Spatial Variability of Explosive Blast Loading and its Effect on Disproportionate Collapse Risks

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ABSTRACT: Disproportionate collapse is often triggered by malevolent or accidental explosive blast loading. Explosive blast loading is subject to inherent variabilities due to complex interactions between chemical reactions, air particles, fireball and shockwave. Explosive field trials have quantified this variability, and described herein is the probabilistic characterisation of spatial variability of airblast for pressure and impulse. In other words, pressure-time measurements from adjacent (close) gauges are not identical, but correlated based on the distance between the gauges. The degree of correlation is moderate if distance between gauges is small, and reduces to a weak correlation for gauges spaced much further apart. The effect of spatial variability of airblast on damage and collapse risks is investigated for a 10 storey reinforced concrete building subject to a vehicle borne improved explosive device (VBIED) attack, and the accidental detonation of explosive ordnance (EO). The structural reliability analysis considered load redistribution for failed columns, dead and live loading variabilities, and blast loading and resistance model errors. It was found that allowing for the spatial variability of airblast decreased disproportionate collapse probabilities by 16-33% when compared to the case of fully correlated airblast. Designing against disproportionate collapse reduced damage risks by over 99%.

1. INTRODUCTION

The phenomenon of blast loading is subject to complex interactions between chemical reactions, air particles, fireball and shockwave. Numerical and empirical modelling of blast pressure and impulse predict a smooth (deterministic) shock wave emanating from an explosion. However, field trials suggest that this is not always the case. For example, Patterson et al. (1972) observed from blast testing "*deterioration or an enhancement of the overpressure and dynamic pressure in the blast wave, causing deviations from the predicted damage to structures, and from the predicted free field blast wave properties*" and "*many perturbations of the shock front*", "*irregularities*" and other "*anomalies*" (see also Rigby et al. 2019, 2020). These observations suggest there is inherent variability of the shock wave and blast loading. This is supported by Smith et al. (1999) who noted that "*levels of variability are inherent features of all explosive events*".

Farrimond, et al. (2022) surmises that blast wave variability is a function of scaled distance due to varying shock front behaviours, with low variability for the extreme near-field ($Z<0.5$ m/kg$^{1/3}$) and far-fields ($Z>2$ m/kg$^{1/3}$), and higher variability for intermediate scaled distances (scaled distance is $Z=R/W^{1/3}$ where R is range and W is explosive mass). Repetitive blast trials involving over 90 shots for free-field detonation of spherical bare charges in the intermediate and far-fields found that blast loads can vary by up to ±20% when range and explosive mass are held constant (Stewart et al. 2020), and that the variability decreased with scaled distance. To be sure, some of this variability may be due to experimental or observation error. However, many of the above studies focused on repetitive testing where a primary goal of the experimental program was to minimise any experimental error.

The variability observed for airblast may be further defined as "spatial variability". For example, pressure-time measurements from adjacent (close) gauges would not be expected to be identical, but correlated based on the distance between the gauges (or the angle between gauges where each gauge has the same radial standoff from the charge). This means that the shock wave emanating from an explosion may not be perfectly smooth, but as observed above is subject to perturbations, irregularities, and other anomalies.

The effect of explosive blast loading on the structural reliability of buildings and structures has been studied by Ellingwood (2006, 2007), Olmati et al. (2014, 2017), Low and Hao (2002), Hao et al. (2016), Le and Xue (2014), Eamon (2007), Asprone et al. (2010), Razaqpur et al. (2012), Kelliher and Sutton-Swaby (2012), Shi and Stewart (2015a,b), Song (2020), Beck et al. (2020, 2022), Qi et al. (2022), and others. However, many of these studies do not consider the effect of inherent variability (or model error), and none have considered the spatial variability of airblast.

The effect that spatial correlation has on blast loads and reinforced concrete column collapse probabilities for a typical 10-storey building is investigated for a variety of terrorist vehicle-borne improvised explosive device (VBIED) scenarios, as well as the accidental detonation of explosive ordnance (EO). The structural reliability analysis builds upon the work of Stewart (2019, 2022) and Stewart and Li (2021) that considered the damage and safety of RC columns exposed to the blast allowing for variability of resistance, dead and live loads, and airblast where blast loads were assumed fully correlated. The present reliability analysis is more realistic as it considers (i) spatial variability of blast loads, and (ii) load sharing from a damaged column to adjacent columns to more accurately estimate progressive collapse. For more details of the analysis and results presented herein see Stewart (2023).

