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Vulnerability Assessment of Masonry Constructions Towards Rockfall Hazard

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Abstract. Impact tests on full-scale masonry panels are undertaken in order to explore the vulnerability of vernacular construction to rockfall hazards in mountainous areas. Seven 2.5 m high walls made of bricks subjected to a static gravity overload are subjected to a dynamic impact load on their centre, provided by ETAG concrete blocks launched at different energies (from 5 to 15 kJ). This experimental campaign is analysed through numerical simulations. Two different approaches have been explored: a micro-modelling based on the discrete element method (DEM) using the free software Siconos from Inria and a macro-modelling based on the finite element method (FEM) using Abaqus. Models have been adapted to the specificity of masonry structures under dynamic stress by hard shock. They show the strong influence of the overload on the resistance of the wall. The present work aims at assessing the damage generated by an impact on a masonry structure in real conditions. It also leads to question the failure characterisation of the structure after impact. On a long-term perspective, this work is intended to provide damage curves for masonry buildings and thus contribute to the development of normative prescriptions for natural hazard prevention.

Keywords: masonry constructions · rockfall hazard · full-scale experiments · FEM · DEM

1 Introduction

The vulnerability of masonry buildings towards dynamic impacts is at stake in mountainous areas where this type of construction is widespread and the rockfall risk is high. Indeed, although protective structures (e.g. rockfall net fences) are set up, a hazard downstream can still occur. Therefore, it is important to better understand the behaviour of constructions subjected to residual rockfall hazard, in order to edict construction requirements.

Literature on the vulnerability of existing buildings to rockfalls is quite scarce. In Switzerland, the Association of Cantonal Fire Insurance Companies (AEAI), for example, bases its building design requirements on unpublished work. Bost *et al.* [4] investigated failure mechanisms and impact strength of reinforced concrete walls during a full-scale test campaign. Two failure modes have been highlighted: punching and bending, depending on the impact characteristics (mass and energy).

Regarding masonry structures, only little data is available concerning the damage generated by the impact of boulders [15]. Although many studies have been dedicated to the dynamic behaviour of masonry structures in the framework of seismic risk assessment [1, 6], they cannot be extended to boulder impact as seismic loading is much faster, with a global effect on the structure, leading to different failure mechanisms. Work can also be found on the effect the impact of vehicles on masonry bridge parapet [10]. In this case, the loading speeds are of the same order of magnitude (between 10 m/s and 30 m/s, i.e. 36 km/h and 108 km/h), the difference coming from the deformation of the impacting vehicle during the loading. The soft shock results in a systematic partial energy dissipation. Thus, these studies on the dynamic behaviour of masonry structures cannot be directly extended to boulder impact considering the differences on the characteristics of the loading mode.

A few experimental works can be found on the impact of a rigid block on a masonry wall [5, 9]. Gilbert *et al.* [9] investigate the resistance of a metric scale brick or concrete block masonry wall, with or without mortar, but without overload, when subjected to a hard shock of a few tens of kJ. Bui *et al.* [5] study the impact behaviour of 1/2 scale masonry walls loaded by an impact of a few kJ. The reduced scale of the structure and the low energy level of the impact make it difficult to draw comparisons with real conditions. Some authors have investigated the behaviour of the constitutive materials of masonry when subjected to an impact [3, 12]. Beattie *et al.* [3] show that depending on the loading speed and the boundary conditions, the mortar joint presents two different failure modes, by shear or tension. Lourenco *et al.* [11] develop dynamic behaviour laws for brick, mortar joints and masonry, with strength characteristics increasing with the loading speed.

A few attempts have been made to develop a model of a masonry structure subjected to a localised hard shock. Gilbert *et al.* [9] propose an analytical model based on a single failure mode. Bui *et al.* [5] complete their reduced scale experimental campaign with a modal analysis. Burnett *et al.* [7] use the finite element method to simulate the tests performed by [9], showing that the model is sensitive to the masonry characteristics, in particular the joint dilatancy; this work has been latter on extended to introduce an overload at the top of the wall [2]. This model relies on 21 parameters, with the dynamic properties of the material remaining difficult to characterise, in particular at the joint interface. Li *et al.* [11] develop a DEM model, where the contacts between blocks have to be defined. Mavrouli *et al.* [13] resort to PFEM to establish a load equivalent to the impact; this equivalent load is then applied in a FEM simulation considering a macro-model for the masonry structure to determine the damage to the structure. Finally, some models taking into account the dynamic behaviour of the components [12, 15] are relevant for higher stress velocities than in the case of a rock boulder impact.

