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THERMAL-BRIDGE SHUNT ELEMENTS MODELLING FOR SEISMIC VULNERABILITY OF BUILDINGS EVALUATION

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Abstract. *Nowadays sustainable constructions imply an objective of energetic performances by reducing the level of thermal conduction. The thermal-bridge shunt elements, an innovative technological element is under study in several countries in Europe. If the thermal benefits have already been proved, the mechanical effects of such a wall-slab connection in a building for the seismic risk have not been assessed. To evaluate the building seismic vulnerability modifications due to these thermal bridges shunt, experimental and numerical developments have to be performed. An experimental campaign is proposed to evaluate the seismic ability of such structural elements and a simplified modelling is proposed aiming at developing numerical framework able to handle parametrical and probabilistic approaches for structural analysis.*

1 INTRODUCTION

Nowadays sustainable constructions imply an objective of energetic performances by reducing the level of thermal conduction. The thermal-bridge shunt elements, an innovative technological element is under study in several countries around Europe. If the thermal benefits have already been proved, the mechanical effects of such as wall-slab connection in a building under seismic risk have not been assessed. To evaluate the building seismic vulnerability modifications due to these thermal bridges shunt, experimental and numerical developments have to be performed.

A two steps analysis is adopted in this work. In order to assess the seismic vulnerability of a building, one has to be able to perform statistic and sensitivity analysis. The numerical models to be developed should be as simple and robust as possible. Firstly the experimental analysis of reduced scale elements in comparison with 3D numerical investigations allow to determine failure mechanisms of thermal shunt elements (made of concrete and steel combinations) subject to earthquake loadings. The thermodynamic internal variables are determined in this stage. Secondly, a macro-scale model for slab-wall connection is derived following the previous analysis and based on irreversible processes thermodynamic assumptions [1]. This model accounts for damage due to shear and flexural combinations, frictional sliding and hysteresis, steel plasticity and stiffness recovery in case of alternate loadings. The finite element numerical implementation has been carried out using an implicit scheme. The model is validated thanks to experimental campaigns achieved under quasi-static loading and seismic.

2 NONLINEAR MECHANISMS IDENTIFICATION

2.1 Thermal bridge shunt elements

This new technique for buildings allows for reducing the thermal conductivity from the inside of the construction to the outside. The thermal bridges are taking place at the wall-slab connection. The role of the thermal bridges shunt elements is to break the thermal connectivity by eliminating any concrete liaison by thermal insulation passive material devices. Different solutions may be adopted, for example in figure 1 two technological solutions allowing breaking the energetic loss.

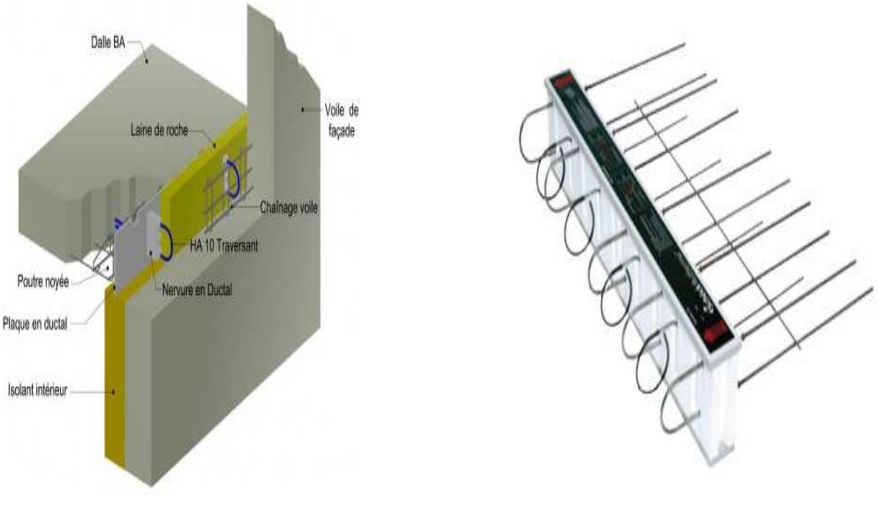

Figure 1: Thermal bridge shunt elements from Lafarge (Ruptal) (left) and Schöck (Rutherma) (right)

2.2 Experimental investigation

The experimental set-up has to be able to reproduce the load transmission mechanism between the wall and the slab when subject to lateral and horizontal acceleration motion due to earthquake loadings. A double shear test as shown in figure 2, preventing any flexion occurrence has been performed on the thermal bridge shunts elements. Four ends steel plates allows to recover the anchored boundary conditions as in the real situation.

