MODELING DEGRADATION AND SELF-HEALING OF MATERIALS ON THE BASIS OF THE CRACK BRIDGING APPROACH

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ABSTRACT

For modeling degradation of polymer composite materials, cracks nucleation and self-healing of cracked structures the concept of the multi-scale crack bridging is used [1]. In the frames of this concept is assumed: a) there are bonds of the different scales between jointed materials (the interface layer); b) any zone of weakened bonds in this layer is considered as a crack with distributed nonlinear spring-like bonds between the crack surfaces (a bridged crack). The bonds properties on the different scales define the stress state at the crack bridged zone and, hence, the fracture toughness of the material. The mathematical background of the problem solution is based on the method of the singular integral-differential equations (SIDE). The bridging stresses are the solution of the system of the SIDE and it can be obtained on an every bridging level. The total bridging stresses are the sum of the contribution of every level of the bridging and it depend on the external loads, bonds properties and the position of bonds on the crack surface [2].

The degradation of this interface layer and cracks nucleation are considered on the basis of the Zhurkov's fluctuation model [3] and it is assumed that: 1) a zone of weakened bonds of the length $2l$ exists on the interface of materials at the initial instant of time; 2) the bonds density at the weakened zone depend on the time and the bonds stresses due to the Zhurkov's fluctuation model; 3) the part of the size $2l_f$ near the center of the weakened zone is considered as nucleated defect without bonds if the bonds density in that part became below the critical value N_{cr} after the nucleation time t_f.

According to the fluctuation theory of fracture the lifetime of bonds (τ_B) at the point x of the crack bridged zone under the external loading is the exponential function

$$\tau_B = \tau_o e^{\frac{U_o - A(x)}{kT}} \tag{1}$$

where τ_0 is the characteristic time (10^{-13}-10^{-12} s.), k is the Boltzmann constant, T is absolute temperature, U_o is the energy of the interatomic bond destruction, $A(x)$ is the work of the deformation per one intermolecular bond at the point x of the bridged zone of the crack. The work per one intermolecular bond can be defined as follows

$$dU(x,t) = \int_o^{u(x)} \sigma(u)du dx \qquad A(x) = \frac{dU(x,t)}{dN_n} \tag{2}$$

where $dU(x,t)$ is the work of bond deformation (on the unit of the body thickness) over part of the crack bridged zone by size dx, $dN_n = \varepsilon\, dn$, dn is number of the bonds over size dx, ε is the number of monomeric links between the crack surfaces. Suppose that the bonds are the chains of polymer molecules and the size of one monomer link is a. If the bond elongation under the external loading is much less of the value a then the number of monomer links between the crack surfaces is

$$\varepsilon \approx \frac{(u_y^2(x,t) + u_x(x,t)^2)^{1/2}}{a} \tag{3}$$

Due to the relations (1)-(3) the lifetime of bonds in the crack bridged zone is the function of the bond position. It's assumed that the time decrease of the bonds surface density $n(x,t)$ is governed by the equation

$$n(x,t) = N_0 e^{-\frac{t}{\tau_B(x)}}, \tag{4}$$

where $\tau_B(x)$ is the lifetime of the bond and N_o is the initial bond density. The decreasing of the bonds surface density over time can be modeled by the changing of the bonds properties in the weakened zone. Let's denote the bond stiffness by k_s. Then the effective stiffness of bonds per unit of an area in the crack brigding zone, k, is determined as follows

$$k(x,t) = k_s n(x,t) = k_0 e^{-\frac{t}{\tau_B(x)}}, \tag{5}$$

where $k_0 = k_s N_0$ is the initial effective stiffness of bonds in the crack bridged zone. Since the effective bonds compliance $c(x,t)$ is the value reciprocal to its stiffness one can write that

$$c(x,t) = c_0 e^{\frac{t}{\tau_B(x)}}. \tag{6}$$

This relation enables us to model the kinetics of the bond rupture (and healing) in the bridged zone of crack by means of the bonds compliance variation over time. The method of the calculation of the time of the defect nucleation and the following crack growth is based on the modeling of the weakened zone as a crack-like zone filled with bonds through the whole length at the initial instant of time. The system of the singular integral-differential equations for the solving of crack bridging problems [1] was extended for the time-steps scheme. On each time step the bond compliances are depended to the density of unbroken bonds as (6) and the SIDE is solved numerically. The supposed initial size of a defect $\alpha = \mathrm{l}_f / \mathrm{l}$ is nucleated on the k-th time step if

$$\bar{N}(t_k) \le N_{cr} \tag{7}$$

where $\bar{N}(t_k)$ is the average density of bonds at the time instant t_k on the interval of size $\alpha = \mathrm{l}_f / \mathrm{l}$.

If in the polymer composite with the healing microcapsules and/or with shape-memory alloy wires the initial crack reaches sufficient size then the self-healing process is started. On this stage of the problem the growth of crack in polymer composite is analyzed. The regeneration of the crack bridged zone is evaluated with accounting of simultaneous destruction of the bonds according to thermo-fluctuation kinetic. The healing time is dependent on the chemical reaction rate of the healing agent, wires properties, crack size and the external loads. The non-local fracture criterion [4] is used to evaluate the fracture toughness and the critical external loading in the frames of the bridged crack model. The decreasing of the stress intensity factors is used as the measure of the healing effect. The model can be use for the evaluation of composite materials durability. The results of computation modeling of cracks nucleation and cracks healing for different types of materials are presented.

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