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Title: **Accounting for manufacturing effects in composites virtual prototyping.**

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Abstract

The presentation will review several examples of the effects of the manufacturing process and of the means to incorporate them, directly or indirectly, in the simulation of the shock or crash events. The use of the virtual material characterization is a key ingredient in addressing these issues (effects of manufacturing and new textile architectures) and it will be presented.

1. Introduction

It is generally felt that the numerical simulation of composite materials has not reached the required level to fully support the long-time promised explosion of the use of composite materials. One of the reasons is that the effects of the manufacturing and assembly processes are not taken into account in the assessment of the mechanical performance of the composite structures (statics, strength and crash). The manufacturing effects include the fiber reorientation, the thickness variations, the local fiber content variations, the fiber waviness, the micro and macro porosities, the degree of cure and of crystallization, the degree of intimate contact, the tows sections deformations, etc. Another reason is the lack of modelling tools for the ever increasing textile architectures put on the market. Because of these large domains of incomplete control of the knowledge and technology, the industry relies on large safety margins, at best involving statistical tools, that lead to add plies and therefore mass, hindering the full fruition of the lightness of the composite materials.

2. Effects of preforming onto dry reinforcement impregnation

In this section, one will start by reporting about the effects of the preforming onto the reinforcement impregnation.

a. Example of the impregnation of a hemisphere.

This example is one of the first example reported, it traces back to the 2002 german SAMPE (1) and is due to a team of the InstitutfürVerbundwerkstoffe at Kaiserlautern, Germany. The figure 1 shows the RTM (Resin Transfer Molding) impregnation of a dry fabric placed in an hemispherical mold using a pole injection and the finite element simulation based on the Darcy equation using a uniform permeability (one can see a filling time contour plot showing a circular radial flow front evolution). One reminds that the Darcy equation relates the flow front velocity (V) through a porous medium to the pressure (P) gradient using the resin viscosity (μ) and the preform permeability ([k]) material properties:

V= [k]/μ .grad (P)

One can observe a clear discrepancy between the experimental results and the numerical simulation results.

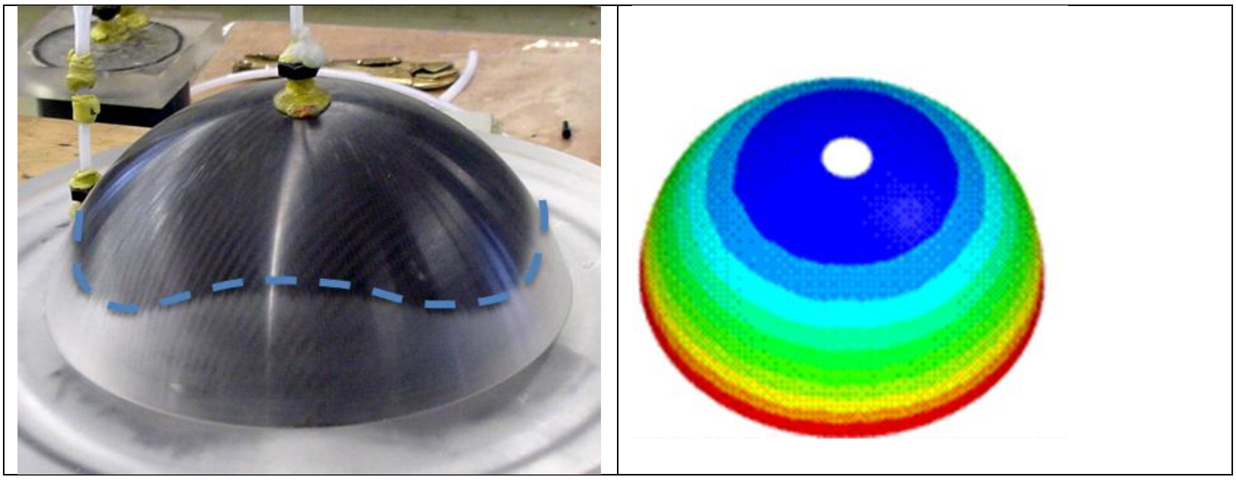

Figure 1: RTM injection of an hemisphere: experiment and simulation

Actually, the permeability is not a number but a tensor and one must use the permeabilities of the warp and of the weft direction. But this is not sufficient to obtain a correct simulation. During the preforming of the dry preform, there is a reorientation of the fibers that happens and significant shearing up to nearly 40° can be observed over the preform as can be seen on the figure 2.

