

Analysis of the 3-dimensional draping and permeability characteristics of woven fabric and optimization of the technological process for the complex shape aerospace structures

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Abstract

In this study modelling of the fibre volume content and porosity of the plain, satin, twill weaving and 3D woven fabrics were analysed in DFMA program. The simulation of the multilayer composite was presented. The influence of weaving pattern on the duration of the impregnation process by vacuum infusion was also studied in the PAM-RTM. The satin fabric has the highest porosity, which allows to accelerate the resin impregnation. The results show that it is necessary to consider the influence of the coefficient of permeability in the z-plane K_{zz} with increasing laminate thickness more than 2 mm.

1. Introduction

Advanced composite materials are widely used in modern aviation, aerospace structure and other application, which is associated with their good mechanical, thermal and other properties, as well as high reliability. Carbon fibre reinforced plastics are one of the most popular structural materials, since they have high strength to weight ratio, stiffness and unique thermophysical properties [1, 2]. In the development of new structure, the range of operating loads expands, temperatures and pressures increase, which requires the development of new materials and moulding technologies that meet these requirements. However, the cost of products from carbon fibre reinforced plastics is higher than others when using traditional structural materials, which is largely due to the duration of the forming process and the high cost of prepregs used [3]. The use of products made of autoclave carbon fibre reinforced plastic during the curing process leads to a substantial increase in their cost, which largely limits their field of application. The most widely used out of autoclave technologies in the composite fabrication are vacuum infusion and resin transferred moulding. The main technological operations of these technologies are: the manufacture of a binder, fabric pattern, laying up, impregnation and curing [4, 5]. Quality losses can occur at each of these technological operations, but the most complex is the fabric layout on the surface of the complex shaped mould and impregnation operation. These mechanical characteristics of final products depend on the fabric structure, including the type of weaving. When laying up the fabrics on the mould with double curvature surface and complex shaped, then in the process, all structures of the unit cell are deformed, which leads to a change in the porosity and consequently the values of permeability coefficients. Vacuum Infusion can significantly reduce the manufacturing cost; however, the porosity of such parts is higher, which leads to a decrease in their mechanical characteristics. That is why at the present time there are numerous studies related to the optimization of technological modes of moulding and quality improvement.

The aim of the research is to study the influence of the weaving pattern structure of the fabric on the volume content of the fibre, porosity and kinetics of the impregnation process of aircraft fuselage in the polymer composite manufacturing.

2. Mathematical models

The structure of the woven fabric was considered in accordance with the theory of P.L. Chebyshev [6-7], according to which two families of lines intersecting on the surface and form a network, to study the forming characteristics of the fabric to determine the amount of fibre content and the porosity of the fabric. Fabrics have their own characteristics, depending on the structure of weaving pattern. The unit cell of the fabric is shown in Fig. 1.

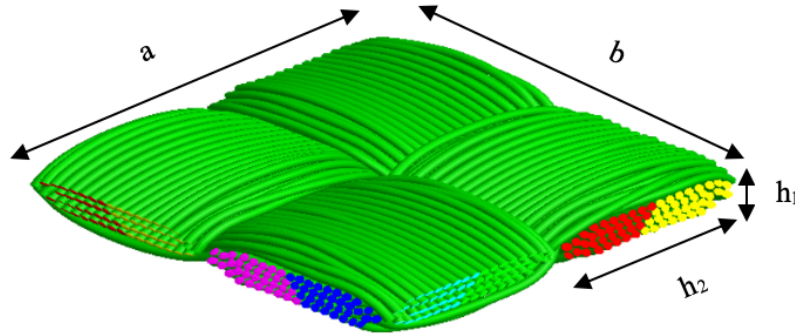


Figure 1: Fabric unit cell structure

At the first stage, it is necessary to determine the porosity of the fabric to obtain initial data in the simulation. The porosity of the fabric P depends on the volume of the unit cell V and the volume of fibre in the unit cell V_f .

$$P = 1 - \frac{V_f}{V} \quad (1)$$

In the undeformed state, i.e. the volume of the initial fabric unit cell structure V_{ini} is

$$V_{ini} = abh_1 \quad (2)$$

where a , b , h_1 are the geometric characteristics of the fabric unit cell structure.

