

Investigation of Residual Stresses and Deformations of a Pultruded Thin Beam Profile

Endija Namsone

Institute of Materials and Structures
Riga Technical University
Riga, Latvia
endija.namsone@inbox.lv

Abstract - In the present study, a coupled 3D transient thermo-chemical analysis together with 2D plane strain mechanical analysis is carried out for the pultrusion process. For the mechanical analysis, a cure hardening instantaneous linear elastic (CHILE) approach is used of a thin beam profile made of glass fibre and epoxy resin. The applied approach is efficient and fast to investigate the residual stresses and deformations together with the distributions of temperature and degree of cure obtained from the thermo-chemical analysis.

Keywords - finite element method, pultrusion, residual stresses, thermo-mechanical.

I. INTRODUCTION

Characterization of mechanical behaviour is not only an important study for entire structures under loading [1]-[3], but also for the separate parts in time of their production [4] since stresses and deformations caused by the process may occur.

Pultrusion is a continuous and cost-effective process and is widely used for a production of high strength fibre-reinforced polymer composite profiles with different cross-sections [5], [6]. During pultrusion, the fibres are saturated with the resin in a tank and after that are continuously pulled through a heated die. In literature, many different numerical and experimental techniques are carried out to design pultrusion processes. Mostly, thermo-chemical modelling in transient and steady state analyses are developed for a better understanding of pultrusion processes to analyse the distributions of temperature and degree of cure inside the die, using the finite element methodology [7]-[9] finite difference methodology [10], [11], based on the nodal control volume method.

It is well known, that in time of manufacturing process of thermoset matrix composites, material characteristics of

resin vary during the glass transitions from rubbery to solid state. It follows that, this change of resin material directly influences its mechanical properties, which are temperature- and degree of cure-dependent and can occur as unwanted residual deformations. Therefore, the investigation of process-induced variations like residual stresses and deformations should be performed for a better control of mechanical behaviour of pultrusion process.

In addition of thermo-chemical studies in literature, a thermo-chemical-mechanical analysis of pultrusion for glass-fibre reinforced profiles are developed in [12]-[14]. For this reason, in the present study a thermo-mechanical analysis is applied by coupling a 3D thermo-chemical model with a 2D plane strain mechanical model, like described in [15], [16]. The thermo-mechanical finite element model is created in the finite element code ANSYS Mechanical, based on the cure hardening instantaneously linear elastic method (CHILE) as in [17] to investigate the residual stresses and deformations of pultruded beam profile made of glass fibre and epoxy resin.

II. MATERIALS AND METHODS

A. Formulation of multi-physical problem

The simulation of 3D thermo-chemical pultrusion process can be solved by three governing energy equations:

$$\rho c_p \frac{\partial T}{\partial t} - \frac{\partial}{\partial x} \left(k_x \frac{\partial T}{\partial x} \right) - \frac{\partial}{\partial y} \left(k_y \frac{\partial T}{\partial y} \right) - \frac{\partial}{\partial z} \left(k_z \frac{\partial T}{\partial z} \right) = 0 \quad (1)$$

$$\bar{\rho} \bar{c}_p \left(\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} \right) - \frac{\partial}{\partial x} \left(\bar{k}_x \frac{\partial T}{\partial x} \right) - \frac{\partial}{\partial y} \left(\bar{k}_y \frac{\partial T}{\partial y} \right) - \frac{\partial}{\partial z} \left(\bar{k}_z \frac{\partial T}{\partial z} \right) - q = 0 \quad (2)$$

$$\left(\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} \right) = R_r \quad (3)$$