Reliability analyses have also been performed in order to assess masonry structure behaviour loaded by a boulder impact [8, 16]. These approaches rely on the definition of the failure modes and criteria which, in the current state of the knowledge, struggle to reflect the complexity of the structure behaviour.

As a conclusion, the works presented in the literature do not make it possible to define curves characterising the damage of masonry walls subjected to the impact of a rock

boulder. Moreover, experimental results are too few to have a critical and constructive approach to the models already developed.

The present work aims at providing supplementary experimental data in order to enhance the simulations of masonry construction exposed to rockfall.

2 Experimental Design

A full-scale experimental campaign is undertaken to assess the vulnerability of masonry panels subjected to a boulder impact at University Gustave Eiffel test site in Montagnole near Chambéry (France).

Walls of height $H = 2.50$ m and length $L = 3.00$ m have been built and tested. They are made up 10 layers of 7 single-wall bricks with dimensions of $0.425 \times 0.282 \times 0.249$ m and density $\rho_m = 0.795$ (Table 1), laid dry or jointed with a specific mortar designed for these bricks. The coefficient of friction ϕ_m between the blocks was estimated at 0.75 and the tensile strength of the mortar at 0.072 MPa. The geometrical and physical characteristics of the experimental walls are given in Table 1.

Table 1. Geometrical and physical characteristics of the experimental walls.

Brick	Length l (m)	0.425
	Width w (m)	0.282
	Height h (m)	0.249
	Density ρ	0.795
	Compressive strength f (MPa)	10
	Friction coefficient φ	0.75
Mortar	Tensile strength (MPa)	0.072
Wall	Length L (m)	3.000
	Width W (m)	0.282
	Height H (m)	2.500

The first bed of each wall is blocked, to simulate a rock foundation of the same nature as the blocks of the wall. On the edges, two limit conditions are explored: the wall is either constrained in a metallic frame, in order to simulate the presence of shear walls, or left free. Finally, a static overload of 20 kPa, simulating the effect of an upper floor and/or a roof, is applied at the top of the wall.

The test consists in impacting the centre of the wall with a block launched normally to its front face. Impacting blocks conform to ETAG (European Technical Approval Guidelines) recommendations: they are polyhedral (rhombicuboctahedron) reinforced concrete blocks of two different specific lengths (Fig. 1), leading to two different masses of the impacting block (100 and 277 kg). Blocks are launched at two different heights using the pendulum system of the test site, thus corresponding to two different expected energy levels (5 and 15 kJ).

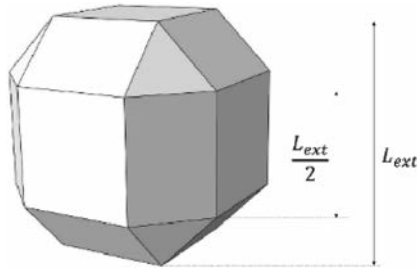


Fig. 1. Rhombicuboctahedron reinforced concrete impacting block of specific length L_{ext} conforming to ETAG 027.

The instrumentation comprises an accelerometer within the impacting block, two high-speed cameras, one at the front and one at the back of the wall, and a camcorder, in order to identify the characteristics of the impact (speed and position) as well as the wall behaviour.

A total amount of seven walls have been tested, with varying conditions in terms of masonry joint, lateral limit conditions, and impacting conditions (mass and energy). The experimental design is detailed in Table 2.

Table 2. Experimental design for full-scale impact tests on masonry panels.

Test	Masonry	Limit conditions	Impacting conditions	
			Mass (kg)	Energy (kJ)
#1	Dry joint	Constrained	100	5
#2	Dry joint	Constrained	277	5
#3	Dry joint	Constrained	277	15
#4	Dry joint	Free	100	5
#5	Dry joint	Free	277	5
#6	Dry joint	Free	277	15
#7	Mortar joint	Free	277	15

3 Full-Scale Test Results and Discussion

The different tests have been analysed with the same protocol. This will be illustrated in this paper on test #2 (Fig. 2).