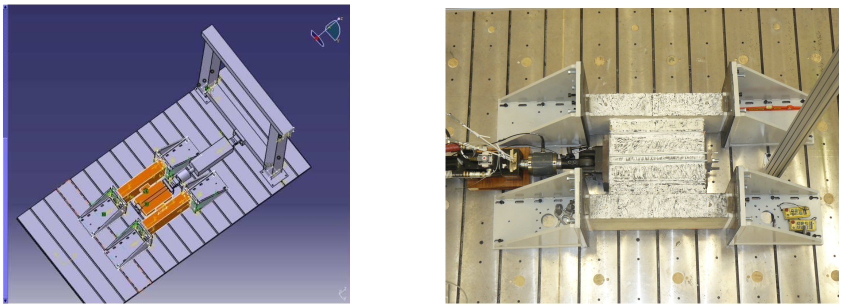

Figure 2: Experimental set-up for a double shear test

The uniaxial load is imposed by a centered hydraulic actuator. Two parallel thermal bridge shunt elements (60 cm long each) allow the load transmission to the two parallel walls. The maximum load capacity for the actuator is 25 tons. LVDT gages have been used to measure the displacements between the walls and the slab as well as digital images for numerical correlation. In the figure 3, one can appreciate an example of a global response, using normalized axis for confidentiality requirements.

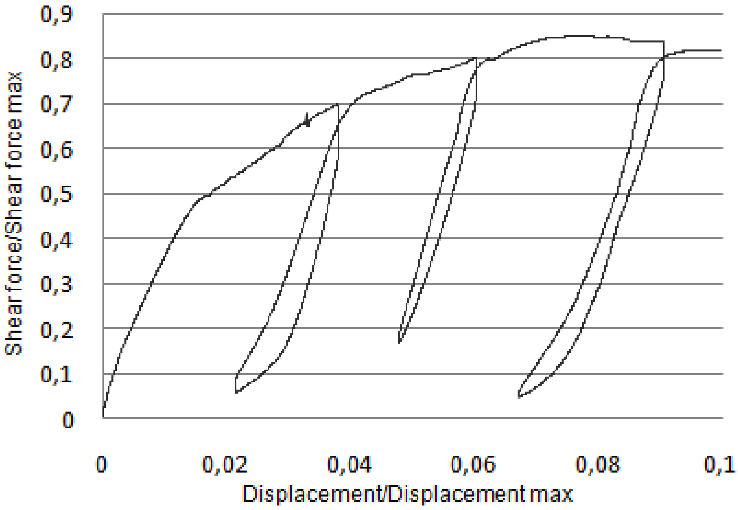

Figure 3: Experimental global response. Normalized axis

Coupling steel plasticity and concrete cracking, the main nonlinear mechanisms can be observed as: stiffness decrease, permanent displacements in unloading, hysteresis loops, nonlinear hardening and softening. This kind of experimental results can be used to develop some modeling allowing the numerical prediction of seismic behavior of building made of such innovative technological elements.

2.3 3D modeling and understanding

The objectives of this section are to proceed to 3D numerical computations on the previous case-study to be able to discriminate the different sources of nonlinearity allowing expressing a constitutive behavior for the connection.

A Finite element model has been established, thanks to the 2 axis of symmetry of the problem. Both steel and concrete have been modeled using 3D cubic elements. A plastic perfectly plastic constitutive equation has been introduced for steel and a continuum damage mechanics based model is used for concrete (wall and slab) and Ductal (connection). The different parameters introduced in the computation are given in table 1.

