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ABSTRACT

It is well known that strong blast waves are lethal for a living creature, while it is believed that weak blast waves are harmless. This might be the case when there is a head-on collision between an on-coming weak blast wave and the considered body; however, a completely different scenario takes place when the initially weak (safe) blast wave hits a body after multiple reflections from existing walls. Such cases take place when a weak blast wave, resulting from a sudden explosion, hits a residential complex.

In the conducted experiment a very simple model of a three level building is subjected to a weak blast wave. The evolved wave pattern inside the building rooms is recorded by a sequence of schlieren photos and the prevailing pressures are deduced from numerical simulations.

INTRODUCTION

While it is well known that strong blast wave are lethal for a living creature, it is commonly accepted that weak blast waves are harmless. While this might be the case when there is a direct impingement of the on-coming weak blast wave on a body, a completely different scenario takes place when the weak blast wave hits a body after multiple reflections from existing walls. Such a case can be found when a weak blast wave, resulting from a sudden explosion, hits a residential complex. Furthermore, explosion injuries can be caused by direct hit of a blast wave, and/or injury caused by flying debris resulting from the explosion, and/or injuries resulting from being dragged/pushed by the blast wave [1]. The present investigation focuses on potential injuries from collision with a multiple reflection of initially weak blast wave.

In the conducted experiments a very simple model of a three level building is subjected to an initial harmless blast wave. Attention is given to find where the most dangerous places inside the building are, places without having death risk, and where are the safest places for people to be. Information given in Table 1 reveals human response to overpressure; this information is used in defining a place as being safe or non-safe.

Initially a weak, planar shock wave propagates inside the shock tube. Upon reaching the tube exit-open-end it immerges into the open atmosphere as a blast wave. The investigated building model is placed in proximity to the shock tube exit as shown in Fig. 1. Supplementing the experimental investigation, numerical simulation of the generated flow field, caused by the blast wave interaction with the building model, is conducted. In urban life blast waves can be generated from a sudden explosion of gas lines placed underground, from a truck carrying explosive substances in a residential environment, and/or from a terrorist attack in the public domain.

Considering weak blast waves, all these examples have one thing in common, i.e., the fact that generally people are not informed of potential risks to their ears or lungs, not to mention life, if they stand in proximity to a wall or near a corner close to where a blast wave propagates. Subsequently it will be shown where are the dangerous places inside a residential building impacted by a weak blast wave.

From a fluid mechanics point of view, the present work deals with the problem of multiple shock/blast wave reflections. Studies concerning shock wave reflections from rigid boundaries can be found in the open literature; e. g. in Ben-Dor [2], Igra *et al.* [3] and more recently, in Volume 2 of the Handbook of Shock Waves by Ben-Dor, Igra and Elperin [4].

Overpressure (kPa)	**Direct effects on human**
<3	?
3 - 5	Irreversible effects
6	People projected on the ground
5 - 7	Danger for eardrums
12 (+/- 5)	Destruction of 1% of eardrums
30	Destruction of 99% of eardrums
40	Danger for lungs
100 – 500 (+/- 20)	Destruction of 50% of lungs
150	1% death
350	99% death

Table 1: Direct effects of blast wave generated overpressure on humans (from [1], [5] and [6]). Direct effect means without considering secondary effects such as flying glass and/or brick debris.

EXPERIMENTAL SET-UP

The present experiments were conducted using an open end shock tube and thereby generating a very weak blast wave. The generated blast waves were sufficiently weak to ensure that they pose no life endangerment to people.

The building model was constructed from Plexiglas in order to allow high speed shadowgraph and schlieren visualizations; the facility used is shown in Fig. 1.

