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Prediction of the thermo-elastic properties of knitted structural composites using FEM

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Abstract: It is a very important and complex task to estimate the thermo-elastic properties of a textile structural composite. In this paper, the finite element method (FEM) was used for the prediction of the orthotropic thermo-elastic properties of a composite reinforced by glass fiber knitted fabric. In order to define the final 3-D configuration of the loop reinforcing structure, the interactions between the adjacent loops, the large displacement and the contact elements without friction were considered. The values predicted were compared with the experimental results.

Key words: textile composite; knitted structure; FEM

Estimating the thermo-elastic properties of a textile structural composite is a complex task. The structural constituents of the composite are combined macroscopically without dissolving one into the other. The interactions of the thermo-elastic properties of the constituents will produce the thermo-elastic properties of the composite. The knowledge of these interactions is essential for the prediction of the composite material properties[1].

A method for analyzing the interaction between the phases in a composite is based on the finite element method (FEM)[2]. The approach consists in replacing the real composite by an equivalent (or effective) material to which response can be described through the generalized version of Hooke's law. This action is developed at two levels[3]. At the micromechanical level, the average (homogenized) properties of the composite can be obtained from the individual properties of the constituents. At the macromechanical level, the stress-strain relationships for the composite are established.

This paper presents a procedure used for predicting the orthotropic thermo-elastic properties of a composite reinforced by glass fiber knitted fabric. The initial data used in the analysis are shown in Tab.1.

Tab.1 The initial data used in the analysis

Knitted fabric-single jersey structure	Wale spacing/mm	2.44
	Course spacing/mm	1.96
	Stitch length/mm	9.25
Yarn—EC11 408 Z28 T6	Diameter-open packing/mm	0.505
	Diameter-closed packing/mm	0.461
	Flexural rigidity/(N · mm^2)	0.086 5
	Bending modulus/MPa	27.1
	Poisson ratio	0.35
Matrix-unsaturated polyester-isotropic	Modulus of elasticity/GPa	2.412
	Poisson ratio	0.35
	Thermal coefficient of linear ext/℃$^{-1}$	130×10^{-6}
Reinforcement-isotropic volume fraction 0.94(*)	Modulus of elasticity/GPa	68.770
	Poisson ratio	0.245
	Thermal coefficient of linear ext/℃$^{-1}$	5.263×10^{-6}

1 Geometry of the Reinforcement

The mechanical properties of a composite are dominated by the orientation of the fibers in the structure. For knitted reinforcement, the following methods can be used to define the loop structure inside the composite: ① geometrical method[4]; ② elastica method[5]; ③ finite element method.

In this work, the finite element method was first used to establish the geometry of the loop. The yarn, initially straight, is bent until the Kawabata's microcell is obtained. The nonlinear analysis was done in 150 steps. Fig.1 shows the shape of the loop axis at 50 step intervals during the simulation.

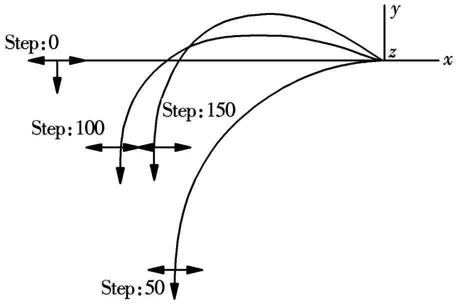

Fig.1 Shape of the loop axis at 50 step intervals

Based on the final axis obtained above in the two

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dimensions, the new geometry of the solid loop in the three dimensions can be derived. In order to define the final 3-D configuration of the loop, as a result of the interaction between the adjacent loops, another finite element nonlinear simulation (involving large displacements and contact without friction between yarns) was done in 100 steps. Fig.2 presents the initial configuration of the loops, together with some dimensional conditions to be achieved at the end of the simulation. Fig.3 illustrates the final configuration of the loops obtained during the analysis.

