Proceedings Paper:

Farrimond, D.G., Rigby, S. orcid.org/0000-0001-6844-3797, Baldam, C. et al. (3 more authors) (2025) MicroBlast: Experimental assessment of charge shape effects on blast loading in urban environments. In: Proceedings of the 27th International Symposium on Military Aspects of Blast and Shock (MABS27). 27th International Symposium on Military Aspects of Blast and Shock (MABS27), 05-10 Oct 2025, Colmar, France. Military Aspects of Blast and Shock (MABS).

MICROBLAST: EXPERIMENTAL ASSESSMENT OF CHARGE SHAPE EFFECTS ON BLAST LOADING IN URBAN ENVIRONMENTS

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Key words: charge shape, *MicroBlast*, small-scale experiments, urban blast

ABSTRACT

Rigorous and accurate quantification of blast loading in urban environments is a topic of increasing importance. This work discusses the ongoing development of a new experimental facility, MicroBlast, to study urban blasts at small-scale; typically 1-10g PE10 explosives. In this paper in particular, the effects of charge shape on the form and magnitude of loading within a complex array of reduced-scale building forms are investigated. Experiments are performed using three different charge shapes (hemispheres, cubes, and rotated cubes) and three different environments (free-air and two urban layouts: regular and irregular). A significant finding from this work is that whilst charge shape has a significant influence on free-field blast parameters, loading in an urban environment is largely dependent on the urban layout only, and charge shape effects are secondary.

INTRODUCTION

The need to understand and rapidly predict the effects of urban blast events could scarcely be more timely. For the first time in a generation, industrial-scale warfare is taking place in both Europe and further afield, with targeted attacks aimed at degrading civilian infrastructure and systems. Current methods of predicting these effects are generally deterministic, and either slow and computationally expensive, or too simple to be of much use. There is currently a lack of rigorous experimental data of blast in complex environments, and therefore high-fidelity modelling approaches have not yet been validated in situations where complex, cumulative, and nonlinear blast wave interactions occur. Quantifying these interactions, their significance and dependence on the urban environment, and ultimately their *predictability*, is a critical first step in developing a broader and more holistic understanding of blast wave propagation with a view to creating a new suite of fast-running engineering models.

This paper presents the results from a detailed experimental study of small-scale explosions in urban environments, with a particular focus on the effects of charge shape on both free-field and urban blast loading parameters. An accompanying numerical modelling study is presented in Ref [1] that focusses on the influence of obstacle orientation.

LITERATURE REVIEW

Rose & Smith [2] performed some of the earliest experimental work on urban blast, where it was found that street widths less than 4.8m/kg$^{1/3}$ would reflect and confine the blast wave significantly enough to amplify pressure in what is widely known as the *urban canyon effect*. This has since been confirmed numerical, e.g. by Codina et al. [3].

Fouchier et al. [4] investigated the blast pressure arising from explosions at several typical road junction layouts, where the main finding was that direct line-of-sight from a monitoring point to the explosion was a fundamental parameter in governing loading. By extension, points where the blast had to travel an elongated path were seen to exhibit reduced values of pressure and impulse. This aligns with the findings in Smith et al. [5], where the authors performed experimental and numerical modelling to study the effects of areal density (defined as the percentage of the footprint area consisting of obstacles) using random, more complex arrays of buildings that featured direct and non-direct paths from the explosion origin to measurement locations. Whilst areal density was shown to be important, it was found that loading differed substantially depending on the locations of obstacles relative to the charge given a consistent areal density, i.e. the route the blast was forced to take from explosion to monitoring point, and how much this deviated from the free-field, straight line equivalent.

Typically, studies on urban blast will simplify the structures as regular parallelepipeds, however there is some evidence to suggest that a more true-to-life representation of building frontages may slightly alter the scattering and coalescence of shock waves [6]. In situations of high nonlinearity (i.e. in the near-field), this may result in knock-on effects at later times, i.e. a slightly weaker shock interaction *here* may lead to a later reflection *there*, which may cause two subsequent wavefronts to miss each other entirely.

