Supplementary Blast and Fragmentation Calculations for Witnesses in Donetsk Regional Academic Drama Theatre - Mariupol

Analysis

The following analysis is based on Kingery-Bulmash[1], Gurney[2] and Bowen[3] curves from the witness testimony of eight (8) individuals situated in the basement, the ground floor and first floor of the Mariupol Drama Theatre. These tables (and the colours annotated) should be viewed in conjunction with the PowerPoint presentation provided. The mass of bare explosive is taken as 198 kg TNT from previous work conducted and is consistent with the mass of explosive available in certain Russian Federation air-dropped munitions[4].

- Table 1 depicts the nature of the incident blast overpressure, reflected blast overpressure and impulse duration at distances where each witness was situated (PowerPoint Slides 1, 2 and 3).
- Table 2 depicts the lethal distance for fragmentation from the epicentre of the explosion (PowerPoint Slide 1). This is the line-of-sight distance, with structural implications being explained in the narrative.
- Table 3 provides the root data used to calculate the blast and fragmentation characteristics at each distance.
- PowerPoint slide 4 indicates the estimated munition position in the vertical scale at point of detonation (approximately 0.5 to 1 m above the theatre stage at ground level). This distance may vary due to the lack of evidence relating to the precise fuze setting of the munition.
- Incident overpressure assumes that the blast wave is not attenuated by the theatre's structure at each point. It is the worst-case scenario that each witness would experience based on their location within the theatre.

P_s = Incident overpessure in *KPa* at distance *D*

D = the distance in m from the epicentre of explosion to each witness – direct line of sight

P_r = Reflected overpressure in *KPa* at distance *D*

V = the velocity of the blast wave in ms^{-1} at distance *D*

T = the time in *ms* the blast wave takes to reach distance D from the epicentre of the explosion

I_s = Impulse duration in *ms* at distance *D*

dB = the noise level in *dB* experienced at distance *D*

[1] Kingery C. N., Bulmash G., (1984) "Technical report ARBRL-TR-02555: Air blast parameters from TNT spherical air burst and hemispherical burst", AD-B082 713, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD.

[2] Gordon E. Jones, James E. Kennedy, Larry D. Bertholf (1980). Ballistics Calculations of R.W. Gurney. American Journal of Physics 48, 264–269.

[3] M.M. van der Voort, K.B. holm, P.O. Kummer, J.A. Teland, C.J.A.M. van Doormaal, H.P.A. Dijkers (2016). A new standard for predicting lung injury inflicted by Friedlander blast waves. Journal of loss prevention in the Process Industries.

[4] Collett G.P., (2022). Explosive Engineering Assessment -Donetsk Regional Academic Drama Theatre In Mariupol, Ukraine, Table 3 CST/20221109.

Witness	Distance (D) (m)	Incident Pressure P_s (KPa)	Reflected Pressure P_r (KPa)	P_s (PSI)	Velocity (V) (ms^{-1})	Time (T) (ms)	Impulse Duration (I_s) (ms)	*dB*	Effect
1	28.82	31.90	71.52	4.63	3840	51.57	19.35	184	Serious injuries are common, fatalities may occur in direct line of sight of blast. Fragment wounds may be experienced with 50% mortality. 99% of all exposed glass panes broken. 99% of all exposed glass panes broken. Lower limit of serious structural damage.
2	39.1	19.52	41.97	2.83	3710	79.44	21.53	179	Eardrum rupture likely. Persons knocked down or thrown to ground. Possible death from tertiary blast injuries (being thrown against objects). Lower limit of serious structural damage. 99% of all exposed glass panes broken.
3	23.87	44.56	104.63	6.46	3990	38.68	18.03	186	Moderate damage to massive load bearing walls. Serious injuries are common, fatalities may occur in direct line of sight of blast. Fragment wounds may be experienced with 50% mortality. 99% of all exposed glass panes broken. 99% of all exposed glass panes broken.
4	17.29	83.49	221.66	12.17	4440	22.80	15.54	193	90% probability of eardrum rupture. Probable destruction of building. Threshold of lung haemorrhage. People standing up thrown 5 m or more. Serious fragment wounds at 100% mortality. Most people in direct line of sight of blast are killed.
5	28.82	31.90	71.52	4.63	3840	51.57	19.35	184	Serious injuries are common, fatalities may occur in direct line of sight of blast. Fragment wounds may be experienced with 50% mortality. 99% of all exposed glass panes broken. 99% of all exposed glass panes broken. Lower limit of serious structural damage.
6	45.28	15.72	33.45	2.28	3690	96.46	22.61	177	Threshold of eardrum rupture. Person knocked down or thrown to ground. Possible death from tertiary blast injuries (being thrown against objects). Lower limit of serious structural damage. 99% of all exposed glass panes broken.

