Article:

Rigby, S. orcid.org/0000-0001-6844-3797, Ratcliff, A., Clarke, S. et al. (3 more authors) (2024) Consequences of the 2020 Beirut explosion. Fire and Blast Information Group Technical Newsletter (88). pp. 6-10.

CONSEQUENCES OF THE 2020 BEIRUT EXPLOSION

Written by:
S. Rigby[1,2], A. Ratcliff[1], S. Clarke[1], D. Farrimond[1], S. Fay[3] and W. Wholey[4]
[1]University of Sheffield, Department of Civil & Structural Engineering, UK
[2]Arup Resilience, Security & Risk, UK
[3]AWE, Damage Assessment, UK
[4]Arup Resilience, Security & Risk, USA

On 4th August 2020 one of the largest non-nuclear explosions in history occurred in the Port of Beirut, Lebanon. Approximately 2,750 tons of ammonium nitrate detonated following a warehouse fire, and the resulting blast wave caused considerable infrastructure damage (>$15bn) and loss of life (>200 casualties and >7,000 injuries) as it propagated through the city. There is a clear need for civilian infrastructure to be designed or retrofitted for resilience against the intense loading produced from an explosion, and an integral first step is understanding the behaviour of a blast wave as it moves through a complex obstructed environment such as a cityscape. This paper presents a case study into the 2020 Beirut explosion and efforts to better understand its consequences. First, video footage posted to social media shortly after the explosion is used to derive an approximate yield by compiling the radius-time profile of the blast wave and correlating with well-known semi-empirical relations. Subsequently, a detailed physics-based simulation of the Beirut explosion is performed with this estimated yield, and the results are used to undertake a forensic assessment of observed building damage. This work highlights the importance of improved tools for estimating the consequences of large scale urban explosions to enable more accurate identification of areas at risk of structural damage and high casualty numbers.

1. Introduction

On 4th August 2020 one of the largest non-nuclear explosions in history occurred in the Port of Beirut, Lebanon. Approximately 2750 tons of ammonium nitrate (AN), which had been held in storage since 2014 [5], detonated shortly after 18:07 local time following a fire in the warehouse where it was being stored. The explosion injured over 7000 people and resulted in more than 200 casualties and over $15 billion in infrastructure damage. AN becomes sensitive to detonation at higher temperatures, particularly after prolonged exposure to atmospheric moisture [2], and burns with a distinctive red/brown colour.

Due to the scale, severity, and unusual appearance of the fire, many residents of Beirut were filming at the time of detonation. A number of videos showing the explosion and immediate aftermath were uploaded to social media shortly after the explosion, see Figure 1.

Follow-up studies made use of this so-called "citizen science" data. A particular application is detailed in this paper; detailed analysis of video footage enabled a radius-time profile of the blast wave to be generated, and subsequently the yield of the explosive was estimated. This paper then describes a detailed numerical analysis of blast propagation in the Port of Beirut, and a thorough forensic assessment of observed building damage.

Ultimately, the aim of this work is to better understand the complex nature of explosions in urban environments, with a view to generating improved knowledge of the physical processes. With this, an ability to more accurately and rapidly predict the consequences of large scale urban explosions will enable better identification of areas at risk of damage and casualties, as well as providing clearer guidance for policymakers and forensic studies. The reader is directed to Ratcliff *et al.* [7] for a detailed review on blast loading in the urban environment.

Figure 1 Example video footage of the 2020 Beirut explosion (adapted from [1])

2. Yield estimation using social media footage

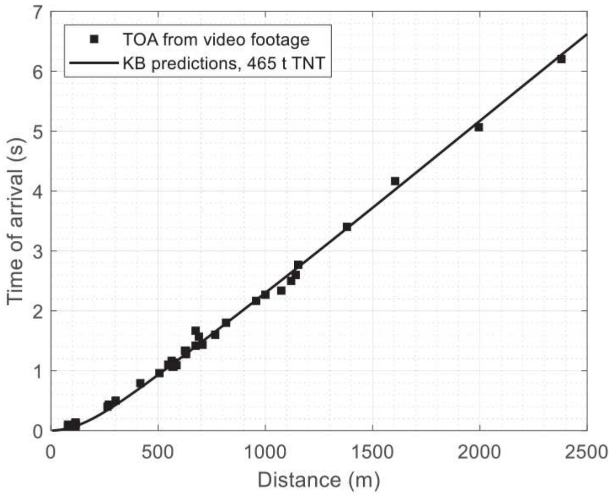
Rigby *et al.* [8] examined 16 videos and quantified time of arrival (TOA) of the blast at 38 locations in the city. Blast wave TOA is known to be a reliable metric for studying blast behaviour and can be quantified with higher precision than other parameters such as peak pressure and peak specific impulse [9]. The TOA data were determined by measuring the delay between the moment of detonation (observed as a bright flash in the videos) and either visual disturbances at recognisable locations in the videos, or a clear spike in the audio signal indicating arrival of the blast at the filming location. The distance from each location to the point of detonation was calculated using Google Earth.

