Reduced-scaled experiments of masonry structures under blast loads

F. MASI[a], I. STEFANOU[a], A. MORSEL[a], P. KOTRONIS[a]

a. Nantes Université, Ecole Centrale Nantes, CNRS, GeM, UMR 6183, F-44000 Nantes, France.
email: {filippo.masi; ioannis.stefanou; ahmad.morsel; panagiotis.kotronis}@ec-nantes.fr

Résumé :

La réponse des structures aux explosions ne peut être étudiée en s'appuyant uniquement sur des analyses numériques et analytiques. Les tests expérimentaux sont d'une importance primordiale pour améliorer la compréhension actuelle et valider les modèles existants. Cependant, les expériences pour des chargements de type explosif sont, à l'heure actuelle, partielles et limitées en nombre, en raison du fait que les expériences à grande échelle présentent de nombreuses difficultés, principalement en raison de la nature de l'action de chargement, des coûts élevés associés, des problèmes de sécurité et d'une répétabilité réduite.
Les expériences à échelle réduite offrent au contraire une plus grande flexibilité. Néanmoins, des lois d'échelle sont necessaires et celles disponibles dans la littérature ne représentent souvent pas une base viable pour la conception d'expériences en laboratoire.
Nous présentons ici un ensemble de nouvelles lois de similarité pour la réponse dynamique de type corps rigide des structures, et en particulier des bâtiments en maçonnerie, soumis à des explosions, jetant les bases d'expériences améliorées à échelle réduite. Contrairement aux lois d'échelle bien connues de Hopkinson-Cranz, les lois d'échelle proposées permettent de concevoir des expériences en réduisant l'intensité du souffle, ce qui est impératif pour des expériences sûres.
Des résultats préliminaires nous permettent de confirmer la validité de la méthodologie proposée et la possibilité d'étudier, à moindre coût et aléa, la réponse aux explosions des structures en maçonnerie, et pas seulement.

Abstract :

The response of structures to explosions cannot be exclusively investigated relying only on numerical and analytical tools. Experimental tests are of paramount importance for improving current understanding and validating existing models.
However, blast experiments are, at present, partial and limited in number, due to the fact that full-scale blast experiments present many difficulties, mainly due to the nature of the loading action, the associated high costs, safety issues, and reduced repeatability.
Reduced-scale experiments offer instead greater flexibility. Nevertheless, scaling laws are mandatory and those available in the current literature often do not represent a viable basis for designing safe laboratory blast experiments.
We present herein a set of new scaling laws for the dynamic rigid-body response of structures, and in particular masonry buildings, subjected to explosions, laying groundwork for improved reduced-scale

experiments. In contrast with the well-known Hopkinson-Cranz scaling laws, the proposed scaling laws allow to design experiments by reducing the blast intensity, which is compelling for safe experiments. Preliminary results allow us to confirm the validity of the proposed methodology and the possibility of investigating, at reduced cost and hazard, the response to explosions of masonry structures, and not only.

Keywords : Scaling laws; Blast loads; Reduced-scale experiments; Dynamics; Masonry.

1 Introduction

The investigation of the response and strength of masonry structures subjected to blast loads is a major issue in protecting such assets against explosions [1, 2, 3, 4, 5, 6, 7]. Yet, research activity in this field is, at the moment, insufficient to draw appropriate preservation strategies and in-situ protections.

Whilst numerous numerical investigations can be found in the literature, experimental tests are of paramount importance. At present, experimental campaigns on the investigation of the response of masonry structures to blast loads are extremely limited and mostly consist of in-situ tests (e.g. [1, 3, 8, 4, 5]). These tests provided some information but reproducing the same conditions is highly demanding due to associated high cost, safety issues, reduced repeatability, technical complications, etc. [9].
Conversely, reduced-scale tests, e.g. [10], offer many advantages over in-situ ones, such as reduced cost, reduced hazard and risk associated to the safety of the testing environment and of the personnel. Yet, the design of small-scale tests requires appropriate scaling laws in order to guarantee similarity, both of the structural response and the blast loads.