When laying up the fabric on the mould surface, its density at different points will be different, due to changes in the network angle α . The volume of the unit cell in the deformed state V_{def} is equal to

$$V_{def} = abh_1 \sin \alpha \quad (3)$$

The theoretical minimum residual porosity P_{min} is 0.09 [4].

The amount of fibre in the unit cell during deformation does not change

$$V_{f_{def}} = V_{f_{ini}} = \frac{h_2 h_1}{2} (a + b) (1 - P_{min}) \quad (4)$$

In accordance with equation.1, the initial porosity P_{ini} of the fabric before laying up on the mould's surface (i.e., in the undeformed state) and after fabric lay-up (i.e., in the deformed state) P_{def} is equal to

$$P_{ini} = \frac{V_{f_{ini}}}{V_{ini}} \quad (5)$$

$$P_{def} = \frac{V_{f_{def}}}{V_{def}} \quad (6)$$

In the work will be considered products with a flat surface, since it does not consider the deformation of the unit cell during the lay-up process. Therefore, P_{ini} will be equal to P_{def} .

Four types of woven weaving pattern were investigated: plain, twill, satin, and 3-D fabric. To determine the volume of fibre content and fabric porosity, the fabric structures were simulated using the DFMA analysis software. The geometric parameters of the warp and weft are equal. The amount of fibre content is determined by the dependence of the type of weaving, the number and cross-section of the filament and density. The results are presented in the figures 2 – 5.

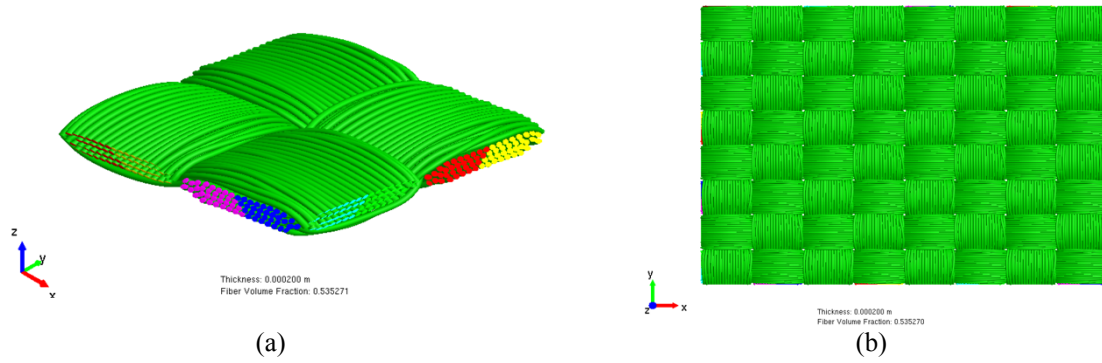


Figure 2: Model of plain fabric No. 1: (a) unit cell; (b) 4×4 cells

The thickness of the layer h_l - 0.2 mm, the volume of the fibre content V_f - 0.51,
 a and b - 1 mm

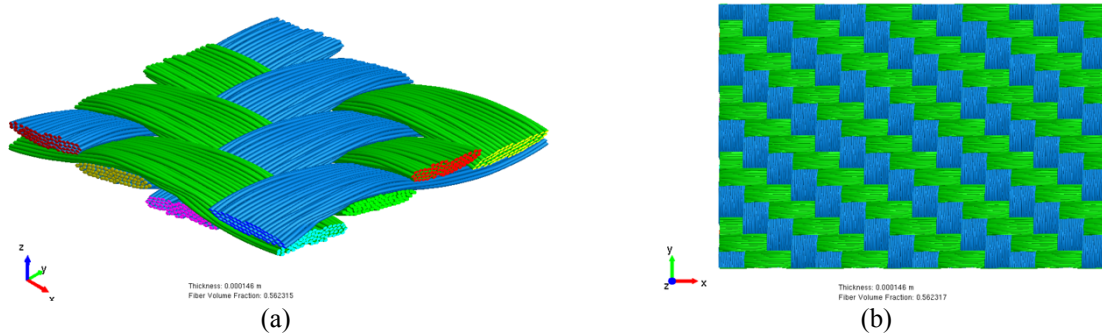


Figure 3: Model of twill fabric No. 2: (a) unit cell; (b) 4×4 cells

The thickness of the layer h_l - 0.146 mm, the volume of the fibre content V_f - 0.48,
 a and b - 2 mm

