DAMAGE AND FAILURE MODELLING IN FIBER-REINFORCED COMPOSITES AT COMBINED LOADING

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This study deals with the investigation of the nonlinear deformation and damage processes in the matrix of the unidirectional fiber-reinforced composite with fibers disordered in transversal plane at combined transversal loading. The nonlinear boundary-value problem for the composite fragments is considered to calculate the stress and strain fields in matrix and fibers of the composite. The macrostress and macrostrain are calculated by averaging these fields upon a sample of the composite fragments. The macrostress-macrostrain curves and macrostrength surface for the glass-epoxy composite are constructed. The comparison with the results for the composite model with the fiber periodic arrangement is performed

INTRODUCTION

The nonlinear deformation and damage processes in matrix of fiber-reinforced composites can take place long before the composite macrofracture occurs. Various micromechanics approaches were used to take account ones and description nonlinear behaviour, initial yield and strength surfaces of the composite (Adams(1), Foye(2), Dvorak and Bahei-El-Din(3), Hahn and Tsai(4), Aboudi(5), Taliercio(6), Скудра and Булавс(7),Соколкин and Ташкинов(8) etc.). However the combined influence of some important factors as fiber stochastic arrangement, multi-axial loading, heterogeneity and nonlinearity of stress and strain fields and damage processes in matrix on predicted overall characteristics of a composite is interesting. For calculation of heterogeneous stress and strain fields in matrix and fibers we use of the method of local approximation based on the principle of locality (8).This principle is that the nearest order takes place in the location and interaction of the stochastic structural elements of a composite. For modelling of damage processes in matrix we utilise procedure of mechanical properties reduction in damage zones. We show results of computer simulation of nonlinear deformation and damage processes in matrix of unidirectional glass/epoxy composite at some combined transversal loading.

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THEORETICAL PROCEDURE

As a geometric model of the unidirectional fiber-reinforced composite disordered in transversal plane we consider quasiperiodic model. This model formed from the periodic by randomly displacing of the fibers in the periodic cells whole boundaries are not crossed. For calculation of nonlinear stress and strain fields in matrix and fibers of the composite we used the method of local approximation(8). Due to this method we simulate these fields near some fibers with the help of a boundary-value problem for the composite fragment containing nine fibers. Fig.1 shows these fragments for the periodic and disordered models of unidirectional fiber-reinforced composite. In every fragment the central stochastic or periodic cell is constructed as illustrated by Fig.1. The boundary conditions for every fragment are adopted to set stress averaged upon the central cell of the fragment to some given macrostress s_{ij}. For the stochastic model we consider boundary value problems for a sample of the structural fragments. So the solution of the stochastic micromechanics problem was got as a sample of stochastic stress and strain fields in the central stochastic cells of the composite fragments. The macrostress and macrostrain were received by averaging these fields upon all the cells. Every boundary problem for the composite fragment is formulated as nonelastic and in-plane one. The system of the equations consist of the equilibrium an Cauchy's equations in traditional form and the constitutive relations allowing to simulate the processes of nonlinear deformation and damage processes in matrix

$$\sigma_{ij}(\vec{r}) = C^{(1)}_{ijkl_1}(\Phi,\omega,I_1)\varepsilon_{kl}(\vec{r}) \;; \qquad (1)$$

$$C^{(1)}_{ijkl}(\Phi,\omega,I_1) = \begin{cases} K^{(1)}\delta_{ij}\delta_{kl} + G^{(1)}[1-\omega(\varepsilon_i)](\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk} - \frac{2}{3}\delta_{ij}\delta_{kl}), & \Phi < 0; \\ K^{(1)}\delta_{ij}\delta_{kl}, \quad \Phi \geq 0, & I_1 < 0; \\ 0, \quad \Phi \geq 0, & I_1 \geq 0, \end{cases} \qquad (2)$$

$$\Phi = p_1 I_2^{1/2} + p_2 I_1 + p_3 I_2^{-1/2} I_1^{-2} + p_4 I_2^{-1} I_1^3 + p_5 I_2^{-1} I_3 + p_6 I_2^{-3/2} I_1 I_3 + p_7 I_2^{-3/2} I_1^4 - 1 \;, \qquad (3)$$

$$I_1 = \sigma_{ij} \;,\; I_2 = \sigma_{ij}\sigma_{ij} \;,\; I_3 = \sigma_{ij}\sigma_{jk}\sigma_{ik}.$$

