DURABILITY OF ADHESIVELY BONDED JOINTS: A PREDICTIVE MODEL COUPLING BULK AND INTERFACIAL DAMAGE MECHANISMS

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Abstract

An advanced model coupling bulk and interfacial damages is proposed in order to predict the durability of adhesively bonded joints.

The underlying theory, based on the principle of virtual power, is briefly presented in the first part of the paper.

The second part is devoted to the validation the cited theory. The model is first implemented to describe the damage behavior of bonded assemblies subjected to either homogeneous tension or shear loading conditions. In each case, the theoretical simulations are compared to experimental data obtained in the same configuration. Such comparisons yield objective indications on the validity of the model.

1 Introduction

Adhesive bonding is getting very popular for the rehabilitation of civil structures. For instance, the repair or strengthening of damaged concrete structure by gluing stiff external reinforcements (CFRP composite plates or carbon fibre sheets) has become a very common application [1]. Moreover, adhesive bonding is also intended for structural assembling in the future, since connections of hybrid concrete/metal bridges or assembling of precast concrete elements could be achieved by this technology.

For these reasons, there is an increasing demand for reliable predictive tools in order to assess the long-term durability of adhesively bonded joints. However, the development of such tools is difficult since it must take into account the influence of various ageing mechanisms, based either on chemical, physical or mechanical phenomena.

This presentation introduces an original model taking into account both volume and interface damaging behaviours and their interactions. It is based on the adaptation of the principle of virtual power introduced in previous papers by Frémond *et al*. [2-4]. The starting assumption is that damage results from microscopic motions, and consequently the power of these microscopic motions is included in the power of the internal forces.

Theoretical basements which are exposed in detail elsewhere [5], are briefly reported in the first part of the paper. In a second part, the validity of the model is discussed for specific mechanical configurations.

2 Theoretical basements of the model

2.1 State quantities and quantities describing damage evolution

A glued assembly is idealized as a system made of two domains Ω_1 and Ω_2, connected to one another by an adhesive interface $\Gamma = \Omega_1 \cap \Omega_2$. This system is subjected both to body forces ($\vec{f}_1$, $\vec{f}_2$) and surface traction ($\vec{F}_1$, $\vec{F}_2$), as shown on fig. 1.

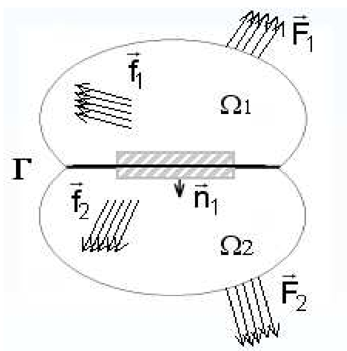

Fig. 1. Schematic description of a glued assembly in the present model

For the sake of simplicity, thermal effects are neglected and we limit our analysis to small perturbation theory.

• For each domain Ω_i (with i = 1, 2) we can define several state quantities that are function of position $\vec{x}$ and time t :

- the macroscopic damage quantity $\beta_i(\vec{x},t)$, which represents the volume fraction of undamaged material. Its value is between 0 and 1 (1 corresponds to the undamaged state and 0 to the completely damaged one),
- the gradient of $\beta_i(\vec{x},t)$, *i.e.* *grad* $\beta_i(\vec{x},t)$, which accounts for the local interaction of the damage at a specific point on the damage of its neighborhood,
- the deformation $\varepsilon_i(\vec{x},t)$.

The quantities which describe the evolution in each domain Ω_i are the velocities of these state quantities.

• At the contact surface Γ, the state quantities are:

- the surface or glue damage quantity $\beta_s(\vec{x},t)$, which represents the fraction of active adhesive links. $\beta_s(\vec{x},t) \in [0, 1]$,
- the gradient $grad_s\,\beta_s(\vec{x},t)$ taking into account the local damage interaction at the surface or in the glue,
- the gap $\vec{u}_2(\vec{x}) - \vec{u}_1(\vec{x})$ which is the difference between two small displacements at the same point of the surface,
- the elongation, a non-local state quantity which describes the variation of the distance of two different points of the surface.