2. EXPLOSIVE FIELD TRIALS

Two explosive field trials incorporating 90 blasts and 640 time-pressure measurements were conducted for scaled distances ($Z=R/W^{1/3}$) of 0.72 m/kg$^{1/3}$ to 3.2 m/kg$^{1/3}$ where R is range (m) and W is explosive mass in kg equal to charge mass W_{mass} multiplied by net equivalent quantity NEQ. For more detail see Stewart et al. (2020).

Eight incident gauge sensors were arranged so they were all in-plane with the explosive's centre of mass and all equidistant from the point of detonation. Each explosive sphere was centre-detonated, and the centre of the explosive was always at the same point in 3-Dimensional space for each detonation, see Figure 1. Hence, the centre-of-mass of the explosive was the same distance – or range (R) – from the eight "in-plane" blast gauges that surrounded the charge.

Figure 1. The explosives range showing the experimental set-up and the location of the explosive relative to all 8 In-plane Incident pressure gauges.

A unique aspect of the field trials was the repeatability of tests. Considerable care was taken to ensure that explosive mass, detonator location, and the distance between the explosive and gauges were near identical for each series of tests.

3. SPATIAL VARIABILITY

Figure 2 shows that the fireball is not homogeneous, suggesting that the passage of the detonation wavefront is variable and so the shock wave may also exhibit non-homogeneity.

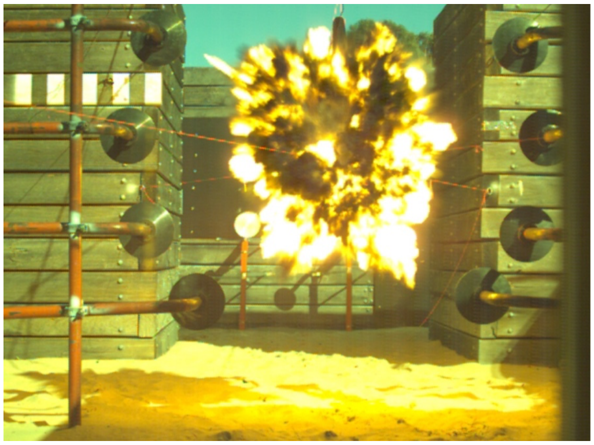

Figure 2. Detonation of a 0.050 kg sphere of PE4.

3.1. Model Error and Inherent Variability

The inherent variability is probabilistically characterised by model error or model uncertainty. This allows recorded pressures and impulses to be normalised and aggregated. Model error (ME) is defined as:

$$\text{Blast Load ME} = \frac{\text{Observed (test) value}}{\text{Model prediction}} \tag{1}$$

The model prediction is based on the widely used Kingery and Bulmash (1984) polynomials for Angle of Incidence AOI=0°, and corrected for temperature and atmospheric pressure.

When corrected for test set-up and measurement errors the lognormally distributed model error statistics for pressure and impulse given in Table 1 represent model accuracy as well as inherent variability. For more details see Stewart et al. (2020).

Table 1. Statistical Parameters for Blast Loading Model Errors.

	Mean	COV
Pressure (ME_P):		
$0.59 \leq Z \leq 3.0$m/kg$^{1/3}$	1.06-0.005Z	0.1175-0.0125Z
$3.0 < Z \leq 6.0$m/kg$^{1/3}$	1.06-0.005Z	0.08
Impulse (ME_I):		
$0.59 \leq Z \leq 3.0$m/kg$^{1/3}$	0.99	0.222-0.044Z
$3.0 \leq Z \leq 6$m/kg$^{1/3}$	0.99	0.06

3.2. Spatial Variability

The above statistical analysis aggregated test data from all gauges as each gauge had the same nominal W and R value. However, the statistical analysis conducted by Stewart et al. (2020) did not consider the spatial variability (or correlation) of blast pressure and impulse between adjacent gauges. The vertical angle between adjacent gauges is used herein to indicate the distance (or closeness) between gauges.

The vertical angle between adjacent gauges varies from 22° - 28°. Figure 3 shows the scatter plot of model error for pressure and impulse for adjacent gauges – i.e. gauges N1 vs N2, N2 vs N3, N3 vs N4, S5 vs S6, S6 vs S7, S7 vs S8.