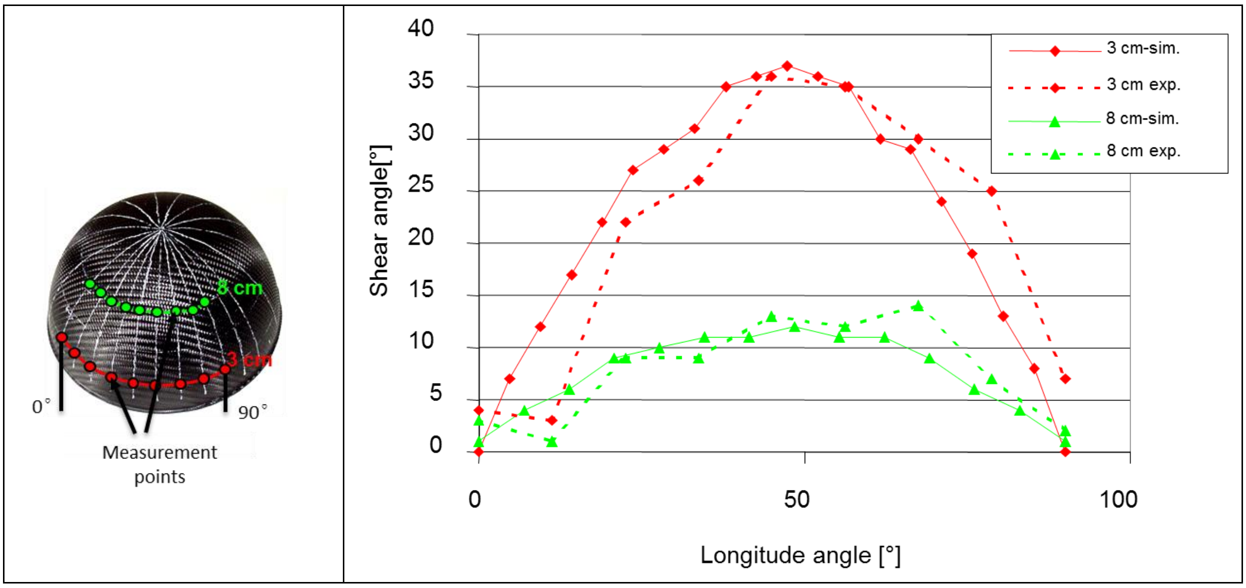

Figure 2: Experimental measurements of the shearing angle along two parallels.

Indeed, using a permeability field varying with the shearing angles and using the contour map of the shearing using a finite element simulation (PAM-

FORM), IVW was able to get a good correlation between the experiment and the simulation – see figure 3.

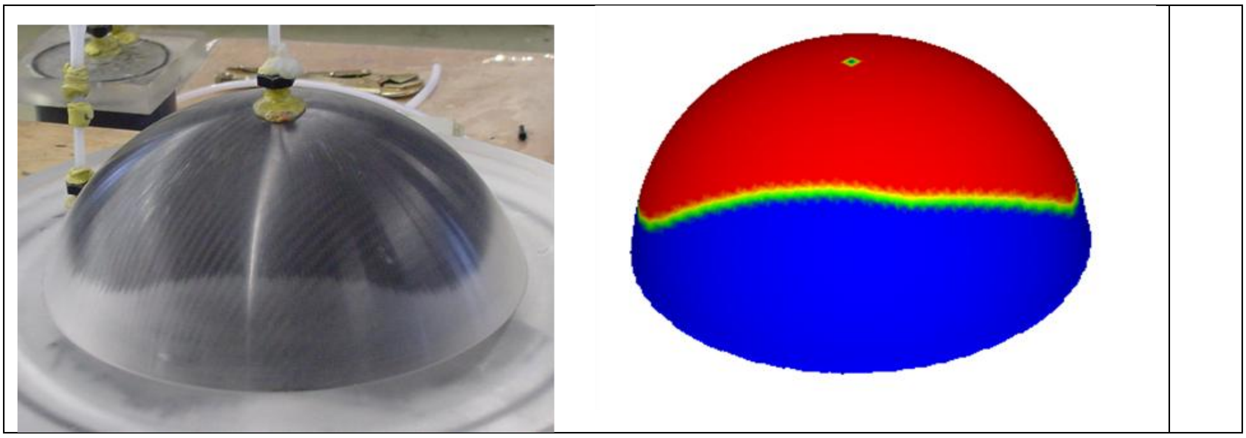

Figure 3: Comparison of the injection experiment and of the simulation based on actual shearing and associated permeability.