Similarly, it is well-known that charge shape has a significant influence on the initial shape of the expanding fireball, with the introduction of bridging waves between two wavefronts – those emanating from different faces and thereby travelling in different directions (i.e. from different faces of a cube/cuboid) – leading to substantial differences in loading form and magnitude, and areas of enhanced variability due to the highly sensitive nature of wavefronts combining [7]. Charge shape effects have been seen to persist well into the far-field [8–10], however exactly how these differences manifest in urban blast, especially given the higher propensity of nonlinear interactions in these settings, is as-yet unknown [11]. There is a clear need, therefore, to better study the effects of charge shape on urban blast loading.

METHODOLOGY

A total of 35 small-scale explosive trials were performed at the University of Sheffield Blast & Impact Laboratory using PE10 charges (nominally 86% PETN with 14% plasticiser/taggant). Testing utilised three different charge shapes – hemispheres, cubes, and cubes rotated by 45° about the vertical axis – and three different layouts were tested:

1. **Free-field** (no obstacles): this allows the loading measured in the obstructed layouts (2 and 3) to be compared against a reliable benchmark (already established in [12]), as well as isolating differences caused by charge shape
2. **“Regular”** domain: reduced scale concrete breeze blocks (98×62×40mm, stacked five bricks high and taped together to total 200mm in height) were arranged in a regular 5×5 grid (with diagonally opposite obstacles removed to house the charge and reflecting gauge block respectively), with equal centre-to-centre spacings. See Figure 1(a)

3. **"Irregular"** domain: as above, but with each obstacle rotated about its vertical axis by a random angle. Note that although the rotation was randomly generated in advance, the arrangement was then made consistent for all tests within this domain. See Figure 1(b).

Three repeat tests were planned as a minimum for each combination of charge shape and layout; 27 in total, plus two commissioning tests using 3g and 7.5g PE10, and six additional tests to account for gauge drop-out and to enhance data redundancy.

The charges were mounted onto a blast table made of 2×6mm-thick MDF sheets, 1.18×1.18m in plan, formed of four quadrants. The sheets were glued together and held rigidly in place during testing. The top MDF layer was laser cut through its entire thickness to house:

- A nominally rigid reflecting gauge block, diagonally opposite the charge, in which three pressure gauges were surface-mounted. See Figure 1(c).
- A thin, single-use steel plate (100×100mm plan) on which the explosives were sat to prevent repeat damage to the test board. A small hole was pre-drilled into the plates to allow the detonator to be inserted from below, which was sat flush with the bottom-centre of the explosive in all cases. See Figure 1(d).
- Mounting boxes (203×203mm plan) for ground-mounted incident gauges, located in-line with the charge at opposite ends. Two gauges were located at each station. See Figure 1(a) and (b).
- All obstacles. The laser cuttings formed a small recess into which the obstacles could be accurately placed for each test.

Kulite piezo-resistive pressure gauges were used in each test. Data were recorded using a digital oscilloscope and TiePie software with a typical sampling rate of 195kHz at 16-bit resolution. The recording was triggered automatically using an 'out window' signal trigger on a bespoke break-wire signal. Pressure was measured at 10 distinct gauge locations, as shown schematically in Figure 1 and detailed in Table 1.

Table 1: Pressure gauge locations and designation

Gauge no.	Designation	Stand-off (mm)	Height (mm)	Scaled distance (m/kg$^{1/3}$)
1	Reflected	967	0	4.11
2	Reflected	967	77	4.13
3	Reflected	967	132	4.15
4	Incident	858	0	3.65
5	Incident	931	0	3.96
6	Incident	858	0	3.65
7	Incident	931	0	3.96
8	Incident	421	0	1.79
9	Incident	349	0	1.48
10	Incident	421	0	1.79

Note that scaled distance is calculated with an equivalent TNT mass of 13g: 12.2g from the explosive assuming a TNT equivalence of 1.22 [13] and 0.8g from the detonator. Values of $1.48 \leq Z \leq 4.17$ were specifically chosen to target the near-to-mid-field range, although near-field gauges (G9–10) are used more so for validation of subsequent numerical modelling studies reported in [1] than they are herein. The reflecting gauge block was 158mm high, 163mm wide, and 124mm deep, with G1–3 located 158, 82, and 27mm from the top edge respectively.

