OPTIMAL PROCESS DESIGN FOR LARGE-SCALE PULTRUSION STRUCTURES

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ABSTRACT

Computational methods for optimal design of the pultrusion process of structural profiles are developed. The methods are based on computational modelling of composite material behavior during manufacturing process, including impregnation of reinforcement, polymerization of thermoset matrix, evolution of residual strains and stresses, formation of process induced defects. Mechanical constitutive models were implemented within the ABAQUS software.

The special simulation scheme was developed in pSeven software for numerical optimization and sensitivity analysis of process parameters. The main goal of process parameters optimization is to maximize pulling speed in order to increase production rate, while satisfying temperature, curing degree, residual stress, and shape distortions constraints. The constraints considered in this study are transverse stress in pultruded profile, maximum temperature of the material and minimum degree of curing at the end of a die zone. Maximum spring-back angle is used to control the shape distortion of the profile.

To validate the simulation tool on a reasonably complex real world case the pultruded C-section of a stair tread panel was manufactured, shape distortions were measured and compared with predicted ones. The approximation model based on Gaussian processes was built. The approximation model allows us to visualize different constraints violation areas. The maximum achieved speed is about 18 % higher compared to the initial one.

1 INTRODUCTION

Last decades, complex shaped composite components are widely used in construction in addition to aerospace and automotive industries. Being rather expensive in contrast with structures made of traditional construction materials, polymer composite structures look more attractive regarding weight and corrosion resistance. However, the production cost of such structures shouldn't increase significantly. Pultrusion is nowadays one of the most cost efficient methods for production of composite materials having constant cross-sectional profiles. During the process reinforcement material is impregnated with resin, followed by a separate preforming system and pulled through a heated stationery die where the polymerization of resin takes place. Pultrusion is a process with little waste of material due to absence of any subsequent finishing steps. Pultruded products have consistent quality. These features make the process attractive and prospective.

The main products that manufactured using pultrusion process are construction profiles. There are several varieties of construction profiles - round, band, L-shape, I-beam, C-shape, square, rectangular and etc. Manufacturers of composite profiles quite often face the problem of distortion. A satisfactory experimental analysis for the production requires considerable time which is not a cost-effective approach. One of the objectives for this study is to develop a virtual process chain for the pultrusion process, which takes into account all the physical phenomena, leading to the emergence of strains and stresses, such as the dependence of matrix thermomechanical characteristics on temperature and degree of polymerization, the anisotropy of properties of composite material, the rate of chemical reaction of thermoset matrix polymerization, and thermal and mechanical contact with a die. Modern pultrusion machines are fully computer controlled. For this case, the role of defining computer program which generates the quality of the product increases significantly. Thereby another objective is to find optimal process parameters - the initial temperature of the resin, temperatures in die zones and the pulling speed, for manufacturing process ensuring high performance and low manufacturing loss at the same time. Process simulation was performed by using the ABAQUS general purpose finite element package and pSeven for process simulation.

2 OUTLINE OF PROCESS SIMULATION

In this study computational and experimental methods for optimal design of the process of pultrusion of structural profiles are developed. Developed methods are based on computational modelling of composite material behaviour during manufacturing process, including impregnation of reinforcement [1], [2], polymerization of thermoset matrix [3], evolution of residual strains and stresses [4], formation of process induced defects [5], [6]. Mechanical constitutive models (linear elastic, path-dependent, and viscoelastic) were implemented within the ABAQUS software, accounting for the dependence of thermomechanical characteristics of resin on the temperature and degree of polymerization, the rate of chemical reaction of thermoset matrix polymerization, and thermal and mechanical contact with die surfaces. Subroutines verification was performed using results presented in available literature [4], [5], [7], [8].

The three dimensional (3D) transient energy equation for the pultrusion process is given in (1), respectively in a Cartesian coordinate system. Here, *x* is the pulling or longitudinal direction; *y* and *z* are the transverse directions. In the energy equation, the convective ($u\partial T/\partial x$) and the source (q) terms are present for the composite part only due to the advection of the material and the internal heat generation of the resin system, respectively.

$$\rho c\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}\right)=\frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial T}{\partial z}\right)+q \tag{1}$$

where T is the temperature of the composite material at any location, u is the velocity of the material in the axial direction, ρ is the density, c is the specific heat and k_x, k_y and k_z are the thermal conductivities in the *x*, *y* and *z* directions, respectively. The velocity u of the composite material in the axial direction is equal to the pulling speed U.