These phenomena are now well understood and can be taken into account in commercial software. The description of the fiber reinforcement reorientation may come from geometric but also directly from the machine creating the preform in case of fiber placement (AFP process, AFP standing for Automatic Fiber Placement) or braiding machines.
Note that additional material data are needed to be able to run such an injection simulation, namely the permeability as a function of the shearing angle of the woven preform.

b. Volume fiber content (V_f) variations around a radius

The permeability is obviously strongly dependent on the fiber volume content: one can refer for example to one of the first model: the Kozeny Carman model (2). Looking at a typical section of the fiber distribution in a radius, one can see again a preforming effect onto the reinforcement impregnation.

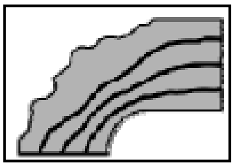

Figure 4: Section of a laminate around a radius showing the higher Vf close to the inner radius and the free space left for an easy resin flow close to the outer radius.

In this section, we only focused on the impregnation consequences of the dry preform. One will see in section 6 that actually the mechanical properties are modified according to the flow velocity and therefore according to the preforming.

3. Effects of textile processing onto subsequent forming steps

In this section, one will cover some additional effects of the textile technology used in the manufacturing.

a. Example of deviations of the fiber paths in the braiding process

For the braiding process, there is no possible direct transfer of machine commands to a full description of the fiber paths to be used in the mechanical simulation tools. One option is the use of analytical formulae. The figure 5 shows a comparison of a specific yarn path using analytical analysis and FE simulation (3). It shows that a full FE simulation is needed if one needs accurate fiber paths.

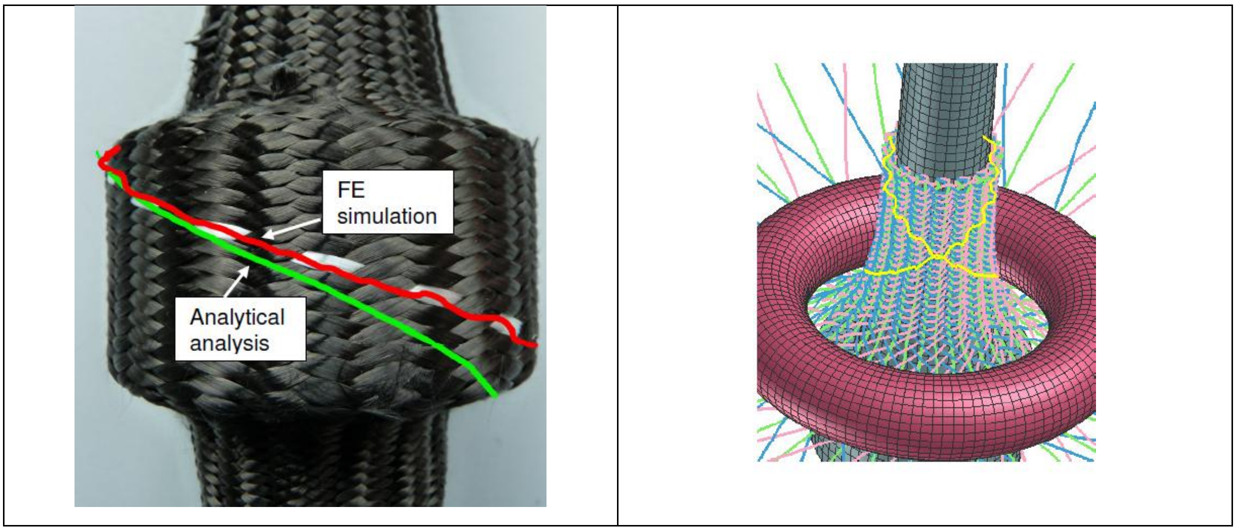

Figure 5: LHS: Manufactured braided preform and a comparison of analytical and FE prediction of a particular yarn path. RHS: view of a braiding simulation.

The last remark can extended to AFP and ATL (Automatic Tape Laying) because when the curvature of the part needs steering, gaps and overlay appear in the preform that departs from the targeted ideal design definition of the reinforcement.

b. Example of tows section modifications in the braiding process

Up to now, we have only considered the fiber paths themselves, but the textile technology also modifies the tows sections during the processing and creation of the fabrics or the braid. One can see on figure 6 a micrograph of a braided preform; to really account for this state of yarns deformations, a FE simulation is necessary.