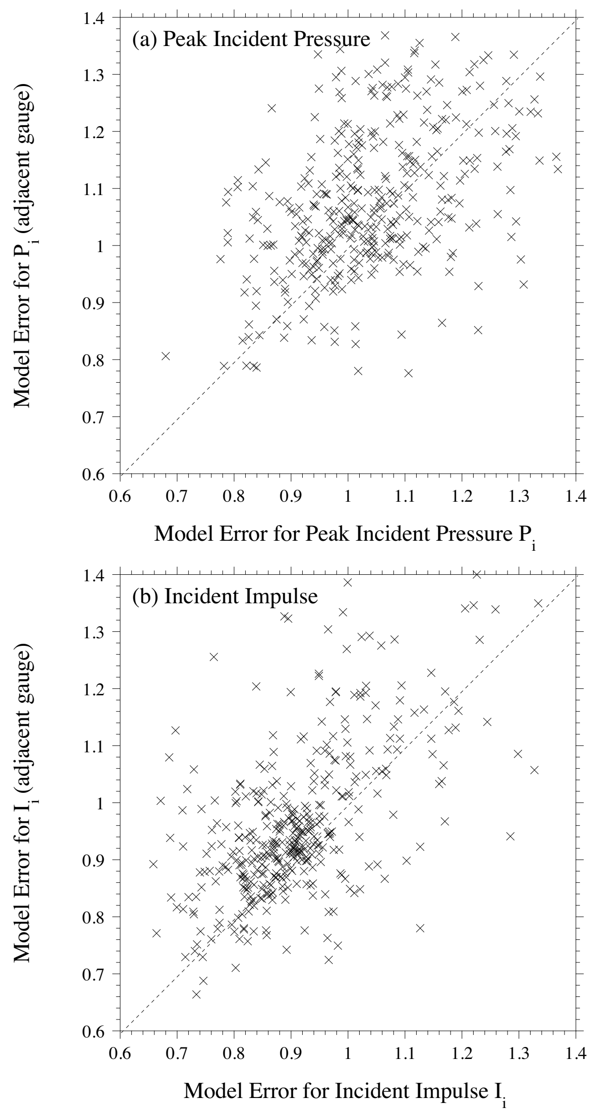

Figure 3. Spatial Correlation for Adjacent Gauges.

The correlation coefficients are ρ_P=0.45 and ρ_I=0.58 for pressure and impulse, respectively. The statistics are not influenced by scaled distance Z. As expected, correlation coefficients of 0.45 and 0.58 indicate medium correlation between adjacent gauges.

The correlation of gauges not immediately adjacent to each other (N1 vs N3, N2 vs N4, S5 vs S7, S6 vs S8) might be expected to have significantly lower correlation as the angles between gauges is about double at 47° - 53°. This is the case for pressure which reduces from ρ_P=0.45 to ρ_P=0.32, thus indicating a weaker correlation. However, for impulse the correlation reduces by only 0.01 to ρ_I=0.57 which is higher than expected, though it is marginally lower than that observed for adjacent gauges.

The largest angle between gauges is 75° - 120° (N1 vs N4, N4 vs S8, S8 vs S5, S5 vs N1) producing the lowest correlations. For pressure the correlation more than halves to ρ_P=0.12 which indicates very weak correlation which may be assumed as statistically independent. However, for impulse the correlation remains relatively high at ρ_I=0.53 which is higher than expected, though it is slightly lower than that observed for adjacent gauges. The higher correlations for impulse may be simply due to the lower volatility of impulse to temporal perturbations in peak pressure.

4. CASE STUDIES

The RC building is 10 stories high, and the RC columns likely to be damaged are the exterior columns – i.e., those closest to the external blast loading (see Figure 4). Two blast scenarios are considered with a range from the middle column is R=10 m, and explosive mass is W_{mass}=1,000 kg: (i) vehicle borne improved explosive device (VBIED) attack, and (ii) the accidental detonation of explosive ordnance (EO). In both cases, the explosive detonates very close to the ground and can be considered a hemispherical charge detonating against a reflecting surface. These assumptions provide the basis for the design of many protective structures. Blast loading is calculated from the Kingery-Bulmash model that also accounts for AOI. The correlation coefficients for airblast variability are ρ_P=0.45 and ρ_I=0.58 for pressure and impulse, respectively. For more details of the reliability analysis see Stewart (2023).

