THE ANALYSIS OF STRESS STATE TYPES OF COMPOSITE CONSTITUENTS IN THE CASE OF TRANSVERSAL LOADING OF UNIDIRECTIONAL LAMINATE

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Abstract

This work contributes to the modelling of manufacturing process of thermoplastic composites. The main aspect of the research is the modelling of possible damages and defects nucleation in thermoplastic composites, which caused by manufacturing temperature cycles. Stress states of thermoplastic matrix material in the case of transversal loading of unidirectional composite are analyzed. Random placement of fibers are imposed into modelling of periodical cells of composites. It is shown for transversal tension loading of unidirectional composite that the most of the matrix material is loaded by biaxial tension. Material model for thermoplastic polymer with taking into account susceptibility to the stress state type is performed. All constants required for stress analysis based on polyetheretherketone (PEEK) thermoplastic material are performed.

1. Introduction

The main purpose of this work is to analyze stress state conditions in thermoplastic matrix material of unidirectional composite in case of presence of residual stresses, which caused by technology temperature cycles. Because of the expense of manufacturing experiments to get required quality of composite products based on thermoplastic matrix material, the modelling of polymer material failure became a competitive and vital for engineers problem. The main difficulty of modelling of polymer material is the dependence of material characteristics on phase state, temperature conditions and type of loading. Models for heterogeneous materials for elastic and plastic conditions, which susceptible to the type of stress state are relatively well developed in a number of solid mechanics areas. Such kind of models can be found developed for rock materials, concreate, ceramics and even for well-known structural material as cast iron. Nevertheless, the most general approach, that can take a broad view on most known plasticity criteria and elastic potential are described in works [1-7]. The idea of this research is to use described in [1-7] approach to plasticity modelling of thermoplastic material and understand the range of stress states that matrix material undergoes during composite laminate loading. Typical residual stress distribution in transversal to fibers direction is shown in figure 1.

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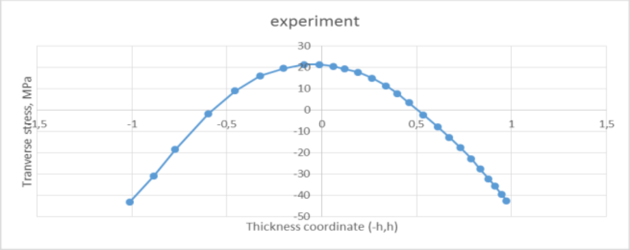

Figure 1. Final distribution of transverse stresses over the thickness of unidirectional APC2/PEEK specimen, corresponding to the temperature cooling regime 35^{0}C/sec [8].

2. Plasticity model

Due to temperature variation during manufacturing process, composite material exhibits the presence of residual stresses. Based on obtained values of residual stresses, the following step should be an evaluation of possible damages within a matrix of a composite material being studied. Such problem can be solved using micromechanical approach based on modeling of periodic cells of composite material. Now let us consider a solution of this problem in terms of transverse tension loading of unidirectional specimen. Such loading case can presumably be considered the most critical and common in a composite laminates under residual stresses. A similar problem was considered in [9] for a thermoset composite. In figure 2, a finite element model of a periodic cell being studied is shown. Periodic boundary conditions are used such that loading is done directly by transverse strains. Arrangement of fibers is done randomly, satisfying periodicity conditions and a given fiber volume fraction.