The rate of internal heat release q is proportional to the rate of reaction of cure and can be expressed as:

$$q=\rho_m H_{tot} R_r(\alpha,T)\left(1-V_f\right), \tag{2}$$

where ρ_m – density of thermoset resin, H_{tot} – specific heat released at complete cure, $R_r(\alpha,T)$ – rate of reaction of cure, V_f – volume fraction of reinforcement in a composite material. The cure degree rate of change depends on temperature and on attained degree of cure, and can be expressed by the following kinetic equation

$$R_r(\alpha,T)=\frac{d\alpha}{dt}=\frac{\partial\alpha}{\partial t}+\frac{\partial\alpha}{\partial x}\frac{dx}{dt}=\frac{\partial\alpha}{\partial t}+\frac{\partial\alpha}{\partial x}u=K_0(1-\alpha)^n exp\left(-\frac{E}{RT}\right), \tag{3}$$

where K_0 – material constant, E – activation energy, n – order of reaction, R – universal gas constant.

Mechanical properties of a resin change during solidification. For the purpose of the present work the Poisson's ratio of a resin is assumed to remain constant (as in [10]), while Young modulus E_m is calculated as follows:

$$E_m(T^*) = \begin{cases} E_m^0, & T^* < T_{C1} \\ E_m^0 + \dfrac{T^* - T_{C1}}{T_{C2} - T_{C1}}\left(E_m^\infty - E_m^0\right), & T_{C1} \le T^* \le T_{C2}, \\ E_m^\infty, & T^* > T_{C2} \end{cases} \quad (4)$$

where $T^* = T_g - T$, T_g – glass transition temperature depending on degree of cure and determined from the equation [11]:

$$T_g(\alpha) = T_{g0} + \left(T_{g\infty} - T_{g0}\right)\frac{\lambda\alpha}{1 - (1 - \lambda)\alpha}, \quad (5)$$

where T_{g0}, $T_{g\infty}$, λ, T_{C1}, T_{C2}, E_m^0, E_m^∞ – material constants.

It is assumed that a coefficient of thermal expansion, β, of an rubbery resin (at $T > T_g$) is 2.5 times higher than CTE of a glassy state. In addition to thermal deformations the so-called chemical deformation (shrinkage) of a composite resulting from rubbery – glassy phase transition of a resin is also considered in calculations [11].

Chemical shrinkage of resin is determined as follows:

$$\Delta\varepsilon_m^{ch} = \sqrt[3]{1 + \Delta V^{ch}} - 1, \quad (6)$$

where $\Delta V^{ch} = \Delta V_{tot}^{ch} \cdot \Delta\alpha$ – resin volume contraction corresponding to the increase in cure degree by $\Delta\alpha$, ΔV_{tot}^{ch} – relative change in a volume of resin at complete cure. Effective chemical shrinkage of a composite is calculated based on analytical models [11].

For stress determination a model of transversely isotropic material is used, where stiffness tensor depends on a phase state of resin (elastic, solid) and changes during cure process. Stiffness tensor at each instant of time is determined as follows: first, the Young modulus of resin is calculated using the equation (4); and then effective characteristics of composite material are calculated based on the micromechanical model [12]. Mechanical and thermal properties of reinforcing fibers are assumed to remain constant over time.

The model described above is implemented within ABAQUS environment by means of the user subroutine mechanism [13]. As cure processes in thermoset composite materials take place over a long period of time their simulation is carried out using the ABAQUS Standard implicit solver.

3 C-SECTION STAIR PROFILE

To validate the simulation tool on a reasonably complex real case the C-section stair profile (see Figure 1) was manufactured, shape distortions were measured and compared with predicted ones. Profile reinforcement is built up of fiberglass rovings oriented in longitudinal direction and the outer layer consisting of two fiberglass fabric layers. The experimental work was conducted in ApATeCh company [14] on pultrusion machine PULTREX [15].

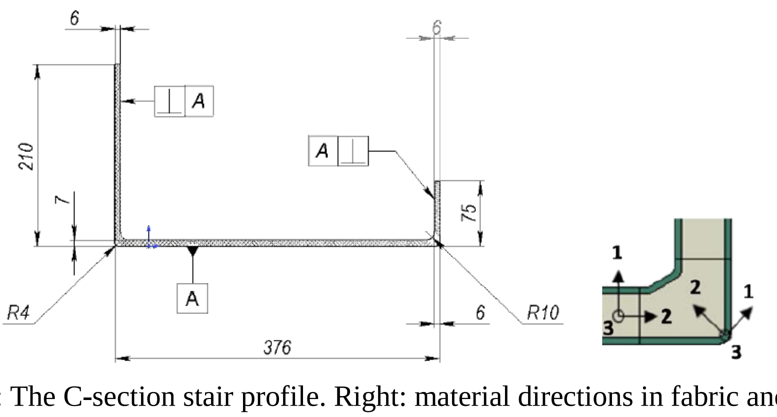

Figure 1: Left: The C-section stair profile. Right: material directions in fabric and roving.