The quantities describing the evolution of the contact surface are once again the velocities of the previous state quantities.

2.2 Equations of the model

The principle of virtual power and a proper use of the constitutive laws leads to partial differential equations describing domains and interface damage evolution. Detailed explanations are available in [5].

2.2.1 Equations in the domains

The equations of the evolution of damage for the domains obtained by using the constitutive laws and equilibrium equations are:

$$div\left[\beta_i\left\{\lambda_i tr\varepsilon_i(\vec{u}_i)1 + 2\mu_i\varepsilon_i(\vec{u}_i)\right\}\right] + f_i = 0 \qquad (1)$$

$$c_i\frac{d\beta_i}{dt} - k_i\Delta\beta_i + \partial I(\beta_i) + \partial I\_\left(\frac{d\beta_i}{dt}\right) \ni w_i - \frac{1}{2}\left\{\lambda_i(tr\varepsilon_i)^2 + 2\mu_i\varepsilon_i : \varepsilon_i\right\} \qquad (2)$$

where:

- λ_i and μ_i are the Lamé parameters,
- $\boldsymbol{c_i}$ is the viscosity parameter of damage, which controls the velocity of the damage evolution,
- the $\boldsymbol{\omega_i}$ coefficient is the initial damage threshold,
- the $\boldsymbol{k_i}$ parameter measures the local influence of a material point on its neighborhood

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 initial conditions is :

$$\beta_i(x,0) = \beta_i^0(x) \text{ in } \Omega_i \qquad (3)$$

The boundary conditions are :

$$\sigma_i\vec{n}_i = \vec{F}_i \text{ in } \partial\Omega_i \setminus \partial\Omega_1 \cap \partial\Omega_2 \qquad (4)$$

$$k_i\frac{\partial\beta_i}{\partial n_i} = 0 \text{ in } \partial\Omega_i \setminus \partial\Omega_1 \cap \partial\Omega_2 \qquad (5)$$

2.2.2 Equations on the contact surface

The damage evolution law for the cohesive interface Γ can be expressed as :

$$c_s\frac{d\beta_s}{dt} - k_s\Delta_s\beta_s + \partial I(\beta_s) + \partial I\_\left(\frac{d\beta_s}{dt}\right) \ni w_s - \frac{\hat{k}_s}{2}(\vec{u}_2 - \vec{u}_1)^2 - k_{s,1}(\beta_s - \beta_1) - k_{s,2}(\beta_s - \beta_2) - \int_\Gamma k_{s,1,2}\,g^2(\vec{y},\vec{x})\beta_s(\vec{x})\exp\left(-\frac{|\vec{x}-\vec{y}|^2}{d^2}\right)d\vec{y} \qquad (6)$$

where:

- Δ_s is the Laplace surface operator,
- $\boldsymbol{c_s}$ is the damage viscosity parameter, which controls the velocity of the damage evolution in the glue.

- ω_s is the Dupré's energy accounting for the cohesion of the glue,
- k_s is the local interaction parameter that measures the influence of damage at a specific point of the surface on its neighborhood.
- $\hat{k}_s$ represents the rigidity of the bonds between the two solids, *i.e.* the rigidity of the glue,
- $k_{s,1}$ and $k_{s,2}$ are interaction parameters which quantifies the importance of the interaction between volume and surface damages,
- $k_{s,12}$ accounts for non local effects, *i.e.* for the elongation of the glue.

The last term of equation (6) account for damage induced by the elongation of the polymer adhesive.

The initial condition is expressed as follow:

$$\beta_s(x,0)=\beta_s^0(x) \text{ in } \partial\Omega_1 \cap \partial\Omega_2 \qquad (7)$$

The boundary condition is:

$$k_i \frac{\partial \beta_i}{\partial n_i} = k_{s,i}(\beta_s - \beta_i) \text{ on } \Gamma \qquad (8)$$

Finally, the evolution of the system is described by the model using a set of 13 parameters:

- 3 parameters for each of the two domains (c_i, ω_i and k_i) with i =1, 2
- 4 parameters for the contact surface (c_s, ω_s, k_s and $\hat{k}_s$)
- 2 interaction parameters ($k_{s,1}$ and $k_{s,2}$) and the non local parameter ($k_{s,12}$).

