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MICROBLAST: THE INFLUENCE OF OBSTACLE ORIENTATION ON THE VARIABILITY OF BLAST LOADING IN URBAN ENVIRONMENTS

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ABSTRACT

Explosions in urban environments, whether deliberate or accidental, are a significant threat to the modern world. The presence of obstacles and reflecting surfaces results in the coalescence of multiple blast wave fronts, leading to highly complex loading profiles that differ significantly from those in free air. Currently, predicting the loads in these domains requires numerical modelling tools that cannot rapidly evaluate the risk posed to a given environment in a probabilistic manner. To achieve this, new methods will need to be developed with an understanding of the most important parameters that dictate loading throughout an urban space. Previous studies have worked towards this goal by exploring the influence of various global geometric parameters including areal density, street width, and building height. However, the role of local obstacle orientation is yet to be explored. By simulating 50 unique layouts, with an experimentally validated solver, that maintain a consistent areal density and obstacle spacing, it is shown that the peak overpressure is largely dictated by two factors: the shortest path of the blast wave to the point of interest, and the orientation/proximity of the reflecting surfaces in the immediate surroundings. This differs from the peak specific impulse that is instead likely to be controlled by global parameters, possibly including the areal density and an approximate travel distance from the charge that represents the flow of the energy from the charge.

INTRODUCTION

The propagation of blast waves in free-field environments is generally well understood. Decades of research has produced a variety of semi-empirical tools and, more recently, Machine Learning (ML) and non-parametric models capable of accurately representing blast effects in these simplified scenarios (e.g. [1, 2]). However, when obstacles are introduced to a domain the free field case no longer applies, and the prevalence of multiple shock interactions increases the complexity of loading throughout the domain. Clearly, being able to predict blast loading in this case is critical when considering urban blasts.

At present, if the complexity of the domain remains limited, fast running tools exist for generating peak parameter predictions in obstructed environments, however they often lack an understanding of the underlying physics (e.g. [3]). Alternative approaches that can leverage such an understanding also exist, such as [4] which isolates shielding and fully describes its presence in the wake of a single, curved obstacle, yet scaling this intelligent methodology to account for complex urban domains is likely to require considerable further study. Increased complexity, and city scale studies therefore require numerical solvers, but in situations when run times or hardware restrictions prohibit their use, e.g., probabilistic methods for risk assessment [5], and iterative inverse blast characterisation [6], there remains no practical alternative.

Studies have focussed on various urban blast scenarios with the aim of understanding the importance of a range of parameters or global properties that could be used to assist in producing rapid predictions. For example, [7] evaluates the influence of areal density on channelling and shielding, [8] explores the influence of adjacent buildings on the loading experienced by a building of interest, providing an approach for developing enhancement factors that can be used to modify free air predictions, and [9] found that a confined street corridor amplified pressure and impulse at the corridor end by up to 4–5 times above free-field conditions, especially at smaller scaled distances.

While global geometric parameters such as areal density, street width, and building height are known to influence wave behaviour, the role of local obstacle orientation is yet to be explored. This study therefore aims to understand the extent to which orientation influences both the peak overpressure and peak specific impulse at various points within a domain. A Monte-Carlo analysis is employed to explore this, generating 50 unique domains each with a constant areal density, and obstacle size and spacing, but with a random rotation of the obstacles about their plan centroids. This works towards developing a better appreciation for the variability in blast loading that can be expected in true urban blast scenarios.

GEOMETRIC BASELINE

This study aims to begin to understand the local and global loading effects caused by varying obstacle orientations in urban environments. To achieve this, Figure 1 illustrates a referential configuration studied herein, annotating the hemispherical charge centre, the gauge locations, and the obstacles centroids; these positions are each held constant throughout the proceeding investigation.