	Materials parameters			
	Young's modulus (GPa)	Poisson's ratio	σ compression (MPa)	σ traction (MPa)
Concrete	25	0,2	25-35	3
Ductal	45-50	0,2	100-150	8
Steel	210	0,3	σy =500 MPa	

Table 1: Material features for the 3D nonlinear computations

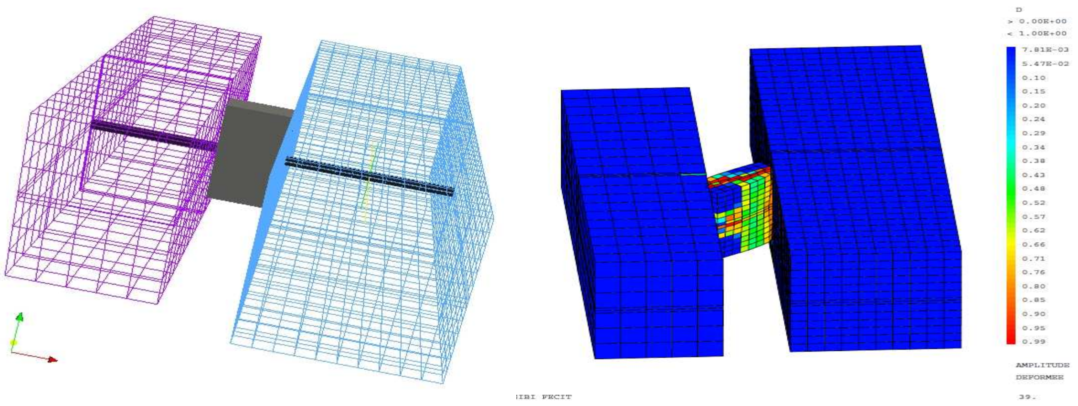

Figure 4: finite element model and results (damage map) of a shear type loading on the connection

The figure 4 presents the finite element model used in the computation as well as a damage map obtained at the end of the analysis. The damage is entirely localized in the Ductal connection zone, inducing flexion of the Ductal block. A good approximation of the experimental response can be fitted as emphasized in figure 5.

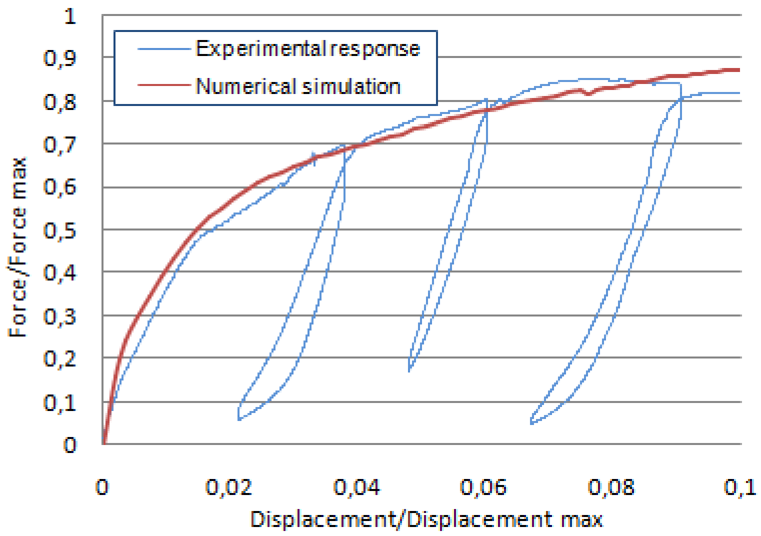

Figure 5: Correlation between 3D numerical analysis and experimental response.

These numerical results will be used in the following section to help one to identify the different evolutions laws for the constitutive equations which has to be expressed.

2.4 Micromechanical analysis

The aim of this section is to analyze the previous numerical/experimental comparisons to be able to define the number of thermodynamic variables which should be introduced in the future modeling, and to calibrate the corresponding evolution laws in case of irreversible processes. For that purpose, the nonlinear behavior of the Ductal square block is analyzed using nonlinear micromechanical models. For example, the stiffness evolution and decrease is computed in different directions according to the increase of a crack in the body. The figure 6 presents the crack propagation in the vertical direction for a vertical load applied on the block.