This kind of result needs to be appreciated with in mind the way this kind of phenomena is handled in the industry and in the academic world. Usually, *a priori* distribution of fibers is assumed or mathematical tools are used to provide some fiber distribution or these variations are accounted for through stochastic methods.

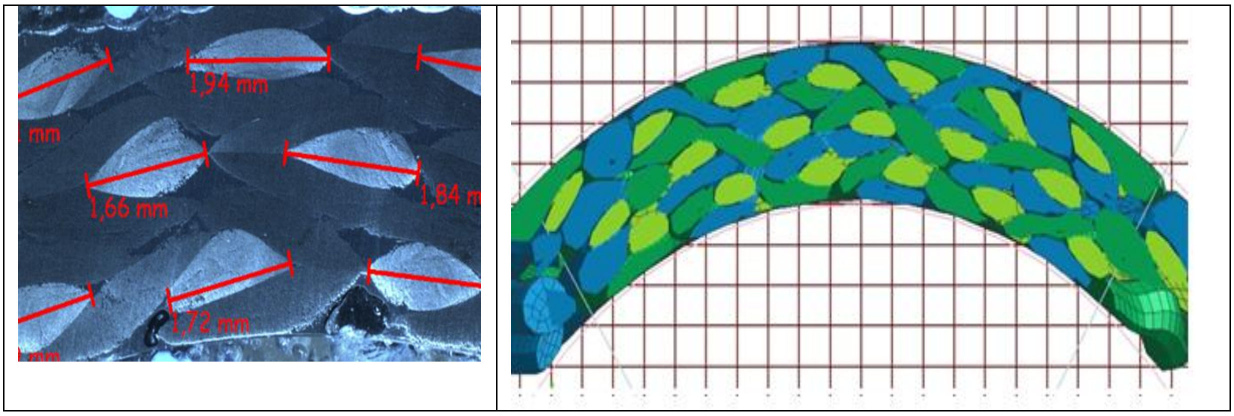

Figure 6: LHS: Micrograph of a braided preform. RHS: section of the associated braiding simulation.

Note that we do not pretend that it is possible to ask to the simulation to provide a comprehensive description of the reinforcement and of the composite itselfin a fully deterministic way. But we claim that manufacturing simulation should be used in order to provide a first realistic description of the composite part and that one should start tackling the various variabilities involved in a composite part earlier in the part manufacturing. That is the variability should be addressed at the yarn level and at the manufacturing process parameters variations level and not at design stage.

4. <u>Effects of preforming onto mechanical performance</u>

In this section, one will report some examples of fiber reorientation onto the mechanical performance.

a. Effect of fiber reorientation on first ply failure analysis

The work reported here was performed in the European FP7 FALCOM project. A four points bending test of an aeronautical frame was performed by EADS/M at Ottobrunn, Germany. Simulations were conducted using the design definition of the fiber orientations and using the fiber orientations coming from a draping simulation. Using commercial software based on idealized fiber orientation and a classical failure criterion like the Tsai-Hill criterion, one calculates a failure at the axis of symmetry. One can see a better prediction of the failure location on the figure 8. This improved result is obtained using the fiber orientation coming from a preliminary simulation of the draping operation (4).

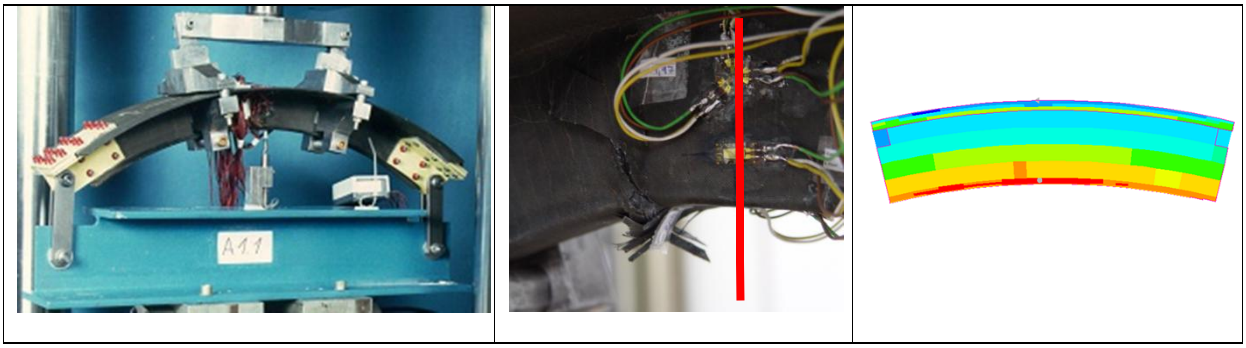

Figure 8: View of the test setting; view of the offset of the failure w.r.t. the (red) axis of symmetry; Tsai-Hill contour plot based on simulated fiber orientation.

