Institution: University of Sheffield		
Unit of Assessment: B-12 Engineering		
Title of case study: Protecting lives and infrastructure through blast research		
Period when the underpinning research was undertaken: 2000–2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Tyas, A.	Professor of Blast Protection Engineering	1993–present
Clarke, S.	Senior Lecturer	2009–present
Rigby, S.E.	Senior Lecturer	2013–present
Warren, J.A.	Research Fellow	2002–2012
Period when the claimed impact occurred: August 2013–August 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Sheffield's blast-loading research has delivered new insights of high-explosive detonations and protective technologies. Government and agency uptake in the UK, the US, Australia, and Germany has saved tens of millions of pounds in defence expenditure; protected lives through underpinning the development of lighter armour systems for vehicles and better informed military operational strategy; influenced defence and security practices and policies; and enabled new technical standards. Furthermore, application of Sheffield's research has raised public awareness; for example it has been critical in dispelling disinformation surrounding the 2020 Beirut blast being communicated to over 506 million people worldwide.

2. Underpinning research (indicative maximum 500 words)

Whilst the physical principles of large blasts over long distances (e.g. atomic bombs) are well understood, modern-day threats presented by close-range explosions are not.

Although structures and materials can undergo some practical testing to determine their resilience against explosions there is a lack of confidence in the reported data due to poor repeatability. Previous thinking had attributed this situation to variability in detonation blast waves. As such, the semi-empirical blast load predictions used mitigating these threats are often viewed as only 'order of magnitude' estimations.

Research at Sheffield proved that blast wave variability was not due to intrinsic properties but was the result of extrinsic (environmental) factors **[R1]**. Parallel studies demonstrated the suitability of the Hopkinson Pressure Bars (HPB) as a robust shock load transducer capable of measuring intense blast loads **[R2, R3]**.

These insights led to the establishment of the Characterisation of Blast Loading (CoBL) facility, which, using HPBs in carefully controlled experiments, allows repeatable blast tests to be undertaken. The CoBL facility provides direct, reliable measurements to validate, inform and extend the predictive capability of computational tools used by end users (e.g. ConWep).

Specifically, Sheffield's research has provided critical insights into blast load characterisation and blast mitigation techniques.

Blast Load Characterisation: Under "far-field" conditions, the loading mechanism involves impingement of an air shock on a target; however, there is uncertainty in the precise loading to be expected from a given detonation. Sheffield undertook a series of scaled, controlled blast tests, resulting in highly consistent, repeatable datasets focusing on three key areas:

1) **Shock wave arrival time**. A maximum difference of 2.5% was observed between the experimental data and predicted shockwave arrival times **[R1]**.
2) **Blast loading on simple surfaces**. For geometrically simple surfaces, a maximum difference of 7% between the experimental blast data and semi-empirical predictions was observed **[R1]**. This and the previous result gave confidence that predictive tools such as ConWep can be used as a first-order approach when quantifying the shockwave arrival time and subsequent blast loading.
3) **Blast loading on complex surfaces.** For geometrically complex surfaces, current prediction tools fail to model accurately a process known as blast wave clearing. Sheffield's experimental results showed that ConWep significantly over-predicts the cleared impulse on a finite sized target (by 22.2–56.8 %), whereas predictions from the lesser known 1955 Nuclear Blast Clearing Hudson Acoustic Pulse method demonstrate excellent correlation (0.86–4.86%) **[R4]**.

Under 'near-field' conditions the loading mechanisms are significantly more spatio-temporally complex. In addition to an air shock, a rapidly expanding explosive fireball impinges on a target and for shallow buried explosives, amplification occurs. However, there was only limited quantitative understanding of this amplification, hindering the design of protection against land mines. Collaborating with Dstl, the Sheffield team developed world-leading experimental diagnostics in the CoBL facility to address this. Work from 2010-2015 definitively quantified the effect of charge confinement, depth, target distance, soil type and moisture content on the nature, magnitudes, and distributions of the loading on a target **[R5]**. A temporal complexity arises from confined explosives, which are often subject to afterburn, a process by which under-oxygenated explosives continue to burn after detonation. The CoBL facility developed a unique testing capability to conduct experiments in inert and oxygen-rich atmospheres. Test revealed that early-stage afterburn significantly influences the reflected near field shock parameters and a 15-20% blast load reduction in an inert atmosphere can be expected **[R6]**.

