FPCM-9 (2008)
The 9th International Conference on Flow Processes in Composite Materials
Montréal (Québec), Canada
8 ~ 10 July 2008

SIMULATION OF RESIN FLOW THROUGH THE LAYERS OF WET WOUND CYLINDER

Dr. Abel Cherevatsky[1], Mandy Buyum[1]

[1] *Israel Military Industries, Ramat Hasharon 47100/66, Israel*
[2] *Corresponding author'Email: abelc@imi-israel.com*

SUMMARY: This work presents a discrete approach to simulation of a resin flow process, during wet winding of a cylinder. The developed iteration procedure includes an expansion of the state equations system according to the number of wound layers and their structure, and may be applied to any number of hoop or helical wound layers. In the initial stage of simulation the known values of process control parameters, mechanical properties of fibers and wound layer geometry parameters values are substituted into the state equations of the first wound layer to calculate the pressure, developed in the resin layer, the quantity of squeezed resin, the displacement of fibers, and to update all process and geometry parameters. In the second stage of the resin flow simulation all process and geometry parameters values are substituted into the updated system of state equations for two wound layers in order to obtain the second generation of all parameters, and so on. Among the applications of this simulation procedure, the distribution of initial fiber tension was determined for glass/epoxy hoop wound pipe (diameter 146 mm, thickness of one wound band 0.2 mm) in order to provide a positive tension of first wound layer throughout all winding operations.

KEYWORDS: wet filament winding, resin flow, fiber tension, iteration procedure, state equations

INTRODUCTION

This paper describes a discrete approach to the simulation of resin flow processes in the cylinder, being wound with a combination of hoop and helical layers. The general ideology of simulation procedure is based on famous pioneering publications [1-4]: the band of wound fibers is treated as a porous medium, the resin flow through the porous medium is described by Darcy's law, where the viscosity of the resin is varied according to the cure kinetics. The famous publications devoted to this theme deal with a continuous approach to the material distribution within the wound stacks [1-6]. The discrete approach, suggested in present paper, based on the main supposition, that the wet winding process may be well simulated by wound band (layer), composed of a stable upper section (upper sublayer) of impregnated fibers, usually keeping its size, and a low section (low sublayer) of resin, which flows through the upper section (sublayer) and changes its thickness, see Fig.1.

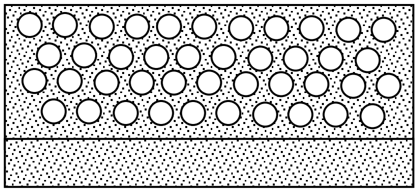

Fig. 1 Structure of the wound band contains the upper section of impregnated filaments and a low section of pure resin.

In each stage of the winding process the position of fibers of a given wound layer is determined by location of all previously wound layers and by the thickness of the resin sublayer of given wound layer. This approach provides the possibility to describe the resin flow through the wound layers and location of each wound layer by variable thicknesses of resin sublayers.

The system of state equations for a wound stack describes the location of each wound layer in the stack, the tension of the fibers, and pressure in each resin sublayer. The iteration procedure is developed to solve the system of state equations.

The developed iteration procedure includes an expansion of the state equations system according to the number of wound layers and their structure, and may be applied to any number of hoop or helical wound layers and their combination. The expansion of the system of state equations is performed by a simulation procedure, and is based on the found recursive form of the resin flow state equations.

In the initial stage of simulation procedure the known values of process control parameters, mechanical properties of fibers and wound layer geometry parameters values are substituted into the state equations of the first wound layer to calculate the pressure developed in the resin layer, the quantity of squeezed resin, the displacement of fibers, and to update all process and geometry parameters.

In the second stage of the resin flow simulation all process and geometry parameters are substituted to the updated system of state equations for two wound layers in order to receive the second iteration of all parameters, and so on.

STATE EQUATIONS FOR HOOP WOUND STACK

The general system of state equations for the stack of n-hoop wound layers contains four subsystems to calculate the iteration values for main parameters: the pressure in the resin layers is describred by Eqn. (1); the quantities of resin flowing through each wound layer are given by Eqn. (2); the thicknesses of the resin layers by Eqn. (3); and the fiber's tension in each layer by Eqn. (4).