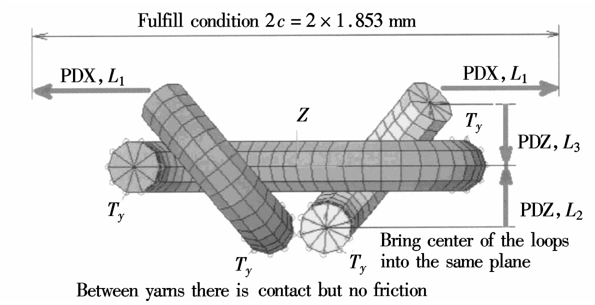

Fig.2 Initial configuration of the loops

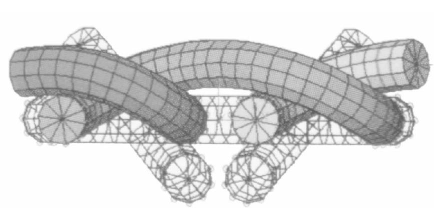

Fig.3 Final configuration of the loops

Using the final 3-D configuration of the loops, the geometry of the reinforcement inside the composite was built as shown in Fig.4.

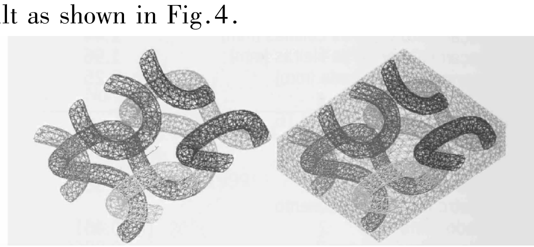

Fig.4 Geometry of the reinforcement inside the composite

2 Thermo-Elastic Properties of the Composite

The dimensions of the composite unit cell (UC) depicted in Fig.4 are 4.88 mm × 3.92 mm × 1.24 mm. These dimensions were chosen for four loop structures[2]. The volume was meshed through a finite element (FE) mesh generator, each one containing only one material, reinforcement (loops) or matrix (resin). The number and direction of loads applied to the UC mainly depends on the number of independent engineering constants required to fully characterize the composite material. In the case of an orthotropic material, it is necessary to introduce 9 independent engineering constants such as: three distinct Young's moduli (E_1, E_2, E_3), three distinct shear moduli (G_{12}, G_{13}, G_{23}) and three distinct Poisson's ratios (μ_1, μ_2, μ_3). In addition, three distinct coefficients of thermal expansion ($\alpha_1, \alpha_2, \alpha_3$) have to be introduced too. Fig.5 shows the loading directions for the UC when the prediction of thermo-elastic properties is done in the loop wale direction.

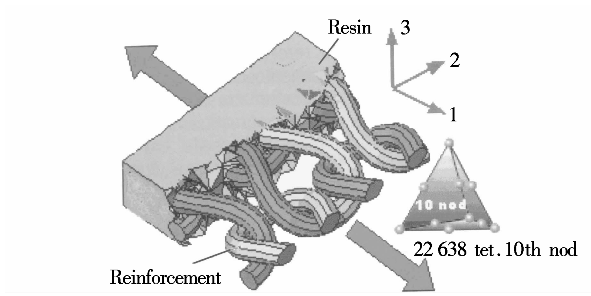

Fig.5 Loading in the loop wale direction

Because the internal geometry of the composite is highly irregular, it is expected that the mesh is also highly distorted and irregular, and therefore it is necessary to give a strict control over the precision of the results. A method for qualifying the imprecision of a particular mesh consists at using the same mesh to analyze a similar problem but with the theoretical or experimental solution already known. The mesh imprecision coefficient (IC) is defined as the ratio between the theoretical solution and the FEM one[6]. In order to define the IC, a mesh to "predict" the elastic properties was used for a UC made completely from aluminum with the following isotropic properties: E = 69.637 GPa, μ = 0.36, G = 25.602 GPa, α = 23.58 × 10^{-6} ℃$^{-1}$. The results of the simulation and the corresponding IC are presented in Tab.2.

