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### ► **To cite this version:**

I. Ousset, D. Bertrand, M. Brun, A. Limam, M. Naaim. Vulnerability assessment of reinforced concret structures submitted to out-of-plane loadings: application to a protective structure impacted by snow avalanches. 2012 International Snow Science Workshop ISSW, Sep 2012, Anchorage, United States. p. 703 - p. 706. <hal-00744583>

**HAL Id: hal-00744583**

**<https://hal.science/hal-00744583v1>**

Submitted on 23 Oct 2012

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## VULNERABILITY ASSESSMENT OF REINFORCED CONCRETE STRUCTURES

### SUBMITTED TO OUT-OF-PLANE LOADINGS :

#### APPLICATION TO A PROTECTIVE STRUCTURE IMPACTED BY SNOW AVALANCHES

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**ABSTRACT :** In the global warming context, more and more people are threaten by natural hazards. This paper focuses on the physical vulnerability assessment of RC (reinforced concrete) structures loaded by pressure distributions coming from snow avalanche flows. Risk analysis is a relevant tool to reduce the exposure of elements at risk and thus protect people against snow avalanches. In this framework, both the natural hazard and the vulnerability of the exposed elements at risk have to be describe. Therefore, the mechanical response of a typical RC structure subjected to out-of-plane dynamic loading has been modeled and analysed. The studied structure is a RC wall with a L-like shape. Experimental pushover tests have been performed and consisted in applying a uniform pressure distribution until the total collapse of the wall. A 2D Finite Element Model (FEM) has been developed to simulate the mechanical response of the structure under quasi-static and dynamic loadings, and simulations have been compared to experimental data. The transient loading of the snow avalanche is taken into account and several simulation campaigns are used for deriving the vulnerability of the RC wall as a function of the loading magnitude.

### 1. INTRODUCTION

Avalanche hazard threatens structures or buildings in mountainous regions, where the lack of space and the urbanization development induce a continuous increase of the vulnerability of human communities. In the framework of risk analysis, these latter have to take into account not only the natural hazard description but also the physical vulnerability of the exposed structures. In the last decades, research projects have been essentially devoted to improve the comprehension of the processes involved in snow avalanche flows and to the description of the avalanche loading on buildings or structures. Some studies ((Berthet-Rambaud et al., 2007) (Bonnevie et al., 2003), (Bui et al., 2009), (Daudon et al., 2009), (Bertrand et al., 2010), ...) deal with the interaction between avalanche and structures in terms of civil engineering. But the physical vulnerability component is still poorly known and has to be improved. Thus, there is a real need to identify and analyze the mechanical response of civil engineering structures subjected to snow avalanche loadings. This pa-

per deals with the physical vulnerability of concrete buildings or protection structures impacted by out-of-plane loadings and especially involved by snow avalanche flows.

### 2. STUDIED STRUCTURE

A RC wall with a L-like shape (Figure 1) is considered, inspired from a protective RC wall of Taconnaz (Chamonix, France), which is dedicated to deflect rare but huge snow avalanches.

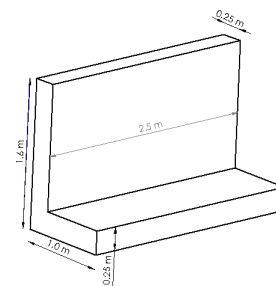


Figure 1 : The studied structure.

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Geometry and material properties of the studied wall are given in Table 1.

Parameter	Symbol	Value	Unit
Shear wall geometry			
Height	$h$	1,60	m
Thickness	$e_p$	0,25	m
Length	$L$	2,50	m
Base geometry			
Width	$l$	1,00	m
Thickness	$e_p$	0,25	m
Length	$L$	2,50	m
Concrete properties			
Density	$\rho_b$	2500	kg/m <sup>3</sup>
Young modulus	$E_{yb}$	38840	MPa
Poisson's ratio	$\eta_b$	0,2	-
Compressive strength	$f_{cb}$	68,4	MPa
Tensile strength	$f_{tb}$	6,4	MPa
Steel properties			
Density	$\rho_a$	7500	kg/m <sup>3</sup>
Young modulus	$E_{ya}$	217000	MPa
Poisson's ratio	$\eta_a$	0,3	-
Maximum elastic stress	$f_{ea}$	575	MPa
Ultimate stress	$f_{ua}$	620	MPa
Maximum elastic strain	$\varepsilon_{ea}$	0,002650	-
Ultimate strain	$\varepsilon_{ua}$	0,037000	-

Table 1 : Geometry and mechanical properties of the structure (Limam, 2005).