$$P_n^{i-1} = \frac{T_n^{i-1}}{\left(R + \sum_{i=1}^{n} h_i^{i-1} + (n-1)d\right)w} \tag{1}$$

$$P_m^{i-1} = \frac{T_m^{i-1}}{\left(R + \sum_{j=2}^{m+1} h_{j-1}^{i-1} + (m-1)d\right)w} + P_{m+1}^{i-1} \text{ ; } 1 \le \mathrm{m} \le \mathrm{n} - 1$$

$$Q_m^{i-1} = \frac{k_m^{i-1}\left(P_m^{i-1} - P_{m+1}^{i-1}\right)}{\mu_m^{i-1} d} \Delta \mathrm{t} * 60 \text{ ; } 1 \le \mathrm{m} \le \mathrm{n} - 1$$

$$Q_n^{i-1} = \frac{k_n^{i-1} P_m^{i-1}}{\mu_n^{i-1} d} \Delta \mathrm{t} * 60 \tag{2}$$

$$h_1^i = h_1^{i-1} - \mathrm{Q}_1^{\mathrm{i-1}}$$

$$h_m^i = h_m^{i-1} - \mathrm{Q}_{\mathrm{m}}^{\mathrm{i-1}} + \mathrm{Q}_{\mathrm{m-1}}^{\mathrm{i-1}} \left(1 - \frac{\mathrm{h}_{\mathrm{m}}^{\mathrm{i-1}} + d}{\mathrm{R} + \sum_{k=1}^{m} h_k^{i-1} + (m-1) * d} \right) \text{ ; } 2 \le \mathrm{m} \le \mathrm{n} \tag{3}$$

$$T_m^i = T_m^{i-1} - E * \mathrm{d} * \mathrm{w} * \frac{\sum_{k=1}^{m} \left(h_k^{i-1} - h_k^i\right)}{R + \sum_{k=1}^{m} h_k^{i-1} + (m-1) * d} \text{ ; } 1 \le \mathrm{m} \le \mathrm{n} \tag{4}$$

where:

R	mm	Radius of the mandrel
T_n	kg	Tension of the fibres in the n-th layer
T_n^0	kg	Initial tension of the fibres in the n-th layer
h_1	mm	Thickness of the resin film under the n-th layer
h_n^0	mm	Initial thickness of the resin film under the n-th layer
P_1	kg/mm^2	Pressure in the resin film under the n-th layer
d	mm	Thickness of a single fibre
w	mm	Width of a single fibre
E	kg/mm^2	Elastic modulus of a fibre
μ_n	kg∗s/mm^2	Viscosity of the resin film in the n-th layer
k_n	mm^2	Permeability of the n-th wound layer
Q_n	mm	Resin flow quantity through the n-th wound layer
t	min	time
Δt	min	time interval for each iteration

STATE EQUATIONS FOR HELICAL WOUND STACK

The general system of state equations for helical wound stack on the cylinder contains five subsystems: Eqn. (5) for pressure in each resin layer; Eqn. (6) for resin flow quantities; Eqn. (7) for thickness of the resin layer; Eqn. (8) for deviation of the winding angles; and Eqn. (9) for the fiber tension values.

$$P_n^{i-1} = 2*\sin^2\varphi_n^{i-1}\frac{T_n^{i-1}}{\left(R+\sum_{i=1}^{n}h_i^{i-1}+(n-1)d\right)w}$$

$$P_m^{i-1} = 2*\sin^2\varphi_m^{i-1}\frac{T_m^{i-1}}{\left(R+\sum_{j=2}^{m+1}h_{j-1}^{i-1}+(m-1)d\right)w}+P_{m+1}^{i-1}\ ;\ 1\le \mathrm{m}\le \mathrm{n-1} \tag{5}$$

$$Q_m^{i-1} = \frac{k_m^{i-1}\left(P_m^{i-1}-P_{m+1}^{i-1}\right)}{\mu_m^{i-1}d}\Delta\mathrm{t}*60\ ;\ 1\le \mathrm{m}\le \mathrm{n-1}$$

$$Q_n^{i-1} = \frac{k_n^{i-1}P_n^{i-1}}{\mu_n^{i-1}d}\Delta\mathrm{t}*60 \tag{6}$$

$$h_1^i = h_1^{i-1} - \mathrm{Q}_1^{\mathrm{i-1}}$$

$$h_m^i = h_m^{i-1} - \mathrm{Q}_\mathrm{m}^{\mathrm{i-1}} + \mathrm{Q}_{\mathrm{m-1}}^{\mathrm{i-1}}\left(1-\frac{\mathrm{h}_\mathrm{m}^{\mathrm{i-1}}+d}{\mathrm{R}+\sum_{k=1}^{m}h_k^{i-1}+(m-1)*d}\right)\ ;\ 2\le \mathrm{m}\le \mathrm{n} \tag{7}$$

$$tg\varphi_m^i = \frac{R+\sum_{k=1}^{m}h_k^i+(n-1)d}{R+\sum_{k=1}^{m}h_k^{i-1}+(n-1)d}tg\varphi_m^{i-1} \tag{8}$$

$$S_m = L\sqrt{1+tg^2\varphi_m}$$

$$T_m^i = T_m^{i-1} - E*\mathrm{d}*\mathrm{w}*\frac{S_m^{i-1}-S_m^i}{S_m^{i-1}}\ ;\ 1\le \mathrm{m}\le \mathrm{n} \tag{9}$$

where:

