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A damage model to predict the durability of bonded assemblies – Part II: Parameter identification and preliminary results for accelerated ageing tests

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ABSTRACT

A new damage model has been developed in order to predict the durability of adhesively bonded joints. This model, whose theoretical basis is outlined in a previous paper (part I), takes into account both bulk and interfacial damaging behaviours as well as their interactions. The present paper (part II) is dedicated first to describing a parametric study in which we attempted to understand the physical meaning of the model parameters and second to elaborating on an identification procedure for the theoretical parameters. Preliminary results are presented for accelerated ageing tests.

1. Introduction

Adhesive bonding is becoming more and more popular for the rehabilitation of civil structures. For instance, the repair or strengthening of damaged concrete structures by gluing stiff external reinforcements (CFRP composite plates or carbon fibre sheets) has become a very common application [1–3]. Moreover, adhesive bonding could also be used for future structural assemblies, since connections of hybrid concrete/metal bridges or assemblages of precast concrete elements could be achieved by this technology. Thus, for such types of assemblies, debonding is the most important failure mode and has received much attention in recent years [4–7].

A new model has been introduced by Freddi and Frémond [8] in order to predict the durability of adhesively bonded joints. It takes into account both bulk and interfacial damaging behaviours and their interactions. A simplified version is presented in a joint paper (part I) of this journal [9]. This model is based on the principle of virtual power. The process of damage is caused by microscopic motions, the power of which is taken into account in the virtual power of the interior forces. This contribution of power is assumed to depend, besides on the strain rate (velocity discontinuity for the interface), both on the damage velocity and on its gradient (damage velocity discontinuity for the interface).

Three parameters for each material are proposed to describe the damaging phenomenon: a cohesion parameter, an extension parameter and a viscosity parameter. This model must be able to answer the following questions about the damage, such as:

- When does the damage appear (cohesion parameter)?
- Does the damage extend or remain concentrated in thin zones (extension parameter)?
- Does the damage evolve slowly or rapidly (viscosity parameter)?

This model has been applied to several cases of bonded assemblies and the damage parameters can be ordered in different ways to describe different failure mechanisms of the materials of the assembly as illustrated in [8] and in part I [9]. These three parameters proved to be sufficient to correctly predict most complex physical phenomena. Raous et al. [10] have also used this predictive theory with these three main parameters and applied it to model damage and friction phenomena.

Concerning the glue, in addition to the three parameters previously mentioned, three more extension parameters can be introduced to describe non-local interactions within the glue and between it and its neighbouring materials, as well as another parameter accounting for the stiffness of the bonded interface.

This paper is divided into two main parts; the first is devoted to a sensitivity analysis of the model parameters and

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the second to the identification of the model parameters with typical tests.

First, however, in the next few paragraphs we quickly restate the global equations that govern our model, for more details see [8,9,11,12]. Let us consider a system made of two domains Ω_i for $(i = 1, 2)$ in the undistorted natural reference configuration subjected to mixed boundary conditions and glued together on an adhesive interface $\Gamma = \partial\Omega_1 \cap \partial\Omega_{2-}$. For the sake of simplicity, thermal effects are neglected, and our analysis is limited to small perturbation theory.

For each domain Ω_i, the state quantities are the macroscopic damage quantity $\beta_i(\underline{x}, t)$, its gradient $\underline{grad}\ \beta_i\ (\underline{x}, t)$ and the strain tensor $\underline{\underline{\varepsilon}}_i\ (\underline{x}, t)$. These variables depend on the position vector $\underline{x}$ and on time t; they are indexed by i, which can take the value of 1 or 2 according to the studied domain: Ω_1 or Ω_2. The values of $\beta_i(\underline{x}, t)$ are between 0 and 1, where 1 represents the undamaged, and 0 the completely damaged, states. The damage quantity β_i may be understood as the volume fraction of active links or of undamaged material.