The results were correlated with well-known semi-empirical predictions [4], as shown in Figure 2. A regression analysis was performed and the best-fit yield was determined to be between 409-500 t TNT equivalent, found by minimising mean absolute error (MAE), mean error (ME), and root mean square error (RMSE) respectively of the observed datapoints against the Kingery and Bulmash arrival time. Herein, the explosive yield is taken as 465 t TNT, taken as the mean of the three best-fit yields and the revised value (489 t) presented in Ratcliff [6] after taking into account inter-frame detonation times.

3. Numerical analysis of the Beirut explosion

Numerical analyses were performed with Viper::Blast (hereafter shortened to Viper); a finite volume computational fluid dynamics tool for simulating the airblast environment resulting from detonation and combustion of high explosives and other energetic materials. The primary purpose of Viper is to model blast loads on structures of non-trivial geometry, and uses a variant of the explicit AUSMDV numerical scheme combined with a MUSCL-Hancock scheme. Viper solves the inviscid Euler equations in 1D-3D, and has been validated against a wide range of test data as well as against other numerical codes [10]. Viper utilises hardware acceleration of the AUSMDV numerical scheme, which has been targeted at NVIDIA GPUs, in order to further reduce analysis times and project costs.

A 465 t TNT explosion was simulated in a 2250 × 3650 × 475 m region of the Port of Beirut and its surroundings [11]. A simulation domain in Viper is a voxelised volume where cells inside obstacles are flagged as obstacle cells and those outside are flagged as fluid cells. Complex geometries may be imported as triangulated surface meshes in the form of stereolithogrophy (STL) formatted files or similar. Ground terrain and surface topography can also be imported from GeoTIFF formatted files derived from Lidar, satellite-based data sources, or photogrammetric surveys.



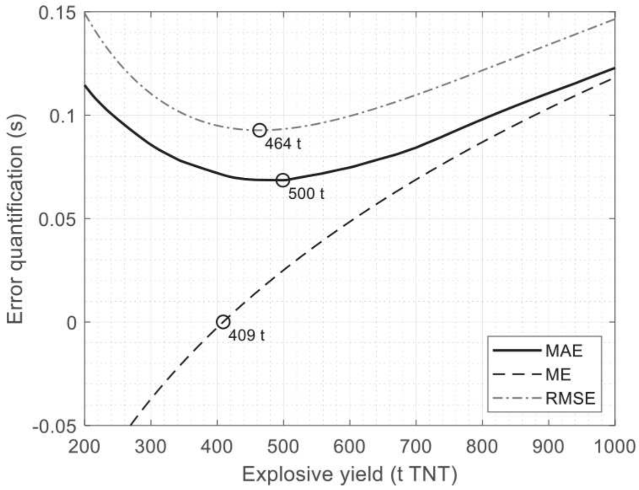


Figure 2 Time of arrival versus radius data determined from video footage of the Beirut explosion [left]; Results of regression analysis to determine best-fit yield [right]

The explosive was modelled as an equivalent fully-detonated mass using the 'iso-thermal burst' model. This approach dramatically simplifies modelling the detonation process whilst still providing highly accurate predictions of the pressure field in the surrounding environment, even in regions very close to the charge [10]. The blast was simulated in 2D out to a distance of 40 m (approximate distance to the grain silo) before being remapped into 3D. The 3D model comprised ~490 million cubic elements of 2 m side-length, and the simulation was performed on an Alienware Area-51 R5 PC with two GTX1080Ti's, an 18-core intel i9 CPU (64GB RAM) and an RTX Titan (24GB VRAM). 9 s of analysis time took ~7½ hours computational time. Data was post-processed in ParaView. Example stills from the numerical model are shown in Figure 3.

4. Damage assessment

Select observations are made at a number of locations in the city, shown in Figure 4, for which pre- and post-explosion images are available [3]. Locations 1-3 are approximately 593 m, 1860 m, and 2180 m from the explosion centre respectively.