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where T is the temperature, u is the pull speed, c_p is the specific heat, ρ is the density, k_x, k_y and k_z are the thermal conductivities in x, y and z directions, q_b is the rate of energy, α is the degree of cure. Accordingly, $\bar{\rho}$ is the lumped density, \bar{c}_p is the lumped specific heat, \bar{k}_x, \bar{k}_y and \bar{k}_z are the lumped thermal conductivities of the composite material in x, y and z directions. The generative term q in a relation of internal heat generation and due to the exothermic reaction of resin can be expressed by the following equation:

$$q = V_r + \rho_r + H_{tr} + R_r \quad (4)$$

where V_r is the resin volume fracture, H_{tr} is the total heat of reaction, ρ_r is the density of resin and R_r is the resin reaction rate, which can be described as in [18]:

$$R_r(\alpha, T) = \frac{\partial \alpha}{\partial t} = \frac{1}{H_{tr}} \frac{dH(T)}{dt} = K(T) \cdot f(\alpha) \quad (5)$$

$f(\alpha)$ is the reaction function and $K(T)$ can be defined by the Arrhenius relationship:

$$K(T) = K_0 \exp\left(-\frac{E}{RT}\right) \quad (6)$$

where R is the universal gas constant and E is the activation energy. E and K_0 could be determined by a fitting procedure of the experimental heat flow curves obtained from differential scanning calorimetry tests.

For the thermo-chemical simulation of pultrusion process in this study, the equations above are solved using the finite element code ANSYS Mechanical and the nodal control volume method is applied to obtain the evolution of temperature and degree of cure.

Since the resin state changes during the process from rubbery to glassy state, the CHILE approach method is applied to capture the transition mechanically for the thermo-mechanical analysis. In this case, the resin modulus is described:

$$E_r(\alpha, T) = \begin{cases} E_r^0 & T^* < T_{C1} \\ E_r^0 + \frac{T^* - T_{C1}}{T_{C2} - T_{C1}} (E_r^\infty - E_r^0) & T_{C1} \leq T^* \leq T_{C2} \\ E_r^\infty & T^* > T_{C2} \end{cases} \quad (7)$$

where E_r^0 and E_r^∞ are the uncured and cured resin moduli, T_{C1} and T_{C2} are the critical temperatures at the begin and completion of the glass transition and T^* is the difference between the instantaneous glass transition and resin temperature: $T^* = T_g - T$. The evolution of the glass transition is described as:

$$T_g = T_g^0 + (T_g^\infty - T_g^0) \frac{\lambda \alpha}{1 - (1 - \lambda) \alpha} \quad (8)$$

T_g^0 and T_g^∞ are the temperatures of glass transition of uncured and cured resin, λ is a constant fitting parameter.

The chemical shrinkage of resin is calculated:

$$\Delta \varepsilon_r = \sqrt[3]{1 + \Delta V_r} - 1 \quad (9)$$

where $\Delta V_r = \Delta \alpha \cdot V_{sh}$ - the incremental volume resin shrinkage as a function of change in the degree of cure and total volume shrinkage $V_{sh} = 6.9\%$.

The thermo-mechanical problem is solved by using the obtained distributions of temperature and degree of cure from the thermo-chemical analysis. For the finite element simulations in ANSYS, the incremental linear elastic approach is applied to calculate the residual stresses and deformations. The incremental thermal strains:

$$\Delta \varepsilon_i^{th} = \alpha_i \cdot \Delta T \quad (10)$$

Mechanical properties of fibre and resin, fibre volume fracture and as well as the chemical resin shrinkage strains are affecting the incremental chemical shrinkage strains. Assuming the fibre phase mechanical properties are cure independent $\Delta \varepsilon_{1f} = \Delta \varepsilon_{2f} = \Delta \varepsilon_{3f} = 0$, then incremental chemical strain:

$$\Delta \varepsilon_1^{ch} = \frac{\Delta \varepsilon_r E_r (1 - V_f)}{E_{11f} V_f + E_r (1 - V_f)} \quad (11)$$

$$\Delta \varepsilon_2^{ch} = \Delta \varepsilon_3^{ch} = (\Delta \varepsilon_r + \nu_r \Delta \varepsilon_r) (1 - V_f) - (\nu_{12f} V_f + \nu_r (1 - V_f)) \Delta \varepsilon_1^{ch} \quad (12)$$

where E_{11f} and ν_{12f} is the longitudinal elastic modulus and Poisson's ratio of the fiber, E_r and ν_r - of the resin, V_f is the fibre volume ratio. $\Delta \varepsilon_1^{ch}$ - incremental chemical strain in the longitudinal direction, $\Delta \varepsilon_2^{ch}, \Delta \varepsilon_3^{ch}$ - in the transverse directions.