These constitutive relations include the equations of deformation theory of plasticity and the equations of stiffness reduction in damage zones where $\Phi \geq 0$. If the strength criterion is broken, we consider to possible variants of the material stiffness reduction in the damage zones: the full loss of carrying capacity in the zones where $I_1 > 0$ and remaining the capacity to resist only to hydroststatic compressible load in the zones where $I_1 < 0$. The fibers are linear elasticity, no damage processes in fibers are considered. The full adhesion conditions on the interphase surface are taken. The special developed computer program complex was created to solve this nonlinear boundary-value problem by FEM. Fig.1,g shows the computer generated finite element mesh for the fragment with periodic arrangement of the fibers.

RESULTS

We consider periodic and disordered models of unidirectional glass/epoxy composite with fiber volume fraction is 0.58. The number of various trajectories of biaxial tensile-compression and shear loads for the periodic model is 27 and for the disordered one it is only 10. The number of structural fragments included in the stochastic model is thirty. The components of macrostress tensor s_{ij} are set by steps as follows

$$s_{ij}^{(k)} = s_{ij}^{(0)}(1+\alpha k) \quad , \quad k=0,1,2,... \qquad (4)$$

The material properties for matrix are $K^{(1)}$ =42 529 MPa , $G^{(1)}$=30 579 MPa (Удрис and Упитис (9)), and for fiber are $K^{(2)}$= 3 236 MPa, $G^{(2)}$= 1 031 MPa (7). Fig.3,a shows $\sigma_i - \varepsilon_i$ curve for matrix (9). The coefficients for the matrix strength criterion calculated due to experimental date (9) are p_1=1.58 10^{-2} MPa, p_2=2.84 10^{-3} MPa, p_3=-2.47 10^{-3} MPa p_4=-4.58 10^{-3} MPa, p_5=1.56 10^{-3} MPa , p_6=-9.09 10^{-4} MPa , p_7=-3.62 10^{-6} MPa. Tab.1 shows the initial macrostress tensor components for some load trajectories.

TABLE 1 - Initial macrostress tensor components $s_{ij}^{(0)}$

Trajectory	$s_{11}^{(0)}$, MPa	$s_{22}^{(0)}$, MPa	$s_{12}^{(0)}$, MPa	Trajectory	$s_{11}^{(0)}$, MPa	$s_{22}^{(0)}$, MPa	$s_{12}^{(0)}$, MPa
T_1	0.0	0.0	5.0	T_9	-40.0	-40.0	0.0
T_2	5.0	5.0	0.0	T_{10}	10.0	2.5	1.2
T_3	5.0	0.0	0.0	T_{11}	-40.0	-5.0	0.0
T_4	-20.0	0.0	0.0	T_{12}	-40.0	-15.0	0.0
T_5	-40.0	-20.0	0.0	T_{13}	-40.0	-40.0	5.0
T_6	-40.0	-30.0	0.0	T_{14}	5.0	-20.0	0.0
T_7	-40.0	-10.0	0.0	T_{15}	2.5	-20.0	0.0
T_8	5.0	2.5	0.0	T_{16}	-20.0	0.0	2.5

