

# NUMERICAL MODELLING OF THE FILAMENT WINDING PROCESS

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## SUMMARY

A new model allowing the simulation of the filament winding process of either thermosettings or thermoplastics is described. The physical and thermo-chemical phenomena interacting at the layer/laminate level were analytically described and a numerical code was developed. Results were compared to previously published models.

*Keywords: filament winding, consolidation, compaction, process model*

## INTRODUCTION

The filament winding process is a manufacturing technique in which a resin-impregnated continuous filaments band is wound over a rotating mandrel. The synchronized movement of both the mandrel and the delivery head accomplishes the precise positioning of the fibres on the mandrel surface, leading to the desired lay-up pattern. A large number of user-controlled and process inherent parameters acts at the layer/laminate level. The ability to control the process variables may allow improvements in the final geometry of the component, the process optimization and the strength of the wound parts.

The main process user-controlled parameters are the initial fibre's tension, the winding speed, the winding angle, the bandwidth, the processing temperature, the initial fibre/resin fractions, the geometry and the materials systems used. These parameters influence several other process inherent properties that vary during the process and are not directly controllable. The main process inherent variables are, then, the consolidation pressure, the resin flow through the laminate, the resin viscosity and degree of cure, the resin mixing between adjacent layers, the fibre's motion, the fibre bed compaction and permeability, the fibre/resin fractions, the stresses and strains.

A few filament winding process models have been presented in the last decades. Lee and Springer [1] modelled the winding process of thermosetting composite cylinders proposing the sequential compaction approach. Cai and Gutowski [2] presented a squeezed sponge model. Mantell and Springer [3] published manufacturing process models for thermoplastic composites applicable also to filament winding. Song [4] developed a filament winding model for thermoplastics. Zhao et al. [5] used the finite elements method to model the filament winding of thermosetting composites. These

approaches model the physical phenomena taking place at the layer/laminate level in slightly different ways.

In this paper it is presented a new filament winding process model in which both thermosetting and thermoplastic material systems are considered, alternatively. Analytical descriptions of the physical phenomena taking place during the processing period and their coupling strategy were established and a numerical code, ModeFil, was developed. A description of the sub-models and their arrangement, together with the results of comparison and testing procedure are due in the following sections.

## PROCESS MODEL

This global model for the filament winding process was developed under several simplifying assumptions. The modelled phenomena are assumed to occur in one dimension, along the radial direction,  $r$ , across the laminate's thickness. Apart from the curing/crystallization mechanisms, which are modelled differently in the Resin Viscosity sub-model, the behaviours of either thermosetting or thermoplastic resins are assumed similar in respect to the physics of the process. Figure 1 schematically represents the simplest case in filament winding, the hoop (circumferential) winding.

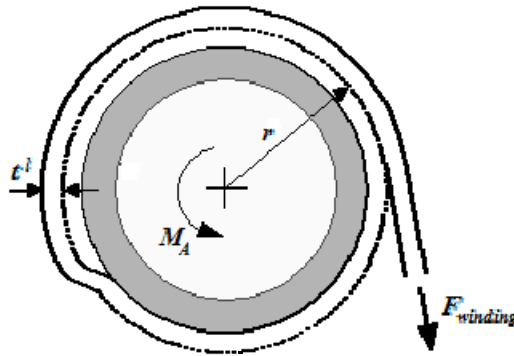


Fig. 1 - Cross-section schematic representation of circumferential (hoop) winding

The decoupled analytical descriptions of the phenomena are presented in this section.

### Consolidation Pressure

As a new layer is wound, a radial compaction pressure is applied, creating a pressure gradient in the previously wound layers. From the analogy with the stress state of a thin-walled cylinder subjected to internal pressure, the pressure applied by the newly wound layer to the previously wound layers is given by [2][6]

$$p_r = \frac{F_{winding} \sin^2 \phi}{r b} \quad (1)$$

where  $F_{winding}$  is the winding force,  $\phi$  is the winding angle,  $r$  is the radial position of the new layer and  $b$  is the bandwidth at the new layer. The radial pressure acting in the  $i$ th layer,  $p_r^i$ , due to the winding force is the sum of the radial pressures acting in the layers that lie on it and is given by

$$p_r^i = \sum_{j=i}^n \frac{F_{winding} \sin^2 \phi}{r^j b^j} \quad (2)$$

where  $F_{winding}$  is the winding force,  $\phi$  is the winding angle,  $r^j$  is the radial position of the  $j$ th layer,  $b^j$  is the bandwidth at the  $j$ th layer and  $n$  is the total number of deposited layers.