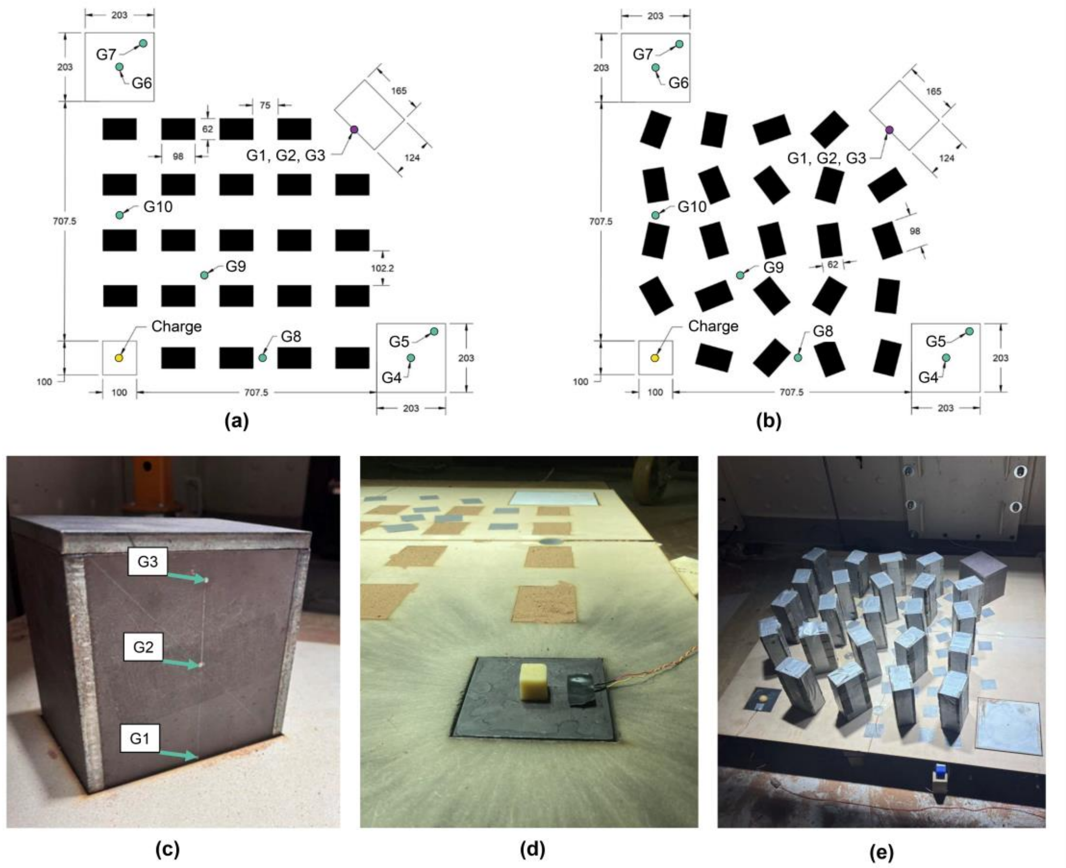

Figure 1: Details of the experimental work: (a) schematic of the “regular” array; (b) schematic of the “irregular” array; (c) photograph of the reflected gauge block; (d) photograph of a cube charge in a free-field environment – the plate housing gauges 4 and 5 is visible at the top of the image; (e) photograph of an “irregular” domain test set-up – the charge is visible bottom-left.

RESULTS

Free-field results for G3 (reflected: Z=4.15m/kg$^{1/3}$) and G5 (incident: Z=3.96m/kg$^{1/3}$) are shown in Figure 2. At this point it is worth clarifying that for the cube tests, all gauges are orientated with the flat face of the charge, *except for* G1–3 and 9. Conversely, for the rotated cube, *only* gauges G1–3 and 9 are orientated with the flat face. Pressure histories emanating from the corner of a cube/cuboid charge have been shown to be higher than those from the flat faces [14], and this is borne out in the data presented herein also: the loading recorded at G3 is highest for the cube (corner-on), whereas the loading recorded at G5 is highest for the rotated cube (but which is also corner-on to this gauge).

