Institution:	Imperial College London
Unit of Assessment:	12 Engineering
Title of case study:	Building Design for Resilience against Fire and Blast

Period when the underpinning research was undertaken: January 2000 – December 2020

Details of staff conducting the underpinning research from the submitting unit

Name(s):	Role(s) (e.g. job title):	Period(s) employed:
Prof Guillermo Rein	Professor of Fire Science	2012 – present
Prof John Dear	Professor of Mechanical Engineering	2000 - present

Period when the claimed impact occurred: 1 August 2013 – 31 December 2020

Is this case study continued from a case study submitted in 2014? No

1. Summary of the impact

The resilience of buildings to fire and blast is an important engineering objective, particularly for buildings in high profile locations and for national infrastructure. Imperial research in this area has led to new engineering methods for protection against these threats. The methodologies have been used in dozens of iconic projects and are now codified in UK and international standards by ISO, CPNI and BS. The engineering firm Arup, who co-sponsored most of this research, were first to apply the new methodologies, later followed by other firms. Some examples of buildings where Imperial's fire and blast research has been used since 2014 are the Qatar 2022 World Cup Venues, the refurbishment of Battersea Power Station, One and Two New Ludgate, and 52 Lime Street. Impact on outreach includes explaining Fire Science at five exhibitions/festivals attended by over 100,000 visitors, over 20 media engagements on TV, on radio or in popular press, explaining and promoting the relevance of science to millions of viewers, listeners and readers.

2. Underpinning research

The resilience of a building refers to its capacity to recover quickly from extreme loads and spring back into operation. Resilience to fire and blast is an important engineering objective, particularly for large structures in high profile locations like iconic high-rise buildings, and national infrastructure like government buildings. By regulation, engineers must design their structures to sustain fire and blast loads as well as loads due to gravity, wind and earthquake.

Two groups at Imperial's Department of Mechanical Engineering work on building resilience: **Professor Rein** on fire engineering, and **Professor Dear** on blast protection. Both groups have much in common and their work relies on combining high-fidelity computational models with real-scale experiments to produce design methodologies along with validated tools that then have been used in real buildings and codified in international standard.

Professor Rein's group studied the structural fire engineering of buildings and advanced the design methodology of travelling fires, a name that he coined. Until this work, worldwide

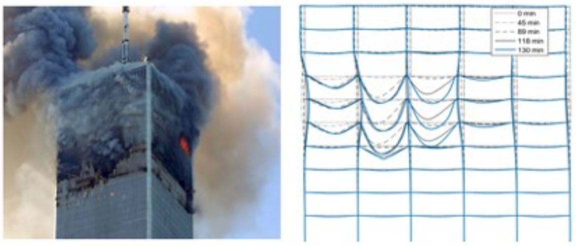

Figure 1: Left) Fires burning inside the World Trade Centre towers on Sept 11 2001. Right) Predicted deformations in a multi-storey structure subjected to a travelling fire [2].

structural design for fire was based solely on the untested assumption that the worst case for structural collapse is a flashover fire. Flashover is where the whole of the room is burning. However, this contradicted careful observations of how fires moved inside the World Trade Centre towers in September 11, 2001. Later on, experiments conducted by Prof Rein showed that in large, enclosed spaces like open plan offices, flashover does not happen. Instead fires travel across the space, producing additional stresses and deformations in columns and beams that can lead to collapse [Figure 1]. Prof Rein's team advanced the design methodology and showed that travelling fires can produce more onerous thermal conditions for the structure than traditional design fires [1] and [2]. Paper [1] puts forward an analytical formulation of travelling fires for design. Paper [2] provides a computational framework of design based on high-fidelity transient simulations, the results of which show that travelling fires trigger previously overlooked structural mechanisms. Paper [3] validates and benchmarks the thermomechanical model at the core of the computational framework.

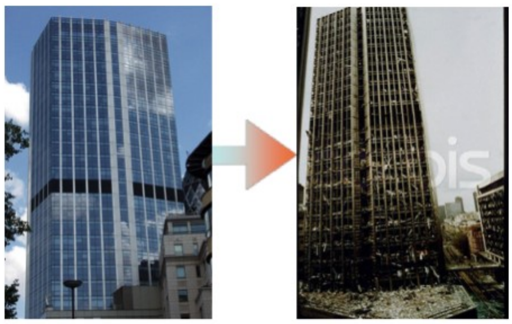

Figure 2: 99 Bishopsgate, 24th April 1993 – Before (left) & After (right) - Courtesy of Arup

As large, glazed frontages become increasingly popular, concern regarding the danger posed by large panels shattering in terrorist or other blasts (for example 99 Bishopsgate in 1993 [*Figure 2*]; South Quay Plaza Docklands in 1996). This is likely to be largest cause of death and injury. Arup has therefore supported Professor Dear's group working on blast mitigation for laminated glass facades. Imperial research has shown that the key factors that dominate blast resistant design are good retention of the laminated glass within the frame, avoidance of tearing of the polymer interlayer and transfer of loads from the frame to the building structure.