The base of the structure is partially clamped (between 0,65 and 1 meter).

Experimental push-over tests on this structure have been performed. They give a complete and accurate database which allows to calibrate the proposed numerical model (Figure 2).

### 3. NUMERICAL MODEL AND RESULTS

#### 3.1 The numerical model

The numerical studies were conducted with the element finite software Cast3M ((Millard, 1993)). The RC structure is modeled in two dimensions using QUA4 elements (4 nodes quadrilateral element) to discretize the concrete and SEG2 elements (two nodes linear elements) for the steel. A perfect adhesion between concrete and steel has been assumed.

The concrete behavior is modeled by a nonlinear constitutive law developed at INSA Lyon and extensively used in the last decade for engineering structures submitted to seismic loading ((Ile and Reynouard, 2000), (Ile and Reynouard, 2005)). It's an elasto-plastic law using the smeared and fixed crack

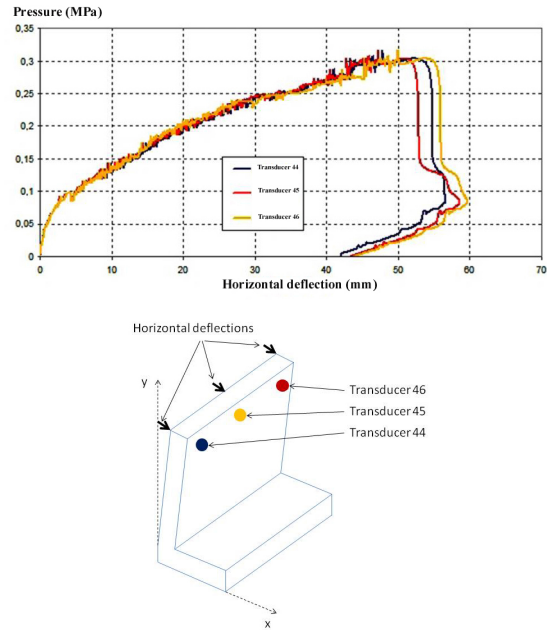


Figure 2 : Experimental results.

theory.

The elasto-plastic framework allows to represent the steel's behavior.

#### 3.2 Model calibration under quasi-static loading

The numerical model has been calibrated in quasi-static conditions, with a step of calculation time of 0,01 s. A good agreement between experimental data and simulation results has been obtained (Figure 3).

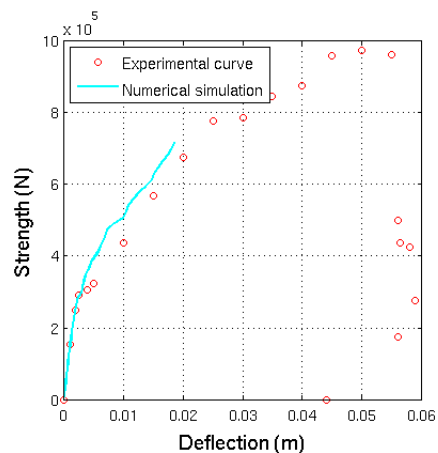


Figure 3 : Comparison between experimental and numerical results in terms of evolution of the pressure as a function of the deflection.

First cracks are obtained at the same deflection than in the experimental tests. However, the numerical modeling fails to obtain the last shear crack which reads on the total collapse of the structure.

### 3.3 Dynamic avalanche loading

In a second time, an *in-situ* measured snow avalanche loading (Thibert et al., 2008) is applied on the RC wall. The measurements come from an experimental test site of IRSTEA located in France. This loading is adapted in terms of applied pressure onto the structure in order to damage (cracks, plastic flows, etc.) the RC wall until its collapse. The pressure is supposed constant along the vertical direction and the time evolution is plotted in the Figure 4. It is worth noting that the time evolution of the deflection follows the time evolution of the pressure applied. It underlines the quasi-static response of the RC wall (Figure 4).

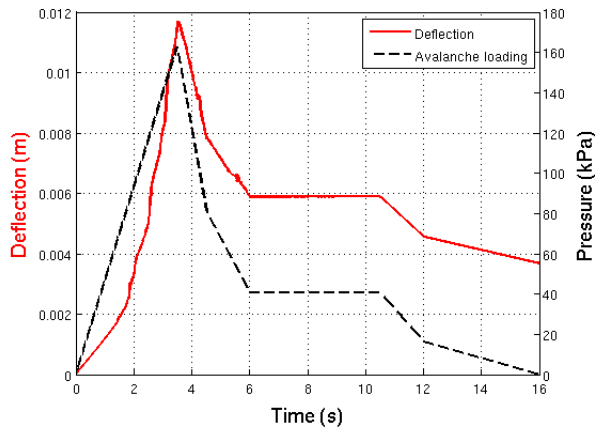


Figure 4 : Deflection evolution during the avalanche loading.