Fig.2 shows some typical calculated macrostress-macrostrain curves. It can be seen from the Fig.2, that curves corresponding to uniaxial and biaxial tensile loads and tensile with shear loads are linear up to last point where the avalanchlike damage growth in matrix occurs. The curves for biaxial compression loads and some curves for biaxial compression with shear loads are mainly nonlinear with deflection growing up to 50%. This is due to the appearance of the equilibrium damage zones in matrix where I_1 <0. Fig.2 shows the evolution of these zones for some loads for periodic model. Shape of macrostress-macrostrain curves is scarcely affected by disordered arrangement of fibers. The differences between the corresponding curves plotted on base of periodic and stochastic models range from 5% on the initial part of the curves to 15% on the last part of ones. This fact takes place because some composite fragments of the stochastic model are completely fractured at these loads. We determine ultimate strength of the composite when the continuous cluster of the damage zones appears in along a side of the central cell or in along the interphase boundary. Damage accumulation in matrix of composite can be equilibrium or avalanchlake, in the last case the iteration procedure of the finite element technic don't converge. Fig.3 shows the calculated strength surface at a plane deformation of the composite. The shaded region on Fig.3 corresponds the loads where equilibrium damage zones in periodic model of the composite occur. The character of nonlinear deformation and damage processes are illustrated on a number of the calculated fractogramms (Fig.2,3). The difference between the values of the macrostrength calculated by the periodic and stochastic models is range from 5% for the compressible loads to 25% for the tensile loads. The calculated strengths at transversal compression and tensile correspond to experimental date(7).

CONCLUSIONS

We present the method for computer solving the stochastic nonlinear problem of micromechanics for unidirectional fiber reinforced composites at transversal loads and the model of the composite with elastic-plastic and damage evolutionary relationship for matrix. The capability to predict the nonlinear deformation and strength of the composite at arbitrary transversal loading has been demonstrated. Comparison calculated strength with experimental date has been made (Fig.3,a). It is found that the equilibrium damage processes can take place in matrix at some biaxial compression with shear loads and these processes have great influence on the overall behaviour of composite.

SYMBOL USED

σ_{ij} = microstress tensor (MPa)
ε_{ij} = microstrain tensor
$C^{(1)}_{ijkl}$ = matrix elastic modula tensor (MPa)
σ_i = microstress intensity (MPa)
ε_i = microstrain intensity
$\omega(\varepsilon_i)$ = matrix plasticity function
I_1, I_2, I_3 = microstress tensor invariants (MPa, MPa^2, MPa^3)
δ_{ij} = Kronecker delta
s_{ij} = macrostress tensor (MPa)
ε_{ij}^* = macrostrain tensor
Φ =strength criterion
K = bulk modulus (MPa)
G = shear modulus (MPa)
α = size of step for load trajectories
k = number of step for load trajectories
$p_1, p_2 p_3, p_4, p_5, p_6, p_7$ = coefficients of the matrix strength criterion (Mpa)

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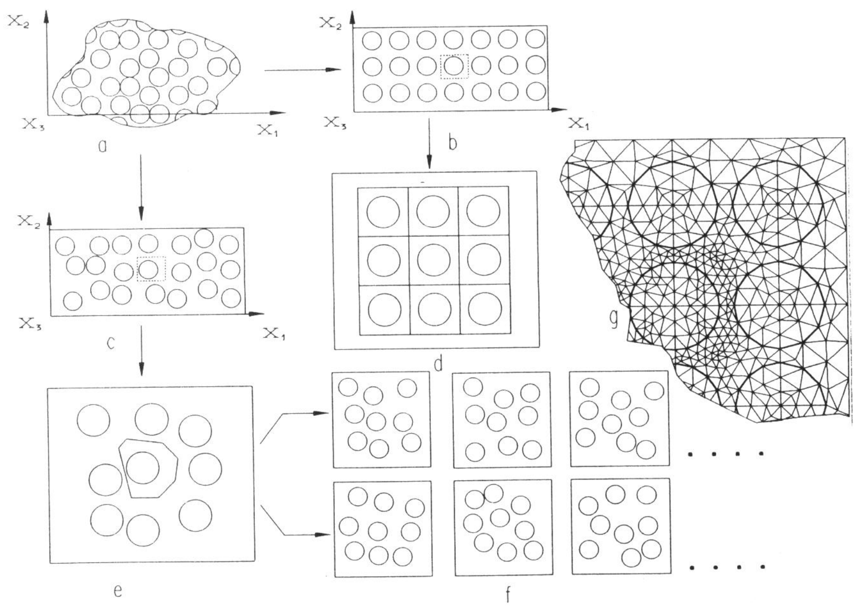

