



HAL
open science

Durability of Bonded assemblies: A predictive theory coupling bulk and interfacial damage mechanisms

Karim Benzarti, Pierre Argoul, Francesco Freddi, Michel Frémont, Thi Hoa Tam Nguyen

► **To cite this version:**

Karim Benzarti, Pierre Argoul, Francesco Freddi, Michel Frémont, Thi Hoa Tam Nguyen. Durability of Bonded assemblies: A predictive theory coupling bulk and interfacial damage mechanisms. European Journal of Environmental and Civil Engineering, 2009, 13 (9), pp.1141-1151. 10.1080/19648189.2009.9693179 . hal-04957134

HAL Id: hal-04957134

<https://hal.science/hal-04957134v1>

Submitted on 20 Feb 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

Durability of bonded assemblies

A predictive theory coupling bulk and interfacial damage mechanisms

Karim Benzarti* — **Pierre Argoul**** — **Francesco Freddi*****
Michel Frémond* — **Thi Hoa Tam Nguyen***

* *Université Paris-Est, Laboratoire Central des Ponts et Chaussées*
58, bld Lefebvre
F-75732 Paris cedex 15
benzarti@lcpc.fr

** *Université Paris-Est, UR Navier, Ecole des Ponts ParisTech*
6-8, av. Blaise Pascal – Cité Descartes, Champs-sur-Marne
F-77455 Marne-la-Vallée cedex 2
argoul@lami.enpc.fr

*** *Laboratoire Lagrange, Dept. of Civil-Environmental Engineering and Architecture, University of Parma, Parma, Italy*

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.

RÉSUMÉ. Un modèle prédictif couplant les mécanismes d'endommagement volumique et surfacique est proposé. La théorie sous-jacente basée sur le principe des puissances virtuelles est d'abord présentée. Une seconde partie est ensuite consacrée à la validation du modèle. Ce dernier est appliqué à la description du comportement ultime d'assemblages collés soumis soit à une sollicitation de traction homogène, soit à un cisaillement. Les simulations numériques sont ainsi comparées aux données expérimentales obtenues pour chacune des configurations.

KEYWORDS: damage modelling, bonded assembly, durability, adhesive joint.

MOTS-CLÉS: modèle d'endommagement, assemblage collé, durabilité, joint adhésif.

1. Introduction

Adhesive bonding is getting more and more 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 (Karbhari *et al.*, 2000). 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 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 (1987, 2001) and Nedjar *et al.* (1996). The starting assumption is that damage results from microscopic motions, and consequently the power of these motions is included in the power of the internal forces. It is shown that three parameters are sufficient to correctly model the damage within a zone (volume or interface): a cohesion parameter, an extension parameter and a viscosity parameter.

Theoretical basements which are detailed in Freddi *et al.* (2006), 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 Figure 1. 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 neighbourhood;
- the deformation $\varepsilon_i(\vec{x}, t)$.