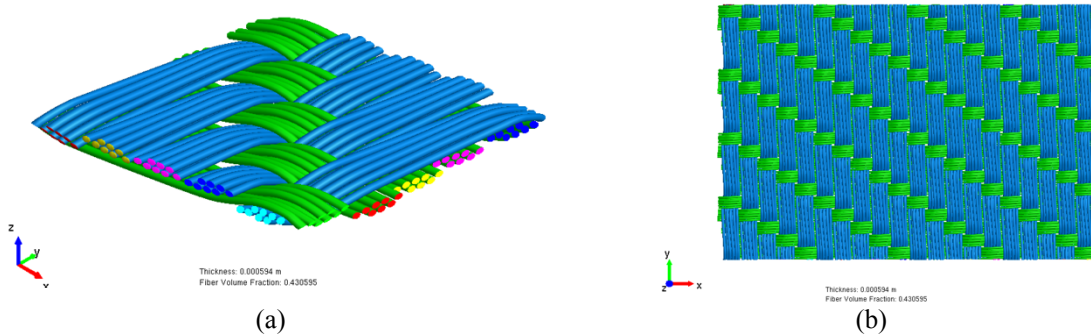


Figure 4: Model of satin fabric No. 3: (a) unit cell; (b) 4×4 cells

The thickness of the layer h_l - 0.594 mm, the volume of the fibre content V_f - 0.42,
 a and b - 3 mm

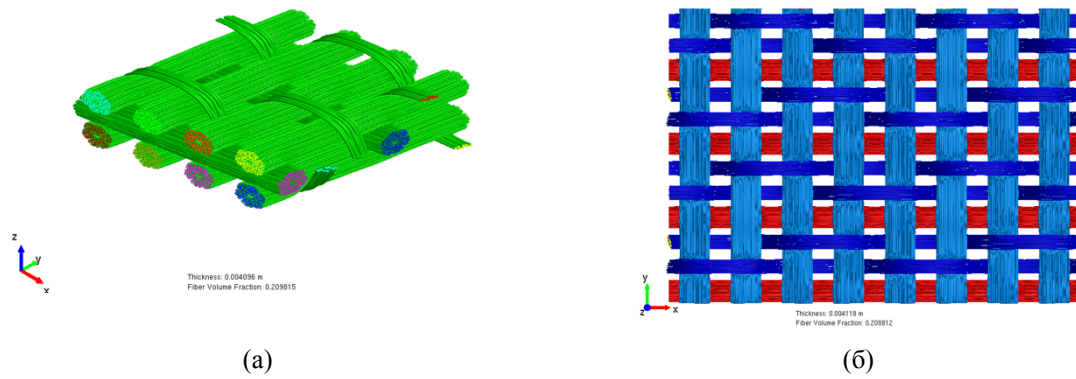


Figure 5: Model of 3D fabric No. 4: (a) unit cell; (b) 2x2 cells

The thickness of the layer h_l - 0.4 mm, the volume of the fibre content V_f - 0.20,
 a and b - 3 mm

3. Results

The obtained simulation results were used in calculations to determine the porosity of the fabric. An analytical calculation of the volume content of the fibre is carried out. A comparison of theoretical and simulation results is shown in the figure 6.