The main goal of this work is to provide a new set of scaling laws for masonry structures subjected to explosions and guide towards a new experimental setting. In particular, based on the developments of the rigid-body response of monolithic structures against blast loads [11], we derive here scaling laws for masonry structures in a blast event. In contrast with the well-known Hopkinson-Cranz [12, 13] similarities, the proposed scaling laws allow to design experiments by reducing the blast intensity, which is compelling for safe experiments.

2 Methodology

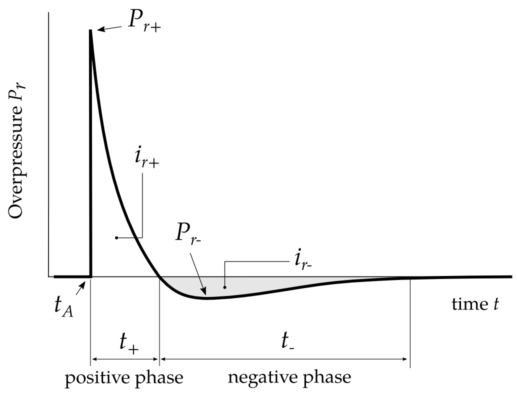
Let us consider a masonry structure, of arbitrary shape, composed of masonry units, interacting one with the other through interfaces with friction angle φ, (non-)associative sliding behavior, and zero cohesion and tensile strength [14]. The structure is subjected to the load of an explosion and undergoes a rigid-body motion. The loading force is characterized by the total specific thrust $\mathcal{P}$ and the total specific impulse $\mathcal{I}$.

Figure 1 shows schematically the time evolution of blast loading, in terms of the overpressure P_r, which is determined by the arrival time of the shock wave, t_A, the overpressure peak, P_{ro}, the positive phase duration, t_o, the negative phase duration, t_{o-}, and the underpressure peak, P_{ro-}. These parameters are functions of the stand-off distance, R, for the explosive source and of the explosive weight, W (conventionally expressed in TNT equivalent). Here blast loads are modeled using empirical approximations [11, 15]. Accordingly,

$$\begin{aligned} &P_{r+} = \hat{P}_{r+}(Z), \quad t_+ = W^{1/3}\hat{t}_{w+}(Z,W), \quad i_{r+} = W^{1/3}\hat{i}_{rw+}(Z,W), \\ &P_{ro-} = \hat{P}_{r-}(Z), \quad t_- = W^{1/3}\hat{t}_{w-}(Z), \quad i_{r-} = W^{1/3}\hat{i}_{rw-}(Z,W) \end{aligned} \tag{1}$$

where the superposed caret serves to distinguish the function from its value and Z is the scaled distance, $Z = R/W^{1/3}$.

We denote the geometry of the structure by (i) a characteristic length l (e.g., the height of the structure in Figure 1), (ii) dimensionless length ratios l_i, which relate all other lengths to the characteristic one, and (iii) generalized angles α_i. The structure is further characterized by a uniformly distributed mass m, mass moment of inertia J about some specific axis, and non-dimensional mass moments of inertia ratios J_i, which relate all other components of the rotational inertia tensor to the characteristic mass moment of inertia. We denote the gravitational acceleration with g and the friction coefficient of the interfaces with $\mu = \tan\varphi$. Coulomb friction is adopted. The material has density ρ. For each block constituting the structure, we identify the sliding distance, x, the linear velocity and acceleration, respectively $\dot{x}$ and $\ddot{x}$, the rocking angle, θ, and the angular velocity and acceleration of the blocks, $\dot{\theta}$ and $\ddot{\theta}$, respectively.



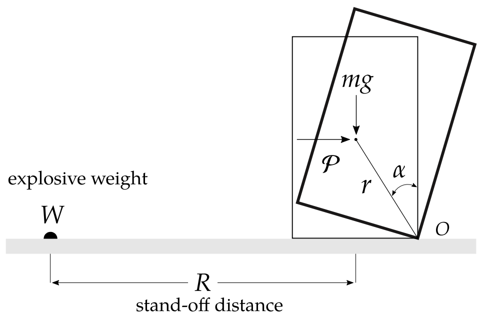


Figure 1: Time evolution of overpressure due to an explosion acting on a target, first-order approximation (left) and representative scheme of the problem, e.g. a multi-drum column under blast loading due to the detonation of a W TNT equivalent explosive weight, at stand-off distance R (right).