Two significant findings arise from the free-field tests. First, the test data is, in general, highly consistent. Each of the subplots feature three tests overlain (with the exception of the cube test at G5, which shows only two tests), and the pressure and impulse traces form a close grouping for each charge type. Second, as alluded to previously, charge shape has a significant effect on the mid-range free-field blast parameters.

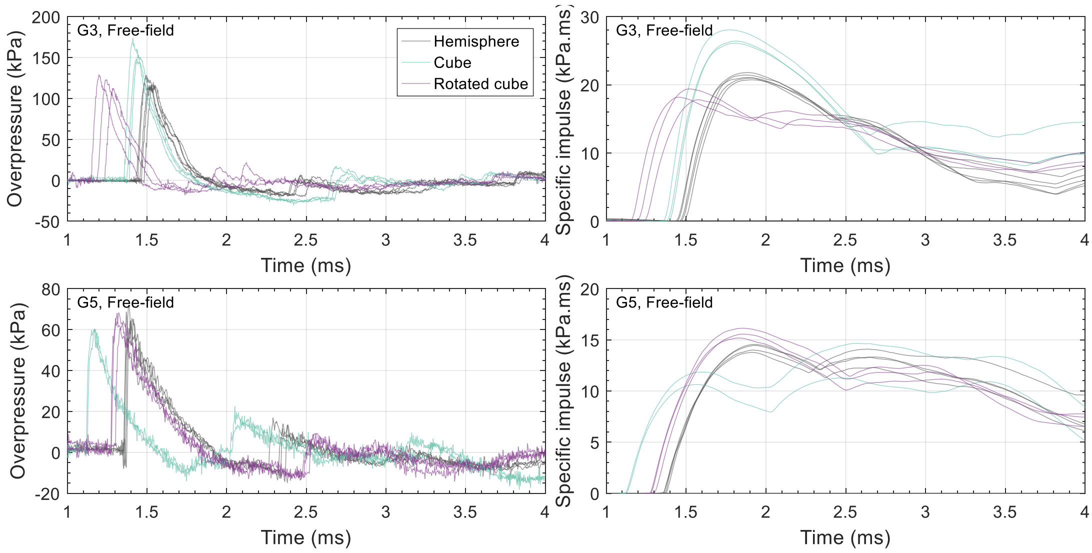

Figure 2: Pressure and impulse histories from G3 and G5 in free air.

Figure 3 shows pressure and impulse histories in the regular urban environment, for G3 (reflected: Z=4.15m/kg$^{1/3}$), G5 (incident: Z=3.96m/kg$^{1/3}$), and G9 (incident: Z=1.48m/kg$^{1/3}$, with only one trace being available for each charge shape for this gauge).

What is immediately apparent is that any variations caused by charge shape have all-but disappeared when comparing Figure 2 to Figure 3, i.e. when considering the pressure and impulse values in an obstructed, as opposed to free-air environment. At the reflected gauge (G3) in the regular obstructed domain, hemispherical charge peak pressure is 115–130kPa, the cube charge peak pressure is 150–175kPa (corner-on to the gauge), and the rotated cube charge peak pressure is 110–130kPa. Specific impulses range from 21–22kPa.ms (hemispheres), 26–28kPa.ms (cubes) and 18–19kPa.ms (rotated cubes), or typically +/-25% variation from the baseline hemispherical case. Conversely, the traces at G3 in the regular domain (Figure 3) all exhibit remarkably similar traces, to the extent that peak pressures and impulses no longer form distinct groupings by charge type. This is in contrast to the results in Figure 2, which do show clear groupings by charge type.

Whilst the traces at G3 resemble the well-known Friedlander exponential blast pulse, albeit with considerably more low-level pressure transients apparent in the data, which gives the traces an appearance of extra “fuzziness” compared to the free-air traces. Those at G5 exhibit much more complexity, with distinct multiple peaks in the traces. As such, peak pressures and specific impulse histories exhibit noticeably higher variability in the regular obstructed environment compared to the free-field tests. However, all tests appear to sit equally within this banding, and again there are no discernible effects of charge shape.