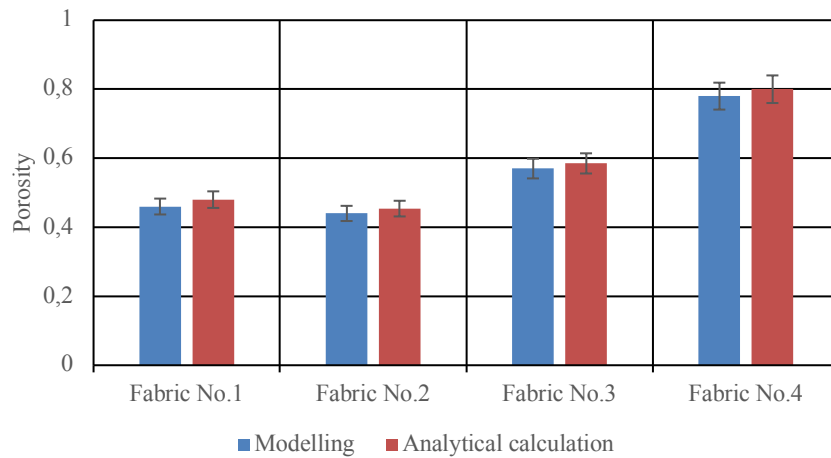


Figure 6: Comparison of porosity between the results of modelling and analytical calculations

As a result of the research it was found that the difference between the results of modelling and analytical calculations is not very significant. This allows to increase the adequacy of the simulation to determine the amount of fibre content and fabric porosity. In the manufacturing process, multi-layer fabric laminates are used. Therefore, it is necessary to determine the volume content of the multi-layer fabric laminate. A simulation of 2-D multilayer woven laminates was carried out in DFMA analysis program (Fig. 7). The results obtained show that the fibre volume content of a fabric for the plain weaving pattern is 0.53, for twill 0.51 and for satin 0.45.

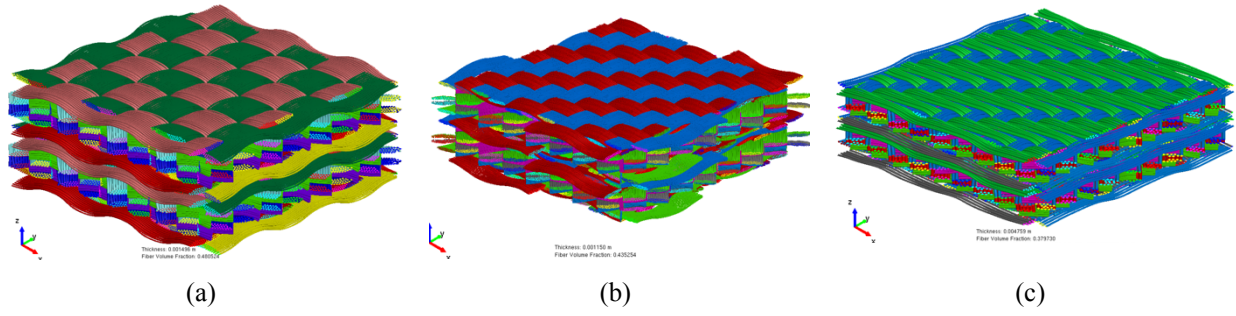


Figure 7: Model of 8 layers ($0^\circ, \pm 45^\circ, 90^\circ$)² laminate package:

- (a) Plain weaving pattern: laminate thickness –1.49 mm, volume of fibre content - 0.53
- (b) Twill weave pattern: laminate thickness - 1.115 mm, volume fibre content - 0.51
- (c) Satin weaving pattern: laminate thickness - 4.7 mm, volume of fibre content - 0.45

4. Analytical models of impregnation process

The coefficient of permeability is the one of the most influence parameters of the fabric in resin impregnation process. The values of coefficient of permeability can be written by equation

$$K_{xx \text{ or } yy} = \frac{1}{L} \sum_{i=1}^N t_i K_i \quad (7)$$

where t_i - thickness of i - layer, K_i – coefficient of permeability i - layer, N – number of layers, L – length of specimen, $K_{xx \text{ or } yy}$ – coefficients of permeability in X and Y direction.