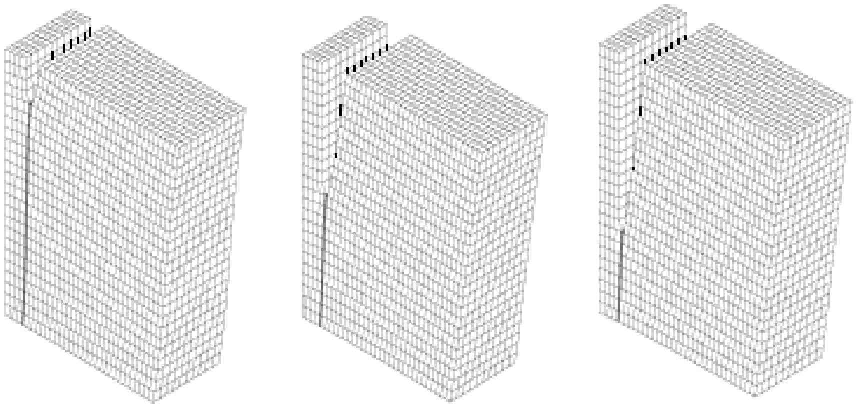

Figure 6: Crack propagation in the ductal block subject to vertical loading

The stiffness decrease is evaluated in the vertical and horizontal directions in the figures 7. Two computations are plotted in the figure 7: the results of the full 3D computation using the modeling of figure 6 and the analytical computations based on the Timoshenko’s beam theory. The main conclusion is that a kind of anisotropy appears in the behavior and should be accounted for in the future modeling. The same analysis may be carried out for a cyclic loading. The reverse loading leads to crack openings and closing in different zones of the Ductal block.

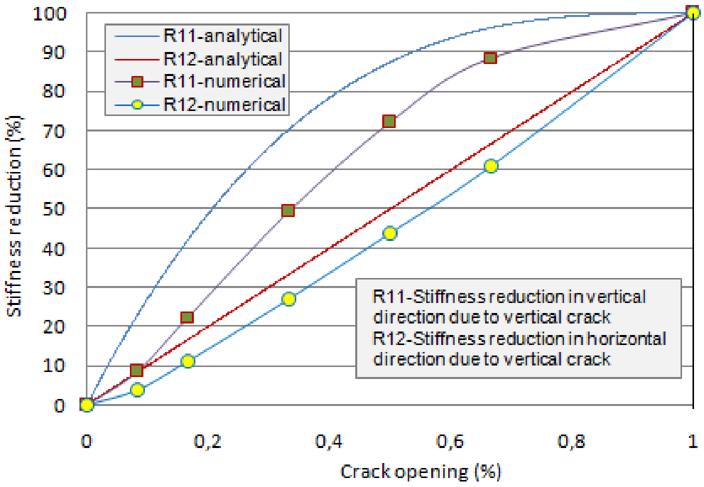

Figure 7: Stiffness reduction in different directions for a vertical crack propagation

The conclusions which could be assessed leads to the definition of two different damage variables for the two major directions of solicitations (horizontal and vertical) allowing accounting for the damage decrease in these directions. Regarding the different zones affected by crack openings and closings, two different damage variables could be introduced to account for unilateral effects and damage deactivation.

2.5 Damage evolutions

After defining the type of variables (damage ones), this section has to be able to calibrate the evolution laws of these thermodynamic quantities. Two more complete 3D computations, based on the model of figure 4, are performed to point out the effect of the steel and the Ductal block. In figure 8, the numerical results are presented by comparing the global force/displacements responses using the 3 different configurations. These comparisons allow to identify in the linear regime, the contribution of each one of the materials to the global stiffness and in the nonlinear regime to express the stiffness reduction only due to crack propagation allowing to evaluate damage variable evolution law.

