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Dependence of the blast load penetrating into a structure on initial conditions and internal geometry

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ABSTRACT

An experimental study investigated the dependence of the blast load penetrating into a structure on initial conditions and internal geometry. The imposed pressure and impulse profiles at the structures' frontal façades were varied to generate initial conditions with very different pressures but similar peak impulses to which structural models of varying complexity were exposed. Results show that the peak impulse recorded at the models' back wall, the target wall, is independent of internal geometry. However, the pressure profiles at the target wall depend heavily on internal geometry in terms of both peak overpressure and wave diffraction pattern. Moreover, the pressure profile developed inside the structure depends strongly on the imposed impulse rather than the imposed pressure profile at the frontal façade. Repeated reflections inside the structure were found to effectively filter out high-frequency pressure changes inside the structure, leading to the possibility of rapid prediction tools for more complex structures. For the first time, a strong indication was found that a scalable time constant can be attributed to a complex structure that characterizes the load developing inside. Based on these findings, an application is presented in which forming a similar impulse is sufficient for correctly simulating large explosions in scaled-down models.

1. Introduction

The start of the 21st century marked an alarming rise in global terror attacks targeting civilians. The increasing number of incidents, combined with their expanding variety and sophistication, has alerted security authorities to the need for developing tools to respond to this unexpected reality. Urban centers have been prone to various threats including car bombs, suicide attacks, improvised explosive devices (IEDs), mortars, and more. The payloads used in such circumstances can range from several hundreds of grams up to several hundreds of kilograms of T.N.T.-equivalent charge. Most civilian structures cannot withstand explosive events, nor are they designed to do so. Addressing these vulnerabilities calls for new security protocols for structural design and for sensitive buildings to be retrofitted with countermeasures. In order to integrate a variety of security concerns, structural engineers must be able to resolve complex questions. For example, in order to evaluate the load penetrating a building in the event of an external explosion, should one consider the blast pressure or the positive impulse applied on the building's frontal façade? How do various internal designs affect the developing load in a specific room? What simplifying assumptions are appropriate in facilitating prompt decision-making in the face of imminent attacks?

Currently, tools are available to answer these difficult questions; however, they require considerable resources, rendering them impractical for wide applications. This study aims to understand the fundamental physics governing load development inside structures and to highlight the dominant parameters involved. The insights realized here are useful in developing more rapid prediction tools for assessing blast survivability inside structures.

Studies regarding shock and blast wave interaction with structures can be divided into two main groups. The first group usually deals with the physical mechanisms of shock-structure interaction, development of flow fields, and material response while the second group includes studies more focused on applications to structural design, load assessment, and survivability following an explosive event.

Limiting the discussion to studies concerning the gas dynamics associated with blast and shock impingement, one finds a large body of research concerning the propagation of shock waves through sets of geometrical obstacles. These obstacles include baffles [1–4], plates [5–9], porous materials [10–14], aqueous foams [15–17], granular media [18–20], and more. These studies are generally performed in a laboratory setup in which intricate shock

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diffraction and reflections can be recorded and very accurate pressure measurements can be performed [21]. These types of experiments constitute a foundation for new design methodologies, even though they are rarely tested outside of the laboratory.

The study of explosive events in urban scenarios in a more integrative manner can be limited owing to the complex or expensive experimental and numerical tools required. The most conclusive investigative method involves conducting full-scale experiments that yield "fail/pass" results, validating a design beyond a doubt [22–24]. These experiments are usually carried out in a specifically oriented experimental field, require meticulous planning, are expensive, and usually involve long preparations [25,26]. Furthermore, the destructive nature of such experiments makes the use of accurate, delicate diagnostics problematic. To address some of these challenges, numerical simulation has found its place in the design of protective structures over recent decades. The use of a numerical simulation allows not only estimation of the developed loads on structures subjected to explosion events but also estimation of the damage caused and their dynamic responses [23,25–32]. Numerical tools are also widely used in basic and parametric studies of shock wave–structure interactions [33,34]. While powerful, numerical simulations require validation and calibration using experimental data. In complex explosive scenarios, appreciable computational power is required to resolve the loads developed on structures and structural response. Additionally, these numerical simulations cannot entirely incorporate the complicated physics involved in the shock wave reflection process and the interaction of the reflected shocks with the induced fast turbulent flow. The numerical tools used to simulate explosive events are usually based on schemes that neglect viscosity, a parameter that has been proven to be substantial in shock wave-structure interactions [25,35–40].