$$K_{i,xx} = \frac{8R_f^2 (1 - V_f)^3}{c_1 V_f^2} \quad (8)$$

$$K_{i,yy} = c_2 \left(\sqrt{\frac{V_{fmax}}{V_f}} - 1 \right)^{5/2} R_f^2 \quad (9)$$

For the rectangular shape of fibre placement

$$c_1 = \frac{16}{9\pi\sqrt{2}}$$

$$c_2 = 57$$

$$V_{fmax} = \frac{\pi}{4}$$

The coefficient of permeability in Z- direction

$$K_{zz} = \frac{N\pi n_f R_f^4 \sin\beta}{8A} \quad (10)$$

The 3D coefficient of permeability of the carbon fabric with different types of weaving pattern can be determined experimentally and analytically. The analytical results are shown in table 1.

Table 1. Coefficients of permeability of carbon fabrics

Fabric model	Weaving pattern	V_f , %	Thickness of monolayer, mm	R_f , μm	Linear density, tex	Coefficient of permeability	
						K_{xx}, K_{yy} , $\text{m}^2 (\times 10^{-11})$	K_{zz} , $\text{m}^2 (\times 10^{-11})$
92110	Plain	51	0,23	4,3	400	1,4	1,34
92125	Twill	48	0,3	5,9	200	1,62	1,54
92140	Satin	42	0,17	5,7	200	1,9	1,71

The results obtained show that the coefficient of permeability of the plain weaving fabric have smaller than the other fabric. These results were used to simulate the impregnation process of CFRP specimen (600 mm \times 300mm) in PAM-RTM with and without K_z (through thickness permeability). The comparison results are shown in figure 8.

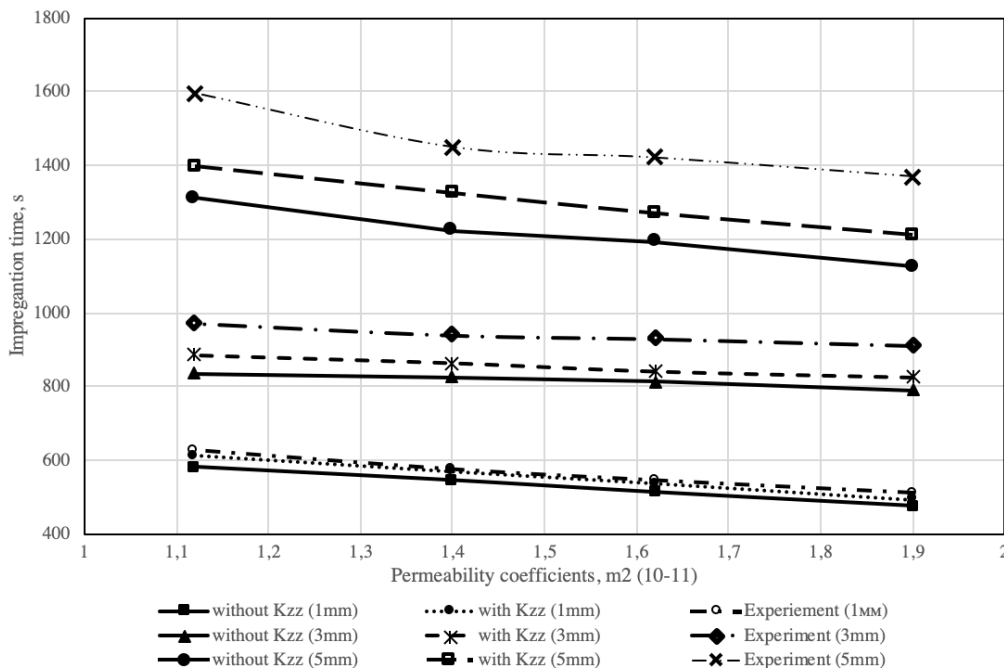


Figure 8: Comparison results of the modelling with and without through thickness permeability coefficient

The results of theoretical and experimental studies of the kinetics of the impregnation process depending on the moulding regimes were carried out. It has been established that considering the 3-dimensional coefficient of permeability along the x, y, z axes allows to increase simulation accuracy. As a result of the research it was found that with increasing laminate thickness more than 2 mm, it is necessary to consider the influence of the coefficient of permeability in the Z-plane. Simulation error without considering the through thickness permeability coefficient increases from 6% to 20%.