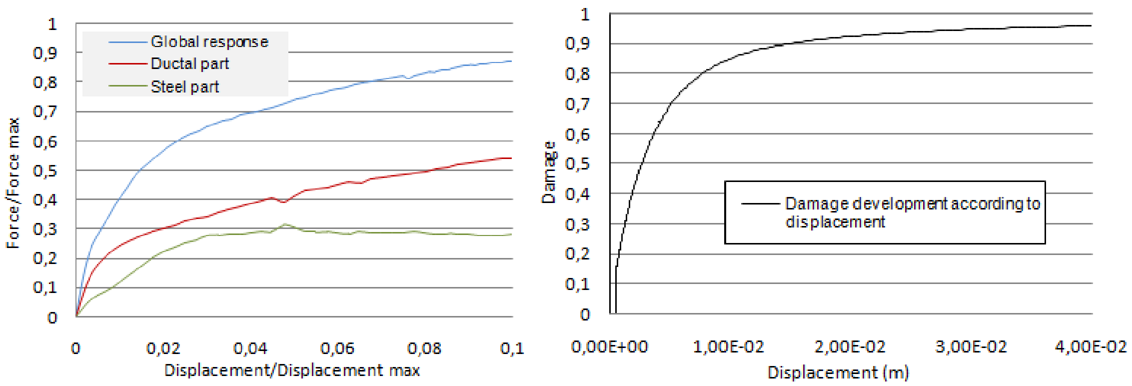

Figure 8: Contribution of the different materials to the global response (left). Damage law identification based on the numerical simulations

3 MODELLING

Regarding the ability of a model to proceed to the seismic vulnerability evaluation of a structure, the model should be, at the structural level, as simple as possible allowing performing probabilistic analysis and parametrical approaches. The choice made is to introduce the nonlinear behavior in the connection thanks global modeling based on the generalized strains and stresses concept (beam theory). The Finite Element supports are Timoshenko beams using a unique Gauss point for the numerical integration. This feature guarantees a uniform state of stresses and strains in the element.

The following sections present the thermodynamic framework detailing the developments concerning the structural element constitutive equation.

3.1 Free energy and state laws

The framework of irreversible processes thermodynamic is chosen to express the model. The previous experimental and numerical investigations allows for defining the number of thermodynamic variables, their couplings and evolutions. A choice is made concerning the thermodynamic potential from which the state laws will be derived. Expressed in different terms due to the contribution of concrete cracking, frictional sliding, steel plasticity and hardening, the potential takes the following form,

$$\rho\Psi = \frac{1}{2}K_b(1-d)D^2 + \frac{1}{2}K_b.g(d).(D-D^\pi)^2 + \frac{1}{2}K_a(D-D^p)^2 + f(V_k) \tag{1}$$

Where ρ is the density, ψ the Helmholtz free energy, K_b et K_a are the concrete stiffness and steel stiffness respectively, D is the total displacement, D^π is the displacement associated to frictional sliding, D^p is the steel plastic displacement, g(d) is a function insuring the coupling between the level of damage and the friction, in a first approximation it is chosen as g(d)=d, V_k are the other internal variable linked to hardening.

From this free energy, one can obtain the expressions of the state equations by simple derivatives. The total forces vectors are expressed below:

$$F = \rho\frac{\partial\Psi}{\partial D} = \underbrace{K_b(1-d)D + K_b d(D-D_\pi)}_{Béton} + \underbrace{K_a(D-D_p)}_{Acier} \tag{2}$$

$$F_\pi = -\rho\frac{\partial\Psi}{\partial D_\pi} = dK_b(D-D_\pi) \tag{3}$$

$$F_a = -\rho\frac{\partial\Psi}{\partial D_p} = K_a(D-D_p) \tag{4}$$

And the damage energy release rate,

$$Y = \rho\frac{\partial\Psi}{\partial d} = -\frac{1}{2}K_b D^2 + \frac{1}{2}K_b(D-D_\pi)^2 \tag{5}$$

3.2 Thresholds functions and evolution laws

To define the nonlinear evolutions, one has to define thresholds function. The model is based on damage mechanics, the first and major irreversible mechanisms to be checked is damage evolution. A simple law, based on the original work of [2] allows a simple damage threshold implying associated flow rule,

$$f_{di} = Y_{di} - (Z_i + Y_0) \tag{6}$$

Z_i is the thermodynamic variable associated to isotropic hardening and Y_0 is the initial threshold.