A number of small-scale experiments were conducted using this arrangement of gauges and obstacle centroids, including tests with no obstacles, the regular array of obstacles shown in Figure 1, and an irregular array of obstacles where the rotation of each obstacle was randomly selected whilst preserving the centroid positions. A detailed review of these results can be found in [10].

Each obstacle in the array is 200mm in height, whereas the reflection block is 158mm tall. The charge is a 10g hemisphere of PE10 that is centrally detonated at its base by a non-electrical detonator of 0.8g TNT equivalent mass. The gauges are positioned on a rigid ground plane with Gauges 4 & 6 and 1 & 3 positioned at the same distance away from the charge. Gauge 2 is the only gauge that is positioned with a vertical reflecting surface behind it. It should be noted that the gauge numbers used in [10] have been simplified for this work.

The results of the experiments are used for the validation of a numerical solver, which is then used to reliably simulate additional irregular obstacle cases for the purposes of a Monte-Carlo investigation of load variability.

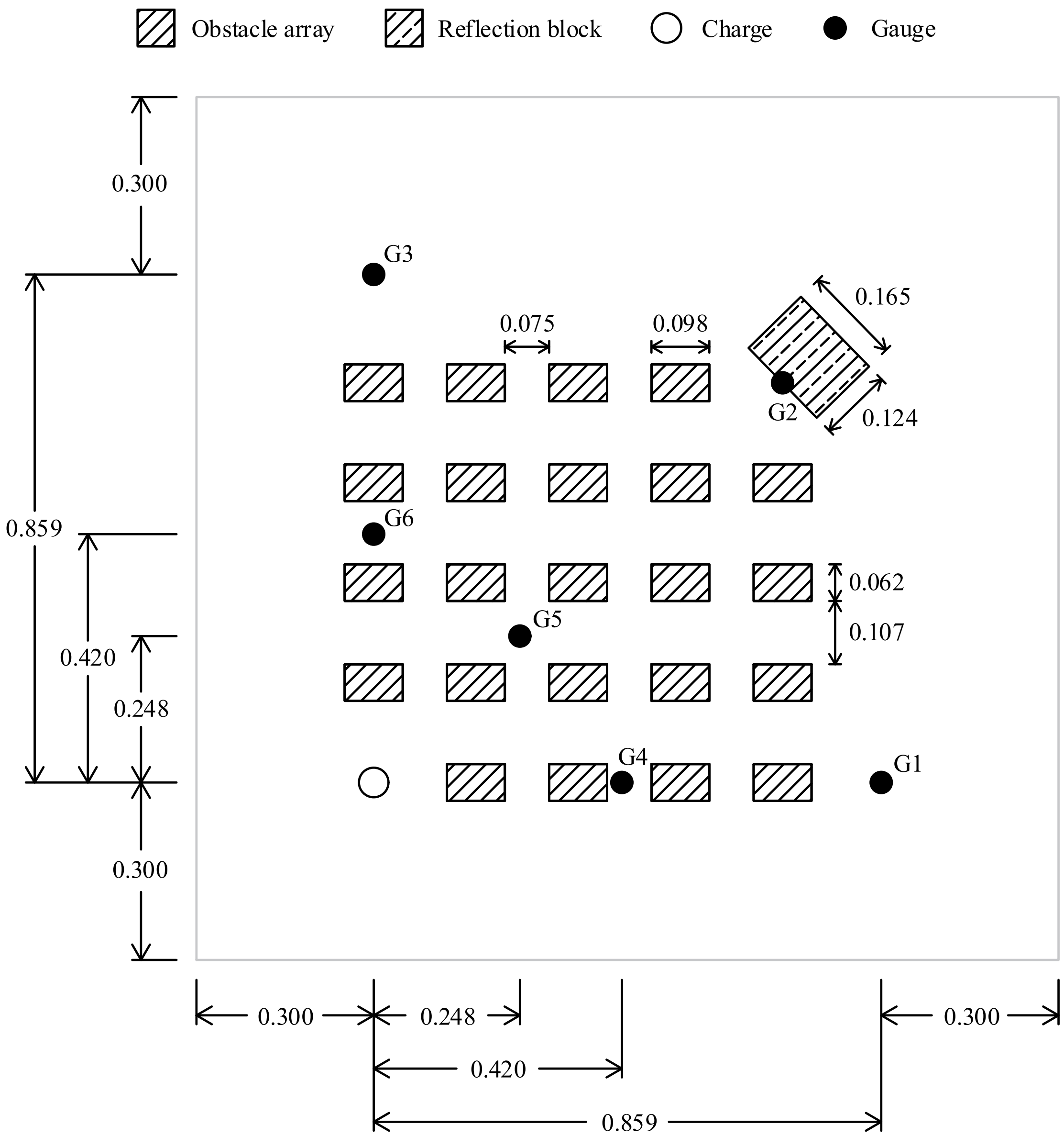

Figure 1: Baseline geometry showing the regular array of obstacles, the charge position, and the locations of each gauge. All dimensions are in meters. Numerical model domain boundaries shown in grey.

EXPERIMENTAL VALIDATION

Each domain in this study is simulated using walair++, a GPU based Computational Fluid Dynamics (CFD) solver produced and maintained by Thornton Tomasetti Defence Ltd. To validate the use of this tool, a comparison is made between its outputs and those from an experimental trial where the regular array of obstacles was present.