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

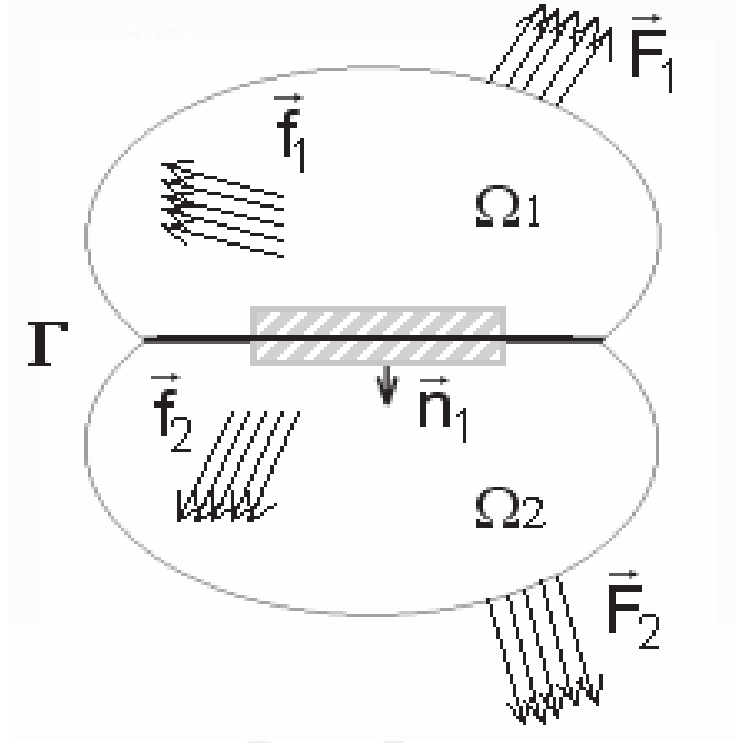


Figure 1. Schematic description of a glued assembly in the present model

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.

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 evolutions. Detailed explanations are provided by Freddi *et al.* (2006).

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 as follow:

$$\operatorname{div}[\beta_i \{\lambda_i \operatorname{tr} \boldsymbol{\varepsilon}_i(\vec{u}_i) \mathbf{1} + 2\mu_i \boldsymbol{\varepsilon}_i(\vec{u}_i)\}] + f_i = 0 \quad [1]$$

$$w_i - \frac{1}{2} \{\lambda_i (\operatorname{tr} \boldsymbol{\varepsilon}_i)^2 + 2\mu_i \boldsymbol{\varepsilon}_i : \boldsymbol{\varepsilon}_i\} \in \quad [2]$$

$$c_i \frac{d\beta_i}{dt} - k_i \Delta \beta_i + \partial I_{[0,1]}(\beta_i) + \partial I_{(-\infty,0]}(\frac{d\beta_i}{dt})$$

where:

- λ_i and μ_i are the Lamé parameters;
- c_i is the viscosity parameter of damage, which controls the velocity of the damage evolution;
- the ω_i coefficient is the initial damage threshold;
- the k_i parameter measures the local influence of a material point on its neighborhood.

$\partial I_{[0,1]}(\cdot)$ and $\partial I_{(-\infty,0]}(\cdot)$ stand for the sub-differentials (generalized 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 initial condition is:

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

The boundary conditions are:

$$\sigma_i \vec{n}_i = \vec{F}_i \text{ in } \partial\Omega_i \setminus \partial\Omega_1 \cap \partial\Omega_2 \quad [4]$$

$$k_i \frac{\partial \beta_i}{\partial n_i} = 0 \text{ in } \partial\Omega_i \setminus \partial\Omega_1 \cap \partial\Omega_2 \quad [5]$$

2.2.2. Equations on the contact surface

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

$$\begin{aligned} w_s - \frac{\hat{k}_s}{2} (\vec{u}_2 - \vec{u}_1)^2 - k_{s,1} (\beta_s - \beta_1) - k_{s,2} (\beta_s - \beta_2) \\ - \int_{\Gamma} k_{s,1,2} g^2(\vec{y}, \vec{x}) \beta_s(\vec{x}) \exp\left(-\frac{|\vec{x} - \vec{y}|^2}{d^2}\right) d\vec{y} \in \\ c_s \frac{d\beta_s}{dt} - k_s \Delta_s \beta_s + \partial I_{[0,1]}(\beta_s) + \partial I_{(-\infty, 0]} \left(\frac{d\beta_s}{dt} \right) \end{aligned} \quad [6]$$

where:

- Δ_s is the Laplace surface operator;
- 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;
- \mathcal{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] accounts for damage induced by the elongation of the polymer adhesive.

The initial condition is expressed as follows:

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

The boundary condition is:

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

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

- 3 damage parameters for each of the two domains (c_i , ω_i and k_i) with $i = 1, 2$;
- 3 damage parameters + 1 parameter for the rigidity of the glue for the contact surface (c_s , ω_s , k_s and \tilde{k});

- 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 actions.

Recently, the damage model was introduced in the finite element code CESAR-LCPC (see official website). This operating tool allows to make 2D numerical calculations.