b. Effect of fiber reorientation on progressive damage simulation

The effects of the manufacturing process on catastrophic failure seen in the last section are the result of the evolution of damage in the composite part. One reports here the effects of the manufacturing process onto the progressive damage evolution itself. The mathematical model of the damage used in this example is the popular Ladevéze model(5). In the works of L. Greve and A.K. Pickett (6), the material characterization tests usually run to be able to simulate with the Ladevéze model are done not only for the undeformed coupon from the roll but also for pre-sheared sample, that is at the four following pre-shearing values, +10°, - 10°, +170 and -17°. The characterization is used to punch various deformable dics with various pre-shearing values and the results are seen on the figure 9 extracted from (6).

Note again that additional material testing is required if one wants to simulate the actual composite discs.

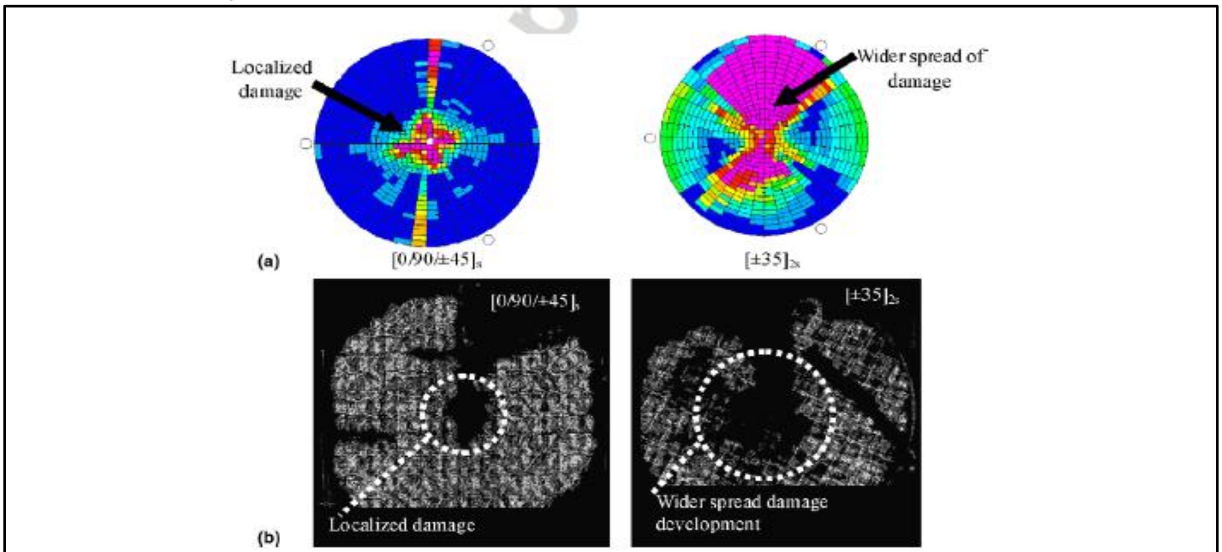

Fig. 17. Comparison of computed matrix damage development and ultrasonic C-Scans for the NCF composite discs: (a) qualitative comparison of computed average matrix damage development in a quasi-isotropic $[0/90/\pm45]_s$ NCF disc and a pre-sheared $[\pm35]_{2s}$ NCF disc transversely loaded using the large (∅50 mm) punch, (b) ultrasonic C-Scans of the quasi-isotropic $[0/90/\pm45]_s$ NCF disc and the pre-sheared $[\pm35]_{2s}$ disk showing different degrees of internal damaging (dark regions) after transverse loading with the (∅ = 50 mm) punch.

Figure 9: Results of progressive damage analysis on two punched pre-sheared composite discs.

5. <u>Effects of textile processing onto mechanical performance</u>

Having the objective to use the manufacturing results in mechanical performance simulation, generating the manufacturing process simulation results is not enough to improve the mechanical performance assessment. In this section, one would like to stress the need for having mechanical simulation software that can actually use these simulation results.