Fig.1 The schemes of the method of local approximation

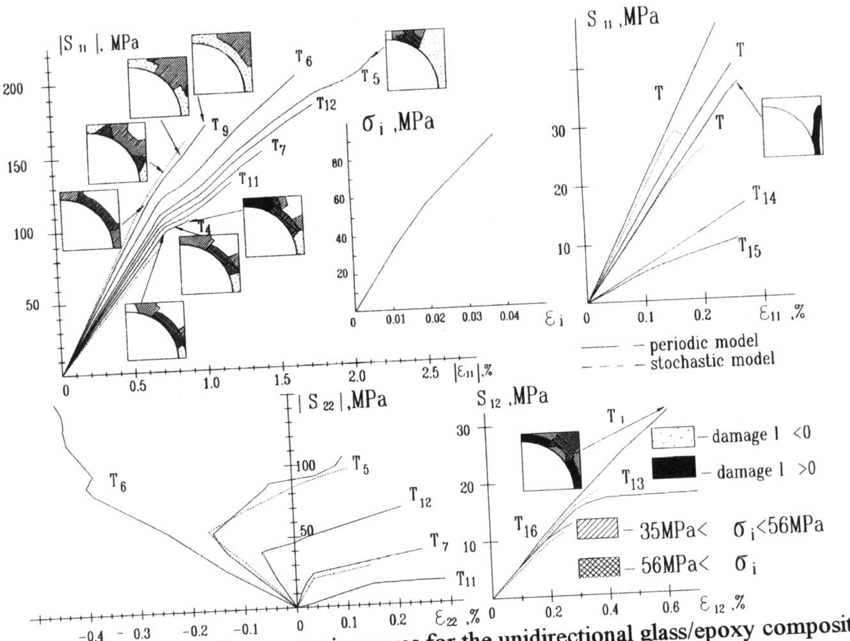

Fig.2 The calculated stress-strain curves for the unidirectional glass/epoxy composite under transversal loading

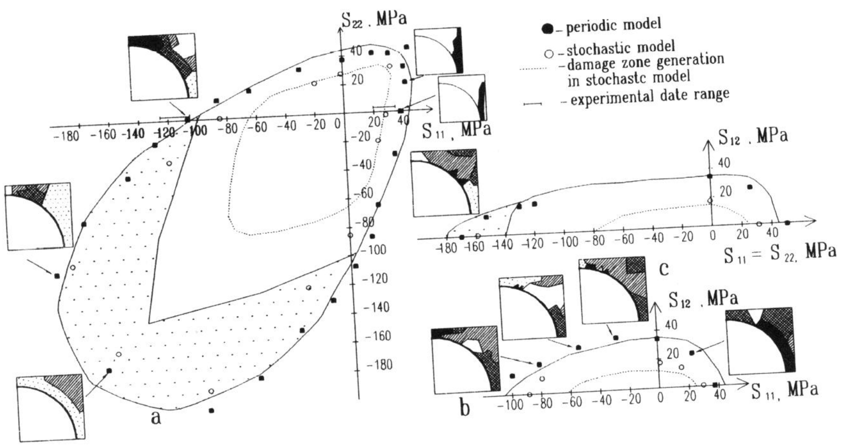

Fig.3 The calculated transversal strength surface for the unidirectional glass/epoxy composite.