Test wall #2 is a dry joint wall, which edges displacements have been constrained by a metallic frame (Fig. 2a). It has been tested by launching a 277 kg block on the centre of the panel normally to its front face at an expected energy of 5 kJ.

The accelerometer enables to identify the different phases of the impacting block trajectory (Fig. 3a), from the release of the impacting block at $t = 0$ s to the impact of



Fig. 2. Full-scale experimental wall #2 prior (a) and after (b) impact.

the wall, around $t = 3$ s. The high-speed cameras records are exploited using Tracker video analysis (Fig. 3b), revealing that the impacting block is entering in contact with the front face of the wall at a speed of 22.3 km/h, corresponding to an energy of 5.3 kJ, which is consistent with the expected value of 5 kJ.

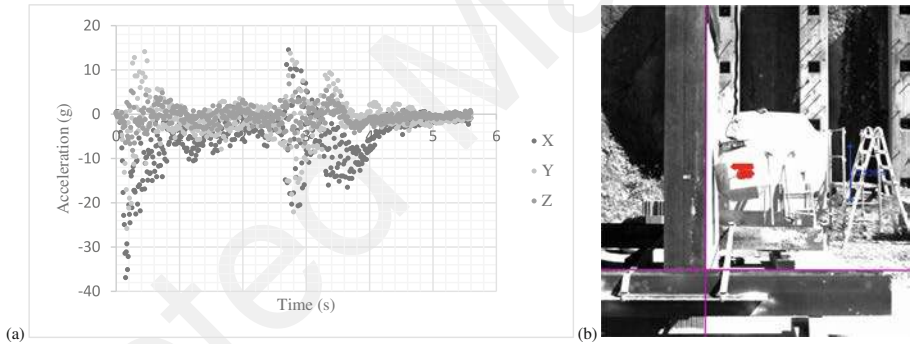


Fig. 3. Accelerometer measurement (a) and video speed analysis (b) of the impacting block for test #2.

When analysing the wall after impact (Fig. 2b), it can be noted that the wall did not succeed in stopping the block. The test led to the destruction of 5 to 8 blocks around the impact area, with a more failure important surface at the back than at the front of the wall. Nevertheless, the test did not lead to the collapse of the wall.

Similar analyses can be made on the other tests. In all the configurations explored, the impacting block was not stopped by the wall. Yet, the impact did not lead to the collapse of the structure but to the complete or partial destruction of the masonry bricks located around the impact area (between 5 to 10 equivalent blocks), close to the punching behaviour observed on reinforced concrete panels tests [4]. Nevertheless, contrary to what have been observed on concrete structures, the failure mode was similar for all tests, and did not depend on the mass or energy of the impact.

4 Numerical Simulations and Preliminary Validations

The experimental campaign has been completed by numerical simulations. These simulations aim at reproducing the specific behaviour of masonry structures when exposed to a hard shock. They will be validated using the experimental results presented in Sect. 3, and then used to perform parametric analyses. In this work, two modelling approaches have been explored: a micro-modelling using DEM (Fig. 4a) and a macro-modelling using FEM (Fig. 4b).

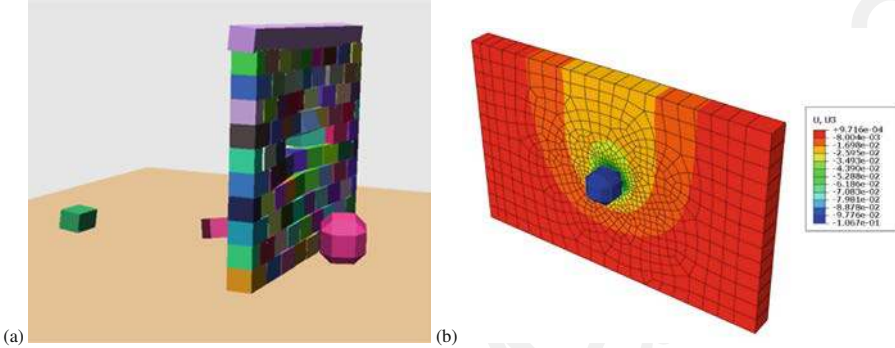


Fig. 4. Numerical simulations of the experimental tests by discrete element method using Siconos (a) and finite element method using Abaqus (b)

4.1 Discrete DEM Approach

The micro-modelling approach (Fig. 4a) is performed using the DEM software Siconos. Siconos is an open-source scientific software developed at Inria Grenoble for the simulation of non-smooth dynamic systems. It has already been used to simulate the behaviour of masonry structures under static loads and the trajectory of rockfall. This study aims at evaluating the capacities of the software to simulate the behaviour of masonry structures under the impact of a boulder.