### Resin Viscosity

Thermosetting and thermoplastic resin systems have different consolidation behaviours. The formers cure under an exothermal chemical reaction while the latter crystallize while cooling from the melting processing temperatures. Thus, the resin viscosity must be calculated in different ways for these two configuration possibilities. The heat transfer in either thermosetting or thermoplastic configuration is modelled by the one-dimensional energy equation

$$\rho C \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( k_r \frac{\partial T}{\partial r} \right) + \rho \dot{Q} \quad (3)$$

where  $\rho$ ,  $C$  and  $k_r$  are the density, the specific heat and the thermal conductivity of the composite, respectively,  $T$  is the temperature,  $t$  is the time,  $r$  is the radial position and  $\dot{Q}$  is the rate at which heat is generated/absorbed by the curing/crystallizing resin. Equations 4 [7] and 5 [8] relate the heat generation term of equation 3,  $\rho \dot{Q}$ , to the rate of degree of cure/crystallization (thermosettings/thermoplastics).

$$\rho \dot{Q} = \rho_r V_r \left( \frac{d\alpha}{dt} \right) H_u \quad (4)$$

$$\rho \dot{Q} = \rho_r V_r \left( \frac{dc}{dt} \right) H_u \quad (5)$$

$\rho_r$  and  $V_r$  are the resin density and volume content, respectively,  $H_u$  is the total heat of the resin consolidation,  $\alpha$  is the degree of cure (thermosettings) and  $c$  is the degree of crystallization (thermoplastics).

Regarding thermosetting resins, the rate of the curing reaction is a function of the temperature and the degree of cure. Analytical expressions for different resin systems are found in the literature [9][10][11][12][13]. Equations 6 and 7 [9] model the rate of the curing reaction for the Hercules<sup>®</sup> 3501-6 epoxy resin. Two other epoxy resins, Hexcel<sup>®</sup> 8552 and Cytec Fiberite<sup>®</sup> 977-3 HM, are modelled with equation 8 [10]. Equation 9 models the behaviour of the epoxy resin Fiberite<sup>®</sup> 976 [13].

$$\frac{d\alpha}{dt} = (K_1 + K_2\alpha)(1-\alpha)(B-\alpha) \quad \alpha \leq 0,3 \quad (6)$$

$$\frac{d\alpha}{dt} = K_3(1-\alpha) \quad \alpha > 0,3 \quad (7)$$

$$\frac{d\alpha}{dt} = K_1\alpha^3 - K_2\alpha^2 + K_3\alpha + K_4 \quad (8)$$

$$\frac{d\alpha}{dt} = \frac{H_r}{H_u} [K_1 + K_2(\alpha - \alpha_0)^a] [B - (\alpha - \alpha_0)]^b [1 - (\alpha - \alpha_0)^d]^c \quad (9)$$

$$K_i = A_i e^{\frac{-\Delta E_i}{RT}} \quad i = 1,2,3 \quad (10)$$

$A_i$ ,  $B$ ,  $a$ ,  $b$ ,  $c$  and  $d$  are constants,  $E_i$  are the activation energies,  $R$  is the universal gas constant and  $\alpha_0$  is the initial degree of cure.

In semi-crystalline thermoplastics, crystallization governs the consolidation. The rate of crystallization is a function of temperature and degree of crystallization. Solutions for PEEK based thermoplastics have been presented [8][14][15][16]. Crystallinity functions for the heating [14] and cooling stages [8] are as follows

$$\frac{dc}{dt} = -c_{in} K \left( 1 - \frac{(c_{in} - c)}{c_{in}} \right)^n, \quad K = K_0 e^{\left( \frac{E_i}{RT} \right)} \quad (11)$$

$$\frac{dc}{dt} = \left( A_1 \ln \left( \frac{dT}{dt} \right) + A_2 \right) - (1 - c_r) \frac{d e^{\left( \frac{A_3 T + A_4}{RT} \right)}}{\left( \frac{dT}{dt} \right)^{n-1}} \quad (12)$$

where  $c_{in}$  and  $c_r$  are the initial and relative crystallinity,  $A_i$ ,  $K_0$  and  $n$  are constants.