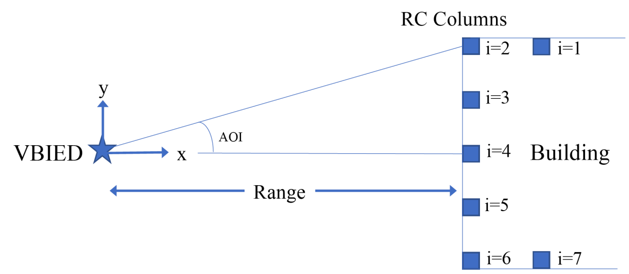

Figure 4. Layout of Explosive and Building RC Columns.

Table 2 shows the statistical parameters for the reliability analysis.

Table 2. Statistical Parameters.

	Mean	COV	Distribution
Column size	1.005	0.04	Normal
Column height	1.00	0.03	Normal
Long. reo.	1.02	0.05	Modified Lognormal
Trans. reo	1.03	0.06	Modified Lognormal
Conc. compressive strength	1.06	0.15	Normal
Yield stress	1.15	0.05	Normal
ME for axial capacity	1.01	0.08	Normal
ME for P-I curves	1.00	0.05	Normal
Dead load	1.05G	0.10	Normal
Arbitrary point-in-time live load	0.5 kPa	0.72	Gamma
Airblast ME	Table 1		Lognormal

Loads from the most heavily damaged column will likely be redistributed to adjacent columns if the building is a special moment resisting frame (e.g., seismic design for strength, continuity, and ductility), or specifically designed against progressive collapse. Load sharing will decrease collapse loads leading to reduced collapse probabilities. In this case study, it is assumed that progressive collapse will occur if a column on either side of the most heavily damaged column is unable to support their redistributed loads. This may be treated as a Daniels system comprising N=2 elements (columns) in parallel. The probability of at least two columns failing is modelled as a series system of 6 possible pairs of failed columns based on the Daniels System (i.e., collapse occurs if one or more pairs of columns i=1-2, 2-3, 3-4, 4-5, 5-6, 6-7 fail). The columns around the corner of the building (i=1, 7) are assumed undamaged by airblast.

4.1. VBIED Terrorist Scenario

The terrorist blast scenario involves a VBIED containing home-made ANFO (ammonium nitrate fuel oil). Terrorists in Western countries tend to be self-starters or lone-wolves (e.g., Mueller and Stewart 2011, 2016). This means they do not have access to commercial or military explosives, or to high grade bomb making materials, often lack any training, and lack the opportunity to test their product (Stewart and Mueller 2020). Hence, home-made explosives are likely to be of a lower grade – i.e., a low net equivalent quantity (NEQ) with high variability of explosive mass. It may be assumed for sake of illustration that the NEQ of home-made ANFO may be significantly lower than commercial grade ANFO with a range of 0.0 to 0.8 modelled as a uniform distribution (COV=0.58). The variability of charge mass can be high as well; for example, there may be inaccuracies in measuring the quantity of materials that comprise home-made explosives. If it is assumed that there is ±10% accuracy in charge mass (W_{mass}), and if these limits represent 95% percentile bounds of a normal distribution the COV of charge mass is 0.05. The explosive mass is $W = NEQ \times W_{mass}$.

The anticipated location of a VBIED is also subject to uncertainty. The VBIED location will be variable in x and y directions. The variability of range is measured along the x-axis. If the VBIED is located within a car spacing of ±2 m tolerance, then if these limits represent 95% percentile bounds of a normal distribution, the standard deviation of R is σ_x=1.0 m. Added to this is the uncertainty of where along the building the VBIED will be placed. A reasonable assumption is it will be desired to have it centrally placed (i.e., directly in front of the middle column) with a 95% tolerance of ±3 m leading to a standard deviation of σ_Y=1.5 m assumed normally distributed. This threat scenario is hypothetical, but is instructive in shaping how terrorist capability may influence the extent and variability of blast loading (for a fuller discussion see Stewart 2018, 2019).

4.2. EO Scenario

An example of a scenario with low blast load variability is an explosive ordnance (EO) scenario in which the type of explosive and range are quite certain as explosives are generally stored in a facility or location designed for this purpose. In such a case, collapse risks would be significantly lower than those calculated for the VBIED terrorism scenario. For example, consider a scenario where (i) variability of NEQ is reduced to zero with NEQ=0.82, (ii) there is 50% more certainty about charge mass with only ±5% accuracy of stored mass, and (iii) standard deviation of range reduced to a ±1 m tolerance in the x and y directions.