The simulation of the impregnation process of the whole fuselage of the trainer aircraft can be carried out in the PAM-RTM program (Fig.9). The process of impregnation has been taken place with different values of the inlet pressure of the resin with a viscosity of 0.1 Pa·s (Table 2).

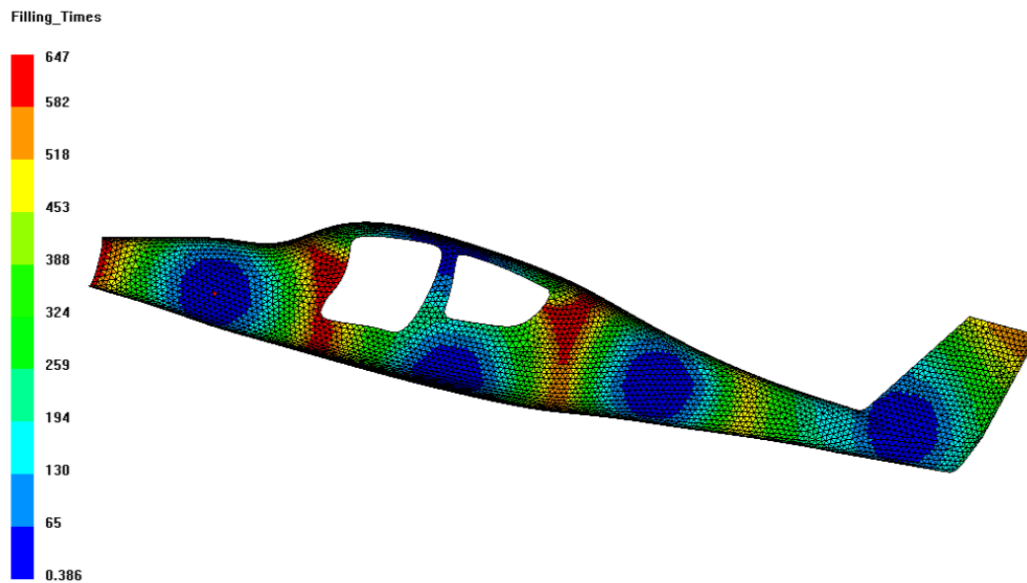


Figure 9: Simulation of resin impregnation process of aircraft fuselage

Table 2. The simulation results of the impregnation process

Fabric	Resin inlet pressure, [MPa]		
	0,2	0,25	0,3
Duration, [s]			
Plain fabric	5200	5040	4890
Twill fabric	4800	4550	4320
Satin fabric	4120	3860	3520

The simulation results allowed to establish that the fabric with satin weaving has the highest porosity, which allows to accelerate the process of resin impregnation among the 2D multi-layered laminates. The duration of the moulding process decreases with increasing the resin inlet pressure.

5. Conclusion

Analytical calculations were performed to determine the porosity of the fabric with different weaving pattern. The mathematical models of the unit cell and the structure of the fabric have been created, which make it possible to determine the volume of fibre content depending on its weaving structure. Also, modelling of the multilayer composite laminate with different reinforcing angles was carried out, which leads to increase the accuracy of determining the porosity and resin impregnation time. The results of the modelling of multilayer laminate with different reinforcing angles are simulated in the DFMA analysis program. The influence of fabric weaving pattern on the duration of the impregnation process by vacuum infusion and was also studied in the PAM-RTM program. The results of theoretical and experimental studies of the kinetics of the impregnation process depending on the moulding regimes were carried out. It has been established that considering the 3-dimensional coefficient of permeability along the x, y, z axes allows to increase simulation accuracy. As a result of the research it was found that with increasing laminate thickness more than 2 mm, it is necessary to consider the influence of the coefficient of permeability in the z-plane. Simulation error without taking into account the through thickness permeability coefficient increases from 6% to 20%.

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