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Reduced-scale Testing of Masonry Structures to Explosions

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Abstract **-** In recent decades, the number of historical and ancient structures exposed to blast loads has steadily increased, either due to accidental or deliberate explosions, such as the archaeological site of Palmyra in 2015 and Beirut explosion in 2020. It is important to protect such assets against blast loading. However, investigating how structures respond to explosions cannot rely solely on numerical and analytical tools. Experimental tests are necessary to enhance our current understanding and validate existing models. Large-scale experiments can only be conducted in specialized testing areas with restricted access, safety concerns, and limited repeatability. An alternative approach for studying the effects of blast loads on structures is to rely on reduced-scale experiments in laboratory conditions. Reduced-scale experiments offer a high level of repeatability, moderate cost, and reduced hazards associated with environmental safety. Presented here is a new design setup for studying masonry assets based on reduced-scale experiments for the rigid-body response of structures. Blast waves and loading are emulated by detonating wires triggered by high-voltage discharges from a capacitor. These experiments take place within a controlled laboratory environment, ensuring both repeatability and safety.

Keywords**:** Blast loads, Exploding wires, Fast-dynamics, Masonry, Scaling laws.

1. Introduction

History demonstrates that extreme loads, such as explosions, pose a significant threat to our cultural heritage. Additionally, explosions present a risk to our modern built environment, which should exhibit high resilience while minimizing the potential for human injury and loss. Therefore, there is the need to more effectively assess the threat of explosions intended to damage our structures. Moreover, there are numerical works in the literature that studies the fast dynamic response of structures under explosions cf. [1-2].

To gain a better understanding of the fast-dynamic behavior of masonry structures and identify the primary factors influencing their response to blast load, we design and present a novel reduced-scale experimental platform. Reduced-scale experiments offer a high degree of repeatability and enable testing under conditions that are difficult to replicate in full-scale experiments. However, appropriate scaling laws are essential to design the reduced-scale experiments and to assure similarity between the prototype (full scale structure) and the model (reduced scale structure). The concept of similarity involves creating the essential conditions for conducting reduced-scale experiments based on full-scale ones and predicting the structural response of the latter from the analysis of the model [3].

The explosive source and load are represented by surrogate, (aluminium) exploding wires. When a sufficiently large electric charge is discharged through a thin conductive wire, its temperature increases considerably. This rapid temperature increase causes the wire to undergo a phase transition, generating a shock wave that travels through the air and impinges the surrounding (i.e., the model). The system is composed of a capacitor, a switch and a wire (with length l_w, and diameter d). Moreover, by changing the properties of the wire, such as its length, diameter, and the materials used, it becomes possible to create various explosion loads.

In this paper, we present the main components of the proposed reduced-scale experimental platform (see Fig. 2), the robustness and high repeatability offered by exploding wires for mimicking real blast waves, as well as preliminary results on the dynamics response of blocky structures.

2. Methodology

2.1. Scaling law

Consider a masonry structure of arbitrary shape, composed of masonry units (blocks) that interact with one another through interfaces with a frictional coefficient μ, see [4]. The structure is subjected to a blast load and undergoes a rigid-body motion. We assume that deformations are negligible with respect to the rigid-body response. This hypothesis is realistic for masonry structures under low confinement, e.g., for columns and retaining walls or during rocking-like collapse of interior partitions. The consequences of the assumption are further discussed in [4]. Following [4], two scaling factors have to be considered:

- The geometric scale factor $\lambda = \tilde{l}/l$.
- The density scale factor $\gamma = \tilde{\rho}/\rho$.

where l, ρ are the length (m) and density (kg/m^3) in the prototype, respectively (the symbol ~ is used to describe the model parameters). It is also assumed that the model and the prototype share the same gravitational field and friction coefficient.