Tab.2 Imprecision coefficient (IC)

Engineering constants		$IC = \frac{(C_{pred} - C_{exp})}{C_{pred} \times 100}$
Tension in Dir.1	E_1 = 70.603 GPa	1.37%
	μ_{12} = 0.326	-10.43%
	μ_{13} = 0.379	5.01%
Tension in Dir.2	E_2 = 72.363 GPa	3.77%
	μ_{23} = 0.412	12.62%
Tension in Dir.3	E_3 = 70.034 GPa	0.57%
Shear 1-2 plane	G_{12} = 25.602 GPa	≈ 0%
Shear 1-3 plane	G_{13} = 25.602 GPa	≈ 0%
Shear 2-3 plane	G_{23} = 25.602 GPa	≈ 0%
Thermal	$\alpha_1 = 23.624 \times 10^{-6}$ ℃$^{-1}$	≈ 0%
	$\alpha_2 = 23.597 \times 10^{-6}$ ℃$^{-1}$	≈ 0%
	$\alpha_3 = 23.583 \times 10^{-6}$ ℃$^{-1}$	≈ 0%

The predicted values for the knitted structural composite are presented in Tab.3. At the same time, the values of the orthotropic engineering constants already corrected with the IC, are presented in the last column of the table.

Tab.3 Predicted values for the knitted structural composite

Predicted	IC	Corrected
E_1 = 6.989 GPa	1.37%	E_1 = 6.893 GPa
E_2 = 5.990 GPa	3.77%	E_2 = 5.764 GPa
E_3 = 4.986 GPa	0.57%	E_3 = 4.986 GPa
μ_{12} = 0.110	– 10.43%	μ_{12} = 0.121
μ_{13} = 0.474	5.01%	μ_{13} = 0.450
μ_{23} = 0.374	12.6%	μ_{23} = 0.327
G_{12} = 1.659 GPa	0%	G_{12} = 1.659 GPa
G_{13} = 3.200 GPa	0%	G_{13} = 3.200 GPa
G_{23} = 1.186 GPa	0%	G_{23} = 1.186 GPa
$\alpha_{12} = 47.89 \times 10^{-6}$ ℃$^{-1}$	0%	$\alpha_{12} = 47.89 \times 10^{-6}$ ℃$^{-1}$
$\alpha_{13} = 70.63 \times 10^{-6}$ ℃$^{-1}$	0%	$\alpha_{13} = 70.63 \times 10^{-6}$ ℃$^{-1}$
$\alpha_{23} = 99.92 \times 10^{-6}$ ℃$^{-1}$	0%	$\alpha_{23} = 99.92 \times 10^{-6}$ ℃$^{-1}$

A comparison between experimental and FEM predicted values for E_1 (in the loop wale or longitudinal direction) and E_2 (in the loop course or transversal direction), is presented in Tab.4.

Tab.4 A comparison between experimental and FEM predicted values

Experimental values	Predicted values	Error
E_1 = 6.480 GPa	E_1 = 6.893 GPa	6.4%
E_2 = 3.448 GPa	E_2 = 5.764 GPa	40%

3 Conclusions

Including the transverse isotropy for the reinforcement (see Tab.1) can decrease the level of errors in the transversal direction. Besides, constraining the faces of the model to maintain plane during all FE simulations, the predicted values for the engineering constants of the composite can be improved. The prediction of some (if not all) engineering constants can decrease the overall design cost of a composite. In addition, it is known that there is a great difficulty in obtaining reliable shear properties of composites by testing methods. The compressive testing of a composite is also one of the most difficult testing to be carried out. In these cases, FEM prediction of engineering constants can be more reliable than the experimental values.

Finally, it is necessary to derive the stress-strain relations for the composite at the macromechanical level, which means to establish the compliance and stiffness matrices of the material. When the engineering constants of the material are obtained, building these matrices can be considered as an easy task.

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使用有限元法预测针织结构复合材料热–弹性性能

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摘　要　预测纺织增强复合材料的热–弹性性能是一项十分重要和复杂的课题.本文采用有限元方法对玻璃纤维针织结构增强复合材料的正交各向异性热弹性性能进行了预测分析,并和试验结果进行了比较.为了得到针织线圈增强结构的三维空间形态,本文考虑了相邻线圈之间的相互滑移作用和大位移变形,采用不考虑摩擦作用的接触单元建立线圈有限元模型.

关键词　复合材料; 针织物结构; 有限元分析

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