For each domain Ω_i, the motion equations read:

$$\underline{div}\,\underline{\underline{\sigma}}_i(\underline{x}, t) + \underline{f}_i(\underline{x}, t) = \underline{0} \tag{1}$$

with $\underline{\underline{\sigma}}_i(\underline{x}, t) = \beta_i(\underline{x}, t)\underline{\underline{\underline{\underline{C}}}}\,\underline{\underline{\varepsilon}}_i(\underline{x}, t)$ where $\underline{\underline{\underline{\underline{C}}}}$ is the classical fourth order elasticity tensor for the domain Ω_i.

And the equations for the evolution of damage:

$$w_i - \frac{1}{2}\beta_i\,\underline{\underline{\varepsilon}}_i : \underline{\underline{\underline{\underline{C}}}} : \underline{\underline{\varepsilon}}_i \in c_i\,\partial\beta_i/\partial t - k_i\Delta\beta_i + \partial I_{[0,1]}(\beta_i) + \partial I_{(-\infty,0]}(\partial\beta_i/\partial t) \tag{2}$$

where Δ is the Laplace operator; c_i, k_i and w_i are the bulk damage coefficients, i.e., the viscosity of damage (N.s/m^2), the damage extension parameter (N), and the damage threshold (N/m^2) in the domains Ω_i, respectively. $\partial I_{[0,1]}(\cdot)$ and $\partial I_{(-\infty,0]}(\cdot)$ stand for the sub-differentials (generalised derivatives) of the indicator functions on the intervals $[0,1]$ and $(-\infty, 0]$ respectively. In particular, $\partial I_{[0,1]}(\beta_i)$ forces the phase parameter β_i to assume values only in the interval $[0,1]$, as $\partial I_{[0,1]}(\beta_i) = 0$ if $\beta_i \in]0,1[$, $\partial I_{[0,1]}(0) = (-\infty, 0]$ and $\partial I_{[0,1]}(1) = [0, +\infty)$. In mechanical parlance, the elements $\partial I(\beta_i)$ and $\partial I\_(\partial\beta_i/\partial t)$ contain reactions which forces β_i to remain between 0 and 1 and $\partial\beta_i/\partial t$ to be negative, to account for the irreversibility of damage.

The term on the r.h.s of Eq. (2) can be specialised to reproduce different failure mechanisms for each material as described in part I.

The initial conditions:

$$\beta_i\,(\underline{x}, 0) = \beta_i^0\,(\underline{x}) \text{ in } \Omega_i$$
$$\beta_s(\underline{x}, 0) = \beta_s^0\,(\underline{x}) \text{ on } \Gamma$$

And the boundary conditions:

$$\underline{\underline{\sigma}}_i.\underline{n}_i = \underline{F}_i \text{ on } \partial\Omega_i - \Gamma$$
$$k_i\frac{\partial\beta_i}{\partial\underline{n}_i} = 0 \text{ on } \partial\Omega_i - \Gamma$$

where n_i is the external normal to $\alpha\Omega_i$.

At the interface, the damage evolution law for the cohesive interface reads:

$$\begin{aligned} & w_s - \frac{\hat{k}_s}{2}\beta_s(\underline{x}, t)(\underline{u}_2 - \underline{u}_1)^2 - k_{s,1}(\beta_s(\underline{x}, t) - \beta_1(\underline{x}, t)) - k_{s,2}(\beta_s(\underline{x}, t) - \beta_2(\underline{x}, t)) \\ & - \int_\Gamma k_{s,1,2}\,g^2(\underline{y}, \underline{x})\beta_s(\underline{x}, t)\exp\left(-\frac{|\underline{x}-\underline{y}|^2}{d^2}\right)d\underline{y} \\ & \in c_s\frac{\partial\beta_s(\underline{x}, t)}{\partial t} - k_s\Delta_s\beta_s(\underline{x}, t) + \partial I_{[0,1]}(\beta_s) + \partial I_{(-\infty,0]}(\partial\beta_s/\partial t) \end{aligned} \tag{3}$$

where Δ_s is the surface Laplace operator and $g(\underline{y}, \underline{x}) = 2(\underline{y} - \underline{x}) \cdot (\underline{u}(\underline{y}) - \underline{u}(\underline{x}))$ is a function traducing the actions at a distance; $\frac{\partial\beta_s(\underline{x}, t)}{\partial\underline{n}_s} = 0$ on $\partial\Gamma$ with. $\underline{n}_s$ the external normal to $\partial\Gamma$.