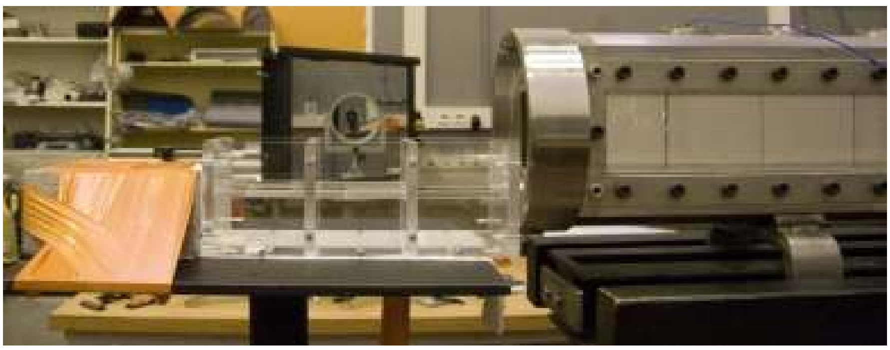
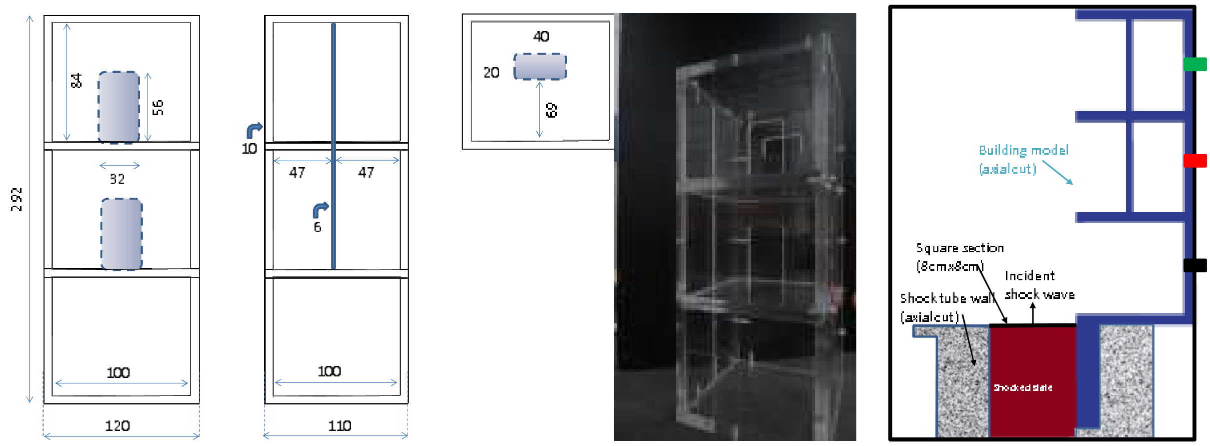


Figure 1: View of the Plexiglas building model and its location close to the shock tube exit.

Detailed description of this shock tube can be found in [7]. The building model consists of three cubic boxes simulating three levels of one-room-apartments. All apartments had no frontal wall and no glass windows; this was done for avoiding broken glass or flying brick segments. The first floor consists of an empty box. The second was an identical box but it had a dividing wall and an open door in its center. The third level had the same dividing wall to which an opened window was added on the box back wall. Description of the Plexiglas building is given in Fig. 2.



(a) (b) (c)

Figure 2: Description and dimensions (in mm) of the tested building model. (a) Schematic drawing of the model; (b) photograph of the Plexiglas building model, and (c) its location (in cm) relative to the shock tube exit.

NUMERICAL SIMULATION

All computations were performed for air; due to the relatively low Mach number of the incident shock wave it can be treated as a perfect gas. The conservation equations for ideal compressible fluids (the Euler equations), indicating conservation of mass, momentum and energy were solved**.** Details regarding the used numerical solution can be found in.

RESULTS AND DISCUSSION

A sequence of schlieren photos showing blast wave interaction with the building model is shown in Fig. 3. At t=33 μs the blast wave just started its interaction with the building model. With progressing time, the blast wave penetrated into the building and at t=200 μs it is clearly seen inside the first floor, approaching the room ceiling. From the color intensity of the blast wave it is apparent that the part which penetrated into the building first floor is weaker than the part propagating in the open atmosphere. At t=300 μs the following waves are visible: the progressing main blast wave starts penetrating into the building second floor while the part penetrated into the first floor is seen now reflected from the first floor ceiling and the blast segment that propagated earlier toward the wall separating between the two rooms of the first floor has now penetrated into the second room. As noticed earlier, the strongest part of the blast wave, at t=300 μs, is the one propagating through the open atmosphere. However, the color intensity of the regular reflection of the blast wave from the ceiling of the first floor second room increases, indicating a strengthening blast wave at this location; see in Fig. 3 at t=300 and 333 μs. Further confirmation of the local pressure increase prevailing around the blast reflection in the considered time is evident in Fig. 4 where computed over-pressure is shown. A significant pressure increase is noticed at t=433 and 466 μs in the corner area between the ceiling of the first floor and the room wall; an overpressure, Δp of 10 kPa, is seen in Fig. 4. It is apparent from Fig. 3 that the cause for this overpressure increase near the corner is the blast reflection from the room ceiling and wall. This is the strongest overpressure inside the building model witnessed during the experiment. As is evident from Table 1 this overpressure is not fatal, however it can cause damage to human eardrums. A slightly stronger blast wave could result in irreversible damage, i.e., fatal results. At later times, $t \geq 600$ μs the reflected blast wave from the corner weakens while it propagates towards the room floor; see Fig. 4 at t = 600 and 666 µs.