Depending on the values of the interaction and non local parameters, three variations of the model can be considered:

- a model without coupling of bulk and interfacial damages, and without elongation effects ($k_{s,1} = k_{s,2} = k_{s,12} = 0$)
- a coupled model without elongation effects ($k_{s,12} = 0$)
- a coupled model with elongation effects, *i.e.* the complete model with every physical action.

Recently, the damage model was introduced in the finite element code CESAR-LCPC. It is now an operating tool which allows to make 2D numerical calculations.

3 Model-experiment comparison

A comparison has been made between experimental data and theoretical simulations, in order to validate our damage model. For this purpose, two different mechanical configurations have been chosen: homogeneous tension and shear loading conditions.

3.1 Tension loading conditions

A set of experiments was carried out on glued assemblies made of two steel cylinders bonded together by an epoxy adhesive joint. A typical specimen is shown on fig. 2.

The specimens were submitted to a constant tensile load of 5.5 kN, which corresponds to 70% of the ultimate load. The opening displacement of the adhesive joint was then monitored as a function of time by means of LVDT extensometers.

A typical evolution curve is depicted on fig. 3. The sudden increase of the joint opening displacement observed on the final part of the curve results from the catastrophic failure of the specimen.

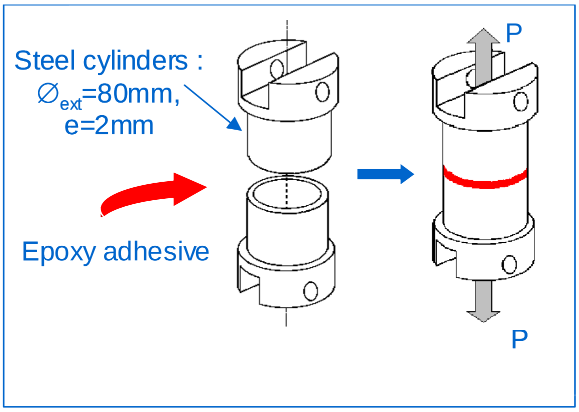

Fig. 2. Glued assemblies used for tension loading experiments.

The damage model was then implemented considering the same test conditions. In this configuration, the following assumptions can be made:

- volume damage in the metallic pieces is negligible (high stiffness of steel compared to the polymer adhesive). Therefore, we consider that volume and surface damages are not coupled in this case, *i.e.*, $k_{s,1} = k_{s,2} = 0$.

- due to the homogeneous loading conditions, the Laplace operator term in the damage evolution equation (6) is equal to 0. Subsequently, the parameter k_s is not active in the model.

In these conditions, the best theoretical curve matching the experimental evolution of the joint opening displacement *versus* time is obtained using the following model parameters: $\hat{k}_s$ = 1.15 x 10^3 MPa.mm^{-1} ; c_s = 1500 MPa.mm.s ; ω_s = 2 x 10^{-3} MPa.mm ; $k_{s,12}$ = 0.

As shown on Fig. 3, a good agreement is found between simulations and experiments, except at the end of the curve, as the rupture of the joint occurs. Such a deviation may be explained by the fact that the small perturbation theory (which is a pillar of the model) is no more valid at this level of degradation.

Additionally the model predicts a decrease of the damage quantity (β_s) as a function of time, which accounts well for the progressive rupture of active adhesive links.