Witness	Distance (D) (m)	Incident Pressure P_s (KPa)	Reflected Pressure P_r (KPa)	P_s (PSI)	Velocity (V) (ms^{-1})	Time (T) (ms)	Impulse Duration (I_s) (ms)	dB	Effect
7	26.75	36.30	82.72	5.26	3900	46.12	18.82	185	Moderate damage to massive load bearing walls. Serious injuries are common, fatalities may occur in direct line of sight of blast. Fragment wounds may be experienced with 50% mortality. 99% of all exposed glass panes broken. 99% of all exposed glass panes broken.
8	43.22	16.82	35.89	2.44	3700	90.78	22.27	178	Threshold of eardrum rupture. Person knocked down or thrown to ground. Possible death from tertiary blast injuries (being thrown against objects). Lower limit of serious structural damage. 99% of all exposed glass panes broken.

Table 1: Blast wave characteristics at each witness point - Mariupol Theatre

Fragment Mass (kg)	Material	Lethal Velocity Human (3 Jmm^{-2})	Lethal Range (Line of Sight)	Stopping Point 50 mm concrete	Stopping Point 120 mm brick	Exposure of Witnesss 1 - 8
0.01	Mild Steel (Munition Casing)	312 m/s	207 m	65.4 m	27.7 m	No witness was in direct line of sight to the blast and as such were not impacted by fragmentation from the munition, or the uptake of debris up to 1 kg in mass. Based on witness testimony it is not necessary to model any larger concrete fragments.
0.1	Reinforced Concrete	458 m/s	207.8 m	25.2 m	51.5 m	
1.0	Reinforced Concrete	212 m/s	523.9 m	267 m	187 m	

Table 2: Fragmentation characteristics from munition and theatre debris

Findings

Those occupants of Mariupol Theatre in direct line of sight of fragmentation and blast would have experienced a 99% chance of death up to 21 m from the epicentre of the explosion for reflected blast overpressure, or 207 m for fragmentation. Those witnesses most at risk were on the ground floor (witnesses 3, 4, 5 and 6), although:

- none were in direct line of site to explosion; and
- all were protected by infrastructure.

Witnesses 1, 2, 7 and 8 were far enough away from the blast to avoid serious injury. They were also protected by infrastructure, which attenuated blast energy and captured fragmentation.

PowerPoint slides 2 and 3 demonstrate the Bowen curves used to determine a 1%, 50% or 99% chance of death at any distance from a known quantity of explosive. PowerPoint slide 2 represents incident overpressure (P_s), whilst PowerPoint slide 3 represents reflected overpressure (P_r). Witnesses 1 – 8 fall below the one percentile (1%) for incident overpressure. Witness 4 falls just below the ninety-ninth percentile (99%) for reflected overpressure. Distances of 10 and 21 m are annotated to demonstrate the distance at which death would fall within the ninety-ninth percentile (99%) for both peak overpressures.

As can be seen from witness testimony, those in the basement (1), in the bomb shelter (2), or on the first floor (7 & 8) were protected by the structural integrity of the building, the construction of which ultimately saved their lives. This can be seen in Slides 2 and 3.