In the following example an additional ingredient is introduced in the modeling. The part studied is a composite mudguard (7). But, at the difference of the approach used for the aeronautical frame described in section 3, the stiffness modification is not restricted to a modification of the fiber direction and rotations of the stiffness matrices. Here, all the elastic stiffness coefficients are calculated again using TEXCOMP (8). That enables to take into account the intra-tow deformations resulting from the shearing and from the interactions between the warp fibers and the weft fibers.

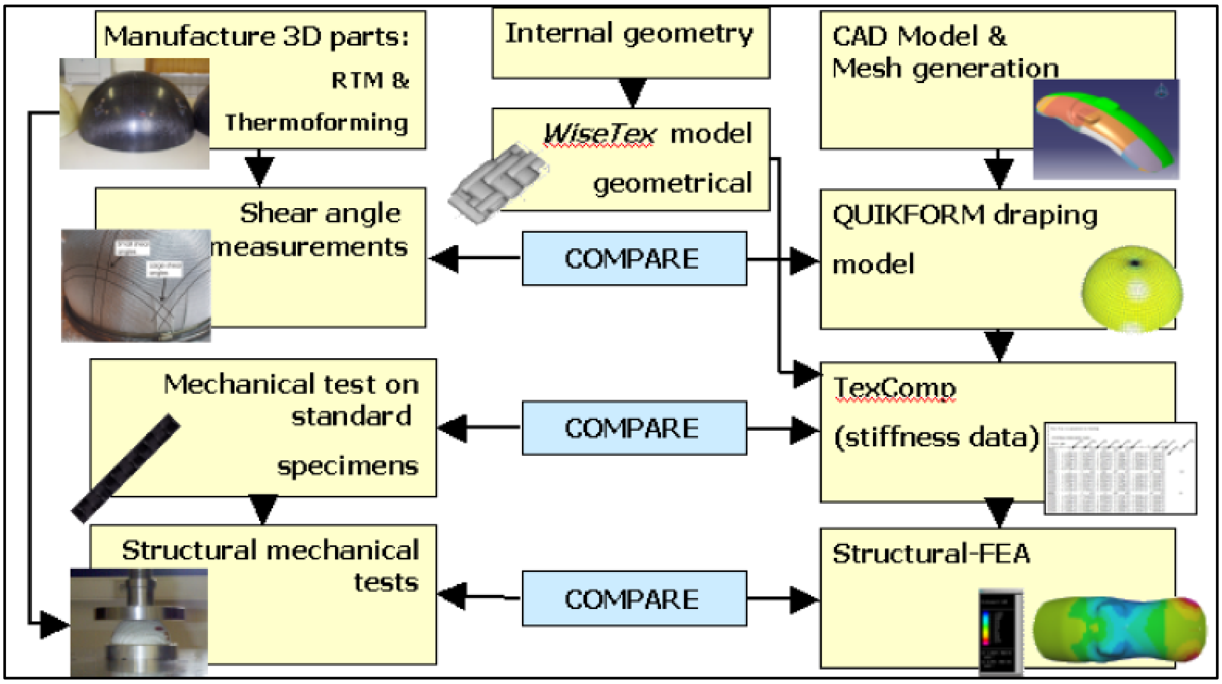

Figure 10: Mechanical analysis integrating local stiffness variations accounting for local tow deformations

6. <u>Effects of RTM process conditions onto mechanical performance</u>

As announced in the section 2, one reports here a few information about the effects of the impregnation onto the final content of porosities and therefore onto the final mechanical part performance. E. Ruiz is one of the first author to report a comprehensive work covering both the prediction of micro and macro-porosities (that is intra and inter-yarn porosities) occurring in the RTM manufacturing of composite parts and also the effects of the porosities onto the stiffness and strength – see the figure 10 from (9). A main outcome of this work is that there is an optimal flow velocity that minimizes the micro-voids (due to too high flow front velocity) and the macro-voids (due to too low flow front velocity). This is a useful observation for process engineers in order to optimize the process. This information can also be used by designers: assuming the knowledge of the stiffness and strength as a function of micro/macro-voids, the designer can run simulations using a contour of mechanical properties calculated from the map of porosities obtained at the end of the RTM process simulation.