3. References to the research (indicative maximum of six references)

University of Sheffield staff and students in **bold**

R1. **Rigby, S. E., Tyas, A., Fay, S. D., & Warren, J. A**. (2014). Validation of Semi-Empirical Blast Pressure Predictions for Far Field Explosions - Is There Inherent Variability in Blast Wave Parameters? *6th International Conference on Protection of Structures against Hazards*. Tianjin, China. http://eprints.whiterose.ac.uk/81237/. Cited by 0.

R2. **Tyas, A.**, & Pope, D. J. (2005). Full correction of first-mode Pochammer–Chree dispersion effects in experimental pressure bar signals. *Measurement Science and Technology, 16*(3), 642–652. https://doi.org/10.1088/0957-0233/16/3/004. Cited by 14.

R3. **Tyas, A.**, & **Watson, A. J.** (2001). An investigation of frequency domain dispersion correction of pressure bar signals. *International Journal of Impact Engineering*, *25*(1), 87–101. https://doi.org/10.1016/s0734-743x(00)00025-7. Cited by 62.

R4. **Tyas, A., Warren, J. A., Bennett, T.**, & Fay, S. (2011). Prediction of clearing effects in far-field blast loading of finite targets. *Shock Waves*, *21*(2), 111–119. https://doi.org/10.1007/s00193-011-0308-0. Cited by 32.

R5. **Clarke, S., Rigby, S., Fay, S., Barr, A., Tyas, A.**, Gant, M., & Elgy, I. (2020). Characterisation of buried blast loading. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *476*(2236), 20190791. https://doi.org/10.1098/rspa.2019.0791 Cited by 0.

R6. **Tyas, A.**, Reay, J.J., **Fay, S.D. Clarke, S.D., Rigby, S.E., Warren, J.A**. & Pope, D.J. (2016). Experimental studies of the effect of rapid afterburn on shock development of near-field explosions. *International Journal of Protective Structures*, *7*(3), 452-465. https://doi.org/10.1177/2041419616665931. Cited by 12.

4. Details of the impact (indicative maximum 750 words)

IEDs are a frequent aspect of current military action. In addition to their use in conventional warfare, IEDs are regularly used in international and domestic terrorism. During the REF period, Action on Armed Violence has recorded 7,729 IED incidents worldwide killing or injuring 113,662 people.

Sheffield's extensive blast protection research has provided critical new insights, developed cutting-edge solutions to combat the global threat of malicious explosive devices, and has "*unquestionably mitigated the risk of terrorist attacks and served to protect the lives of citizens in the UK and abroad."* **[S1]**.

Key examples of the far-reaching impact, achieved during the REF assessment period are:

- Novel insights into the effect of geotechnical conditions on near-field blast loading from shallow-buried explosive charges have been utilised by Dstl and the MoD **[R5]**. Senior Technical Lead for Blast and IED Protection at Dstl states that the research, "*was critical to the development of a new standard UK test method for vehicles against buried charges"*. The test method is now part of Dstl's National Test Annex and this "*has subsequently mitigated tens of millions of pounds in expenditure for test vehicles over the last seven years*" **[S2]**. Furthermore, for the MoD, "*the development of a lighter armour system for military vehicles has also been accelerated by Sheffield's research"* **[S2]**.

- Sheffield's research identifying how soil conditions affect the destructive potential of a buried IED **[R5]** has, according to Dstl Senior Technical Lead for Blast and IED protection, "*enabled predictions of the number of casualties that would be sustained from an IED strike"* **[S2]**. He continued, *"This has better enabled the MOD to formulate safer operational planning for UK armed forces, serving in high-risk areas, choosing the most suitable vehicles for regions where the soil conditions would increase the lethality of the IED threat."* **[S2]**.

- The complex effects from near-field air blasts have been applied by Dstl to advise the Department for Transport on the destructive potential of small IEDs on aircraft, influencing aviation security practises **[R6]**. This work has been recognised internationally and enhanced collaborations between Dstl and government agencies in Germany, Australia, and the US. Dstl Structural Dynamics Fellow stated, "*Professor Tyas' work has influenced the joint test programme between Dstl and the US Transportation Security Laboratory [...], enabling US and UK scientists to better interpret data and accrue considerable savings via enhanced analysis and methodologies.*" **[S1]**. It has also been utilised by the US Air Force Research Laboratory, "*strengthening Dstl's international collaborative collateral, resulting in a more fluid exchange of expertise and valuable data.*" **[S1]**.