2.1 Scaling laws

From the π Theorem [16] and following the procedure in [17], we identify the following fourteen π terms for the rigid-body response of the blocks:

$$\begin{aligned} &\pi_{01} = J_i, \quad \pi_{02} = \alpha_i, \quad \pi_{03} = l_i, \quad \pi_{04} = \frac{x}{l}, \quad \pi_{05} = \theta, \\ &\pi_{11} = \ddot{\theta}\frac{l}{g}, \quad \pi_{12} = \dot{\theta}\sqrt{\frac{l}{g}}, \quad \pi_{13} = \frac{\ddot{x}}{g}, \quad \pi_{14} = \frac{\dot{x}}{\sqrt{lg}}, \quad \pi_{15} = t\sqrt{\frac{g}{l}}, \\ &\pi_{21} = \mu, \quad \pi_{22} = \frac{J}{ml^2}, \quad \pi_{23} = \frac{\mathcal{P}l^2}{mg}, \quad \pi_{24} = \frac{\mathcal{I}}{m}\sqrt{\frac{l^3}{g}} \end{aligned} \tag{2}$$

Terms $\pi_{01} - \pi_{05}$ represent the geometric similarity and terms $\pi_{11} - \pi_{15}$ identify the kinematic similarity, i.e., the response of the system in terms of linear and angular displacements, velocities, and accelerations. The remaining four terms $\pi_{21} - \pi_{24}$ determine dynamic similarity in terms of rigid-body motion.

By imposing the equivalence of the aforementioned π terms, one can investigate and predict the response of a full-scale system (namely, a prototype) by studying the response of a reduced scale system (i.e., a model), satisfying the similarity statements. To this end, we consider that the prototype and the model are subjected to the same gravitational field and we denote with λ and γ the geometric and density scaling factors, respectively

$$\lambda = \frac{\tilde{l}}{l}, \quad \gamma = \frac{\tilde{\rho}}{\rho}, \tag{3}$$

with superscript '$\sim$' denoting model's quantities. Thus, the scaling factors characterizing the rigid-body response are obtained:

$$\begin{aligned} &\Lambda_{J_i} = 1, \quad \Lambda_{\alpha_i} = 1, \quad \Lambda_{l_i} = 1, \quad \Lambda_x = \lambda, \quad \Lambda_\theta = 1, \\ &\Lambda_{\ddot{\theta}} = \lambda{-}1, \quad \Lambda_{\dot{\theta}} = \sqrt{\lambda^{-1}}, \quad \Lambda_{\ddot{x}} = \varsigma, \quad \Lambda_{\dot{x}} = \sqrt{\lambda}, \quad \Lambda_t = \sqrt{\lambda}, \\ &\Lambda_\mu = 1, \quad \Lambda_J = \gamma\lambda^5, \quad \Lambda_{\mathcal{P}} = \gamma\lambda, \quad \Lambda_{\mathcal{I}} = \gamma\sqrt{\lambda^3}, \end{aligned} \tag{4}$$

where $\Lambda_f = \tilde{f}/f$ denotes the scaling factor of a quantity 'f'.

As detailed in [17], the identification of the scaling laws is not trivial as it is impossible to satisfy the expressions for both $\Lambda_{\mathcal{P}}$ and $\Lambda_{\mathcal{I}}$ for a fixed scaled distance factor $\Lambda_W = (\lambda/\lambda_Z)^3$, thus explosive weigth. However, the system of equations (4) can be relaxed if one considers that the blast load is fast enough, compared to the characteristic time of the structure. In this case the blast load is considered as an impulsive load. And one obtain the scaling factor for the scaled distance $\Lambda_Z = Z/\tilde{Z}$, thus the scaling for explosive weight, by solving the following nonlinear algebraic equation

$$\Lambda_Z^{-1} \frac{\hat{i}_{rw}(Z\Lambda_Z)}{\hat{i}_{rw}(Z)} - \gamma\sqrt{\lambda^5} = 0, \tag{5}$$

where $\hat{i}_{rw} = \hat{i}_{rw+} + \hat{i}_{rw-}$ denotes the total scaled reflected impulse.