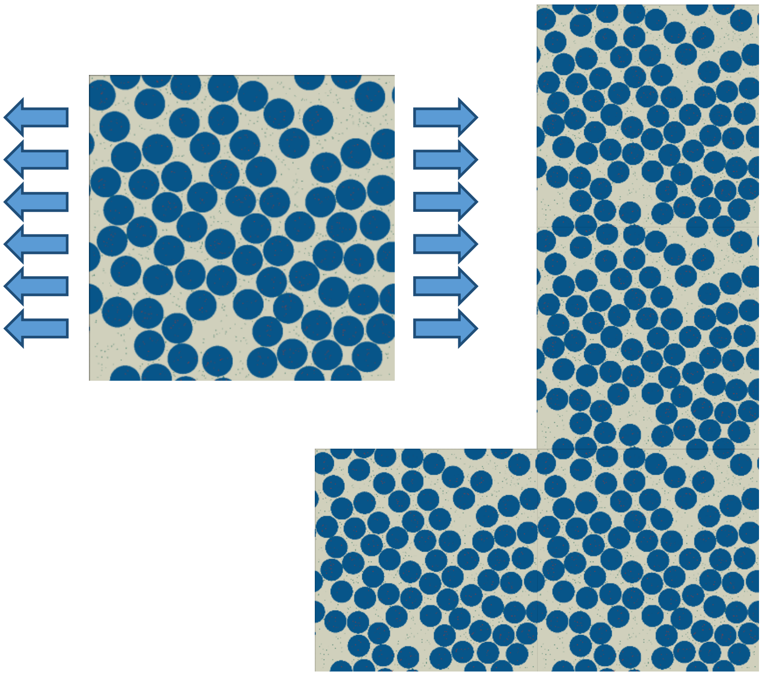

Figure 2. Model of periodic cell of unidirectional composite with a random distribution of fibers. Fiber diameter – 5 μm, relative fiber volume fraction – 0.6.

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The most difficult question is the choice of material model for thermoplastic matrix. Based on available publications a following table has been prepared, containing values of strength parameters of thermoplastic material (PEEK) at room temperature for a maximum degree of crystallinity of 0.37 (see Table 1).

Table 1. Characteristics of PEEK [10-13].

Parameter	Cytec	Bearing Works	Victrex TDS 450G	Wikipedia
Tensile modulus, GPa	3.6	4.34	4	3.6
Tensile strength, MPa	100	110	98	90–100
Ultimate tensile strains, %	70	40	45	50
Bending modulus, GPa		170	200	
Bending strength*, MPa		138	119	
Compressive strength, MPa		138	119	
Compressive modulus, GPa		3.45		
Shear strength, MPa		55.2	53	

*Stresses corresponding to 5 % strain

As is evident from the table 1, the material studied is a strength and modulus dependent on stress state. It is assumed here that the difference in moduli, dependent on loading type, is of no importance to simulation of a chosen limit state of the cell, and that the stiffness modulus of the material is equal to 3.6 GPa. The strength dependence on stress state type in this case plays an important role in damage modeling. Based on works [1-7] the following generalized criterion is used as a plasticity model:

$$f(\xi)\sigma_0 = k, \qquad (5)$$

where $\xi = \sigma/\sigma_0$, $\sigma = \sigma_{ii}/3$, $\sigma_0 = \sqrt{\frac{3}{2}S_{ij}S_{ij}}$, $S_{ij} = \sigma_{ij} - \delta_{ij}\sigma$.

Following [5–7], we consider a linear variant of function $f(\xi)$:

$$f(\xi) = 1 + C\xi.$$

Here constant C is determined experimentally and characterizes the degree of sensitivity to a type of stress state of material. It can be shown that linear dependence of plastic yield criterion on ξ parameter is sufficient to obtain substantial plastic strains in basic limit loading cases given in Table 1. An analogy to linear dependence on triaxiality parameter in case of criterion (5) is a Drucker–Prager law [14], and a corresponding analogy to C constant is the relation of $tg(\psi)$, where ψ – angle of friction or dilatation angle of material.

As a damage criterion, we consider an approach described in [15], according to which a material is deemed damaged if the following condition is satisfied:

$$\int \frac{d\varepsilon^{pl}}{\varepsilon_D^{pl}(\xi,\dot{\varepsilon}^{pl})} = 1, \qquad (6)$$

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where ε^{pl} – equivalent plastic strain, ε_D^{pl} – parameter determined experimentally.