The parameters of materials that were used for modelling are presented in Table 1. The pulling speed was 11cm/min. The distribution of temperature load inside the die is represented in Figure 2. Cooling of stair channel to ambient temperature (after leaving the die) occurs without the usage of special equipment. It was used 2D plane strain model of C-section profile. The results of modeling are presented in Figure 3 and results of geometry control are provided in Table 2. The closest result to experiment was obtained for ΔV^{ch} = 7%. Whereas predicted formation of deformations in ABAQUS are found to agree with experiment, corresponding magnitudes obtained from the simulation differ from experimental results, in particular for the rightside part of channel bar. The predicted spring-back angles from both sides are both equal 0°38'.

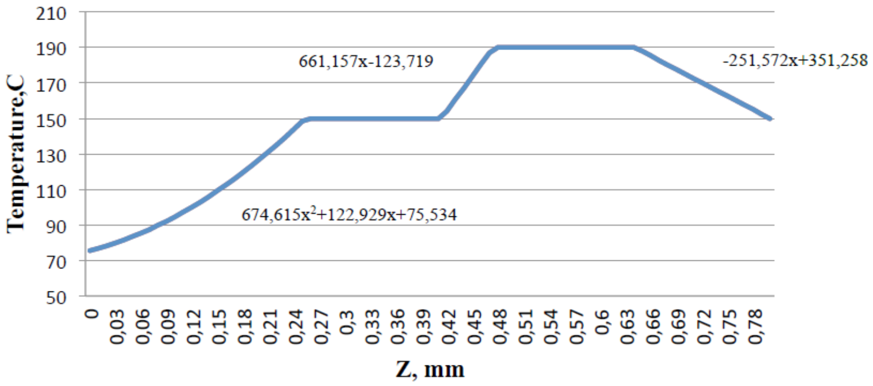

Figure 2: Approximation of the thermal load inside the die.

ρ, kg/m^3	H_{tot}, kJ/kg	E_f,MPa	ν_f	β_f, $1/K$	β_f,MPa	V_f, %
1850	157	71000	0.29	$5.4 \cdot 10^{-6}$	$5.76 \cdot 10^{-6}$	40

Table 1: Mechanical properties.

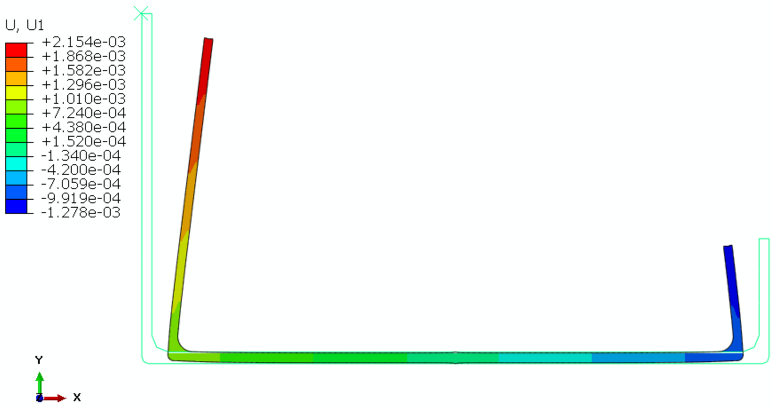

Figure 3: Results of simulation for different volume chemical shrinkage. (Scale Factor is 17).

	Experiment		*Simulation*	
	Displacement (mean)	Angle	Displacement (ΔV^{ch}=7%)	Angle
L_{75}	0.6 mm	0°29'	1.3 mm	0°38'
L_{210}	2.24 mm	0°38'	2.2 mm	0°38'

Table 2: Experimental (mean value from several measurements) and simulation results of shape distortions.