Further details can be found in (Nguyen, 2008) regarding the specific influence of each damage parameter in the modeling, and the determination of these parameters by inverse identification methods.

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 (Bruneaux and Benzarti, 2006).

3.1. Tension loading conditions

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

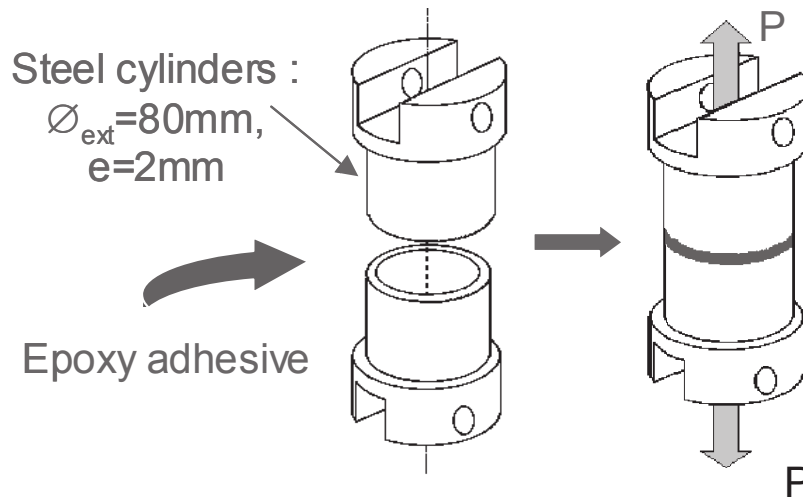


Figure 2. *Glued assemblies used for tension loading experiments*

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 in Figure 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.