- Sheffield's insights have been put into practise by the US Army Engineers Research and Development Centre enabling new predictive capabilities within ConWep to inform protection strategies for army camps and naval bases and to afford anti-terrorism protection to all U.S. government buildings **[R5, R6]**. The work was disseminated to 30 subject-matter experts, including senior leadership. A research civil engineer from the U.S. Army Engineers Research and Development Centre states that "*the University of Sheffield contribution improves ConWep calculations for complex explosive scenarios and the improvements allow us to reduce uncertainties or improve the level of protection*" **[S3]**.
- Blast wave clearing research has been used by the UK Home Office to refine full-scale experimental tests on blast resistant cladding and glazing, contributing to the development of a new international standard: Curtain Walling – Explosion Resistance and its associated Requirements, published in 2020 **[R4]**. As stated by Dstl's Senior Principal Engineer, compliance with this standard, which is used in the design of all government building work, *"can be a very expensive process, with individual tests typically costing several hundreds of thousands of pounds"*. Tyas' work has led to guidance on the most appropriate test set-ups to combine cost-effectiveness, and accurate loading of the test items **[S4]**.
- Blastech Ltd. is a University of Sheffield spin-out company which manages the University's blast laboratory's interaction with practitioners in the blast protection field. It is a vehicle for ensuring rapid take-up of Sheffield's research output. As an example, Blastech managed the liaison with Dstl to turn basic research **[R1, R2, R3]** into the development of the CoBL facility. Blastech subsequently managed eight projects funded by Dstl in which CoBL was used to experimentally characterise blast loading in different aggressive environments **[S1, S2]**. Over the REF2021 assessment period Blastech Ltd. has undertaken experimental work for 32 government agencies and companies in the UK, Europe, and USA **[S5]** with the resulting knowledge enhancing end user capabilities, e.g. the US Army Engineers Research and Development Center **[S3]**.
- Immediately following the Beirut port explosion (August 2020), the BBC's science correspondent contacted Sheffield for expert advice. Through rapid analysis of online videos, Sheffield inverted the Kingery & Bulmash analysis in ConWep to provide an estimate of the explosion size as 1,000-1,500 tonnes TNT **[S6a] [R1]**. This correlated with the expected explosion size from the detonation of the reported amount of locally stored ammonium nitrate, helping quash disinformation on social media purporting that there had been a bomb attack. As more data became available, this initial estimate was refined to 500-1,100 tonnes TNT **[S6b]** and resulted in a story on the BBC News website **[S6c]**. This analysis was covered by MSN, BBC, ITV, most UK newspapers, and dozens

of overseas news of overseas news outlets with a combined global reach of over 506 million people **[S6d]**.

5. Sources to corroborate the impact (indicative maximum of 10 references)

S1. Confidential testimonial letter from the Structural Dynamics Fellow at Dstl (2020). Corroborates a) contribution to collaborative research with Dstl, Department of Transport, US Department of Defence, b) enhancing the reputation of Dstl within the international arena for research collaboration between agencies.

S2. Confidential testimonial letter from the Senior Technical Lead – Blast and IED Protection at Dstl (2020). Corroborates a) cost savings, b) change in MoD operating strategies & c) contribution to military vehicle design.

S3. Press release by US Army Engineers Research and Development Center. September 2020. Reporting the contribution to improving ConWep software blast prediction. (Accessed 25th Sept 2020). https://www.erdc.usace.army.mil/Media/News-Stories/Article/2356759/erdc-partners-with-uk-university-for-survivability-research/

S4. Confidential testimonial letter from a Senior Principal Engineer at Dstl (2020). Corroborates a) contribution to the development of new international standards, & b) associated cost savings due to optimised test set-ups.

S5. Confidential testimonial letter from the Chairman of Blastech Ltd. (2020). Corroborates the range of national and international clients of the University of Sheffield blast protection laboratory.

S6. Collection of published material from press and literature detailing the Tyas groups' work relating to the Beirut grain silo explosion (2020).

a) BBC News: Beirut explosion: What we know so far. (Accessed 17th Nov 2020). https://www.bbc.co.uk/news/world-middle-east-53668493

b) Journal article: **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 https://doi.org/10.1007/s00193-020-00970-z.

c) BBC News: Beirut blast was 'historically' powerful. (Accessed 17th Nov 2020). https://www.bbc.co.uk/news/science-environment-54420033

d) Report from Cision Ltd. (2020). Confirms the reach relating to coverage of Sheffield's Beirut Explosion work.