5 NUMERICAL OPTIMIZATION

For numerical optimization and sensitivity analysis of process parameters, the special simulation scheme was developed in pSeven software. pSeven is a platform for automation of engineering simulation and analysis, multidisciplinary optimization and data mining tasks. The main goal of process parameters optimization is to maximize pulling speed in order to increase production rate, while satisfying temperature, curing degree, residual stress, and shape distortions constraints. The multi-objective surrogate-based optimization (MSBO) algorithm was used. One of the main features of MSBO algorithm realization in pSeven is a possibility to allocate the computational budget (number of model evaluations) [9]. The constraints considered in this study are transverse stress in pultruded profile, maximum temperature of the material and minimum degree of curing at the end of a die zone. Transverse stress is measured in points with maximum values, located on the inner and outer sides on the bend area. Maximum spring-back angle is used to control the shape distortion of the profile.

The process parameters study was performed in two steps: the uniform design of experiments was chosen in order to study the model behavior and sensitivity, and the two-criterion optimization problem was solved to obtain a Pareto-frontier in speed vs. deformation coordinate system. The process parameters and their limits are presented in Table 3.

Parameter	*Initial value*	*Lower limit*	*Upper limit*	*Description*
$T_0, °C$	50	20	50	Initial temperature of material
$T_1, °C$	150	120	160	Temperature in die zone 1
$T_2, °C$	190	150	190	Temperature in die zone 2
$U, mm/s$	1.0	0.75	1.25	Pulling speed

Table 3: Process parameters and their limits.

Latin hypercube sampling method was used to get sampling of 45 points. To estimate how variations in the model output can be attributed to variations in the model inputs the sensitivity analysis was conducted. The approximation model based on Gaussian processes was built with maximum RMS error (based on training sample) of 0.04. Distribution of spring-back angles over parameter space was studied. The angle value (in degrees) is presented in Figure 4 in T1 vs. T2 coordinates for different initial temperatures and pulling speeds. According to results obtained, the maximum spring-back angle is only 0.5 degree. It is important to note that for almost half of possible configurations the spring-back angle does not exceed (is less than) 0.25 degree. The increase of pulling speed does not lead to significant deformation.

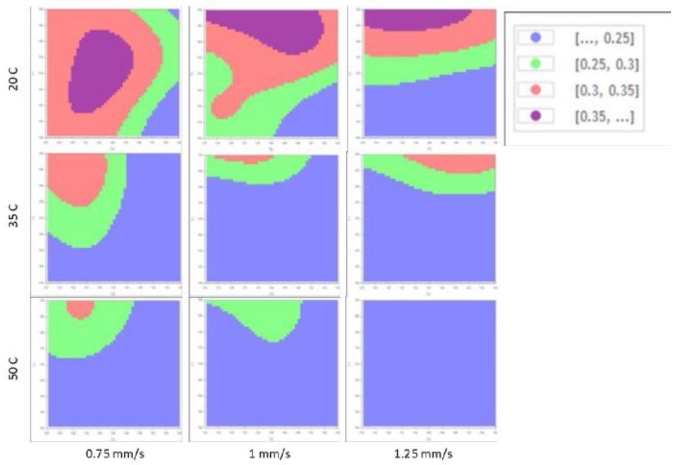

Figure 4: Spring-back angle variance.

According to obtained results the maximum spring-back angle is only 0.5 degree. It is important to note that for almost half of possible configurations it is less than 0.25 degree. The increase of pulling speed does not lead to significant deformation. That is why it is reasonable to expect a flat Pareto-frontier in angle vs. speed optimization problem. The constraints values for the optimization problem are provided in Table 4.

Constraint	*Value*	*Motivation*
Tmax, °C	<200	Prevention of thermal degradation
Cure degree	>0.95	Material quality assurance
Stress, MPa	<11.0	Prevention of cracking

Table 4: Constraints values.

The approximation model allows to visualize different constraints violation areas. Such areas are presented in coordinates T1 vs. T2 for different initial temperatures and pulling speeds within ranges provided in Figure 4.