Witness 4 was the closest to the epicentre of the blast, but thankfully in an enclosed space with both doors closed. He would likely have been killed if the doors had not been closed. The walls and the doors of the room reflected significant energy from the blast wave. Witness 3 was the second closest to the blast on the ground floor, but protected by the structure around him, which absorbed significant energy.

Details of Damage	Blast Overpressure (psi)[1]
Ears	
Loud noise at 143dB	0.04
Threshold for temporary loss of hearing	0.2
Threshold for eardrum rupture	2
50% probability of eardrum rupture	5 – 7
90% probability of eardrum rupture	10 – 14
Wounds	
Minimum for penetration injury by small glass fragments	0.8
Threshold of skin lacerations by fragments	1 – 2
Serious fragment wounds @ 50% mortality	4 – 5
Serious fragment wounds @ 100% mortality	7 – 10
External Injury	
Low personnel risk when inside a resistant structure	1
Personnel knocked down or thrown to ground	1.5 – 2.9
Possible death by persons being projected against obstacles	2
People standing up thrown a distance of 5 metres or more	8 – 16
People lying down on the ground are picked up and thrown a distance of 2 metres or more	12 – 24
Internal Injury	
Threshold of internal injuries	7
Threshold of lung haemorrhage	12 – 15
Glass Failure	
Typical pressure for glass failure	0.15
50% of exposed glass panes broken	0.08 – 0.19
99% of all exposed glass panes broken	0.67 – 1.6
Damage to Houses - General	
Minor damage to house structures	0.7
Partial demolition of house – rendered uninhabitable	1
Nearly complete destruction of houses	5 - 7
Damage to Buildings - General	
Limited minor structural damage	0.3 – 0.4
Doors and window frames may be blown in	0.77 – 1.3
Lower limit of serious structural damage	2 – 3
Moderate damage to massive load bearing wall (multi-storey)	6 - 7
Probable total destruction of buildings	10
Industrial	
Failure of joints and fastening in Al/steel panels + buckling	1 – 2
Building steel frame distorted and pulled away from foundations	3
ISO containers crushed	5
Movement of bridge members on abutments and some distortion of bridge members	5 – 15
Road Vehicles	
Cars and trucks blown over	8 – 12
Sever damage to cars and trucks	20 – 30
Rail Vehicles	
Rail wagons damaged but repairable	5.5 – 11.5
Empty rail wagons blown off tracks by side on loading	5.5 – 6.0
Steel towers blown down	30
Aircraft	
Damage to control surfaces	1 – 2
Total destruction of aircraft	3.5
Trees	

[1] psi is defined as the pressure that results when a force of one pound-force is applied to a one-square-inch area. One psi is approximately 6,895 pascals (N/m^2). A bar is a metric unit of pressure that is defined as exactly 100,000 pascals (symbol: Pa). It is equal to 0.987 atmospheres (101,325 Pa), the unit often used as a reference of standard pressure. One bar is 14.50377 psi.

Peak overpressure	Maximum wind speed	Effect on structures	Effect on the human body
1 psi	38 mph	Window glass shatters	Light injuries from fragments occur
2 psi	70 mph	Moderate damage to houses (windows and doors blown out and severe damage to roofs)	People injured by flying glass and debris
3 psi	102 mph	Residential structures collapse	Serious injuries are common, fatalities may occur
5 psi	163 mph	Most buildings collapse	Injuries are universal, fatalities are widespread
10 psi	294 mph	Reinforced concrete buildings are severely damaged or demolished	Most people are killed
20 psi	502 mph	Heavily built concrete buildings are severely damaged or demolished	Fatalities approach 100%

Fragmentation Impact	Energy Density (Jmm^{-2})
Unprotected human	3
Protected human*	5
50mm concrete	40
120mm brick	90
10mm steel	100
30mm steel	250

Table 3: Root data for blast and fragmentation calculations