These empirical formulations do not take into account the actual conditions (pressure, laminate compaction, fibrous medium and resin mixing) in which the resin consolidates. They are, however, the most approximate models for the resin behaviour under processing conditions.

In thermosetting resins, the viscosity,  $\mu$ , is a function of the degree of cure,  $\alpha$ , and temperature,  $T$ . Different models have been developed for several resins. Most of them are isothermal models and predicts the rheological behaviour of the resin only in a limited range of the chemical reaction. The viscosities of Hercules<sup>®</sup> 3501-6, HBRF-55A and Fiberite<sup>®</sup> 976 epoxy resins are modelled as [6][9][13]

$$\mu = \mu_{\infty} e^{\frac{U}{RT} + K_1 \alpha} \quad (13)$$

A similar analytical model for the Hexcel<sup>®</sup> 8552 and Cytec Fiberite<sup>®</sup> 977-3 HM epoxy resins takes the following form [10]

$$\mu = \mu_{\infty} e^{\frac{U}{RT} + K_1 \alpha^2 + K_2 \alpha} \quad (14)$$

$\mu_{\infty}$  is a constant,  $U$  is the activation energy,  $K_i$  are constants independent of temperature. Sets of the specific values for each resin are also available in literature.

In thermoplastic resins, the viscosity,  $\mu$ , is a function of the temperature,  $T$ . Models for PEEK [3][8] and APC-2/AS4 commercial systems are stated in equations 15 and 16.

$$\mu_m = 1,13(E - 10) \left( e^{\frac{19100}{T}} \right) \quad (15)$$

$$\mu_{mf} = 132,95 \left( e^{\frac{2969}{T}} \right) \quad (16)$$

## Resin Flow

The resin flow in the transverse direction (out of plane) can be evaluated from the resin radial velocity in each point,  $\dot{u}_r^r$ , which is a function of the permeability of the fibre bed,  $S$ , the resin viscosity,  $\mu$ , and the pressure gradient in that direction,  $dp_r/dr$ , through the Darcy's law for flow in porous media as follows

$$\dot{u}_r^r = -\frac{S}{\mu} \frac{dp_r}{dr} \quad (17)$$

The permeability of the fibre bed in the through-thickness direction as a function of material properties and constants which are empirically modified is given in [7].

## Resin Mixing

In the filament winding process, uncured resin from previously wound layers can flow into newly wound layers. The effective viscosity can be calculated by a rule of mixtures. For the  $i$ th layer, the viscosity,  $\mu^i$ , is calculated by a linear combination as follows [6]

$$\mu = \sum_{j=1}^i \Psi_j^i \mu_j^i \quad (18)$$

The relative concentration parameters,  $\Psi_j^i$ , are readily assessed from the knowledge of the resin velocity at the layer boundaries through the process history. The viscosity of each constituent,  $\mu_j^i$ , is assessed from the corresponding cure/crystallization status.

For long winding times, the viscosity of the resin in adjacent layers can be significantly different. In the case of short winding times, that effect may be neglected. For thermoplastic resin systems the viscosity of a previously wound layer is so high that the flow of resin across the fibre bed turns to be minimal.

## Fibre Bed Compaction

Due to the pressure gradient and the resin outward flow across the laminate, the wound layers move inward. The thickness of each layer changes due to the variation of the amount of resin contained in it. From the knowledge of the resin flow history, the radial displacements of the  $i$ th layer due to this phenomenon is calculated by the relation

$$\frac{dv_T^i}{dt} = \frac{dv_r^i}{dt} = A_{RVE}^i \frac{d}{dt} (r_o^i - r_i^i) \quad (19)$$

where  $v_T^i$  is the total volume of the representative volume element (RVE) of the  $i$ th layer,  $v_r^i$  is the volume of resin contained in the RVE of the  $i$ th layer,  $A_{RVE}^i$  is the resin radial flow area of the RVE of the  $i$ th layer (see figure 2),  $r_o^i$  and  $r_i^i$  are the outer and inner radius of the  $i$ th layer, respectively.

As the fibre bed compacts, the fibre volume fraction increases. Because the layer's stiffness depends on the fibre volume fraction, it changes as the compaction progresses [6]. The evolution of the fibre volume fraction in the  $i$ th layer,  $V_f^i$ , is given by

$$\frac{dV_f^i}{dt} = - \frac{v_f^i}{A_{RVE}^i} \frac{d}{dt} \frac{(r_o^i - r_i^i)}{(r_o^i - r_i^i)^2} \quad (20)$$

where  $v_f^i$  is the volume of fibres contained in the RVE of the  $i$ th layer.