Table 1 provides the inputs to walair++ showing how a Jones-Wilkins-Lee (JWL) simulation was used with 1D to 3D remapping to preserve the energy release of the detonation in the full domain. The ground plane was modelled as fully rigid, with all other transmissive boundaries being positioned suitably far from the arrangement such that they have no effect on the output results (see Figure 1). A factor of 1.8 is used to increase the charge size when modelling it as a sphere on a rigid boundary to account for losses to the ground.

Table 1: walair++ simulation inputs. Charge parameters from [11].

Parameter		**Value**	**Unit**
CFL	1D	0.5	-
	3D	0.4	-
Cell size	1D	0.00025	m
	3D	0.0025	m
Simulation distance – 1D		0.1	m
Charge	Mass	0.0192	kg
	Composition	PE10	-
	Shape	Sphere (modelled on rigid ground)	-
	Density, ρ	1550	kg/m^3
	Energy density, e_0	5.18E6	J/kg
	A	3.21E8	Pa
	R_1	4.4	-
	B	9.40E6	Pa
	R_2	1.228	-
	ω	0.271	-
	v_d	7735	m/s
Ambient	Pressure	101325	Pa
	Density	1.225	kg/m^3
	γ	1.4	-
Termination time		6	ms

Figure 2 provides a comparison between the output from walair++ and the experimental readings following post-processing using a low-pass filter to remove noise in the gauge response. Each gauge is shown to be in good agreement with the experimental traces from all three repeat tests. It is also worth noting that this is achieved without any time shifting or corrections being applied to the numerical output.

Generally, the arrival time and decay of the waves are well matched, indicating that the energy release into the domain, and thus the specific impulse, is correctly simulated. The peak overpressures are however slightly more variable, with gauges 4 and 5 showing walair++ to deviate from the experiments by more than 10%. Conversely, the numerical output for gauges 2 and 6 are very closely matched to the experiment throughout the duration of the simulation.

Overall, these results justify the use of walair++ for the study discussed in the remainder of this paper.