Parameter ε_D^{pl} depends on the triaxiality parameter and on the rate of equivalent plastic strain. Therefore, the model can be adjusted to accumulate more continuum damage in case of tensile loading and less damage in case of compressive one.

Proposed elasticity model, and plasticity model with linear dependence on triaxiality parameter and failure condition (6), are standard for ABAQUS finite element modeling suite, thus allowing a researcher to simulate damage in the problem being studied. Table 2 shows parameters proposed by authors for selected models.

Table 2. Modeling parameters for PEEK

Crystallinity	c	Dilatation angle	k, MPa	Tensile, MPa	Equivalent plastic strains	Triaxiality	Strain at failure	Modulus, GPa
0.37	0.53	27.9	77	77	0	-0.333	1.5	3.6
				81	0.1	0	1	
				100	0.5	0.333	0.7	
				101	2	0.495	0.6	

Figure 3 shows values inverse to stress intensities, depending on ξ parameter values corresponding to four loading conditions: tension, shear, compression, and flexure, given in Table 1.

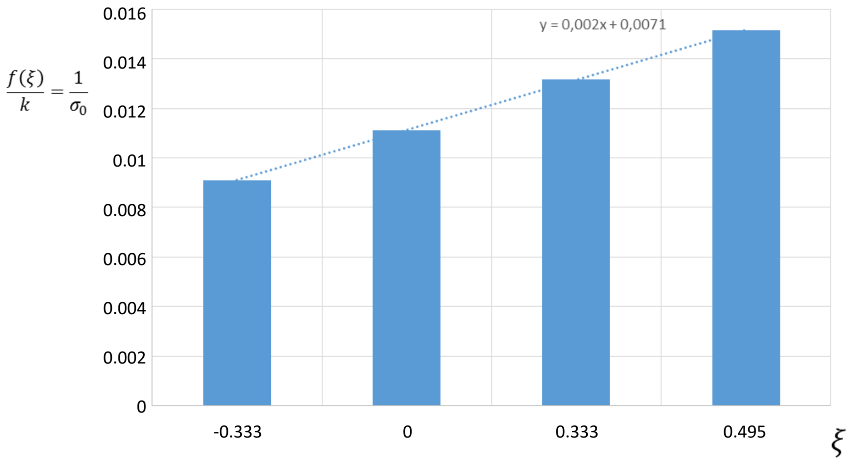

Figure 3. Values of $1/\sigma_0$ at the onset of plastic yield for different loading conditions: compression (ξ= -0.333), shear (ξ= 0), tension (ξ = 0.333), and flexure (ξ = 0.495)

Now let us consider results of loading periodic cells of PEEK based material. Figure 4 shows three variants of cells with different fiber arrangement at the moment of attaining a limit condition. As a fringe, the values of parameter (6) were used.

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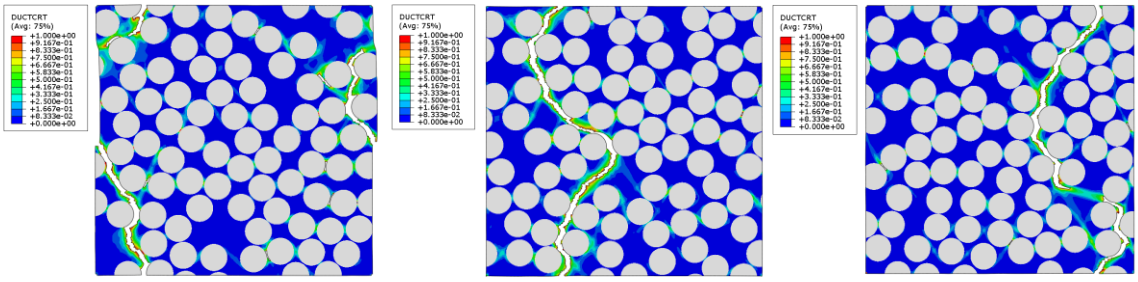

Figure 4. Results of damage modeling in periodic cells of unidirectional composite specimen in case of transverse loading.