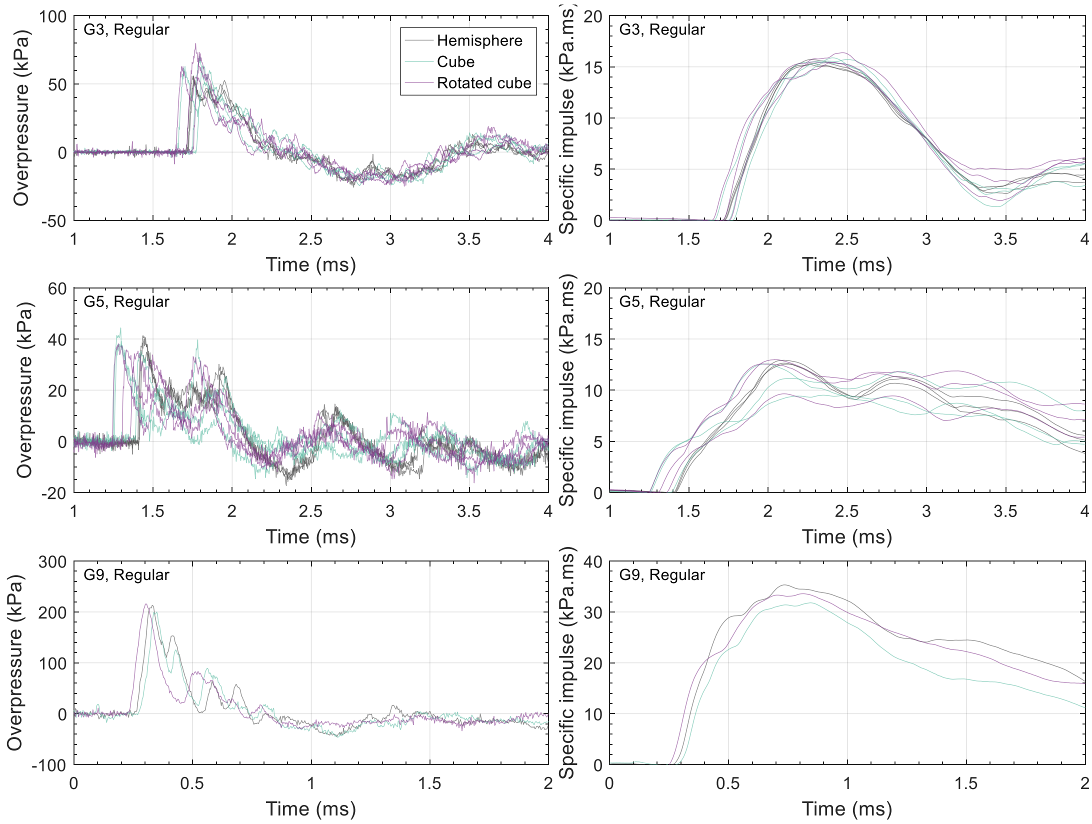

Figure 3: Pressure and impulse histories from G3, G5 and G9 in the regular layout.

The fact that charge shape, whilst clearly significant in free-field testing, appears to be second-order in urban blast, is a finding as surprising as it is significant. This clearly points to the *presence* of the urban layout dominating loading characteristics. Next, the influence of the *form* of the urban layout is considered.

Figure 4 shows pressure and impulse histories for G3 (reflected: Z=4.15m/kg$^{1/3}$) and G5 (incident: Z=3.96m/kg$^{1/3}$) for tests in the irregular array. Again, there is no clear influence of charge shape on display.