It is worth mentioning that the above scaling reduces to the Hopkinson-Cranz similarity law when $\Lambda_Z = 1$ is imposed. However, Eq. (5) is much more general and allow to reduce the scaled distance in function of the geometric and density scaling, thus to reduce the overpressure peak, P_{r+} (see also [17]).
Figures 2-4 display the dependency of the scaling factors on overpressure and impulse with respect to the geometric scaling and scaled distance.

3 Results

Relying on the scaling laws derived above, we investigate their validity for masonry structures displaying rigid-body behavior. In particular, we consider the motivating case of a monolithic block and investigate the prototype and model responses obtained by numerical integration of the nonlinear equations of rocking motion (see [11]).

The target consists of a rectangular (rigid) block with uniformly distributed mass m. The dimensions of the block are $2b \times 2h \times 2w$ and the radial distance from the rocking pivot point O to the center of

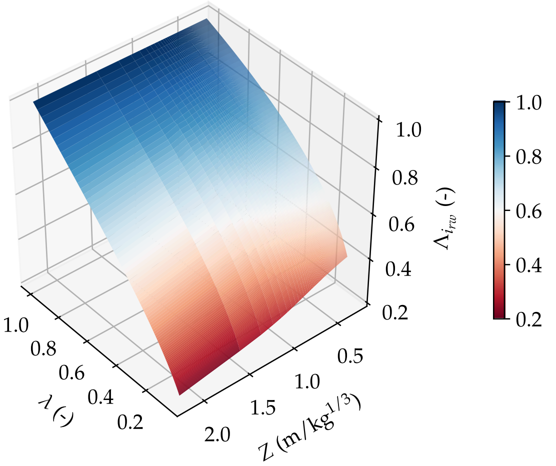


Figure 2: Scaling factor of the total impulse, in function of the geometric scaling factor λ and the scaled distance Z.

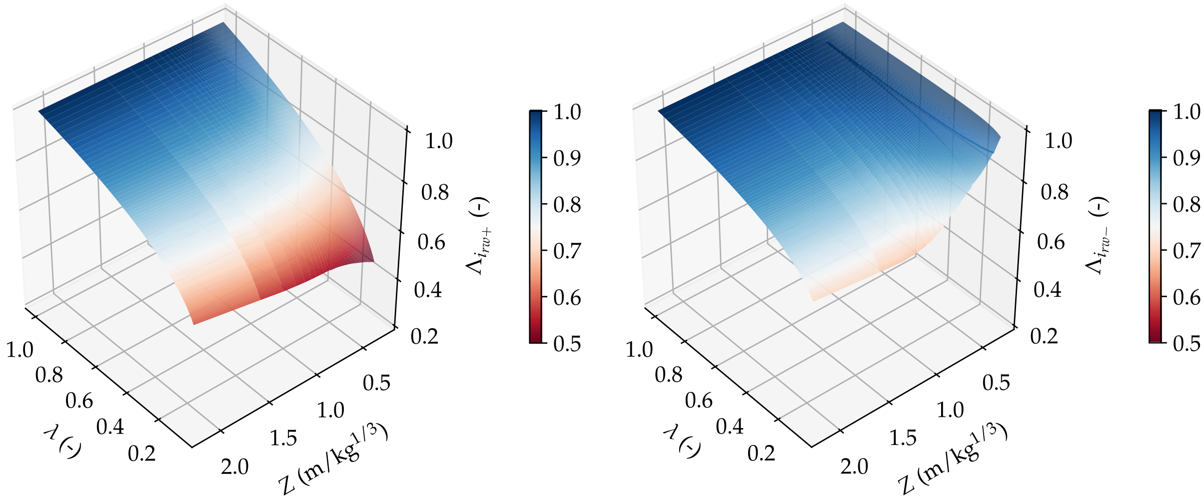


Figure 3: Scaling factor of the positive (left) and negative (right) scaled impulse, in function of the geometric scaling factor λ and the scaled distance Z.