According to associated flow rule, the damage evolution for concrete may be simply and analytically integrated to obtain a direct computation of the damage variable,

$$d_i = 1 - \frac{1}{1 + pY_{di}{}^{q}} \tag{7}$$

Where q and p are material parameters to be identified.

Concerning permanent displacements and frictional sliding, a non associated flow rule based on the works of [3] introducing nonlinear evolutions for kinematic hardening has been adopted for this study. The friction threshold stands as,

$$f_\pi = \left| F_\pi - X_b \right| \tag{8}$$

With X_b the backstress for nonlinear kinematic hardening. The plastic potential is non associated and is classically expressed as,

$$\phi_\pi = \left| F_\pi - X_b \right| + \frac{a_b}{2} X_b^2 \tag{9}$$

The evolution laws are obtained thanks to normality rules applied to the plastic potential,

$$\dot{D}_\pi = \dot{\lambda}_\pi \frac{\partial \phi_\pi}{\partial F_\pi} \quad \dot{\alpha}_b = -\dot{\lambda}_\pi \frac{\partial \phi_\pi}{\partial X_b} , \tag{10}$$

The plastic multiplier is computed using iterative procedure based on return-mapping or Newton procedures.

3.3 Cyclic response

Standing as a first validation case-study, an experimental investigation has been performed on a slab-wall connection made of Shöck thermal bridge shunt elements. A double shear tests has been performed on a mock-up. To emphasize the seismic effect, a cyclic loading has been imposed to the sample (2.5 m long and 1.6 m large). The previous model has been used to simulate the global response and the load-displacement diagram is plotted in figure 9.

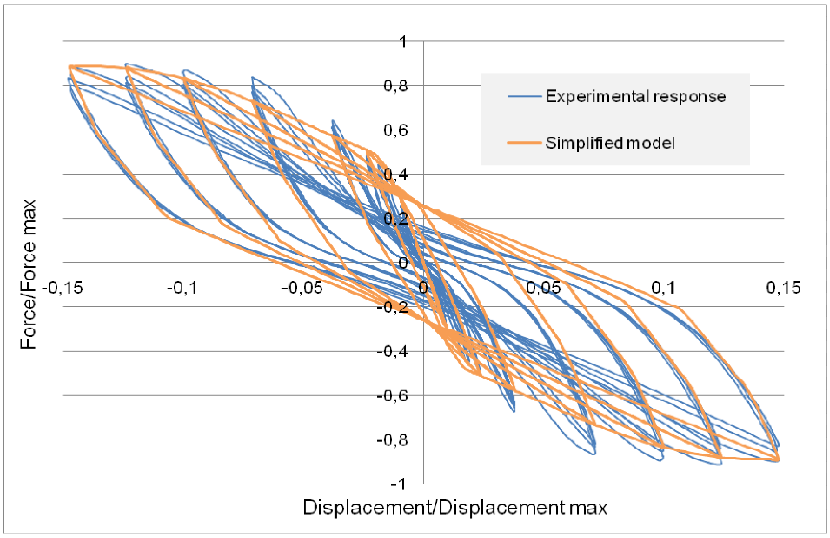

Figure 9: Cyclic loading on a Schöck thermal bridge shunt element. Comparisons between numerical simulations and experimental results.

4 CONCLUSIONS

Considering the nonlinear behavior of innovative wall-slab connection in buildings, an experimental and numerical analysis of the mechanical response of thermal bridge shunt elements is proposed in this work. The experimental part allowed assessing the ability for such structural elements to bear horizontal seismic loadings. Finite elements analysis based 3D nonlinear behaviors help one to discriminate the fundamental thermodynamic variables to be introduced and to evaluate their respective evolution laws linked to the global displacement. At last, a simplified model, based on the beam theory assumption is proposed to predict the nonlinear response of building connections subject to cyclic loading. The next step to achieve will be the assessment of building seismic vulnerability performing probabilistic and parametrical analysis.

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