Coefficients c_s, k_s, w_s and $\hat{k}_s$ are the interfacial damage coefficients, i.e., the viscosity of damage (N s/m), the damage extension parameter (N), the damage threshold (N/m), and the surface rigidity (N/m^3) of the bonded interface Γ, respectively. $\hat{k}_s$ can be expanded into a normal $\hat{k}_s^N$ and a tangential component $\hat{k}_s^T$, which correspond to the vertical u_i^N and to the horizontal component u_i^T of the displacement vector $\underline{u}_i$.

The last term in the first member of Eq. (3) accounts for damage induced by the elongation of the polymer adhesive.

The parameter $k_{s,i}$ measures the interaction between the bulk damage and the interfacial damage (expressed in N/m). When its value is significant, the bulk and interfacial damage are coupled and when it is zero, there is no interaction. The parameter d is a distance which characterizes the extent of the at a distance interaction between two points of the interface $\underline{x}$ and $\underline{y}$ and the coefficient $k_{s,1,2}$ illustrates the non-local effect (expressed in N/m^3).

When the terms related to non-local effect are assumed to be negligible compared to those related to local effects, the boundary conditions become:

$$\underline{\underline{\sigma}}_1 \cdot \underline{n}_1(\underline{x}) = \beta_s\hat{k}_s(\underline{u}_2 - \underline{u}_1) + \partial I_{(-\infty,0]}((\underline{u}_2 - \underline{u}_1) \cdot \underline{n}_1)\underline{n}_1$$
$$\underline{\underline{\sigma}}_2 \cdot \underline{n}_2(\underline{y}) = \beta_s\hat{k}_s(\underline{u}_2 - \underline{u}_1) + \partial I_{(-\infty,0]}((\underline{u}_2 - \underline{u}_1) \cdot \underline{n}_2)\underline{n}_2$$

where $\underline{x} \in \Gamma$, $\underline{y} \in \Gamma$ and the latter terms $\partial I_{(-\infty,0]}((\underline{u}_2 - \underline{u}_1)\cdot\underline{n}_1)\underline{n}_1$ or $\partial I_{(-\infty,0]}((\underline{u}_2 - \underline{u}_1) \cdot \underline{n}_2)\underline{n}_2$ express the reaction of non-interpenetration of both the glued structures.

2. Parameter study – sensitivity of the model parameters

In the proposed model, a global set of 13 parameters intervenes in the evolution equations of damage within the bulk and within the interface. In this section, we applied the parameters to several numerical simulations in order to test their effects on the results. All simulations were computed using the finite element code CESAR-LCPC [13], in which the damage model has been integrated. This study will help us to find some bounds for the values of the parameters. This section is divided into two subsections: the first deals with the parameters that characterise bulk damaging; the second deals with those that characterise interfacial damaging.

2.1. Influence of the parameters that characterise bulk damaging

To study the influence of the three parameters relative to the bulk damaging (w_i, c_i and k_i), a three-point bending test of a concrete beam 3.2 m in length and 0.5 m in height with the assumption of 2D plane deformation is numerically simulated by the model.

It appears that higher values of the damage extension parameter k_i lead to an increase in area of the damaged zone as illustrated in Fig. 1, and to higher values of the damage parameter β_i in the neighbourhood of the application point of the force, i.e., to a local decrease in the damage intensity. The parameter k_i clearly affects the local intensity and the diffusion of the damage (a high value for k_i would cause more diffusion, reducing the fragility of the material).

For the two other parameters, the simulations are not illustrated here, but it was concluded that:

- The higher the value of the initial damage threshold w_i, the higher the value of the maximum stress. More energy must be supplied to initiate damage.