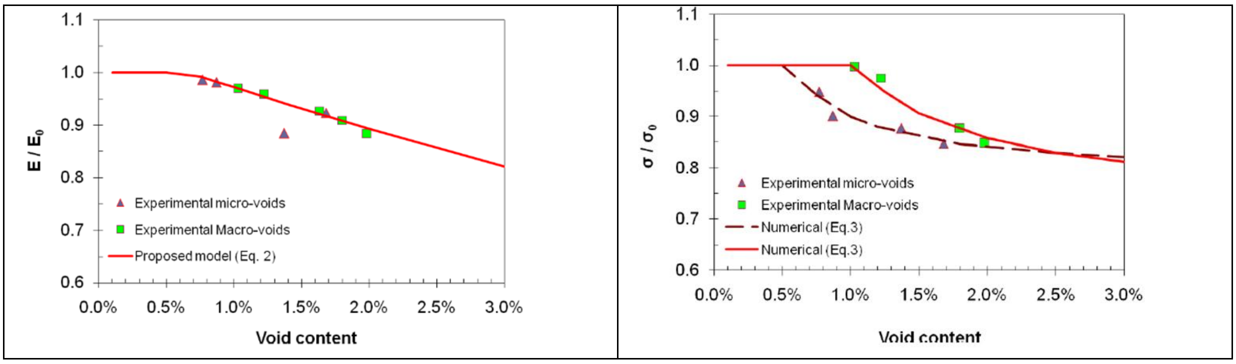

Figure 11: Variations of young modulus and strength with macro/micro-porosities(9)

7. Virtual Material Characterization

As noticed in all the examples afore mentioned, accurate mechanical behavior of a composite structure requires not only the description from the manufactured part but also an enriched material characterization. Not only the standard mechanical properties (elastic stiffness, strength, strain energy release rate, etc.) obtained by testing the purchased material must be available for the mechanical simulations but the properties must also be available as a function of the parameters modified during the various stages of the manufacturing process. The list includes the fiber reorientation, the thickness variations, the local fiber content variations, the fiber waviness, the micro and macro porosities, the degree of cure and of crystallization, the degree of intimate contact, the tows sections deformations, etc.

This requirement represents a significant additional burden to the simulation activity. In this section one report about active explorations of the virtual material characterization that could provide an alternative to expensive physical coupon testing.

The permeability prediction has been shown to be an effective technique as demonstrated for example by the Nottingham University works. The idea is simply to start from a representative unit cell of the studied reinforcement, to inject (numerically) resin from one side (using a CFD software like the FPM method) and using the Darcy equation one can recover the permeability from the pressure drop – see (10) for more details.

Drapeability prediction in order to simulate the draping operation has been tackled through themeso-mechanical modeling of individual tows and stitching yarns in (11).

The prediction of elastic properties is now done more or less on a regular basis, at least in academic world. The prediction of damage properties requires more attention. A recent work shows significant progress in this direction[??]. The figure 11 shows the simulation process used in this work: filament winding simulation, extraction of mechanical properties and final use in a crash tube simulation.