φ_n	rad	helical winding angle in the n-th layer
L	mm	length of cylinder
S_n	mm	half helical circle length in the n-th layer

As an application of the developed simulation the distribution of initial fiber's tension in the different layers was determined for glass/epoxy hoop wound pipe in order to provide a positive tension of first wound layer throughout all winding operations. The internal diameter of the pipe is 146 mm, the thickness of one wound band without resin sublayer is 0.2 mm, and the thickness of a resin sublayer is 0.1 mm. The distribution of fiber tension between wound layers is shown in Fig.2.

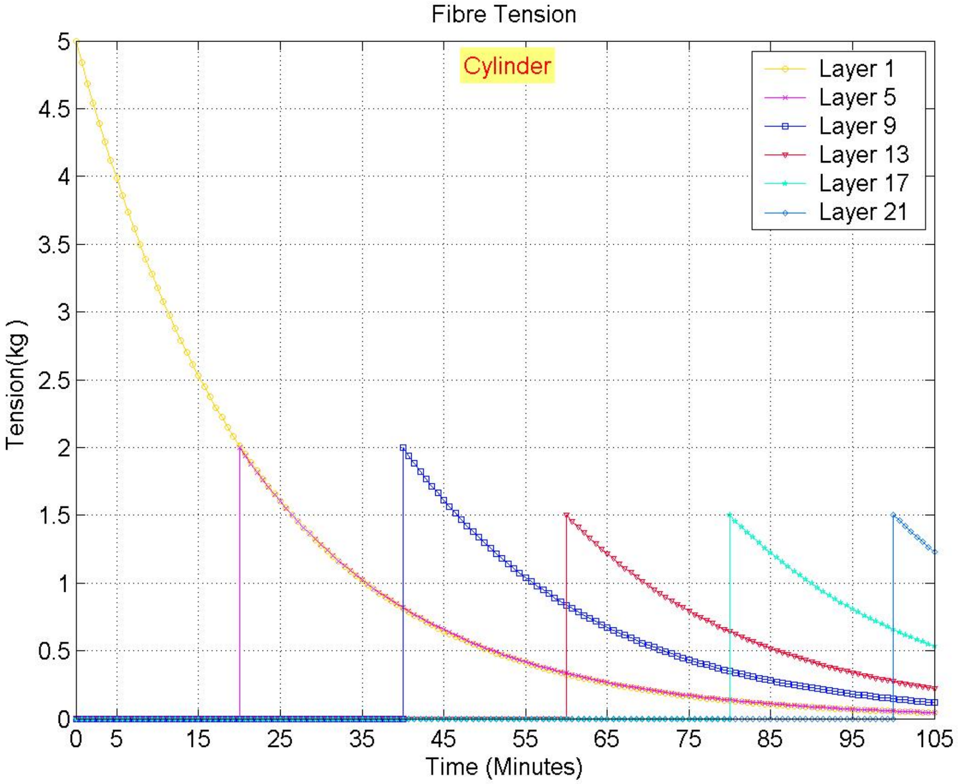

Fig.2. Distribution of fiber tension for wound layers.

REFERENCES

1. S.Y. Lee and G.S. Springer, "Filament Winding Cylinders: I. Process Model", *Journal of Comp. Materials*, Vol. 24, 1990, pages 1270-1298.
2. E.P. Calius, S.Y. Lee and G.S. Springer, "Filament Winding Cylinders: II. Validation of the Process Model", *Journal of Comp. Materials*, Vol. 24, 1990, pages 1299-1343.
3. S.Y. Lee and G.S. Springer, "Filament Winding Cylinders: III. Selection of the Process Variables", *Journal of Comp. Materials*, Vol. 24, 1990, pages 1344-1366.
4. B.E. Spenser, "Modeling the Filament Winding Process", *Proc. of 34-th Intern. SAMPE Symposium*, May 1989, pages 1556 – 1570.
5. Z. Cai, T. Gutowski and S. Allen, "Winding and Consolidation Analysis for Cylindrical Composites Structures", *Journal of Comp. Materials*, Vol. 26, No. 9, 1992, pages 1374-1399.
6. A.C. Loos and J.T. Zeng, "Filament Winding", *Flow and Rheology in Polymer Composites Manufacturing, Composite Materials Series,* Vol.10, Elsevier, 1994, pages 571-591.