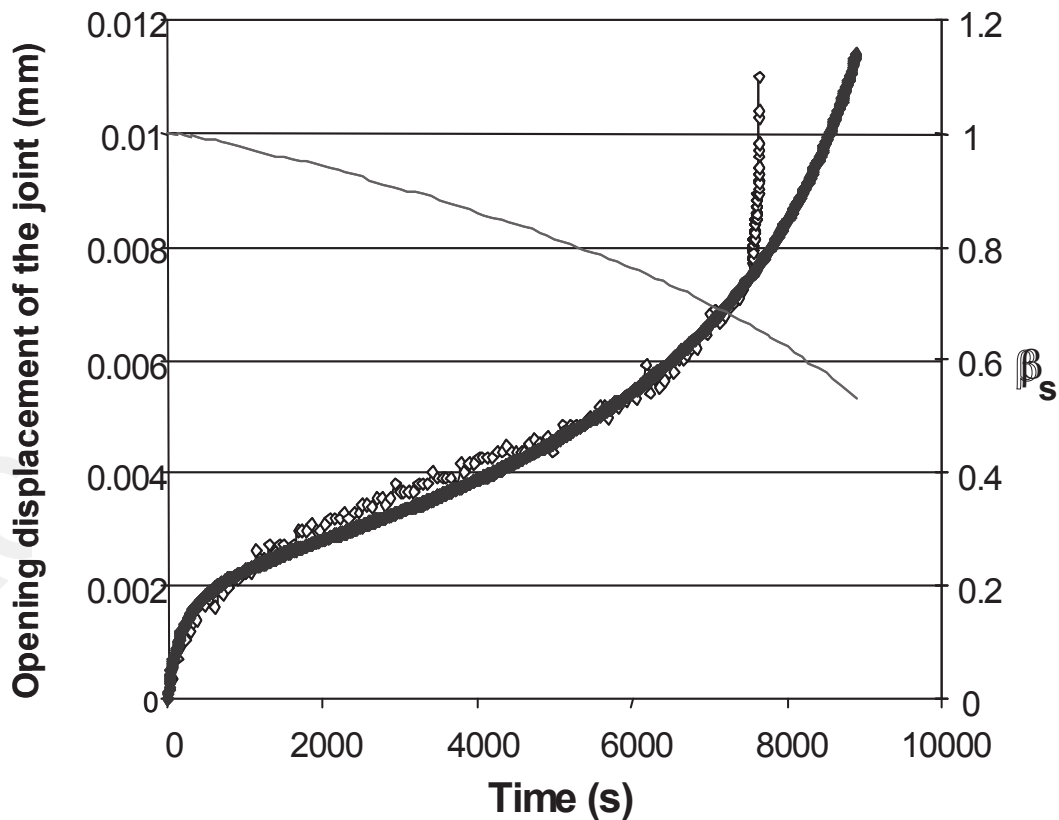


Figure 3. *Model-experiment comparison under tension loading conditions. Experimental values of the joint opening displacement versus time (\diamond), numerical calculations (\blacklozenge), and theoretical evolution of the damage quantity β_s (—)*

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: $\hat{k}_s = 1.15 \times 10^3 \text{ MPa}\cdot\text{mm}^{-1}$; $c_s = 1500 \text{ MPa}\cdot\text{mm}\cdot\text{s}$; $w_s = 2 \times 10^{-3} \text{ MPa}\cdot\text{mm}$; $k_{s,12} = 0$.

As shown in Figure 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) in the interface as a function of time, which accounts well for the progressive rupture of active adhesive links.

3.2. Shear loading conditions

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

We considered the configuration shown in 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 described by Sudret *et al* (2005).

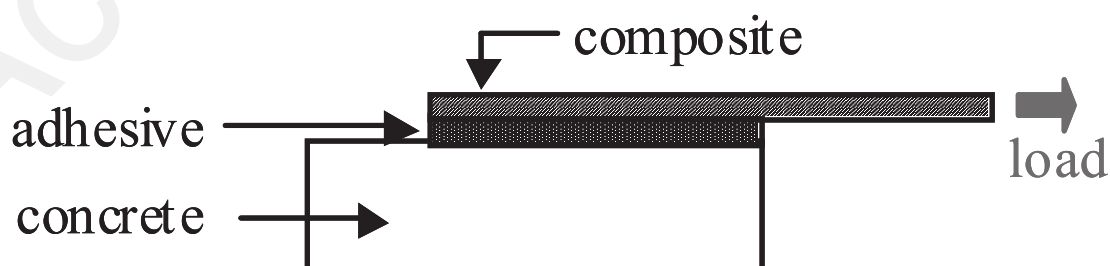


Figure 4. CFRP strengthened concrete specimen. Shear load testing configuration

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 $E = 33000 \text{ MPa}$ and $\nu = 0.2$. The model parameters were $c_1 = 0.002 \text{ MPa.s}$; $\omega_1 = 4 \times 10^{-5} \text{ MPa}$; $k_1 = 0,2 \text{ MPa.mm}^2$;

– *in the composite body*: the longitudinal elastic modulus and Poisson's ratio were respectively $E = 1.8 \times 10^5 \text{ MPa}$ et $\nu = 0.1$. The model parameters were $c_2 = 0.2 \text{ MPa.s}$; $\omega_2 = 2 \text{ MPa}$; $k_2 = 0.1 \text{ MPa.mm}^2$;

– *in the glue*: the model parameters related to the surface damage were $\widehat{k}_s = 5 \times 10^3 \text{ MPa.mm}^{-1}$; $k_s = 0.1 \text{ MPa.mm}^2$; $c_s = 1000 \text{ MPa.mm.s}$; $\omega_s = 5.3 \text{ MPa.mm}$; $k_{s,1} = k_{s,2} = 0.1 \text{ MPa.mm}$, $k_{s,1,2} = 5 \text{ MPa.mm}^{-1}$.

Figure 5 presents the damage field in the specimen after 40 s testing, as provided by the model. Damage is concentrated within the concrete material, at few centimeters from the adhesive joint. Moreover, damage propagates in the concrete along a preferential direction (around 45° from horizontal). This 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 (Figure 6).