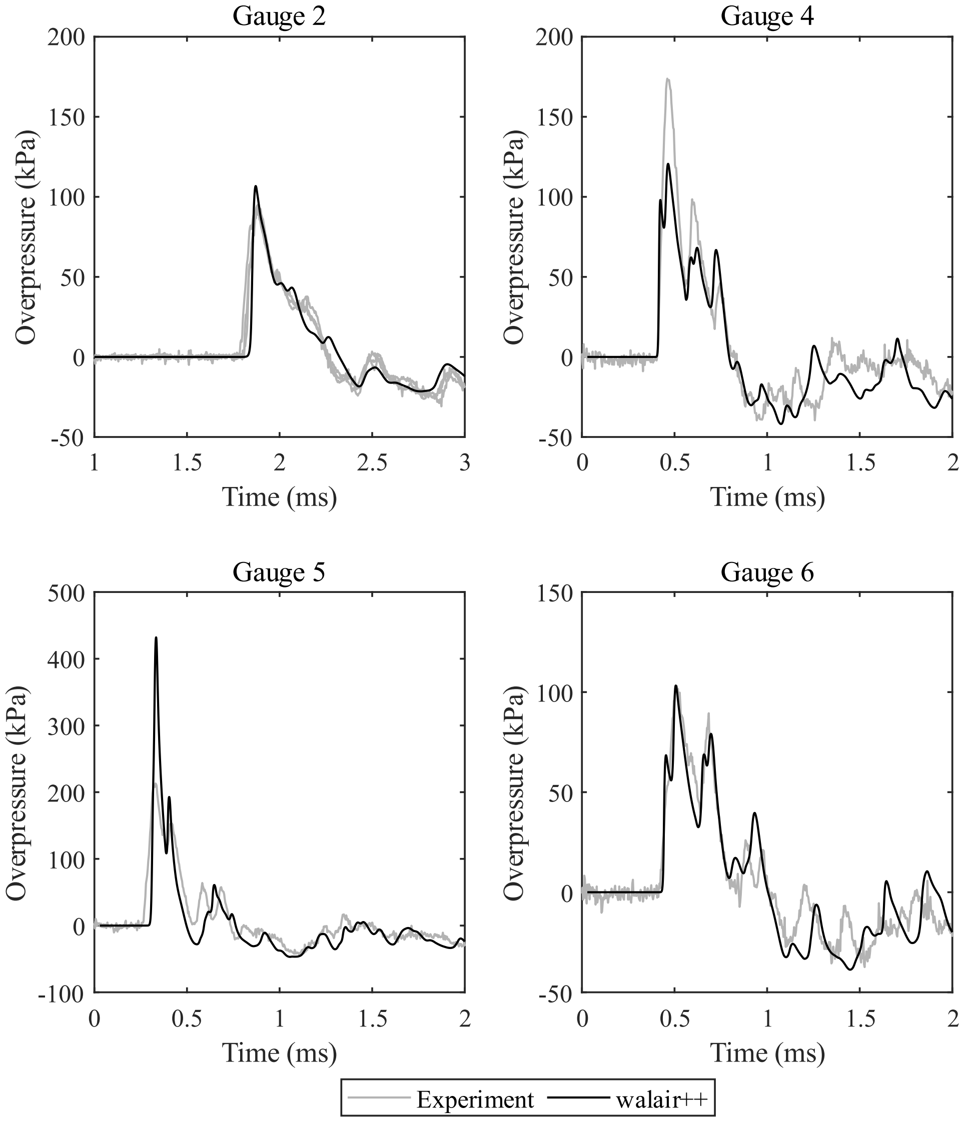

Figure 2: Comparison of experimental pressure-time histories and those extracted from walair++ for when the regular array of obstacles shown in Figure 1 is used. Note that 3 experimental traces are overlain for subplot associated with Gauge 2.

PARAMETRIC OBSTACLE STUDY

Fifty unique domains were simulated with obstacle arrays of fixed centroidal positions and randomly assigned rotation angles between 0 and 180 degrees. Figure 3 shows four examples of these irregular domains. The differences in orientation between cases causes variability in the paths that the blast wave will have to travel to reach each gauge, thus altering the amount of confinement, reflection, and shielding being measured. In each case, the charge mass and position remain unchanged from the Figure 1 reference domain.