B. Thermo-chemical model

A 3D transient thermo-chemical analysis is carried out for a thin beam profile [12]. The pultrusion die for this profile is with following dimensions 915 x 38.1 x 38.1 mm and 1.59 x 12.7 mm for the cross-section of it. The materials used for a production of beam are fiberglass and epoxy resin. The finite element model is created in ANSYS mechanical using 3D thermal solid finite elements Solid 70 and only a quarter is modelled due to the symmetry (see Fig.1). The total number of elements is 11102 and 3660 mm from the die exit of profile is continued to extend the thermo-chemical analysis. The initial conditions:

- at time $t=0$ all nodal points have the room temperature and degree of cure is 0;
- pull speed 20 cm/min;
- solution time step is 4.5 s.

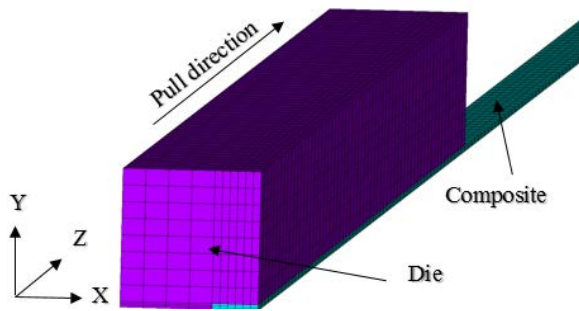


Fig. 1. Fragment of the finite element model for the thermo-chemical analysis.

C. Thermo-mechanical model

During the 2D thermo-mechanical analysis, the cross-section of beam profile is moved through the pull direction. The finite element model of profile cross section in ANSYS Mechanical is created by 2D plane strain solid finite elements Plane 182. The model has following boundary conditions – symmetry boundary conditions on the symmetry line and sliding conditions on the contact surfaces.

The mechanical properties of fibre and resin are given in Table 1. The value of CTE of resin in a glassy state is 2.5 times smaller than in a rubbery state. The critical temperature at the onset and competition of glass transitions is assumed $T_{C1} = -45.7^{\circ}\text{C}$ and $T_{C2} = -12^{\circ}\text{C}$. For the T_g calculation in equation (8), T_g^0 is assumed 0°C and $T_g^{\infty} = 195^{\circ}\text{C}$. The fitting parameter $\lambda = 0.4$.

III. RESULTS AND DISCUSSIONS

It should be noted that all results for the thermo-mechanical analysis should be viewed together with the distributions of temperature and degree of cure obtained

TABLE 1 MECHANICAL PROPERTIES OF FIBRE AND RESIN

| Property | Value | | |
|--|-------------------------------------|----------------------|----------------------|
| | Symbol (unit) | Fibre | Resin |
| Young's modulus | E_r^0 (MPa) | - | 3.447 |
| | E_r^{∞} (MPa) | - | $3.447 \cdot 10^3$ |
| | E_{11} (MPa) | $7.308 \cdot 10^4$ | Eq. 11 [1] |
| | E_{22} (MPa) | $7.308 \cdot 10^4$ | Eq. 11 [1] |
| Shear modulus | G_{12} (MPa) | $2.992 \cdot 10^4$ | Eq. 13 [1] |
| | G_{13} (MPa) | $2.992 \cdot 10^4$ | Eq. 13 [1] |
| Poisson's ratio | ν_{12} | 0.22 | 0.35 |
| | ν_{13} | 0.22 | 0.35 |
| Coefficient of thermal expansion (CTE) | α_1 ($1/^{\circ}\text{C}$) | $5.04 \cdot 10^{-6}$ | $5.76 \cdot 10^{-5}$ |
| | α_2 ($1/^{\circ}\text{C}$) | $5.04 \cdot 10^{-6}$ | $5.76 \cdot 10^{-5}$ |

from the thermo-chemical analysis, which were measured in two different control points. As the temperature and degree of cure distributions are almost uniform all over the cross-section of profile, the results are practically the same for both control points. For this reason, the results of thermo-chemical analysis are presented only for one control point B (see Fig. 2).