In Figure 5, loading diagrams for cells shown in Figure 4 are presented. It is evident that elastic and plastic stages closely match for all three scenarios. A certain difference can only be observed in limit strain regions.

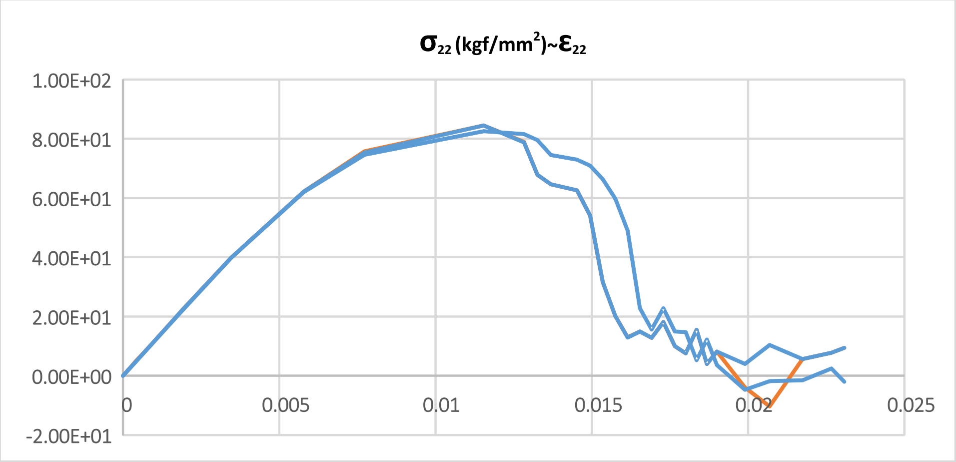

Figure 5. Modelling diagrams for transverse loading of periodic cells in unidirectional PEEK-based composite specimen.

The difference between the typical value of transverse tensile failure stresses [10] for unidirectional PEEK-based composite and the modeling value obtained using characteristics given in Table 2 is less than 2 % (see Figure 5).

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3. Matrix stress state in the case of transversal tension of unidirectional composite

For characterization of the material for particular problem it is important to know the diapason of possible stress states or in terms of stress state parameter the range of ξ parameter. Figure 6 shows areas for high values of traxiality ξ >0.4 in one of periodic cells model. One can see that material with high values of triaxiality has areas with loaded material, or with high values of maximum principle stresses.

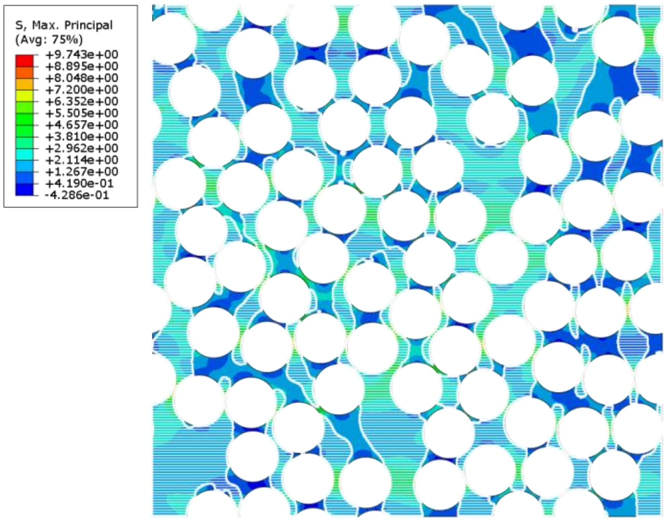

Figure 6. Maximum principle stress (MPa) with highlighted areas (dashed areas) where ξ>0.4.

Next figure 7 shows distribution of triaxiality parameters in previously demonstrated (fig.4) patterns of periodic cells.