The variations induced through this random assignment of obstacle layouts aims to give emphasis to the difference between local loading around an obstacle and global loading throughout the domain with respect to obstacle orientation when all other factors remain unchanged.

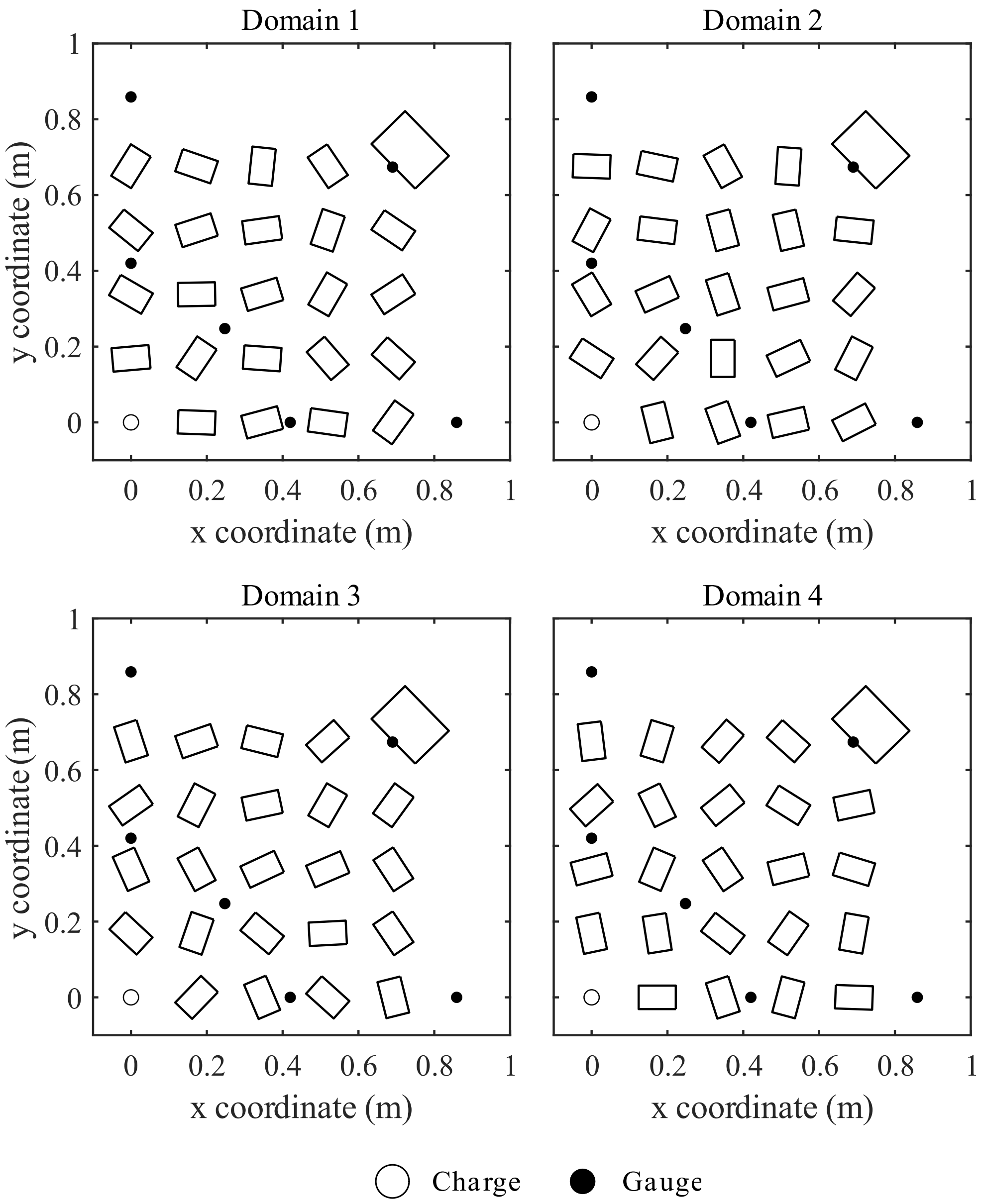

Figure 3: Example domains used in the parametric study based on the regular array given in Figure 1. Each obstacle is rotated by a random angle about its centroid. Gauges, reflected block, and charge conditions remain the unchanged. Charge is positioned at (0,0).