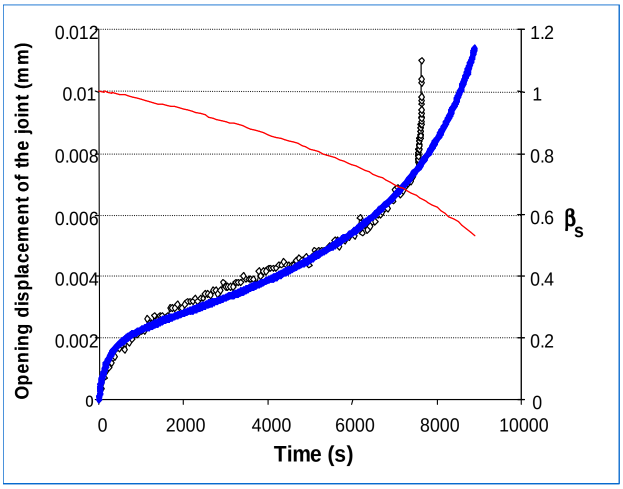

Fig. 3. Model-experiment comparison under tension loading conditions. Experimental values of the joint opening displacement *versus* time (—◇—), numerical calculations (—◆—), and theoretical evolution of the damage quantity β_s (——).

3.2 Shear loading configuration

The second objective was to validate the model under non homogeneous loading conditions.

We considered the configuration shown on figure 4: a concrete prism is strengthened by a glued CFRP unidirectional composite plate. A direct tensile load is then applied to the extremity of the composite plate, which means that the polymer joint is tested under shear loading. Further experimental details are available in reference [6].

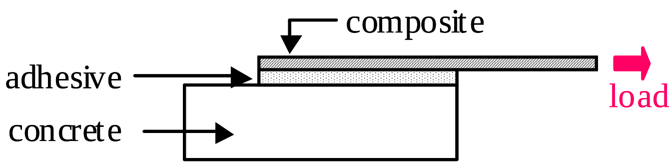

Fig. 4. CFRP strengthened concrete specimen. Shear load testing configuration.

The damage model was implemented using the following values for the mechanical properties and model parameters:

- *in the concrete body*: the elastic modulus and Poisson's ratio were respectively E = 33000 MPa and ν = 0.2. The model parameters were c_1 = 0.002 MPa.s ; ω_1 = 4 x 10^{-5} MPa ; k_1 = 0,2 MPa.mm^2,
- *in the composite body*: the longitudinal elastic modulus and Poisson's ratio were respectively E = 1.8 x 10^5 MPa et ν = 0.1. The model parameters were c_2 = 0.2 MPa.s ; ω_2 = 2 MPa ; k_2 = 0.1 MPa.mm^2,
- *in the glue:* the model parameters related to the surface damage were $\hat{k}_s$ = 5 x 10^3 MPa.mm^{-1} ; k_s = 0.1 MPa.mm^2 ; c_s = 1000 MPa.mm.s ; ω_s = 5.3 MPa.mm ; $k_{s,1}$ = $k_{s,2}$ = 0.1 MPa.mm , $k_{s,1,2}$ = 5 MPa.mm^{-1} .

Figure 5 presents the damage field in the specimen after 40 s testing, as provided by the model. It is found that damage is concentrated within the concrete material, at few centimeters from the adhesive joint. Moreover, it can be noticed that damage propagate in the concrete along a preferential direction (around 45° from horizontal). This result is consistent with the experimental observations of the fractured specimens, since a piece of concrete remains attached to the extremity of the debonded composite plate (Fig. 6).

