit cell.

Minimal manual intervention is required with the exception of minor manual modifications of the mesh when the implemented 3D mesh optimization algorithms of Gmsh locally fail to create acceptable elements – essentially when large volume fractions of fibres are concerned, with very small gaps between the yarns.

Python routines incorporating the TexGen principal functions for creating textiles are used. A very simple example of plain weave reinforcement is shown in Figure 1.a). The geometry description created by TexGen is then used to create a Gmsh geometry illustrated in Figure 1.b). The various geometrical features (points, lines, nurbs, faces, volumes) are automatically numbered and/or named in a consistent way for future application of boundary conditions. Gmsh is then used to mesh the geometry with sub-parametric second order tetrahedra (see Figure 1.c) without the matrix).

Python routines are used to generate the Abaqus input files, including the distribution of orientations for the elements in the yarns (the yarns are assigned transversely isotropic properties computed from a mean field homogenization on a representative volume element of a UD composite). Transverse cracks in the yarns can be specified and are automatically created. The problem is then solved using Abaqus Standard (Figure 1.d).



1.a 1.b

1.c 1.d

**Figure 1.** The four steps of the creation of the finite element model: 1.a: geometrical model in TexGen, 1.b: geometrical model in Gmsh, 1.c: automated meshing in Gmsh, 1.d: input files creation and solution of the FE problem. Figure 1.d shows an internal crack in one of the yarns.

The present contribution is in line with numerous works dealing with the development and use of computational chains for the analysis of the composite microgeometry (e.g. WiseTex [9] or the Digital Element method [10]).

## 3 Preliminary Results

The architecture illustrated in Figure 1 has been used for the sake of illustration of the methodology. The geometry was meshed with approximately 160000 2$^{nd}$ order tetrahedra, corresponding to a similar number of degrees of freedom. In this first example, symmetry boundary conditions were used on all the unit cell faces, which is more constraining (and thus apparently stiffer) than periodic boundary conditions. No specific global (strain energy) or local (local stress values) mesh convergence studies were performed.

The fictitious composite presented here above is subjected to uniaxial loading (load control case) with increasing transverse crack density, assuming the following scenario for the introduction of new cracks (see Figure 2, proposed here for the sake illustration, i.e. not directly supported by a physical observation):

1. No crack
2. Two transverse cracks in YARN1
3. Situation 2 + two transverse cracks in YARN2 (meaning 4 transverse cracks)
4. Situation 3 + two more transverse cracks in YARN1 (meaning 6 transverse cracks)
5. Situation 4 + two more transverse cracks in YARN2 (meaning 8 transverse cracks)

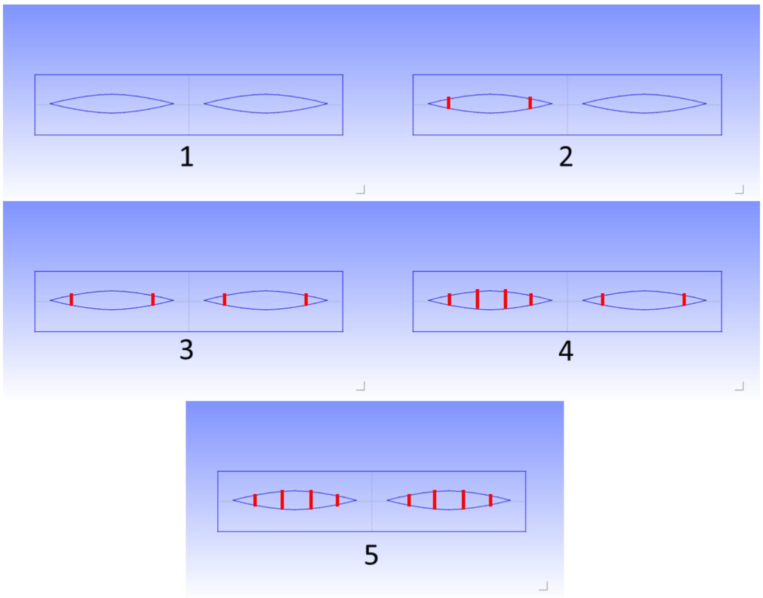


**Figure 2**. Transverse cracks insertion scenario.

In this example, the crack width is limited to the local yarn height, although it is highly probable that the cracks would also run through the adjacent resin rich zones in such a low volume fraction condition. Nevertheless, in more closely packed conditions (e.g. 5HS RTM6 + G0926 IM7 with fibre volume fractions of up to 0.57, see [12]), a crack having the width of a single yarn is realistic due to low fraction of resin rich regions.