DISCUSSION

Following simulation of each of the 50 unique arrangements, the peak overpressures and specific impulses at each gauge were extracted. The peak specific impulse was calculated using the time integral of the recorded pressure-time histories over the 6 ms duration.

This data was then compiled in the box and whisker plots shown in Figure 4. In each plot the associated blast variable was normalised by the outputs from either the free air domain, when no obstacle arrangement was present, or the domain with the regularly orientated obstacle array.

First, all obstacle configurations resulted in a reduction in peak overpressure compared to the free air scenario due to a combination of shielding and a lengthening of the blast wave's travel path. However, significant local variations emerge between cases when the irregular domains are normalised against the loading of the regular array. For certain random configurations, the peak overpressure exceeds twice the value recorded for the regular array at gauge 6, whereas for gauge 5 values can be as low as 40% of the regular

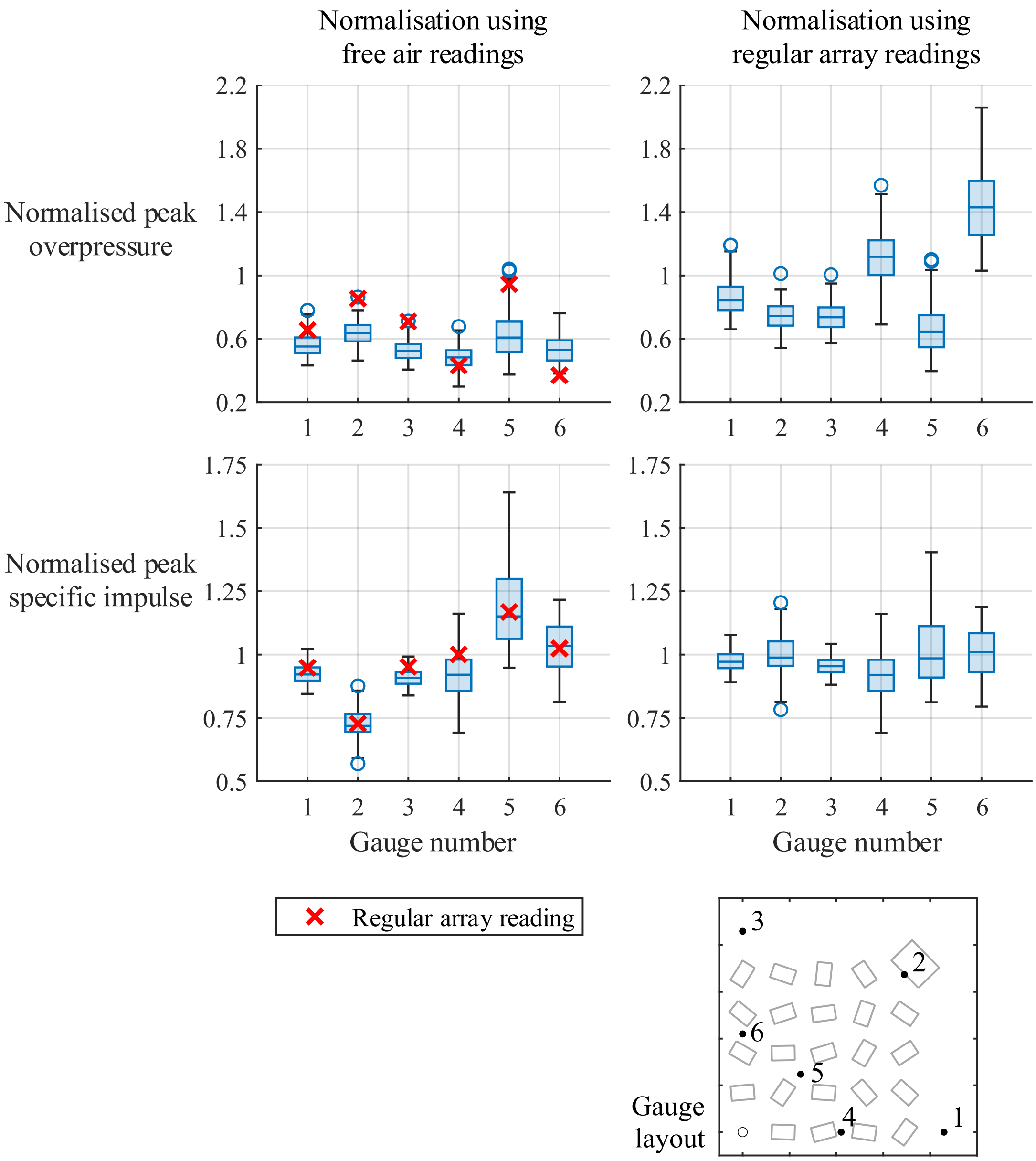

Figure 4: Normalised peak overpressure and specific impulse considering all 50 obstacle array variations. Normalisation performed using readings from the free air domain when only the reflecting block behind gauge 2 is present (Column 1), and when the regular array shown in Figure 1 is used (Column 2).

array output. This is likely to be linked to how the shortest propagation path to each gauge is highly sensitive to the specific layout of the obstacles, and this initial arrival of the wave is typically the cause of the largest spike in pressure above the ambient level (see Figure 2).

For example, in the regular array, the direct path to Gauge 6 is obstructed by obstacles oriented perpendicular to the wave's direction of travel, providing maximal shielding for that location. However, a minor alteration in the orientation of a single obstacle can create a more direct, lower-resistance path for the blast wave. This effect can be compounded by channelling due to reflections from obstacles that are rotated in adjacent columns which may further intensify the pressure at the gauge as multiple wave fronts arrive at a similar time.