With increasing time, 800 µs ≤ t ≤ 1033 µs multiple wave reflection between the room walls, floor and ceiling takes place as is evident in Fig. 3. From the color intensity of these waves as shown in the schlieren photos (Fig. 3), it is clear that these reflecting waves are much weaker than those seen outside the building model.

It is of interest to note from Fig. 4 that at later times, at 400 < t < 500 µs the overpressure experienced by those exposed to the travelling blast wave in the open atmosphere is smaller than that prevailing inside the building near the room corners.

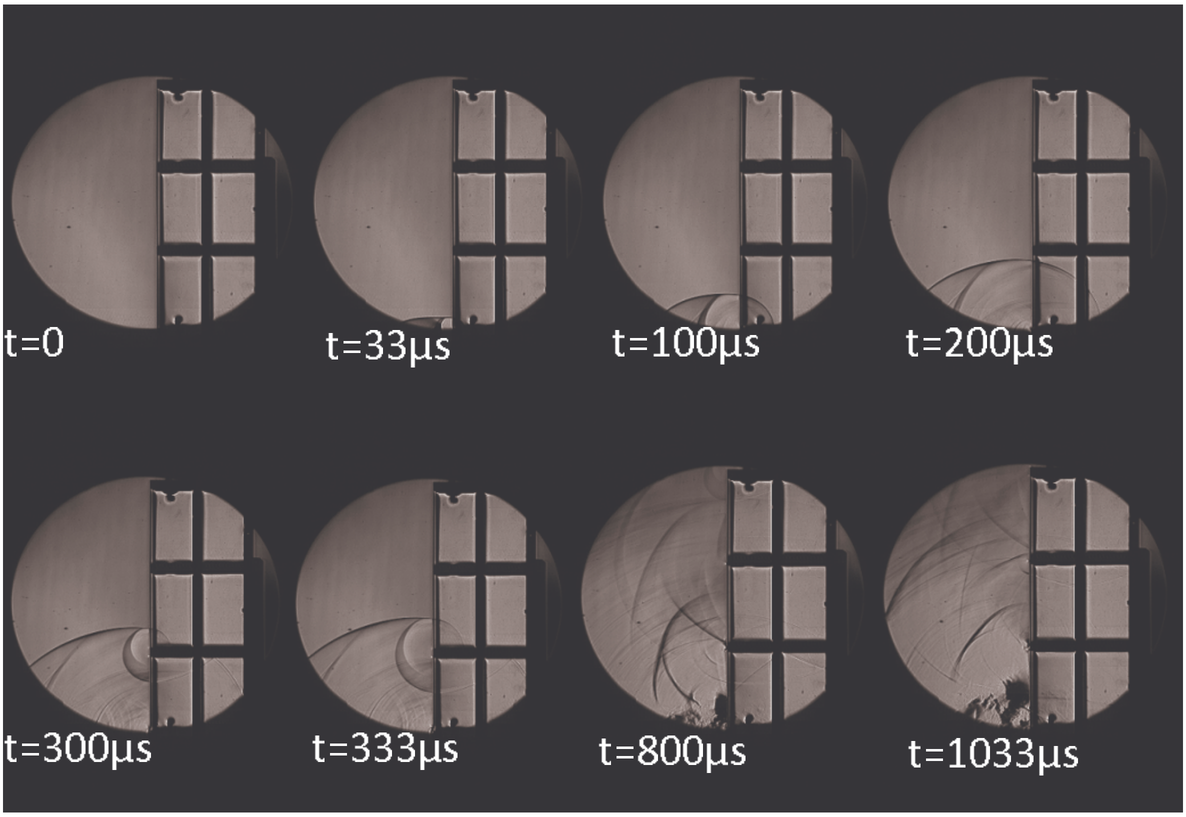


Figure 3: Sequences of schlieren photos showing the evolution and multiple reflections of the blast wave inside the Plexiglas building. The incident shock wave Mach number inside the shock tube is 1.17.