gravity is $r = h/\cos\alpha$, with α being the slenderness angle. The dimensionless equations of motion for a rocking response mechanism are

$$\ddot{\phi} + \frac{1}{\alpha}\sin\left[\alpha\left(\text{sgn}(\phi) - \phi\right)\right] = \left(\chi p_+ + \bar{\chi} p_-\right)\cos\left[\alpha\left(\text{sgn}\left(\phi\right) - \phi\right)\right], \tag{6}$$

where $q = \sqrt{mgr/J_o}$; $s = \sqrt{Sr/J_o}$; $\chi = s^2 P_{r+}/(q^2\alpha)$ and $\bar{\chi} = s^2 P_{r-}/(q^2\alpha)$; with p_+ and p_- the time-histories of the positive and negative phase expressed in term of the dimensionless time $\tau = qt$, $\phi = \theta(\tau)/\alpha$ the normalized rocking angle, $J_o = \frac{4}{3}mr^2$ the moment of inertia with respect to the pivot point (see [11, 18, 19, 20, 21, 22]). Inelastic impacts are considered between the block and the base, see [23]. Blast loads are modeled with the piece-wise linear approximation proposed by [24].

In the following we shall consider two cases: CS-1 and CS-2. In CS-1, we only consider the blast positive phase, while in CS-2 we account for both the positive and the negative phase (see Fig. 1). In both cases, we select the following parameters for the prototype: height $2h$ = 10 m, slenderness

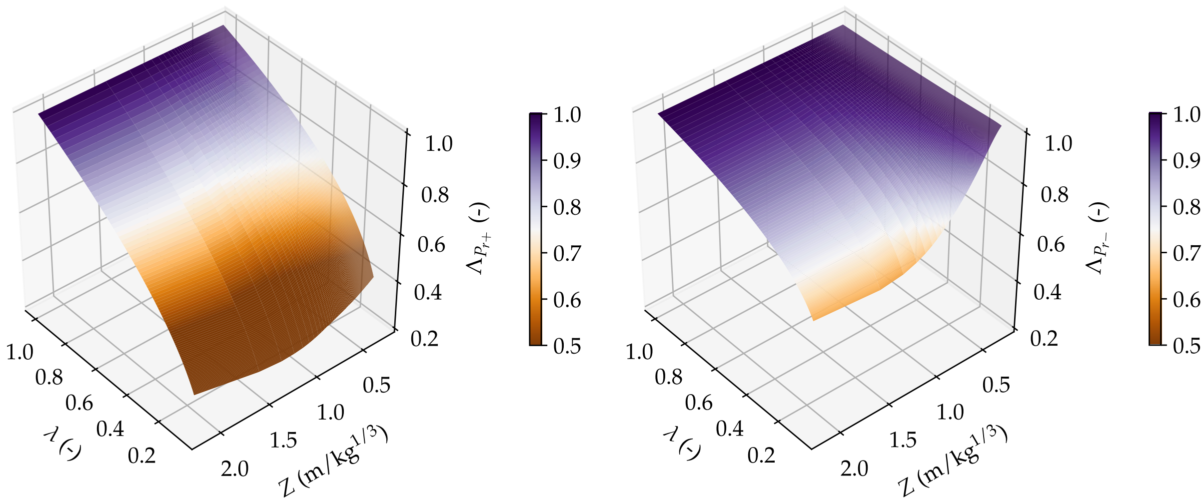
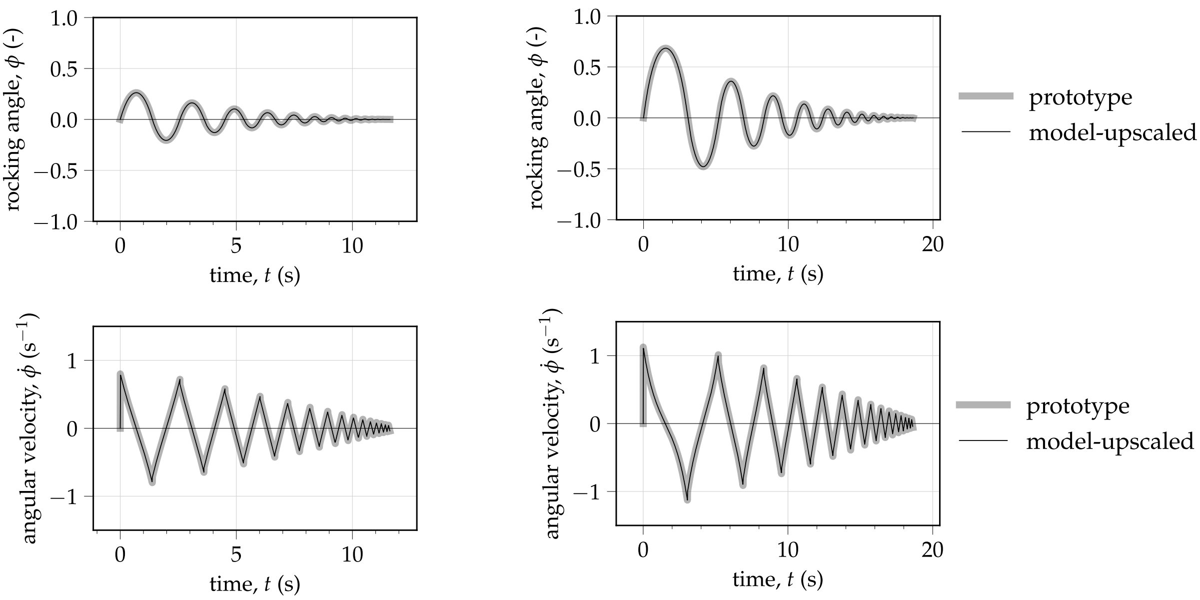