In contrast, peak specific impulse normalised using the regular array results in the median values for each gauge falling within a relatively narrow range of 0.92 to 1.01. This consistency suggests that the total energy imparted by the blast is distributed and channelled throughout the obstacle field in a broadly similar manner, irrespective of the rotations of each obstacle. This behaviour may therefore be governed by a combination of global parameters that can be linked to an approximate travel distance from the charge, representing the flow of the energy as opposed to only considering the shortest path and first shock arrival.

These findings indicate a fundamental distinction between the two metrics: peak overpressure is predominantly governed by local geometric variations, whereas specific impulse is insensitive to such changes and appears to be influenced by global domain properties. This supports previous work that has shown that the shortest path and orientation of the local obstacles around a point of interest are both key factors in rapidly predicting peak overpressure when training a Machine Learning model that has no understanding of the underlying blast wave physics [3,12]. Considering this, future methods that aim to predict specific impulse in urban environments may need to diverge from point-by-point predictions, instead using global parameters and a statistical understanding of the variability expected within a given domain.

Figure 5 provides an interesting view as to what a statistics-based predictive tool could focus on, with the plot showing each of the pressure-time histories for gauge 4 in all the domains that were modelled. It shows that, as expected, the regular array's trace lies within the variability of the traces from the 50 random arrangements, and there is an element of consistency within these such that it creates a banded grey region. Predicting the general form of the trace using an averaged travel path and pairing this with a measure of variability would therefore help to understand the range of potential loads that should be accounted for in risk-based analyses.