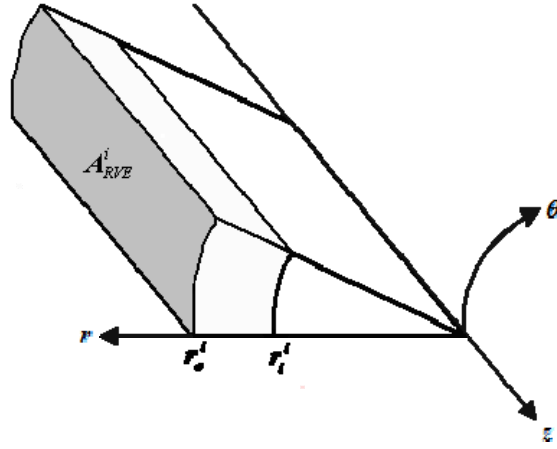


Fig. 2 – Representative Volume Element (RVE) of the  $i$ th layer

### Stress-Strain

As the fibre bed compacts, its stiffness changes due to the increasing of the fibre volume fraction and the fibres repositioning within the moving bundles. The latter promotes a fibre waviness pattern that is characterized by the scalar  $a/L$ , called marcel [17].  $a$  is the characteristic amplitude of the waviness pattern of the fibres, assumed sinusoidal, and  $L$  is the characteristic length. For each layer, the longitudinal,  $E_1^{fb}$ , and transverse (bulk),  $E_b^{fb}$ , fibre bed local stiffness can be evaluated from the following relations [18].

$$E_1^{fb} = V_f^i E^f \frac{\pi/4}{V_a} \quad (21)$$

$$E_b^{fb} = E_2^{fb} = E_3^{fb} = \frac{\frac{\sqrt{V_a}}{\sqrt{V_f^i}} \left[ 5 - \frac{\sqrt{V_f^i}}{\sqrt{V_a}} - 4 \frac{\sqrt{V_0}}{\sqrt{V_f^i}} \right]}{\frac{\beta^4}{3\pi E^f} \left[ \frac{\sqrt{V_a}}{\sqrt{V_f^i}} - 1 \right]^5} \quad (22)$$

where  $V_0$  is a constant dependent of the state of the fibre bundle,  $V_a$  is the maximum available fibre volume fraction [7],  $E^f$  is the Young's modulus of the fibres and  $\beta$  is the ratio between  $a$  and  $L$ .

The local layer's stiffness,  $E_1$ ,  $E_2$  and  $E_3$ , are assessed by the conventional mixing rules, combining the fibre bed and the resin stiffness. The constitutive stress-strain relationship for the  $i$ th layer is given by [1][19]

$$\begin{Bmatrix} \sigma_{zz}^i \\ \sigma_{\theta\theta}^i \\ \sigma_{rr}^i \\ \tau_{r\theta}^i \\ \tau_{rz}^i \\ \tau_{z\theta}^i \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & C_{16} \\ C_{12} & C_{22} & C_{23} & 0 & 0 & C_{26} \\ C_{13} & C_{23} & C_{33} & 0 & 0 & C_{36} \\ 0 & 0 & 0 & C_{44} & C_{45} & 0 \\ 0 & 0 & 0 & C_{45} & C_{55} & 0 \\ C_{16} & C_{26} & C_{36} & 0 & 0 & C_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_{zz}^i - \beta_{zz}^i \Delta T^i - \eta_{zz}^i \Delta \alpha^i \\ \varepsilon_{\theta\theta}^i - \beta_{\theta\theta}^i \Delta T^i - \eta_{\theta\theta}^i \Delta \alpha^i \\ \varepsilon_{rr}^i - \beta_{rr}^i \Delta T^i - \eta_{rr}^i \Delta \alpha^i \\ \gamma_{r\theta}^i \\ \gamma_{rz}^i \\ \gamma_{z\theta}^i - \beta_{z\theta}^i \Delta T^i - \eta_{z\theta}^i \Delta \alpha^i \end{Bmatrix} \quad (23)$$

where  $\sigma^i$  and  $\tau^i$  are the normal and shear stresses,  $\varepsilon^i$  and  $\gamma^i$  are the normal and engineering shear strains, independent from the thermal and chemical effects,  $\beta^i$  are the thermal expansion coefficients,  $\eta^i$  are the chemical shrinkage coefficients,  $T^i$  is the temperature and  $\alpha^i$  is the degree of cure/crystallization in the  $i$ th layer.  $\beta^i$  and  $\eta^i$  are assumed to vary linearly with the degree of cure/crystallization.