Prof. Dear's group was the first to validate the models developed by Arup, in full scale blast trials (up to 500kg of C-4 explosive), using the novel and key experimental methodology of full field deformation profiling of the glass façade, with a combination of 3D speckle and high-speed photography, combined with strain gauging on the support frame (example papers below: [4-6]). Dear's experiments provided independent validation of the displacements from the Arup predictions for full scale explosive charges.

3. References to the research

[1] E. Rackauskaite, C. Hamel, A. Law, **G. Rein**, Improved formulation of travelling fires and application to concrete and steel structures, Structures 3, pp. 250–260, 2015. https://doi.org/10.1016/j.istruc.2015.06.001

[2] E. Rackauskaite, P. Kotsovinos, A Jeffers, **G Rein**, Computational analysis of thermal and structural failure criteria of a multi-storey steel frame exposed to fire, Engineering Structures 180, pp. 524-543, 2019. https://doi.org/10.1016/j.engstruct.2018.11.026

[3] E Rackauskaite, P Kotsovinos, **G Rein**, Model parameter sensitivity and benchmarking of the explicit dynamic solver of LS-DYNA for structural analysis in case of fire, Fire Safety Journal 90, pp. 123-138, 2017. https://doi.org/10.1016/j.firesaf.2017.03.002

[4] Hooper, P.A., Sukhram, R.A.M, Blackman, B.R.K. and **Dear, J.P.**, On the blast resistance of laminated glass, International Journal of Solids and Structures (2012), 49 (6), 899-918. http://dx.doi.org/10.1016/j.ijsolstr.2011.12.008

[5] Del Linz, P., Hooper, P.A., Arora, H., Smith, D., Pascoe, L., Cormie, D., Blackman, B.R.K. and **Dear, J.P.**, Reaction forces of laminated glass windows subject to blast loads", Journal of Composite Structures (2015), 131, 193-206. https://dx.doi.org/10.1016/j.compstruct.2015.04.050

[6] Del Linz, P., Wang, Y., Hooper, P.A., Arora, H., Smith, D., Pascoe, L., Cormie, D., Blackman, B.R.K. and **Dear, J.P**., Determining material response for Polyvinyl Butyral (PVB) in blast loading situations, Experimental Mechanics (2016), 56(9):1501-1517. https://doi.org/10.1007/s11340-016-0179-5

4. Details of the impact

Arup is the first to take up Imperial's work on travelling fires and apply it to the engineering design of multiple high-rise buildings. Their engineers use a performance-based design approach that combines the new travelling fires methodology with traditional fire design. Their computational simulations demonstrated to the authorities that travelling fires were more onerous to the structure and so often defined the worst case scenario [Source A].

The knowledge transfer accelerated when competitors like BuroHappold, Trenton Fire and OFR Consultants were asked by the approving authorities to consider travelling fires in their designs [sources B]. Travelling fires have now been applied in the design of more than 42 iconic buildings in London, Birmingham, and Manchester, including One and Two New Ludgate (City of London building of the year, 2016), 52 Lime Street (the Scalpel), S2 King's Cross, 4 Pancras Square, Kings House, Nova Victoria, UCL Bartlett, and the refurbishment of Battersea Power Station. [source B]. Other buildings in Canada and the Middle East are under design as well [source A]. The success of our research in the application of travelling fire methodology to the structural designs of buildings is clearly demonstrated in Arup and Imperial winning the "**Collaborate to Innovate Award**" in the Built Environment category in 2017 for the structural design of the Scalpel, 52 Lime Street [*Figure 3*] [Source C].

Figure 3: 52 Lime Street - the Imperial-Arup partnership won the **2017 Collaborate to Innovate Award** by The Engineer, for the application of travelling fire methodology to the structural design of The Scalpel [Source C]

The research (specifically that contained in paper [1]) is now being codified in the following standards to be applied worldwide: revised BSI PD7974-1 [source D], revised BSI PD7974-3 [source E], and ISO WD 16733-2:2018(E) [source F]. Also, Travelling Fires Methodology is in advanced panel discussions for adoption in Eurocode EC 1-1-2, and in the Society of Fire Protection Engineering 'Standard on Calculating Fire Exposures to Structures' (international).