The computed evolutions of the strain energy and stiffness (in the direction orthogonal to the cracks) of the unit cell are summarized in table 1.

| Linear crack density (#/mm) | Crack density (mm/mm$^2$) | Normalized strain energy $SE/SE_0$ | Normalized Young's modulus $E/E_0$ |
|---|---|---|---|
| 0 | 0 | 1 | 1 |
| 1 | 0,15 | 1,01049345 | 0,98961552 |
| 2 | 0,3 | 1,02064706 | 0,97976957 |

| | | | |
|---|---|---|---|
| 3 | 0,53 | 1,03118875 | 0,96975354 |
| 4 | 0,76 | 1,04182033 | 0,9598574 |

**Table 1.** Evolution of the normalized strain energy and normalized Young's modulus as a function of the crack density

Table 1 shows that both the strain energy and the Young's modulus evolve linearly with the linear crack density, which means that no saturation has been reached yet. Therefore, it is not possible from these data to already infer a so called resistance to micro-cracking. As in laminates made of stacked UD plies, relatively high crack densities can be reached before saturation, corresponding to a crack spacing which implies no more 'load-carrying capability' of the transverse plies. In the example presented here, only a limited cracked area is introduced, this means that part of the load is still carried or transferred by the matrix and the transverse yarns.

## 4. Conclusion

This contribution presents an automated computational chain for the analysis of transverse cracks in composites with woven reinforcements. Preliminary results are shown on a simple plain weave architecture in order to demonstrate the capabilities of the method. The method is currently being used to analyze the loss of stiffness of $[0]_8$ laminates made of (RTM6 + G0926) plies under uniaxial tension-tension fatigue. The method shall also be compared to standard analytical methods.

## 5. Acknowledgement

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## References

[1] Liu, S., Nairn, J.A., Fracture mechanics analysis of composite microcracking : experimental results in fatigue, in "*Proceedings of the 5th technical conference on composite Materials, American Society of Composites*", East Lansing Michigan, June 11-14, 1990.

[2] Ogin, S.L., Smith, P.A., Beaumont, P.W.R., A stress intensity factor approach to the fatigue growth of transverse ply cracks, *Composite Science and Technology,* **24**, pp.47-59, 1985.

[3] Nairn, J.A., The strain energy release rate of composite microcracking: a variational approach, *Journal of Composite Materials,* **23**, pp.1106-1124, 1989.

[4] Nairn, J.A., Matrix microcracking in composites, in R. Talreja, J.A.E. Manson, Editors , *Fatigue of polymer matrix composites,* Elsevier Science (2001).

[5] Hashin, Z., Analysis of cracked laminates : a variational approach, *Mechanics of Materials,* **4**, pp. 121-136, 1985.

[6] Lafarie-Frenot, M.C., Henaff-Gardin, C., Formation and growth of 90° ply fatigue cracks in carbon/epoxy laminates, *Composites Science and Technology,* **40**, pp. 397-324, 1991.

[7] Chandra Veer Singh, Ramesh Talreja, Evolution of ply cracks in multidirectional composite laminates, *International Journal of Solids and Structures,* **47**, pp. 1338–1349, 2010.

[8] Verpoest, I., Lomov S.V. (2005). Virtual textile composites software WiseTex: Integration with micro-mechanical, permeability and structural analysis. *Composites Science and Technology*, **65**, pp. 2563–2574.
[9] Miao, Y. Eric Zhou, Youqi Wang, and Cheeseman, B. (2008). Mechanics of textile composites: Micro-geometry, *Composites Science and Technology*, **68**, pp. 1671-1678.
[10] Sherburn, M., Geometric and Mechanical Modelling of Textiles, PhD thesis University of Nottingham, 2007
[11] TexGen 3.5.0 software, http://txgen.sourceforge.net
[12] Geuzaine, C. and Remacle, J.-F., Gmsh: a three-dimensional finite element mesh generator with built-in pre- and post-processing facilities, *International Journal for Numerical Methods in Engineering*, **79**, Issue 11, pages 1309-1331, 2009.
[13] Abaqus v6.11, General Purpose Finite Element Software