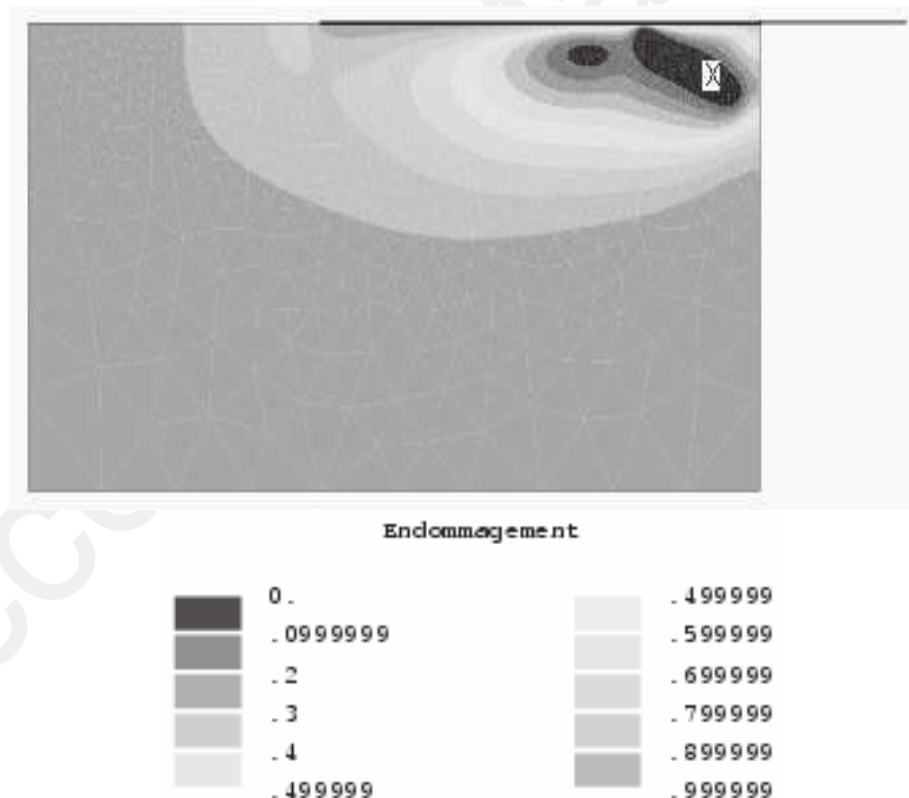


Figure 5. Damage field in the CFRP strengthened concrete specimen after 40 s testing. The colour scale give indications on the theoretical values of the damage parameter β_i within the concrete. Red parts correspond to the most damaged areas

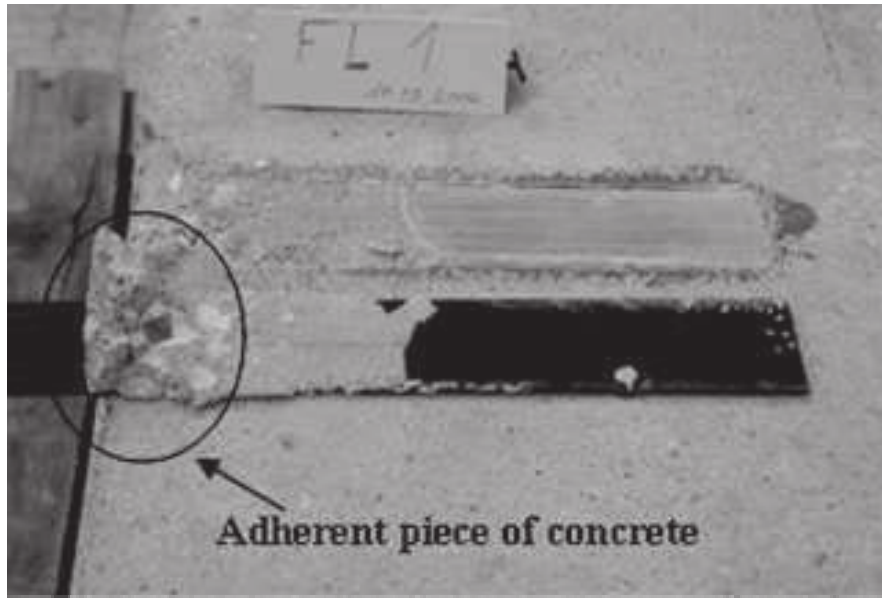


Figure 6. Observation of the fractured specimen. A concrete wedge is still bonded to the composite plate

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.