Another widely accepted method for studying the loads developed in explosive events is by employing small-scale experiments [41–44]. A scaled-down model is subjected to an equivalently scaled explosion, thereby simulating the full-scale scenario. This method is particularly effective since the developing loads and the structural response of the structure act on distinctively different time scales. The structural response due to the dynamic load imposed by a shock wave impingement is much slower than the load application time. Simulating the structural response, however, requires consideration of structural weight and mechanical strength effects on the small-scale response, which might prove impossible. Such attempts have been recorded previously [45]. The disadvantage of using small-scale experiments is that unique problems absent from large-scale experiments are sometimes introduced [37]. These errors are difficult to predict, and the well-known Cranz–Hopkinson "cube root" scaling law [25], which is suitable for self-similar open-field explosions, does not apply directly to urban scenarios. Nevertheless, these challenges can be overcome by careful calibration and validation. Ultimately, small-scale experiments have a strong appeal to researchers and designers because they provide a low-cost, rapid prototyping technique that, under the right circumstances, is able to provide good assessment of the loads to be expected in real large-scale scenarios [36–40,43–50].

The exploding wire (EW) technique lacks most of the safety disadvantages involved with small explosive charges commonly used in small-scale experiments. In this method, a thin metal wire is connected to a charged high-capacity electrical capacitor. The stored energy in the capacitor is then discharged through the wire, causing the wire to undergo an extremely fast heating process that causes it to melt and evaporate virtually without any volume changes. The dense, hot, vaporized metal gas expands rapidly and forms a strong blast wave [36,46,51–54].

Surveying the substantial array of studies published on the subject, one finds a lack of tools to study developing loads inside a structure given an imposed load. While there is, as mentioned, an abundance of studies concerning the propagation of shock waves inside structures and concerning the loads imposed on structures, it is difficult to find studies directly linking the two. A considerable number of works were performed on this subject on a small scale at the Ernst Mach Institute (EMI) in the 1980s–1990s, but the results were not used to link the imposed conditions and the penetrating loads [55].

In this study, the exploding wire technique was implemented to investigate how the pressure and impulse imposed at the frontal façade of a structure together with the structure's internal geometry affect the developing load on the target wall inside the structure. In the next section, a description of the studied problem is presented. A presentation of the experimental setup, results, and discussion follow, entailing the governing physical mechanisms coupled with an example in which the implications of this study prove to be beneficial for simulating large explosions in the laboratory.

2. The investigated problem

This study aims to further the understanding of the physical mechanisms determining the pressure build-up inside a structure following the impingement of an explosion-generated blast wave. Fig. 1 broadly renders the important aspects of the studied problem. The study focuses on a typical single-story building exposed to a blast wave impinging on its frontal façade. The blast wave generates initial conditions on the frontal façade of the structure, namely pressure and impulse. Typically, following the initial impingement, a weaker blast wave enters the structure through openings in the frontal façade, propagates through the structure, and reaches the back wall. Throughout its propagation, the initial wave diffracts and reflects from the internal geometry, sidewalls, and back wall. The diffracted waves reverberate inside the structure, with some pressure exhausting via the building façade openings, until the reflections eventually subside and pressure returns to its atmospheric level. The main point of interest in this study is located at the center of the target wall as seen in Fig. 1.

Resolving the three-dimensional diffraction pattern inside the complex structure is difficult and resource-consuming. Furthermore, wave propagation inside the structure and the resulting flow field depend strongly on the internal geometry. Accurately resolving the internal flow field numerically for every change of initial conditions or internal geometry would require a new solution in each case.

Rather than studying detailed flow features and reflections, this study adopts a different approach to studying the dependence of pressure build-up on important parameters. We examine the scenario presented in Fig. 1 in terms of initial conditions, internal

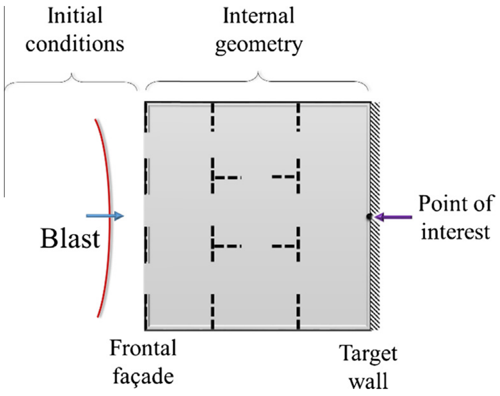

Fig. 1. A schematic description of the investigated problem.