4.3. Threat Dependent Design

The US Department of Defense *Structures to Resist the Effects of Accidental Explosions* (UFC 3-340-02 2014) is typically used in many countries for the design of RC columns. Table 3 shows the designed RC column sizes for a steel yield strength of 500 MPa. The design axial capacity is increased by 120% when compared to a conventional design (see Table 3).

The probability of collapse assuming ≥2 column failures using the Daniels System are shown in Table 3. It is evident that for a conventional design the failure risks are very high for both scenarios, which is to be expected for a structural element not designed to be blast-resistant. The collapse risks reduce by over 99% for blast-resistant columns. The collapse risks are lower for the EO scenario due to reduced variability of R and W, leading to reduced variability of blast loading.

Table 3. RC Column Sizes, and System Probabilities of Collapse Conditional on the Explosive Hazard.

	Conventional Design (Not Blast-resistant)		Threat Dependent Design	
	VBIED	EO	VBIED	EO
Size	500mm	500mm	675mm	675mm
Height	4.2m	4.2m	4.2m	4.2m
Long. reinf. ratio	0.012	0.012	0.025	0.025
Trans. reinf. ratio	0.006	0.006	0.012	0.012
Conc. str.	38MPa	38MPa	40MPa	40MPa
P_{design} (kN)	9,478	9,478	20,799	20,799
$\rho_P=\rho_I=0.0$	0.22	0.12	6.5×10^{-7}	8.4×10^{-9}
Spatially variable	0.22	0.12	1.0×10^{-6}	1.2×10^{-8}
$\rho_P=\rho_I=1.0$	0.23	0.12	1.2×10^{-6}	1.8×10^{-8}
ME=1.0	0.23	0.10	4.9×10^{-7}	2.6×10^{-9}

The spatial variability of airblast has a significant effect. For example, if one column is heavily damaged then this is likely due to a higher than expected blast loading, hence full correlation (ρ=1) of airblast will result in the adjacent columns also experiencing higher than expected blast loads – thus increasing the likelihood of failure of one of the adjacent columns. Conversely, if blast loads are statistically independent for adjacent columns (ρ=0) leads to lower likelihood of damage to adjacent columns. If the statistics for airblast correlation ($\rho_P=0.45$, $\rho_I=0.58$) are incorporated into the analysis, the collapse risks are reduced by 16-33% when compared to fully correlated model errors.

A conventional reliability analysis would assume no model error, and assume that airblast loads for different columns are fully correlated based on the same W and R for each threat scenario (i.e., ME=1). These results are also shown in Table 3, where it is observed that ignoring the spatially dependent model error results in probabilities of building collapse being reduced by at least 50% when compared to those that consider spatial variability.

See Stewart (2023) for full details of the analysis and results presented herein including other threat scenarios, sensitivity analyses, design to the alternate path method, and comparison of collapse risks with target reliabilities.

5. CONCLUSIONS

The paper describes a statistical analysis of explosive field trials comprising of 90 shots to probabilistically characterise the spatial variability of airblast. Correlation coefficients were estimated for pressure and impulse. The degree of correlation is moderate if distance between adjacent gauges is small (i.e., angle between gauges is small where each gauge has the same radial standoff from the charge), and reduces to a weak correlation for gauges spaced much further apart. The effect of spatial variability of airblast on damage and collapse risks was investigated for a 10 storey reinforced concrete building subject to a vehicle borne improvised explosive device (VBIED) attack. The structural reliability analysis considered the uncertainty and variability of range, explosive mass, concrete and reinforcing steel material properties, column dimension, damage prediction model errors, and dead and live loading, as well as airblast model errors including inherent variabilities, and spatial variability of airblast. Damage progression and load redistribution for failed columns were used to predict progressive collapse. It was found that allowing for the spatial variability of airblast decreased progressive collapse probabilities by 16-33% when compared to the case of fully correlated airblast. Designing against progressive collapse using a threat dependent design reduced damage risks by over 99%. This system analysis is idealised and more accurate estimates of progressive collapse may be available from a detailed 3D FEA of the building.

6. ACKNOWLEDGEMENTS

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