The blast resilient design research has been key in validating Home Office and related International guidelines for designing glass façades for high profile landmark buildings, around the world, to resist blast and other threats [source G]. The Imperial research has validated design parameters, e.g. 30 mm adhesive bite depth, providing retention of laminated glass in these Home Office CPNI guidelines [source H].

Figure 4: 100 Bishopsgate (left) World Cup Stadium Qatar (right)

The findings and the CPNI guidelines have been adopted and are now employed in Arup's design procedures for façades and applied to iconic building 52 Lime Street The Scalpel (see *Figure 3*), 100 Bishopsgate, City of London (see *Figure 4*); Canary Wharf Crossrail, London; Qatar 2022 World Cup Venues (*Figure 4)*; Victoria Circle, London and 22 Bishopsgate, London.

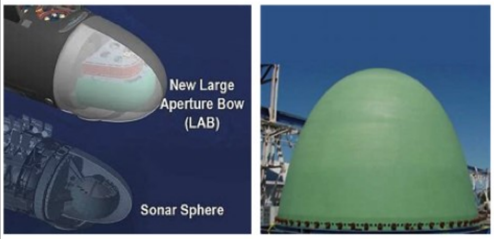

Figure 5: Bow sonar dome design by NUWC applying Dear's research

The techniques of speckle strain mapping (paper [4]) have now been adopted by industry as well as other academics for evaluating full-scale composites structures subject to explosive blast loading. Prof. Dear's group, at Imperial College has been invaluable in providing detailed experimental results on the behaviour of composite structures subject to full-scale explosive blast loading. The data obtained through this research has proven important in designing specialized composite structures for marine applications e.g. composite radar masts, lightweight superstructure with radar absorbent material, bow sonar domes for submarines [*Figure 5*] and composite structures around the submarine's sail (fin/tower on dorsal surface). This work has been used by ONR, General Dynamics Electric Boat, Northrop Grumman and Naval Undersea Warfare Centre, Division Newport [Source I].

Finally Prof Rein's research provided impact through outreach to the general public through exhibitions and media engagements. He and his team organised the "Fire Science" booth at Imperial Festivals in 2017 and 2018 (20,000 visitors each), the Great Exhibition Road Festival in 2019 (60,000 visitors), and took part in New Scientist Live London 2018 and 2019 (40,000 visitors). His work has also featured prominently in a wide range of media (including BBC Two Newsnight (2017), Channel 5 (2017), Channel 4 (2017), Sky News (2015), The Economist (2019), New York Times (2019 x2), Evening Standard (2017), New York Times (2017), Scientific American (2016), Daily Mail (2015), Financial Times (2014), Daily Telegraph (2014), Daily Mail (2014), Wired (2013), Engineering-News Record (2013), BBC 4 Inside Science (2019), BBC Wales (2019), BBC Wales (2016), BBC World Service Click (2016), BBC 4 Inside Science (2014), BBC 4 Material World (2013)) [Source J].

5. Sources to corroborate the impact

A. Letter from Arup on fire engineering and blast design.

B. Letter from OFR Consultants and Chair of the standard drafting committee, confirming Prof Rein's contribution to the BS PD7974 Standard.

C. "Collaborate to Innovate 2017 winners announced", 6 Sept 2017. Announcing Arup-Imperial partnership winning the Award in the application of travelling fire methodology from Imperial to the structural design of the Scalpel building. https://www.theengineer.co.uk/c2i-2017-winners-announced/ Link archived here.

D. BSI PD7974-1 Standard on "Initiation and development of fire within the enclosure of origin". PDF available here.

E. BSI PD7974-3 Standard on "Structural response and fire spread beyond the enclosure of origin". PDF available here.

F. ISO WD 16733-2:2016(E) Standard on Fire safety engineering. PDF available here.

G. Letter from Centre for the Protection of National Infrastructure (CPNI) on Dear's research contributing to CPNI EBP 01/14 guidance note on blast.

H. CPNI EBP 01/14: April 2014 Guidance Note on blast design. https://www.cpni.gov.uk/blast-resistant-measures Link archived here.

I. Letter from Naval Undersea Warfare Centre (NUWC) Newport USA, on Dear's research into blast mitigation of laminated glass contributing to the design of the sonar dome.

J. Demonstration of how fire spreads at Imperial College Science Festival 2017: Fire Sirocco video. https://live.newscientist.com/videos/imperial-hazelab-sirocco-demonstration#/ Link archived here.