The values of effective Young's moduli at the end of the pultrusion process are describing the final stiffness of beam profile. These values are found to be 48 238.5 MPa in the longitudinal direction and 12 439.9 MPa in the transverse direction. Comparing them with the recommended values found in literature [19], which is in the range of 35 000 to 50 000 MPa for glass fibre reinforced composite, it can be concluded that the stiffness of this beam is adequate.

The evolution of corresponding strains are given in Fig.3. In this case, thermal strain is the incremental thermal strain and chemical strain is the linear chemical strain. The total strain is the process induced strain obtained by counting together thermal strain with chemical strain. The maximum value of thermal strain is $\varepsilon_{max}^{th} = 0.01116$.

IV. CONCLUSIONS

In the present study, a thermo-chemical-mechanical analysis was performed with the aim to investigate the residual stresses and deformations for the pultrusion process of a rectangular thin beam profile. For this reason, a 3D thermo-chemical model was coupled with a 2D plane strain mechanical model performed in finite element code ANSYS Mechanical. In order to obtain the resin modulus, which is dependent of temperature and degree of cure, the CHILE based approach was utilized.

During the thermo-chemical analysis, uniform distributions of temperature and degree of cure were obtained all over the profile in both control points, where the process of curing were occurred very similarly at the same time.

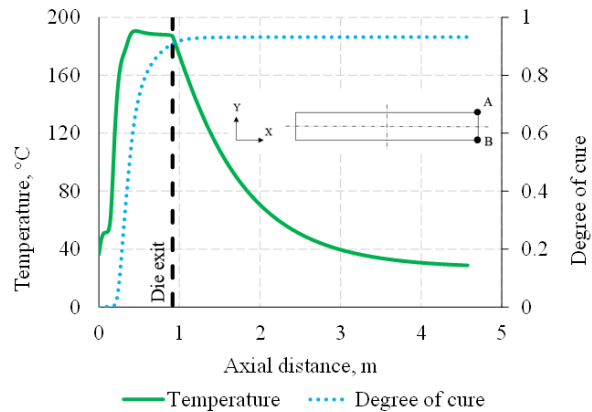


Fig. 2. The distribution of temperature and degree of cure in the control point B.

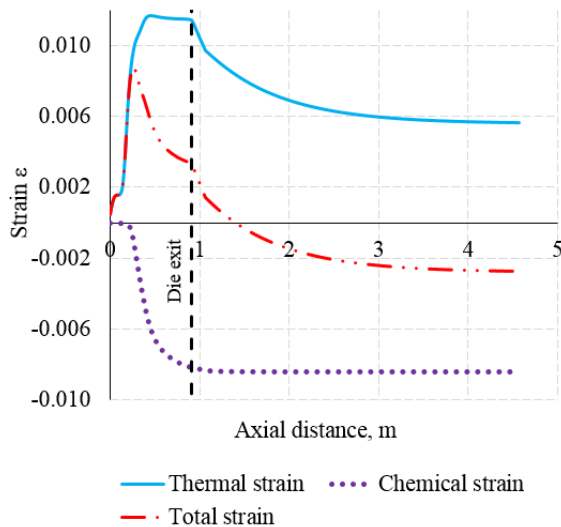


Fig. 3. The strain evolution in the control point B.

The obtained values of the effective elastic modulus of the composite material were analysed and compared with the recommendations in the literature, it can be concluded that the stiffness of beam profile is appropriate.

The applied method was found to be quite fast and efficient for the investigation of the residual stresses and deformations together with the distributions of temperature and degree of cure. It could be performed for further studies also for more complex pultruded profiles for different structures, where the geometrical precision is more important.

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