Figure 4: Scaling factor of the positive (left) and negative (right) overpressure peak, in function of the geometric scaling factor λ and the scaled distance Z.

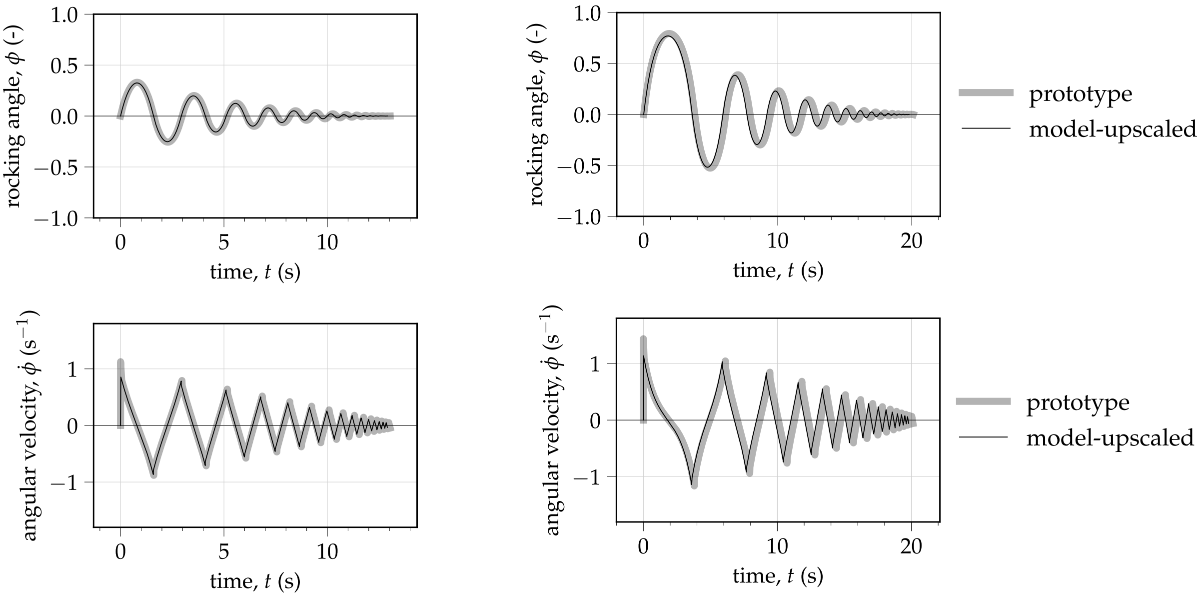
angle $\alpha = 15°$, density $\rho = 2000$ kg/m^3. The model is obtained by considering a geometric scaling $\lambda = 1/200$ and $\gamma = 1$.
Two explosive weights, located at $R = 2$ m, are considered: $W_1 = 50$ kg and $W_2 = 75$ kg, for CS-1, while $W_1 = 75$ kg and $W_2 = 100$ kg, for CS-2.