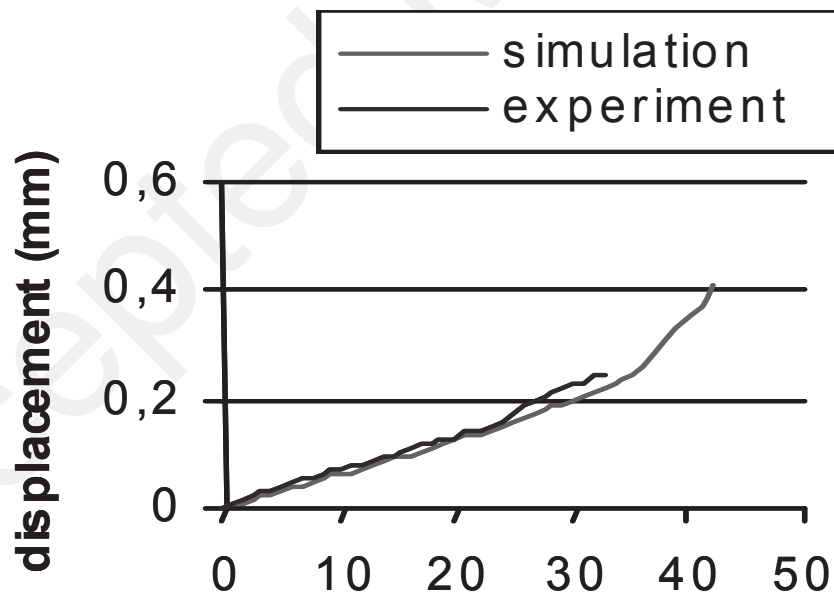


Figure 7. Evolution of the displacement at the point of load application during the shear test. Comparison between numerical and experimental data

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 (Nguyen, 2008):

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

5. References

- Bruneaux M.-A., Benzarti K., « Durabilité des assemblages collés : Modélisation mécanique et physico-chimique », *ERLPC*, n° OA 55, Paris, LCPC Editions, 2006.
- Freddi F., Fremond M., “Damage in domains and interfaces: A couple predictive theory”, *Journal of Mechanics of Materials and Structures*, vol. 1, n° 7, 2006, p. 1205-1233.
- Frémond M., « Adhérence des solides », *Journal de mécanique théorique et appliquée*, vol. 6, n° 3, 1987, p. 383-407.
- Frémond M., *Non-smooth Thermomechanics*, Heidelberg, Springer Verlag, 2001.
- Karbhari V.M., Zhao L., “Use of composites for 21st century civil infrastructure”, *Computer Methods in Applied Mechanics and Engineering*, vol. 185, n° 2-4, 2000, p. 433-454.
- Nedjar B., Frémond M., “Damage, gradient of damage and principle of virtual power”, *International Journal of Solids and Structures*, vol. 33, n° 8, 1996, p. 1083-1103.
- Nguyen T.H.T., Modèle d’endommagement des assemblages collés : Identification et application à la description d’un essai de vieillissement accéléré, PhD Thesis, ENPC, 2008, <http://pastel.paristech.org/5199/>
- Sudret J.-P., Metais G., Clement B., Bligny P., Vitel F., Flety A., Dessertenne J.-P., Wendling L., « Développement d’un essai de cisaillement d’interface collée », *ERLPC*, n° OA 54, Paris, LCPC Editions, 2005, p. 133-141.
- <http://www.cesar-lcpc.com/>, official website for CESAR-LCPC software.