In each case, peak pressure and peak specific impulse on the building surface are exported from the model and compared against iso-damage curves (Figure 8) for toughened and annealed glass in order to make comments on and ratify the observed damage.

4.1 Example 1: Extensive cladding damage

Figure 5 shows before and after images of a building extensively damaged by the explosion. This building is located a short distance from the blast centre, with only low-level warehouse buildings in between. The building therefore did not receive any beneficial 'shielding' effects and was subjected to, effectively, the full reflected pressure load with duration exceeding 300 ms. When mapped onto iso-damage curves for glazing (Figure 8), the applied loading can be seen to clearly exceed the damage levels for even annealed glass, and therefore the level of damaged observed is unsurprising. In addition to total glazing failure, some small stone cladding panels are cracked and removed.

4.2 Example 2: Differing strengths

Figure 6 shows before and after images of two buildings located almost 2 km from the explosion centre. Interestingly, the older building on the left of the photographs appears to have sustained considerable glazing damage, whereas the more modern building on the right hand side appears relatively undamaged. Whilst there are clear differences in support conditions, it is suggested that the primary difference between the two glazing systems is that the older building façade is annealed glass, whereas the newer building façade is toughened glass.

This is clearly borne out when considering the blast loading at the building location, as in Figure 8. The pressure-impulse pair sits between the iso-damage curves for annealed and toughened glass, meaning that damage is expected for the former but not the latter; exactly as borne out in the photographs.

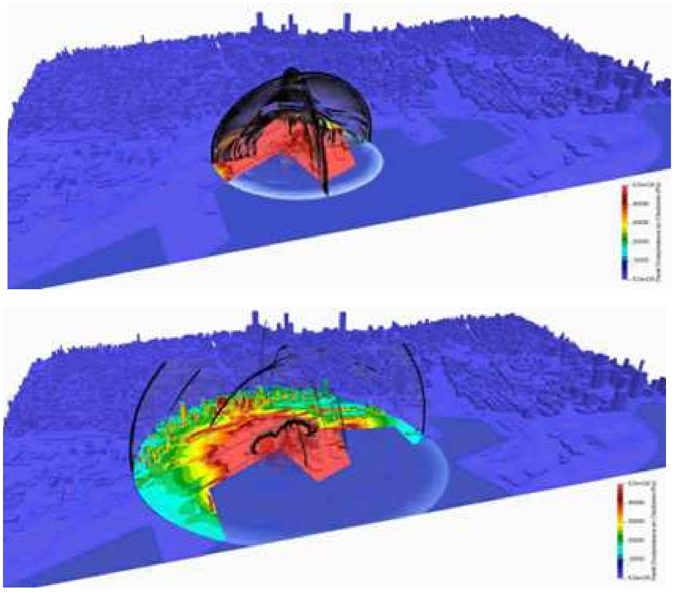


Figure 3 Stills from Viper model of the Port of Beirut

Figure 4 Map of Beirut showing explosion centre and locations of buildings discussed in damage assessment

Figure 5 Extensive cladding damage at Location 1: before [left] and after [right] the explosion [3]

4.3 Example 3: Differing orientation

Finally, Figure 7 shows before and after images of a building >2 km from the explosion centre. In this example, the building is oriented side-on to the blast, such that of the two elevations visible in the photograph, the elevation on the left was subjected to the reflected pressure and impulse loading, whereas the elevation on the right was subjected to the incident loading. It can be quite clearly seen that glazing on the reflected side of the building has been extensively damaged, whereas glazing on the incident side is undamaged.

Again, when mapping the reflected and incident pressure-impulse pairs on the iso-damage curve in Figure 8, it can be seen that the reflected loading sits above the damage curve for toughened glass, and the incident loading sits below the damage curve for annealed glass. This indicates a clear sensitivity to building orientation on glazing damage following an urban explosion. It is encouraging how well these and the previous observations align with the numerical loading data from the estimated yield of the explosion, and this gives confidence in the method outlined in Section 2.