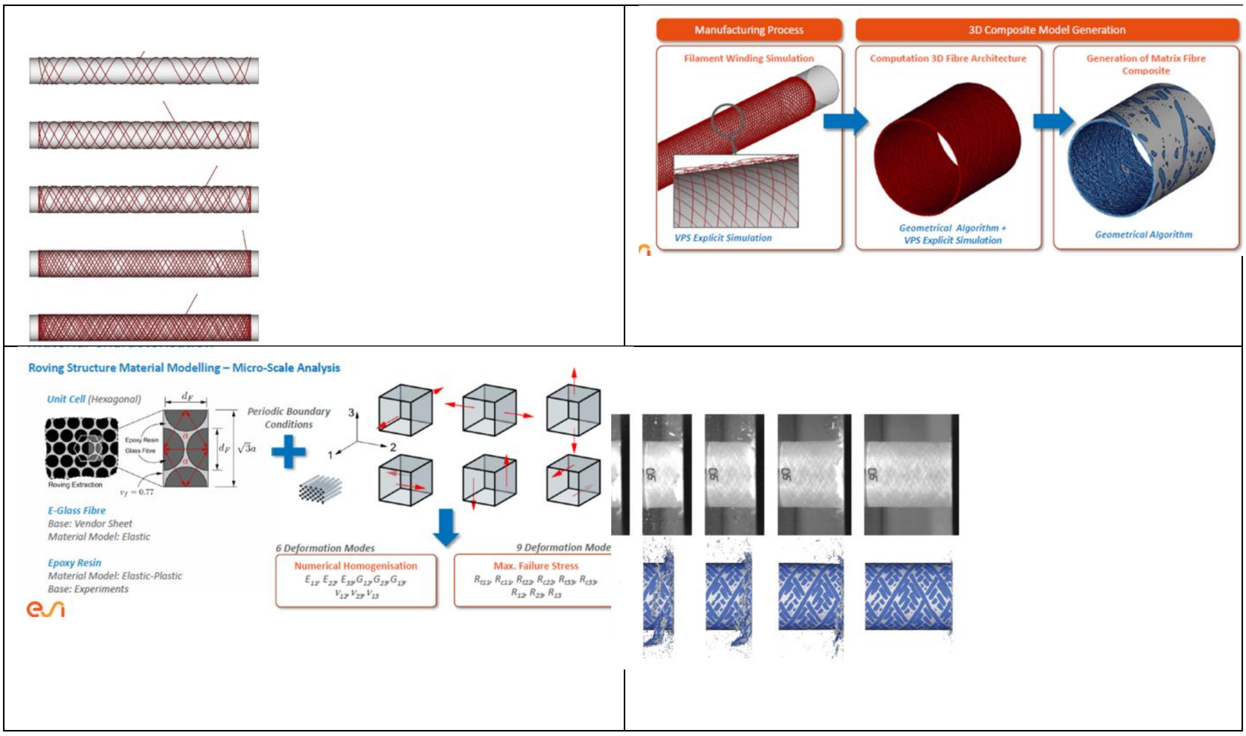

Figure 11: Material prediction and crash simulation: a global approach (12)

8. Conclusion and challenges for E2E composites simulation

This paper has presented an overview of current attempts to develop simulation tools contributing to the accounting of manufacturing effects in the mechanical design ofcomposite parts. Additional tools will be necessary in order to make this complete (end-to-end or E2E) simulation of composite parts a routine activity. We can mention for example tools to map results from one simulation into a different simulation tool using different numerical techniques and physics. The related statistic and reliability analysis tools will need integrating the variability of the material and of the manufacturing process. The composite part development process will iterate over a large loop ranging from material design, process design and part design. The resulting robustness and full control gained over the product development process will enable to decrease the safety margins and eventually really take advantage of the benefits of composite materials.

References

[1] Louis, M.; Huber, U.; Maier M.: HarzinjektionssimulationunterBerücksichtigung des Einflusses derDrapierung auf die Permeabilität, 8. nationales Symposium SAMPE Deutschland e.V., 7.-8. März 2002, Kaiserslautern.

[2] Carman, P.C. 1956. Flow of Gases Through Porous Media. New York City: Academic Press Inc

[3] A. Pickett; A. Erber; T. von Reden; K. Drechsler, Comparison of analytical and finite element simulation of 2D braiding, Plastics, Rubber and Composites, Volume 38, Issue 9-10 (01 December 2009), pp. 387-395

[4] P. de Luca, Y. Benoit, E. Berthé, M. Cabin, L. Dufort, M. Ziane,Predicting Mechanical performance of composite parts though manufacturing simulations, SAMPE Europe 2006, Paris, Proceedings, pp. 519-525.

[5] Ladevéze P., Le Dantec E., Damage modelling of the elementary ply for laminated composites, Compos. Sci. Techno. 1992(43):257-67

[6] Greve L., Picket A.K., Modelling damage and failure in carbon/epoxy non-crimp fabric composites including effects of fabric pre-shear, Composites: Part A, 37 (2006) 1983-2001.

[7] B. Van Den Brouke, F. Tümer, S. Lomov, I. Verpoest, P. de Luca, L. Dufort, Micro-macro structural analysis of textile composite parts: case study, SAMPE Europe Conference proceedings, Paris, 2004.

[8] S.V. Lomov, G. Huysmans, A. Podromou, I. Verpoest, Composites A, 32 (2001)1379-1394.

[9] Leclerc JS, Ruiz E, Porosity reduction using optimized flow velocity in Resin Transfer Molding, Composites: Part A, Volume 39, Issue 12, December 2008, Pages 1859-1868 (2008), doi:10.1016/j.compositesa.2008.09.008

[10] Alain Trameçon, Patrick de Luca, Christophe Binetruy, JörgKuhnert, “Finite Pointset Method (FPM): A Meshfree Approach for Incompressible Flow Simulations Applied to Composite Materials”, FPCM8 proceedings, Douai(F), 2006.

[11] A.Pickett, G.Greech, P.de Luca, Simplified and advanced simulation methods for prediction of fabricdraping, Revue Européenne de Mécanique Numérique, anciennement *Revue Européenne des éléments Finis (1250-6559)*

[12] A. Berger, T. Pyttel , F. Duddeck, Crash simulation of wound composite tubes based on multi-level modelling, International Journal of Crashworthiness, Vol. 20, Iss. 2, 2015