The components of the local stiffness matrix,  $C_{mn}$ , include both effects of the increasing of the fibre volume fraction and the fibre waviness. Therefore it must be continuously re-evaluated during the laminate consolidation process.

### NUMERICAL IMPLEMENTATION

From the analytical descriptions of the physics of the filament winding process at the layer/laminate level, the numerical code ModEFil was written. The modular arrangement of the model is schematically depicted in figure 3.

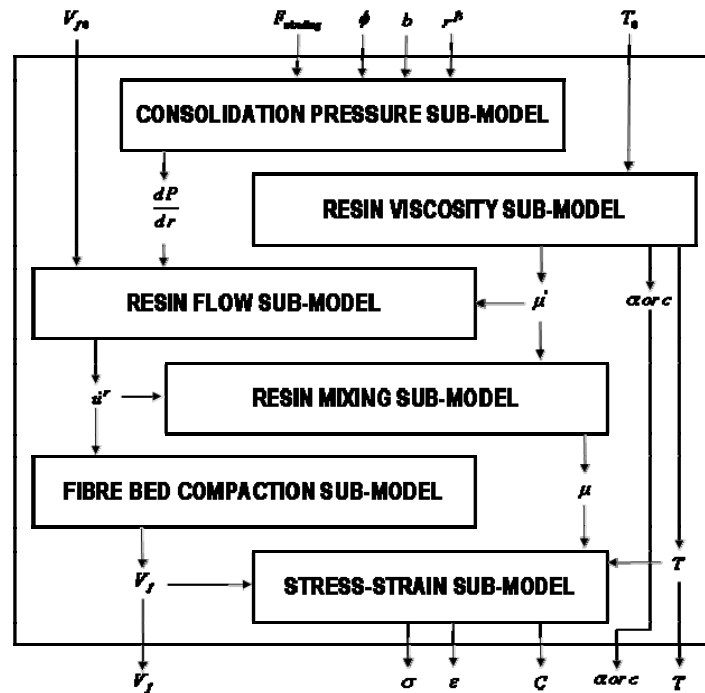


Fig. 3 – Schematic overview of the filament winding process model, ModEFil



Each sub-model corresponds to a specific set of sub-routines which calculate and/or updates the values of the process parameters independently.

This numerical model was coded in FORTRAN<sup>®</sup> and implemented in ABAQUS<sup>®</sup> Explicit finite element software using the VUMAT user sub-routine tool.

The main outputs of ModEFil are the consolidation pressure, degree of cure of the resin, viscosity of the resin, temperature in the laminate, layer position, fibre volume fraction, strains and stresses at every instant.

## TESTING OF THE MODEL

In order to test the ModEFil model, the results were compared to those obtained by the WINDTHICK code presented by Lee and Springer in [1] and validated in [20]. The input data used for the testing example is presented in Table 1.

Table 1 - Input data used in comparison of ModEFil and WINDTHICK results

Wound Section Geometry		Material Properties	
radius of the mandrel, $r_i^1$ [ m ]	0.1524	density of fibres, $\rho^f$ [ kg m <sup>-3</sup> ]	1760
total number of layers, $n$	18	diameter of fibres, $d^f$ [ m ]	$7.0 \times 10^{-6}$
<b>Processing Conditions</b>		modulus of fibres, $E^f$ [ Pa ]	$231 \times 10^9$
winding force, $F_{winding}$ [ N ]	266.9 N	specific heat of fibres, $c^f$ [ J kg <sup>-1</sup> K <sup>-1</sup> ]	889.14
initial fibre volume fraction, $V_f^0$ [ % ]	63	density of resin in cured state, $\rho_c^r$ [ kg m <sup>-3</sup> ]	1267.45
initial ply thickness, $t_{layer}^0$ [ m ]	$2.205 \times 10^{-4}$	modulus of resin in cured state, $E_c^r$ [ Pa ]	$26.00 \times 10^9$
bandwidth, $b$ [ m ]	$3.175 \times 10^{-3}$	specific heat of resin, $c_p^r$ [ J kg <sup>-1</sup> K <sup>-1</sup> ]	1200
winding angle, $\phi$ [ ° ]	$\pm 40$	thermal conductivity of resin, $k_c^r$ [ J s <sup>-1</sup> m <sup>-1</sup> K <sup>-1</sup> ]	0.5
temperature, $T$ [ K ]	449.82	thermal expansion of resin, $\beta_c^r$ [ K <sup>-1</sup> ]	$3.204 \times 10^{-5}$
<b>Material Systems</b>		chemical shrinkage of resin, $\eta_c^r$	0.0125
carbon fibres > Thornel <sup>®</sup> T300		resin cure kinetics	reference [13]
epoxy resin > Fiberite <sup>®</sup> 977-3		resin viscosity	