Figure 6 Different damage observed for different glazing systems at Location 2; before [top] and after [bottom] the explosion [3]

Figure 7 Different damage observed for different glazing orientations at Location 3; before [left] and after [right] the explosion [3]

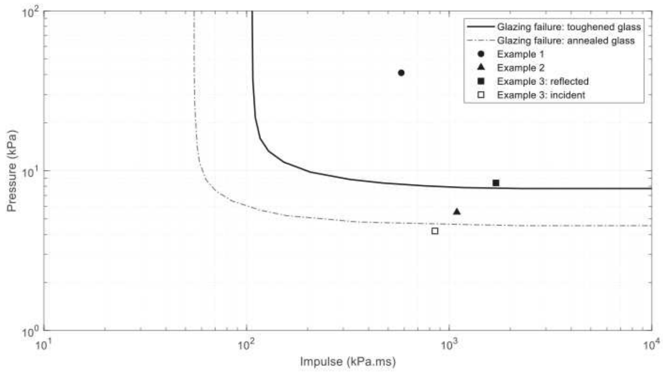


Figure 8 iso-damage curves for toughened and annealed glass, with pressure and impulse pairs determined from the numerical model at locations 1-3 also plotted

5. Conclusions

Explosions in urban environments present a considerable challenge to the blast protection engineering community; not only do such events have the potential to cause significant and widespread damage, but the underlying physical mechanisms governing blast propagation in complex settings are still poorly understood. This work presents a case study of the 2020 Beirut explosion, one of the largest non-nuclear explosions in history. First, video footage posted to social media was used to derive an approximate yield of the explosion. This was then used to inform a high-fidelity physics-based numerical model of a large area of the Port of Beirut using Viper::Blast, a numerical solver specialising in explosion simulations. Finally, results from the numerical model were mapped onto iso-damage curves for toughened and annealed glazing, at select locations in the city, and were compared to available before and after photographs detailing damage caused by the explosion.

Three examples were considered. In the first, extensive cladding damage was observed, which correlated well with the applied loading being well in excess of the iso-damage level and highlighted the level of damage to be expected on buildings located close to the explosive source. In the second example, differences in glazing type were assessed; the applied loading was between the damage curves for toughened and annealed glazing, and different damage levels were observed for two different-aged buildings with, presumably, each of these respective glazing types. In the third example, it was shown that building orientation has considerable influence on damage accrued; windows loaded by the reflected pressure and impulse were seen to fail, whereas windows loaded by the incident pressure and impulse were not.

This clearly shows the benefit of this type of forensic work. Linking real-life observations with the output from sophisticated modelling, with insights gained from approximate, first-order analyses, allows for a better fundamental insight into the nature of urban explosions. From this, it is hoped that more robust and accurate predictive approaches can be developed.

References

[1] Daragahi B., 2020, twitter.com/borzou/status/1290675854767513600, 4th August 2020, retrieved 3rd April 2023.

[2] Dewey J.M., 2021, The TNT and ANFO equivalences of the Beirut explosion, Shock Waves, 31, 95-9

[3] Keane W., Ince R., 2020, August 2020 Beirut Port Explosion Overview, Clarkebond, London, UK

[4] Kingery C.N., Bulmash G., 1984, Airblast parameters from TNT spherical air burst and hemispherical surface burst, Technical Report ARBRL-TR-02555, U.S Army BRL, Aberdeen Proving Ground, MD, USA

[5] Pasman H.J., Fouchier C., Park S., Quddus N., 2020, Beirut ammonium nitrate explosion: Are not we really learning anything? Process Safety Progress, 39, e12203

[6] Ratcliff A., 2021, Estimating the yield of the 2020 Beirut explosion using semi-empirical and indirect methods, MEng dissertation, University of Sheffield, UK

[7] Ratcliff A., Rigby S., Clarke S., Fay S., 2023, A review of blast loading in the urban environment, Applied Sciences, 13(9), 5349

[8] Rigby S.E, Lodge T.J., Alotaibi S., Barr A.D., Clarke S.D., Langdon G.S., Tyas, A., 2020, Preliminary yield estimation of the 2020 Beirut explosion using video footage from social media, Shock Waves, 30, 671-675

[9] Rigby S.E., 2021, Blast wave time of arrival: A reliable metric to determine pressure and yield of high explosive detonations, Fire and Blast Information Group (FABIG) Technical Newsletter, Issue 079, 18-25

[10] Stirling C.G., 2020, Viper::Blast User Manual and Examples for Version 1.17.0. Stirling Simulation Services Limited, Glasgow, UK, ref. VIP18003 201112 CGS V1.0

[11] Wholey W., Abboud J., Rigby S., 2020, Beirut explosion: Preliminary forensic assessment correlating observed damage to predictions from CFD modelling, 7th Workshop of the Australian Chapter of the International Association of Protective Structures, University of New South Wales, Australia, 23rd-24th November

For further information, please contact:

Dr. Sam Rigby
University of Sheffield
E: sam.rigby@sheffield.ac.uk
W: www.sheffield.ac.uk/civil/people/academic/sam-rigby