Masonry is modelled as rigid parallelepipedal blocks interacting at their contact surfaces following a purely frictional contact law of normal restitution e_m and friction angle φ_m . The masonry panel is founded on a rigid support. The interface law between the base of the wall and the support is identical to the interface law between the constituent elements of the structure, as in the experimental campaign. A rigid block of the same length and thickness as the wall is placed at the top of the wall to simulate the overload due to the upper floor or the roof. Two lateral boundary conditions have been explored: blocking all the degrees of freedom, except the translation along the vertical axis (named $\text{Fix}[x,y,X,Y,Z]$), or blocking the horizontal displacement according to the direction of impact (named $\text{Fix}[x]$). In order to allow masonry block displacements, a horizontal gap of 5 mm between blocks is integrated in the model.

The impacting block is simulated as a rigid rhombicuboctahedron interacting with the constituent elements of the masonry structure, also using a frictional contact law of

normal restitution e_b and friction angle φ_b . In addition to the initial mass of the impacting block and its shape, it is necessary to define its location and initial speed.

The impact of the boulder on the structure is modelled as an iterative process in time. The occurrence of an interaction between the different rigid bodies is checked at each time step. In the case of an interaction, an impulse is applied to the rigid bodies in interaction. Displacements of the rigid bodies during impact are calculated using the fundamental principle of dynamics.

4.2 Continuous FEM Approach

The macro-modelling approach (Fig. 4b) relies on Abaqus FEM software.

The masonry panel is constituted of a homogenised material which properties are based on Eurocode 6, with compressive strength ranging from 1.0 to 2.5 MPa, tensile strength from 0.035 to 0.09 MPa, and Young's modulus from 400 to 1670 MPa. The homogenised masonry follows the Concrete Damaged Plasticity (CDP) behaviour law as implemented in Abaqus. This behaviour law includes first a linear elastic part, then a parabolic hardening-softening part, and finally a linear softening part. The behaviour in tension is described by a linear elastic part followed by a softening part. For simplicity reason, the behaviour of the masonry is considered as isotropic, and shear behaviour is not taken into account.

The panel is simulated in 3D using explicit deformable solid finite elements of the quadrilateral type linear with 8 nodes (C3D8R elements). The impacting element is modelled using explicit rigid discrete finite elements of type bi-linear quadrilaterals with 4 nodes (R3D4 elements). The mesh size varies from 2.5 (in the impact zone) to 20 cm for the wall, and is of 2.5 cm for the block.

The wall is embedded at the base and displacement in the direction normal to the wall are blocked on the edges at the back of the wall to simulate the effect of unmodeled shear walls. A vertical pressure field is applied at the top of wall to simulate the action of an upper floor or a roof.

The contact between the impacting block and the wall is created by a general contact type interaction with a tangential friction coefficient $\varphi_b = 0.75$.

4.3 Preliminary Validations and Failure Mode Characterisation

For numerical simulations, three levels characterising the damage of the structure post-impact have been introduced:

- masonry block displacements without collapse, named D1;
- collapse of one or several masonry blocks around the impact area, named D2;
- collapse of one or several masonry blocks at the top of the wall, named D3.

This damage level can be completed by the maximal displacement registered for the wall X^+ , and the number of collapsing blocks N^+ for D2 and D3. The continuous model can also supply complementary global information as stress or strain fields, and plastic damage.

Table 3. Damage characterisation of the impacted walls for DEM and FEM simulations.