Figures 5 and 6 display the evolution of the normalized rocking angle and angular velocity for the prototype system and the upscaled model. The response of the systems coincide, validating the derived scaling laws also when the negative phase is accounted for (cf. [17]).
It is worth noticing that the negative phase plays a stabilizing role in rigid-body like mechanisms (cf. [**?**]), see Figure 7.



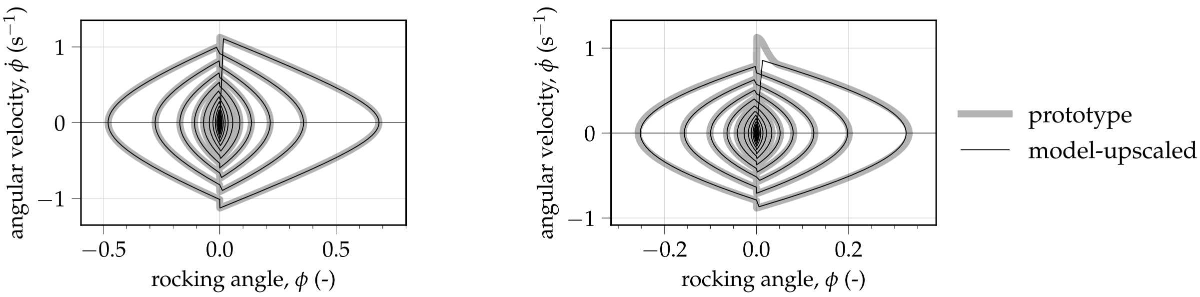
(a) W=50 kg (b) W=75 kg

Figure 5: Comparison between the prototype response and the model response ($\lambda = 1/200$) account for the positive phase (CS-1). The model is upscaled, i.e., all quantities are multiplied by the inverse of the scaling factor. Two explosive weights are considered (cf. prototype): (a) $W = 50$ and (b) $W = 75$ kg.



(a) W=75 kg (b) W=100 kg

Figure 6: Comparison between the prototype response and the model response ($\lambda = 1/200$) account for the positive phase (CS-2). The model is upscaled, i.e., all quantities are multiplied by the inverse of the scaling factor. Two explosive weights are considered (cf. prototype): (a) $W = 75$ and (b) $W = 100$ kg.



(a) CS-1, W=75 kg (b) CS-2, W=75 kg

Figure 7: Phase portrait of the prototype and the model ($\lambda = 1/200$) for an explosive weight $W = 75$ kg, accounting for (a) the solely positive phase and for (b) both positive and negative phases.

While the above motivating examples considered may be rather simple, we emphasize that the proposed scaling laws are general and can be applied to the case of non monolithic (blocky) structures under three-dimensional rigid-body motion. For more details, we refer to [17]. In parallel, relying on similar developments, scaling laws accounting also for the material response (elastic and inelastic) can be obtained, as detailed in [15].

4 Conclusions

Experiments of masonry structures under blast loads are rare in the available literature. Indeed, experimental testing of this kind of elements is particularly challenging due to the complex structural dynamic response of masonry. Furthermore, field testing shows several limitations related to cost, environmental hazards, safety risks, and repeatability.

Conversely, reduced-scale testing offers great advantages. Yet, scaling laws for both the blast loads and the specimens are mandatory to link the model response to the one of the prototype.

We aim at providing scaling laws for masonry structures subjected to explosions. Based on previous works [11, 22], we derived similarity laws for the rigid-body motion of monolithic and blocky-masonry structures, considering empirical models for the blast actions. In contrast with the well-known Hopkinson-Cranz scaling laws [12, 13], the proposed scaling laws allow to design experiments by reducing the blast intensity, which is compelling for safe experiments.

The proposed scaling laws were validated against numerical cases of monolithic prototypes and models, through three-dimensional Finite Element simulations.

It should be mentioned that this work is a first step towards the design of reduced-scale experiments, as shown in Figure 8, providing appropriate scaling laws which assure the similarity of both blast loading and structural dynamic response.

Figure 8: Reduced-scale experimental set-up relying on analogue blast sources for the validation of the proposed scaling laws.

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