Figure 4 shows the evolution of the degree of cure,  $\alpha$ , and the viscosity,  $\mu$ , of the resin at the midpoint of the laminate, i.e., at the interface between the 9<sup>th</sup> and 10<sup>th</sup> layers. The room temperature varies from 285 K at time  $t = 0h$  up to 449.82 K at time  $t = 1h$  and then remains constant until  $t = 3h$ . In the ModEFil model, the initial degree of cure,  $\alpha_0$ , is 0.12. In the scope of following the example presented in [20], this testing assumes that all the layers are wound at one time,  $t = 0h$ . As so, the effect of the resin flow between adjacent layers is not influencing the kinetic behaviour of the resin, since all layers have the same simultaneous conditions. However, the ModEFil model computes the resin flow and mixing phenomena which are relevant when winding layers in different times.

Further comparisons with other models, focusing in different output parameters, are addressed in the continuation of this work.

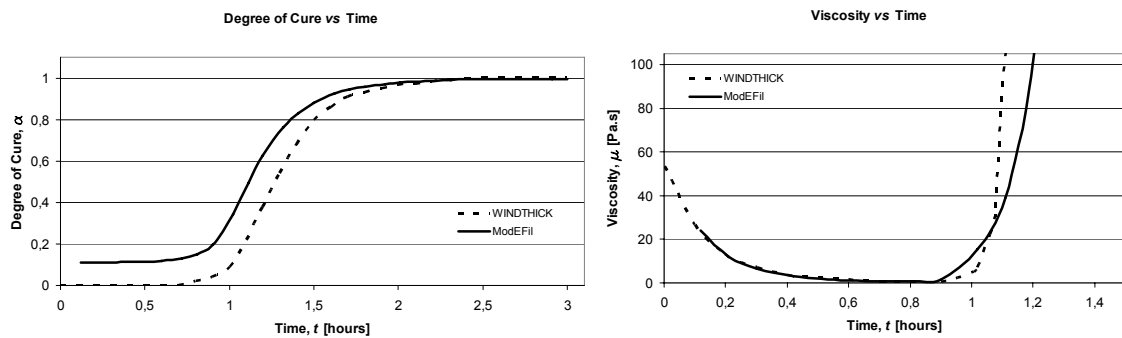


Fig. 4 - Degree of cure and viscosity calculated by the ModEFil and WINDTHICK models. Results shown are at the midpoint of the laminate

## CONCLUSIONS

In this research programme, a filament winding process model was developed. In this new integrated approach, both thermosetting and thermoplastic resin systems are considered and different material systems can be modelled. A numerical code, ModEFil, was created and implemented in ABAQUS<sup>®</sup> FEA software.

The modular methodology followed in this model, allows a decoupled description and calculation of the several physical variables of the process. Moreover, it allows an easy update and/or improvement of the materials library, since they are assessed in an independent sub-routine. The local definition of the several parameters makes this model virtually applicable to any constant cross-section geometry.

The evaluation of this model is made both by comparison of its results with previous published models and experimental tests. The first comparisons with previous models showed good agreement and that the model structure is able to fit the results previously validated by different authors.

In future, this model will be experimentally validated and improvements will be addressed. Many assumptions that were made will need to be further studied. Namely, the applicability of the one-dimensional approach for the heat transfer and resin flow analyses and the curing/crystallization behaviour of mixed layers will be addressed. The stress-strain calculations will also be further developed to include micromechanical aspects of the behaviour of the fibre bundles and more complex geometries.

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