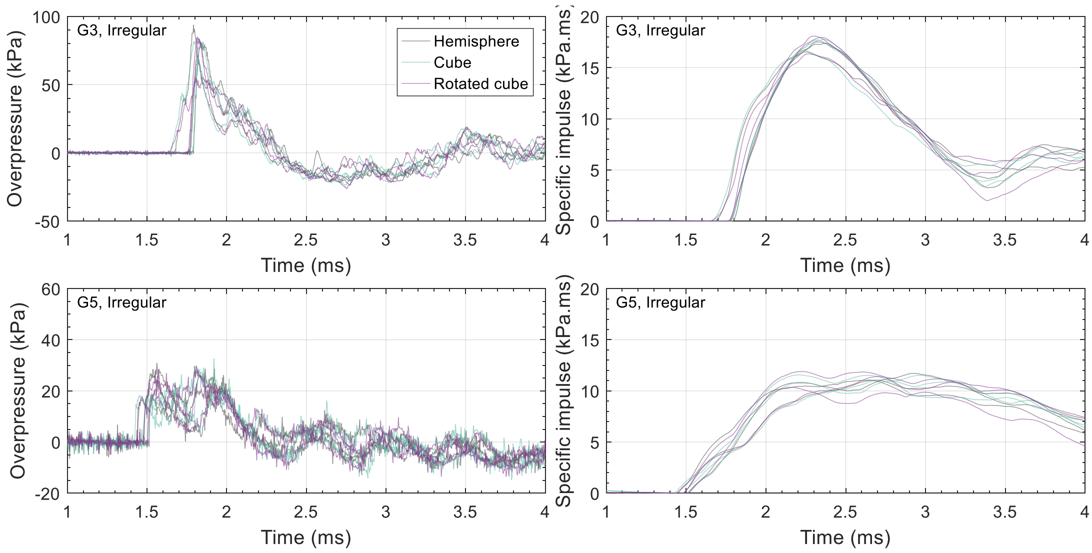

Figure 4: Pressure and impulse histories from G3 and G5 in the irregular layout.

DISCUSSION

Whilst differences between regular/irregular domains are not as stark as those between regular/free-air discussed previously, it is quite clear that loading at G3 is *enhanced* in the irregular array, whereas loading at G5 is *diminished*. This is due to the extended travel path aspects discussed in the literature review: a blast wave which travels a lengthier path will experience an overall reduction in pressure and impulse because of it. In the regular array, the line from charge to G3 is relatively obstructed, whereas in the irregular array this line is somewhat less obstructed and therefore the travel path is considerably shorter. Hence, the pressure increases at G3 in the irregular domain relative to the regular domain. Conversely, the pathway from charge to G5 is relatively simple in the regular case, and somewhat more obstructed in the irregular case, and a reversal is seen: pressure and impulse is *higher* at G5 in the irregular domain relative to the regular one.

It is clear, therefore, that some measure of the "obstructedness" of an urban environment may be used to quantify the resulting blast load, in the same way that areal density has been used previously. To reiterate, the main finding from this work, however, is that despite its clear significance in free-air blast loading, charge shape has a much lesser significance in urban blast.

Figure 5 shows a compilation of normalised peak pressure and peak specific impulse, grouped by gauge type: mid-field reflected (G1–3) and incident (G4–7). Values from each group are divided by the mean value (peak pressure or peak specific impulse) for the free-field, hemisphere case. The height of each bar represents the average normalised value for each group, and the whiskers represent the maximum and minimum values. Groups are typically formed of nine or twelve distinct recordings (three tests, three or four gauges per test). Small differences in scaled distance and angle of incidence (for the reflected gauges) were deemed negligible at this stage, as were any differences in specific impulse at the reflected gauge blocks due to progressive clearing from the top face.

This compilation shows clearly the differing influence of charge shape depending on the environment, most strongly indicated in the pressure and impulse at the reflected gauges. Here, whilst the free-field loadings can be quite clearly ordered in terms of descending magnitude: cube (corner on), hemisphere, rotated cube (face on), this order effectively vanishes in the regular and irregular domains, and the pressure and impulse values are, also noting the error bars, relatively consistent and constant across the different charge shapes.

As mentioned previously, the obstructed values are considerably lower than the free-field values, by as low as 45%, due to the cumulative effects of shielding. Confirming that earlier observations are consistent across the entire dataset, at G3 the environments ordered in terms of descending magnitude are free-field, irregular, regular (on account of the opening up of the pathway diagonally through the domain), whereas at G5 the order is free-field, regular, irregular, on account of the relative closing off/elongation of the horizontal pathway to G5 in the irregular domain.