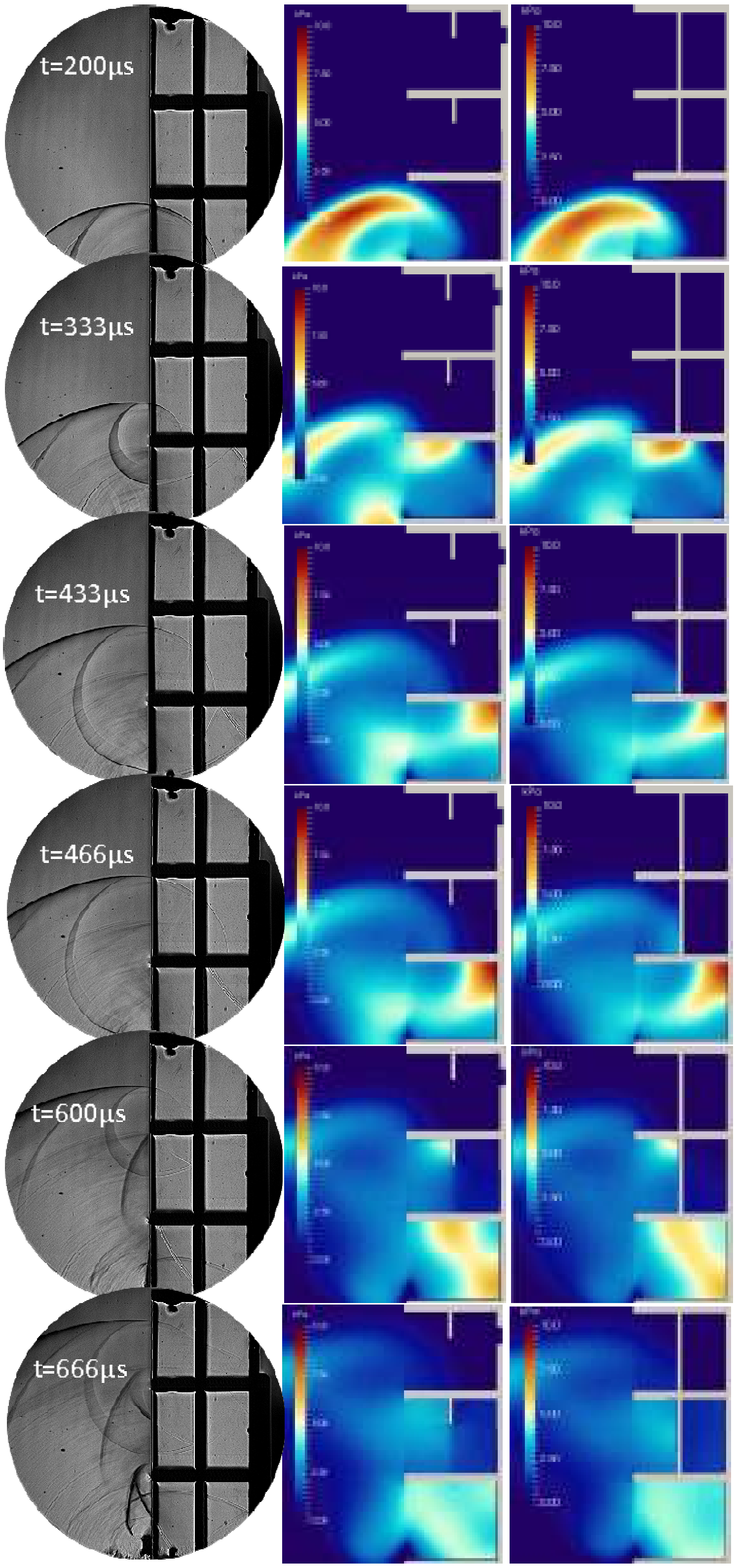


Figure 4. Numerical simulations showing the overpressure encountered within the three floor building model for an incident shock wave, inside the shock tube, having a Mach number of 1.17. Experimental results are shown on the left and appropriate simulations appear on the right.

CONCLUSIONS

It is clear from the present investigation that blast wave damages are higher for people standing near a wall, or even higher when near a corner. Furthermore, at a late time (t > 400 µs) the overpressure behind reflected blast wave from a room corner is significantly higher than that experienced in an open space. This is due to the pressure increase behind the reflected blast wave from the corner between the room ceiling and walls. The present work might be useful in designing building structures complying with safety standards, as well as for people who are not familiar with explosion generated blast waves.

Finally, the present work could also be helpful to validate numerical codes able to predict such effects without taking into account broken construction materials and broken glasses.

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