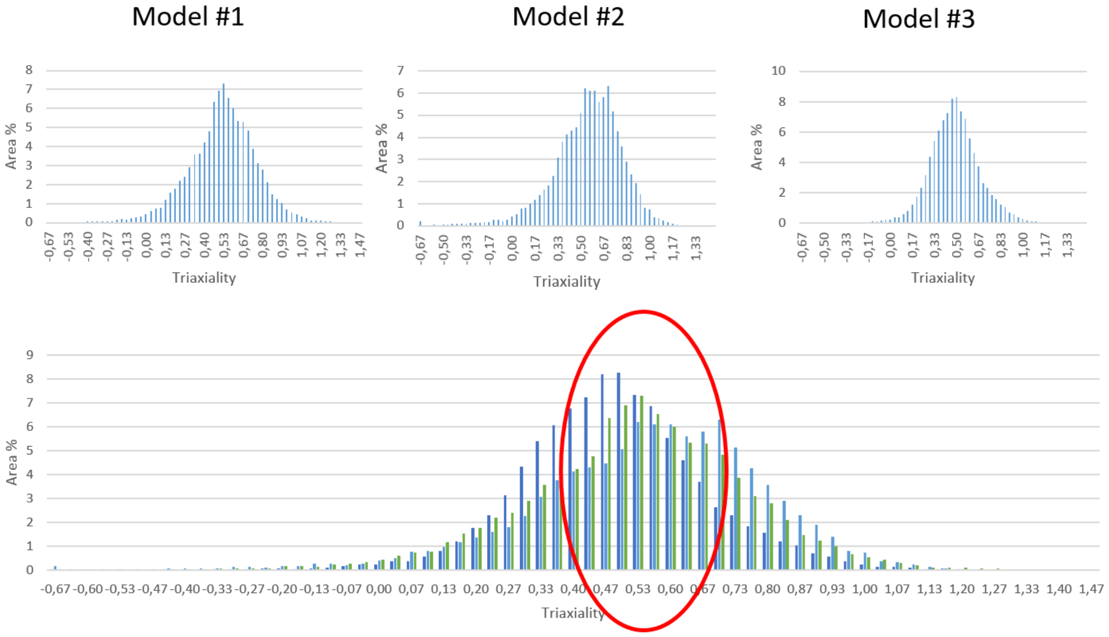

Figure 7. Percentage of the section area of matrix material with corresponding value of the parameter ξ.

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It is possible to see that the most area of unidirectional specimen section occupied by stress state corresponded to the value of $\xi=0.55$. This value of triaxiality parameter approximately means the biaxial tension of the matrix material.

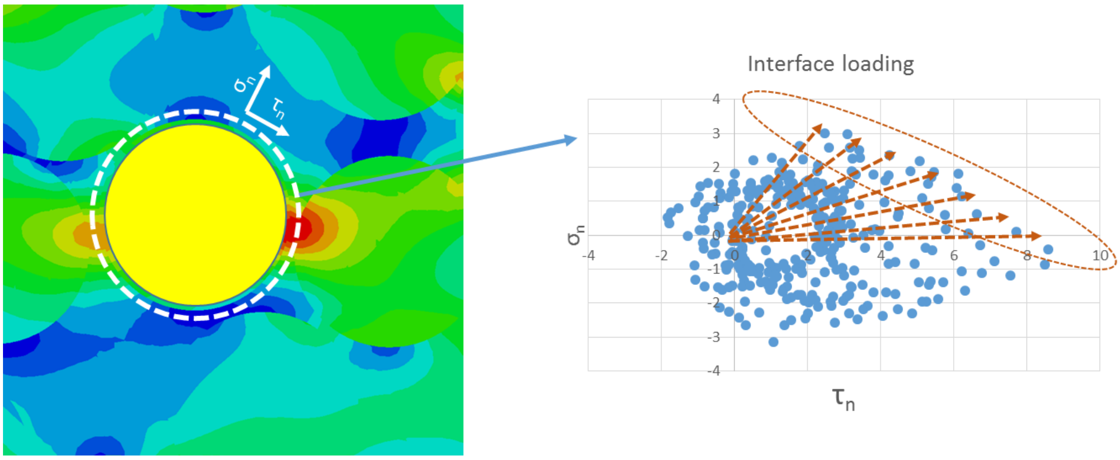

Figure 8. Interface stress componentsin case of transverse tension loading of periodic cells in unidirectional PEEK-based composite specimen.