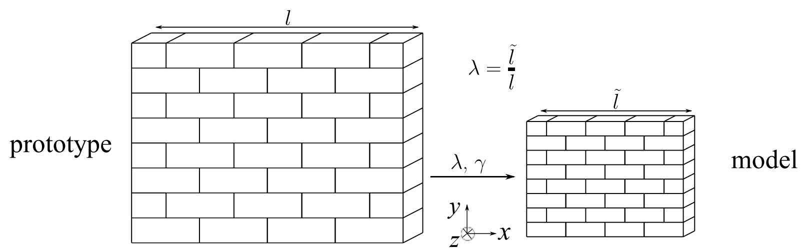

Fig. 1: Wall structure: prototype (left) and model (right), with geometric scaling λ and density scaling γ.

2.2. Experimental setup

The adopted experiment setup at the Research Laboratory of Civil Engineering and Mechanics (GeM) at Ecole Centrale de Nantes (ECN) is presented hereafter. A safety protocol is implemented to ensure the safe conduct of experiments for both scientists and equipment, in accordance with French standards [5].

We considered a room to conduct experiments, in order to achieve safer and more controlled environment, see Fig. 2. The room has dimensions of 4 m in length, 2.3 m in width, and 2.2 m in height. Inside the room the tested structure and the pressure sensors are positioned on an optical table at a distance D from the explosion source (exploding wire). In this setup, an optical table, specially designed to provide a rigid base for assembling high-precision systems, serves as a vibration-isolated platform. It includes pneumatic supports for isolating the table from laboratory noise. A high-speed camera is used to capture the response of the structure.

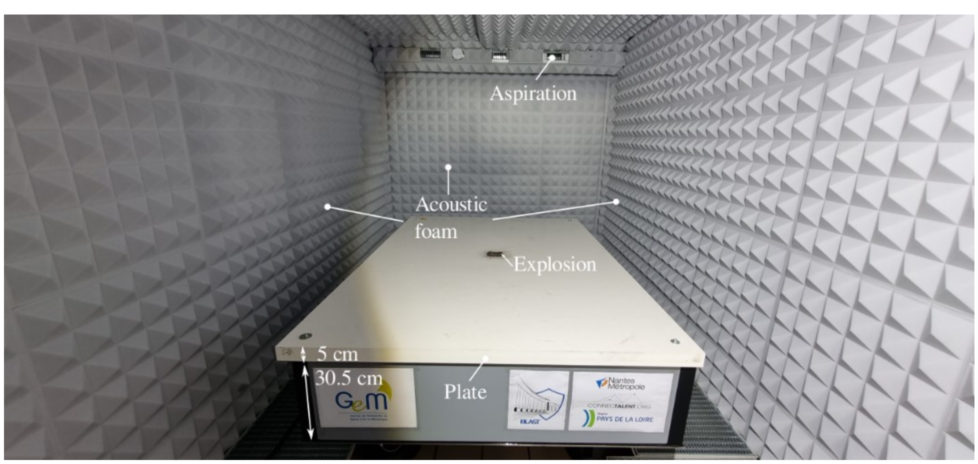

Fig. 2: Experimental platform in the GeM research laboratory

3. Results

Using the experimental setup described above, preliminary results are established to validate the designed setup. This involves studying the effects of stored energy inside the capacitor and assessing the repeatability of the experiments.

3.1. Pressure repeatability

We present the incident overpressure measured using a pencil probe (6233A0050) as a function of time history (see Fig. 3). The distance between the pencil probe and the explosion (D) is 30 cm. The discharge energy (E), wire length (l_w), and wire diameter (d) are 5000 J, 3.6 cm, and 0.6 mm, respectively. In order to ensure experiment repeatability, we conducted three measurements, and the results of these three experiments consistently demonstrate a high degree of repeatability.