It should also be noted that whilst this study is able to consider many unique scenarios using validated numerical modelling, the distribution of the loading data obtained from the cases sampled in this work is likely representative of more typical values of loading. There may, however, exist other arrangements that could produce a significant outlier to the plots shown in Figure 4, thus presenting a worst-case scenario that should be accounted for should a statistical predictive tool be employed for the purposes of blast protection design or for an assessment of risk.

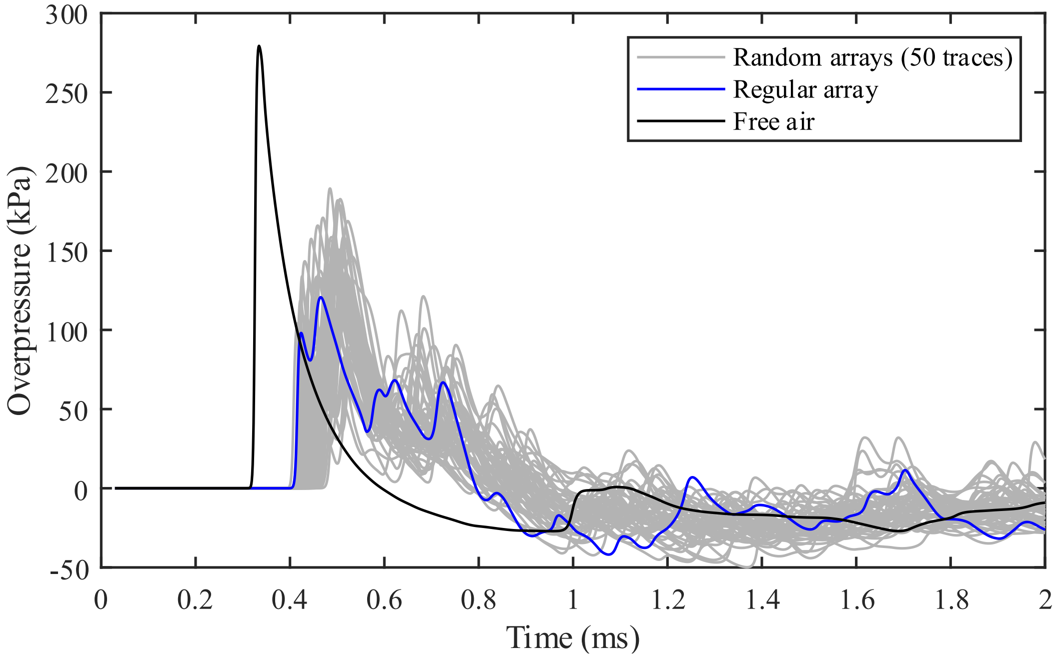

Figure 5: Pressure time histories for gauge 4 for all 50 numerical models with randomised obstacle rotations compared to the output from a free air domain and the regular array domain.

CONCLUSIONS

To conclude, our understanding of free air blasts and isolated obstacle interactions is well established, with many numerical models and fast running methods being able to predict loading in these environments with high accuracy. However, when considering urban blast events, multiple obstacles cause the coalescence of many shock fronts, and this complexity means that simple tools are not yet able to account for variability that could occur throughout the domain.

This study therefore made use of a validated numerical solver to simulate 50 unique arrangements with randomly rotated obstacles. This aimed to explore the influence of orientation on blast loading both locally and globally when other parameters including the areal density and obstacle spacing remained constant. It was shown that the peak overpressure is likely to be dictated by the shortest path of the blast wave from the charge to the point of interest, and the orientation/proximity of the environmental features. This contrasts with the peak specific impulse that is instead mainly altered by global parameters, possibly including the areal density and the approximate travel distance from the charge that represents the flow of energy to each specific point.

Developing this understanding will help to produce predictive methods that account for the variability of urban environments. Future work will therefore aim to explore different baseline arrangements, with focus applied to different characteristics of the domain. This will include increasing the number of measurement locations, modifying the areal density and obstacle shapes, and examining the importance of charge shape at a range of scales.

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