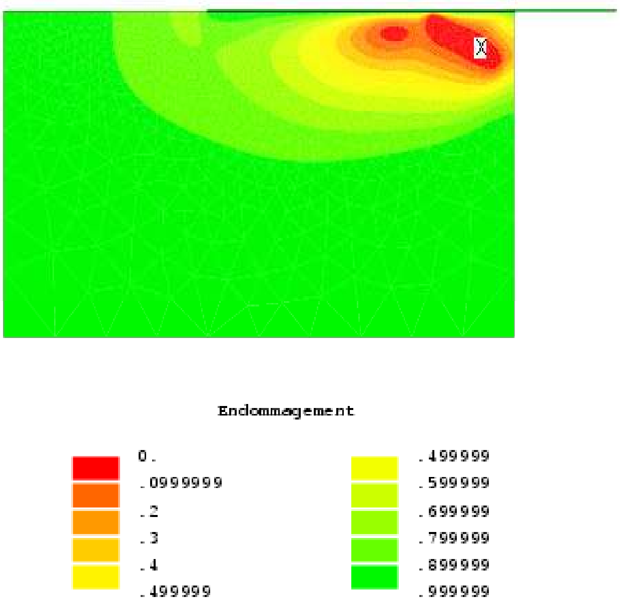

Fig. 5. Damage field in the CFRP strengthened concrete specimen after 40 s testing. The colour scale give indications on the theoretical values of the damage parameter β_i. Red parts correspond to completely damaged areas.

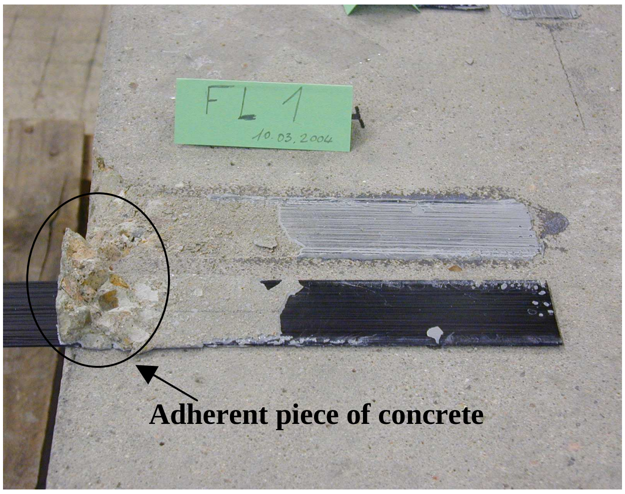

Fig. 6. Specimen fractured under shear loading conditions. An adherent piece of concrete is still attached to the debonded CFRP plate.

Figure 7 shows the evolutions of the experimental and calculated displacements at the point of load application, as a function of time. Here again, a good agreement is found between simulations and experiments.

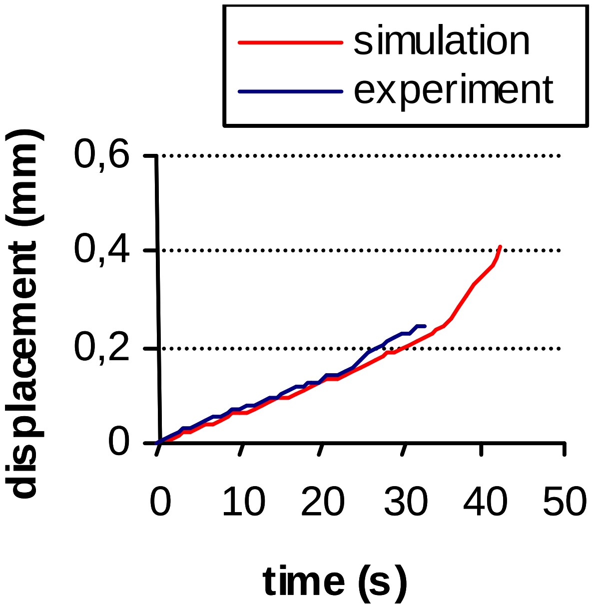

Fig. 7. Evolution of the displacement at the point of load application during the shear test. Comparison between numerical and experimental data.

4 Conclusions and perspectives

A new model coupling volume and surface damages has been introduced.

This model was validated by comparing theoretical and experimental data in cases of homogeneous or non homogeneous loading conditions. A fairly good agreement was found between theory and experiments.

In a further step, investigations will focus on the possibility of introducing the ageing behaviour of the adhesive into the model:

- accelerated ageing tests will be performed on glued assemblies (for instance in a wet environment), and experimental evolutions of the mechanical properties will be assessed,

- then, evolution laws of the model parameters will be derived by using an inverse identification method. In the end, we hope that the model will be able to predict the evolutions of the mechanical properties as a function of ageing time.

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