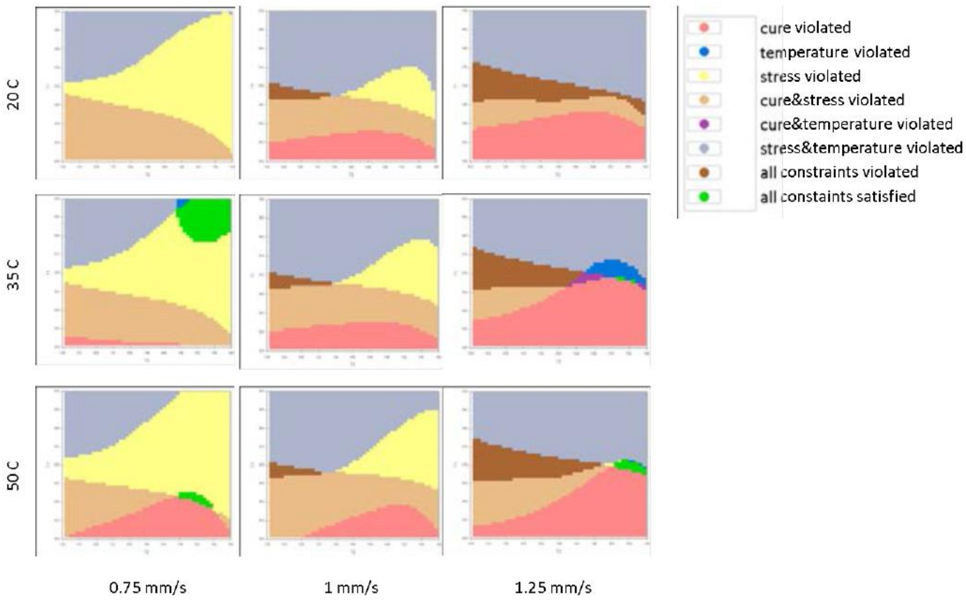

Figure 4: Constraints violation areas.

The area satisfying all constraints is quite small. It means that Pareto-frontier for the optimization problem may become degenerated. For two-criterion optimization problem the minimization of spring-back angle and maximization of the pulling speed were considered. The results are shown in Figure 5. The Pareto-frontier seems practically degenerated with respect to the total range. All Pareto configurations demonstrate very small spring-back angles, so the problem effectively becomes a one-criterion optimization problem. The pulling speed is limited by stress constraints. The maximum achieved speed is about 18 % higher compared to initial one.

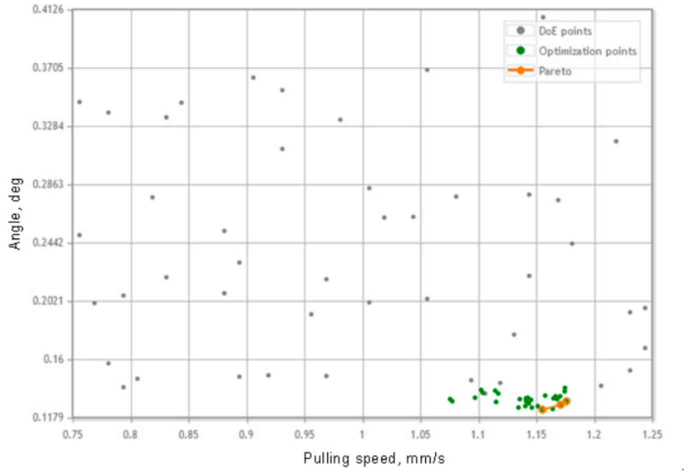

Figure 5: Constraints violation areas.

Initial and optimal parameters are presented in Table 5.

Parameters and goals	Initial configuration	Optimum configuration
T_0, °C	50	44
T_1, °C	150	160
T_2, °C	190	168
U, mm/s	1	1.18
Spring-back angle, deg.	0.24	0.13
Constraints		
T_{max}, °C	195	189
Cure degree	0.99	0.96
Stress, MPa	11	11

Table 5: Optimization results.

9 CONCLUSIONS

The computer program for modeling of pultrusion process was created on the basis of developed mathematical model and implemented for numerical simulation in ABAQUS environment. In order to verify the proposed model of pultrusion process and its implementation in ABAQUS several test problems were solved and found to agree with results described in literature. Additionally, to verify the developed model full-scale experiment was conducted. C-section stair profile was manufactured in ApATeCh company and shape distortions were measured and compared with predicted ones using developed simulation tool. Whereas predicted formation of deformations in ABAQUS are found to agree with experiment, corresponding magnitudes obtained from the simulation differ greatly from experimental results. The difference in the results can be explained by the fact of presence of various additives in the resin and non-uniform heating of material inside the die. A numerical optimization method of pultrusion process parameters was presented. As an example, the two-criterion optimization of process parameters for pultrusion of glassfiber reinforced C-section profiles was considered. Objective functions of two-criterion optimization were the pulling speed and the maximum spring-back at the end section. With total computing budget of the problem of only 80 points, a Pareto-front of optimum configurations in two-criterion problems has been obtained. A pulling speed increase of 18 % has been achieved, satisfying all constraints. Suchwise developed simulation tool is a cost effective approach for prediction of shape distortions of pultruded profile and selection of optimal process parameters.

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