Impacting conditions		Simulation	Damage level	Max. displacement X^* (cm)	Collapsing blocks N^*	Impacting block stop	
Mass (kg)	Energy (kJ)						
100	5	DEM/Fix[x,y,X,Y,Z]	D1	10.6	–	Yes	
		DEM/Fix[x]	D1	10.7	–	Yes	
		FEM/Fix[x]	D1	12.3	–	Yes	
	15	DEM/Fix[x,y,X,Y,Z]	D1	19.2	–	Yes	
		DEM/Fix[x]	D2	24.3	1	Yes	
		FEM/Fix[x]	D2	/	3	No	
	50	DEM/Fix[x,y,X,Y,Z]	D2	33.1	1	Yes	
		DEM/Fix[x]	D2	59.7	12	No	
		FEM/Fix[x]	D2	/	7	No	
	277	5	DEM/Fix[x,y,X,Y,Z]	D2	33.1	1	Yes
			DEM/Fix[x]	D1	35.9	–	Yes
			FEM/Fix[x]	D1	11.1	–	Yes
15		DEM/Fix[x,y,X,Y,Z]	D2	37.4	1	Yes	
		DEM/Fix[x]	D2	34.2	5	Yes	
		FEM/Fix[x]	D2	/	4	No	
50		DEM/Fix[x,y,X,Y,Z]	D2	29.4	12	Yes	
		DEM/Fix[x]	D3	46.0	24	No	
		FEM/Fix[x]	D2	/	7	No	
800		5	DEM/Fix[x,y,X,Y,Z]	D1	29.4	–	Yes
			DEM/Fix[x]	D1	34.9	–	Yes
			FEM/Fix[x]	D1	11.2	–	Yes
	15	DEM/Fix[x,y,X,Y,Z]	D2	23.1	–	Yes	
		DEM/Fix[x]	D2	59.2	9	Yes	
		FEM/Fix[x]	D2	/	6	No	
	50	DEM/Fix[x,y,X,Y,Z]	D3	41.5	24	Yes	
		DEM/Fix[x]	D3	45.5	26	No	
		FEM/Fix[x]	D2	/	10	No	

Modelling have been carried out on 9 different impact conditions corresponding to 3 different impacting block masses from 100 to 800 kg, and 4 different level of energy from 5 to 50 kJ. Results are presented in Table 3.

Simulations show that for the same range of impact conditions as the experimental ones (masses from 100 kg to 277 kg and energy from 5 to 15 kJ, in light grey in Table 3), modelled walls succeed in stopping the impacting block in almost all the cases, except for the continuous model with the 277 kg block at 15 kJ. This difference between simulations and experiments can be explained by the low strength of the experimental bricks; complementary tests using stone blocks or complementary simulations integrating masonry block crushing should be performed in order to confirm this hypothesis.

Complementary simulations have been performed in order to undertake a parametric analysis. These tests have led to a reflection on the characterization and quantification of the failure mode of masonry constructions under a boulder impact and the vulnerability of a structure towards rockfall hazards.

5 Conclusion

This study deals with the vulnerability of masonry constructions to rockfall hazards. This issue is at stake in the context of the protection of buildings in mountainous areas.

The literature has shown that the subject has been little explored. Although the static or seismic behaviour of masonry structures has been the subject of a large number of

publications, their response to a hard shock has been very little explored, both from simulation and experimentation points of view. Indeed, experiments have been confined to reduced scales and low energy levels. This work aims at developing a better understanding of the behaviour of masonry constructions under dynamic stress caused by hard shock.

A full-scale experimental campaign has been carried out in order to identify the damage generated by an impact on a masonry structure in real conditions, and to calibrate numerical simulations. For the different experimental configurations explored, only one failure mode by punching has been identified. This can be due to the low strength of the masonry blocks used in the experiment; new tests with stone block could confirm this hypothesis.

In addition, numerical simulations adapted to the specificity of the masonry structures under hard shock dynamic loading have been developed. Two numerical models have thus been proposed: a discrete model based on the free software Siconos from Inria, and a continuous model using Abaqus. Simulations make it possible to explore the capacities of the two approaches to describe the behaviour masonry structures under impact. They prove the strong influence of the limit conditions. Finally, they have led to a reflection on the question of the failure mode of the structure and on the definition of indicators to characterise the level of damage to the structure after impact.

As a long-term perspective, this action aims at defining damage curves for masonry buildings, and thus contribute to the prescription of normative requirements for building construction in mountainous areas.

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