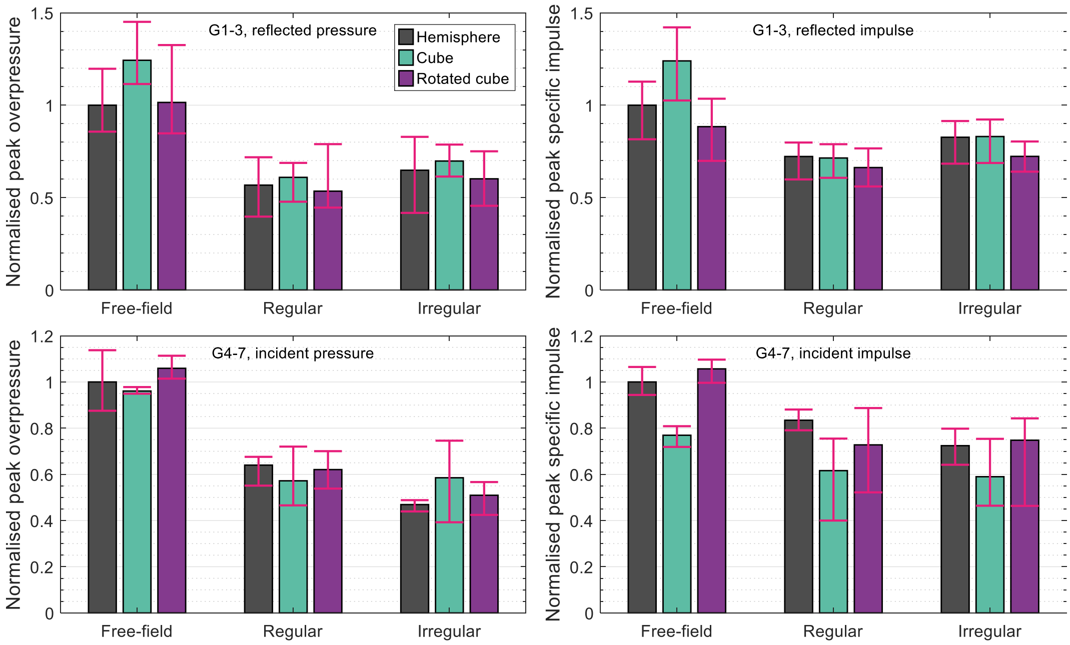

Figure 5: Compiled normalised peak pressure and peak specific impulse for reflected (G1–3) and incident (G4–7) pressure gauges. Values normalised against mean of hemispherical free-air parameter. Whiskers show maximum and minimum values of pressure or impulse across an entire test grouping.

SUMMARY AND OUTLOOK

Urban blast is a topic of increasing importance globally. Whilst broad behaviours relating to the presence and areal density of confining obstacles are generally well understood, there is still: (i) a lack of definitive, robust, and well-controlled experimental data on urban blast, and (ii) a lack of understanding of how complex nonlinear interactions are influenced by the form/order of the internal environment, and if non-spherical blast waves behave significantly differently in these environments.

A total of 35 tests were performed at the University of Sheffield Blast and Impact Laboratory, using PE10 formed into either hemispheres or cubes in two orientations (flat faces aligned with the obstacle grid, or rotated 45°). Three layouts were considered: free-air, a regular domain of obstacles, or an irregular domain where each obstacle was rotated by a random amount.

The results show that although charge shape has a significant effect on free-air blast parameters, its influence on urban blast is secondary, with mid-field pressure traces appearing near-identical regardless of charge shape. Here, the form of the urban environment dominates, and generally how obstructed or clear a pathway is from the charge to a point of interest, i.e. how elongated the blast propagation is, appears to be a significant contributor to attenuating blast pressures and impulses through shielding.

ACKNOWLEDGEMENTS

Experimental work was funded by the Engineering and Physical Sciences Research Council (EPSRC) as part of the *MicroBlast* project, EP/X029018/1. S Rigby gratefully acknowledges financial support from the Royal Academy of Engineering under the *Industrial Fellowships Round 17* programme.

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