Figure 8 shows types of interface loadings taken from different fibers from modelled periodical cells (fig. 4). It is possible to see that the most critical types of loadings are in the range $0<\sigma_n/\tau_n<1$.

3. Conclusions

The approach to model damage in thermoplastic material was performed. All required for modelling constants and parameter dependencies for PEEK thermoplastic material are shown. The analysis of stress states of the matrix material in case of transversal tension loading of unidirectional laminae with random placement of fibers demonstrated that most of the material are loaded by biaxial tension. Moreover it was shown that most critical interface loads in terms of normal to fiber surface stresses are in the range $0<\sigma_n/\tau_n<1$.

Acknowledgments

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References

[1] Lomakin E.V., Constitutive relations of the strain theory for dilatant media. 1991. Izv. AN SSSR. MTT Mechanics of Solids 66-75.

[2] Lomakin E.V., Deformation of a dilatant medium near crack tip under plane stress conditions.. 1996. Izv. AN. MTT Mechanics of Solids 99-109.

[3] Alexandrov S., Jeng Yeau-Ren, Lomakin E., Effect of pressure-dependency of the yield criterion on the development of plastic zones and the distribution of residual stresses, ASME Journal of Applied Mechanics, 78, № May. 031012-1-031012-5

Excerpt from ISBN 978-3-00-053387-7

[4] Lomakin E.V., Mel'nikov A.M., Plane stress state problems for notched bodies whose plastic properties depend on the form of the stress state, Mechanics of Solids, Allerton Press Inc. (United States), 46, № 1, c. 62-69

[5] Lomakin E.V., Melnikov A.M., Fedulov B.N. Constitutive models for anisotropic materials susceptible to loading conditions, Mechanics and Model-Based Control of Advanced Engineering Systems, Springer Verlag GmbH, Berlin, 2013

[6] Lomakin E.V., Constitutive models of mechanical behavior of media with stress state dependent material properties. Mechanics of generalized continua. Adv Struct Mater (2011) 7:339–350

[7] E.V. Lomakin, B.N. Fedulov, Plane Strain Extension of a Strip Made of a Material with Stress State Type Dependent Properties and Weakened by Cuts with Circular Base, Mech. Solids. 48 (4), 424-430 (2013)

[8] Chapman T. J., Gillespie Jr. J. W., Pipes R. B., J.-A., Manson E., Seferis J. C., Prediction of Process-Induced Residual Stresses in Thermoplastic Composites, Journal of composite materials 24(6) (1990): 616-643

[9] Yang L, YanY., Ma J., Liu B., Effects of inter-fiber spacing and thermal residual stress on transverse failure of fiber-reinforced polymer–matrix composites, Computational Materials Science 68 (2013): 255–262

[10] Cytec, Technical data sheet APC-2-PEEK thermoplastic polymer www.cytec.com/sites/default/files/datasheets/APC-2_PEEK_031912-01.pdf

[11] Bearing Works, Inc., PEEK data sheet www.bearingworks.com/content_files/pdf/retainers/PEEK%20datasheet.pdf

[12] Victrex, Victrex TDS 450G data sheet, Victrex.com

[13] en.wikipedia.org/wiki/PEEK

[14] Abaqus manual, Providence, RI, USA.

[15] Hooputra H., Gese H., Dell H., Werner H., "A Comprehensive Failure Model for Crashworthiness Simulation of Aluminium Extrusions," International Journal of Crashworthiness, vol. 9, no.5, pp. 449–464, 2004.

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