Figure 5 compares results of the simulation in quasi-static conditions with a push-over loading and a simulation with an avalanche loading in dynamic conditions. It shows too that the response of the structure can be considered as quasi-static because the beginnings of the two curves suit the same gradient.

Then, the maximal deflection is obtained. This latter is considered as a vulnerability parameter (Bertrand et al., 2010) describing the overall damage state of the RC wall.

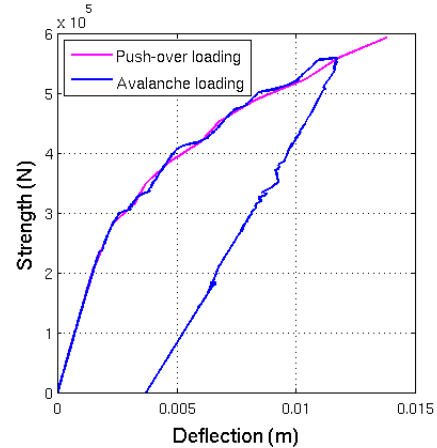


Figure 5 : Avalanche load - deflection curve of Taconnaz L-shaped wall.

### 3.4 Vulnerability curve

Thus, in order to describe the vulnerability of the structure, a vulnerability curve can be derived varying the maximal pressure applied on the wall ( $P_{max}$ ). A vulnerability curve is a monotonous curve, with values ranging between 0 and 1, describing the variation of a damage index according to the natural hazard intensity. The global damage index can be defined for example as the ratio  $\frac{\delta_{max}}{\delta_u}$  where  $\delta_{max}$  is the maximum displacement,  $\delta_u$  the ultimate displacement before collapse and the natural hazard intensity is defined as the peak of pressure  $P_{max}$  (Bertrand et al., 2010). The vulnerability curve obtained for the L-shaped wall with this damage index  $\frac{\delta_{max}}{\delta_u}$  is plotted in Figure 6.

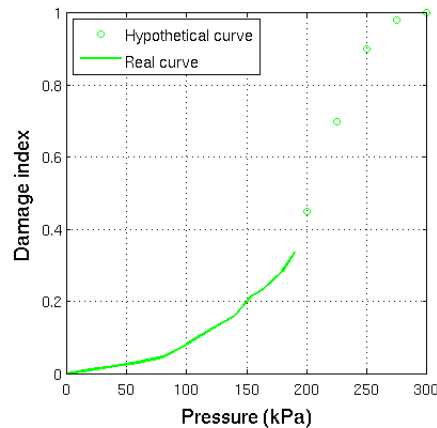


Figure 6 : Vulnerability curve of a RC wall subjected to an avalanche-like dynamic loading.

The end of the curve couldn't be regrettably ob-

tained because of the divergency of the model beyond a maximal pressure value of 190 kPa.

#### 4. CONCLUSIONS AND PERSPECTIVES

In order to better understand the mechanical response of RC structures subjected to dynamic snow avalanche loadings and thus improve the assessment of their physical vulnerability, pushover experimental tests on a physical model have been carried out. In addition, a numerical modeling of the RC structure has been proposed and calibrated from experimental measurements. The influence of quasi-static and dynamic snow avalanche loading signals has been investigated. The results seem to demonstrate that the wall's response could be considered as quasi-static. Furthermore, vulnerability curves can be derived from the FEM modeling by defining the global damage of the structure as the ratio between the maximal displacement reached during the loading application on the ultimate displacement before the structure's collapse. However, depending on the complexity of the constitutive law linking stress and strain in the concrete, the convergence of the computer algorithm is not always possible and thus the calculation can not be done until the real collapse of the structure.

In order to obtain the crack which leads to the total collapse of the structure which can't be obtained with the constitutive law of the concrete used in this study and based on smeared and fixed cracks, an other constitutive law of the concrete will be tested. This last one is implemented in Cast3M under the name URGC concrete. It's a viscoplastic damage model using a regularization allowing to better assess cracks and their localization (Georgin et al., 2004).

Finally, a parametrical study of avalanche loadings will be realised to study the influence of different parameters of the avalanche loading to the behavior of the structure. The loading speed which can lead to a quasi-static or dynamic behavior of the structure, the cyclic aspect of avalanches's action, the spatial load distribution and the direction of the avalanche's action compared with the one of the impacted wall will be at least studied. It perhaps will allow to give some additional recommendations for design of RC structures.

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