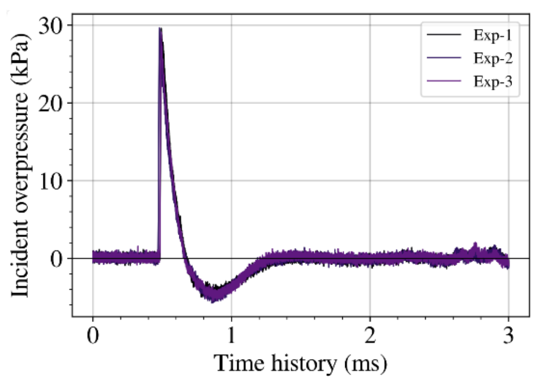

Fig. 3: Incident overpressure time history (E= 5000 J, D = 30 cm, l_w = 3.6 cm)

3.2. Effect of stored energy

The incident overpressure time histories for wire diameter 0.6 mm are presented across a range of stored energies E (from 500 J to 10000 J). It is worth noticing that as the stored energy value increases, the pressure value also rises (see Fig. 4).

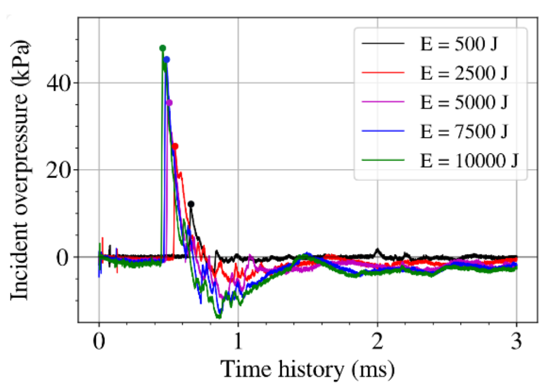

Fig. 4: Incident overpressure time history for different discharge energy (E= 500 ÷ 10000 J, D = 30 cm, l_w= 3.6 cm)

4. Conclusion

Experiments of masonry structures under blast loads are limited in the available literature [6-7]. Indeed, experimental testing of this kind of structures is particularly challenging due to the complex, 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.

We presented and developed a novel experimental setup for quantitatively studying the response of (blocky, masonry) structures subjected to explosions, offering high controllability and repeatability of the denotation of exploding wires and the resulting blast waves. It should be mentioned that this work is a first step towards studying the structures response at reduced-scale experiments. We carried out preliminary experiments for investigating the response of blocky (masonry) structures, Fig. 5, providing appropriate scaling laws which assure the similarity of both blast loading and structural dynamic response. Moreover, stored energy effect is studied where the pressure increases as the stored energy increase. Additionally, the experiments demonstrate high degree of repeatability.

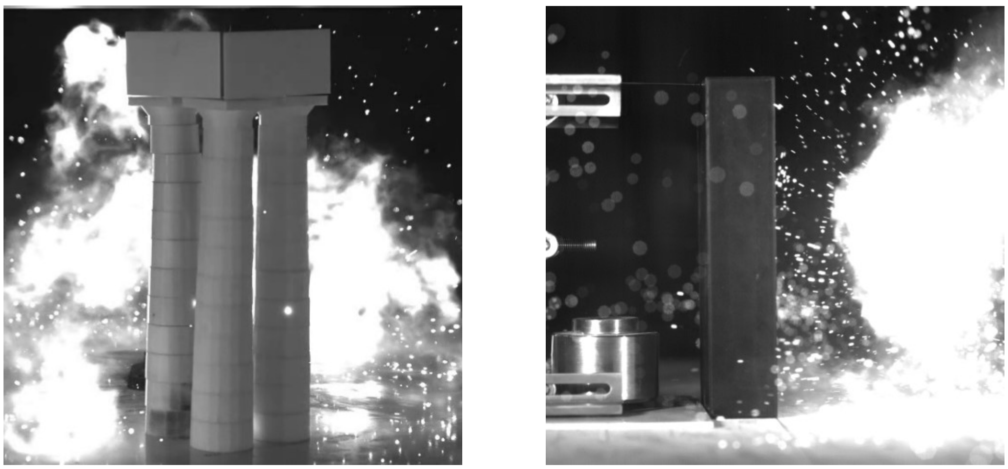

Fig. 5: Models (rocking structures) subjected to the fast-dynamic excitations arising from the denotation of an exploding wire.

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