Institution: Edinburgh Research Partnership in Engineering – ERPE (Heriot-Watt /Edinburgh)

Unit of Assessment: B15: General Engineering

Title of case study: Fire Safety: Transforming Building Design

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

Enhanced public safety and transformation of structural design for fire has resulted from improved building design through ERPE researchers' development of new and unique design methodologies, frameworks and tools for analysing fire spread. Fire safety engineering research within ERPE has created an improved scientific understanding of the effect of fire on structures and materials. Structural and fire safety engineers across UK, EU, USA, Canada as well as those who are members of international fire safety bodies have subsequently implemented significant advances for the design of safer, more economical, sustainable, and architecturally innovative buildings.

ERPE research has thus assisted the design and construction of increasingly optimised, sustainable, and economical buildings globally with significant changes in building design and regulation, particularly during 2009-2013.

2. Underpinning research (indicative maximum 500 words)

This research team comprises Professors: Bisby, Torero; and Usmani, Senior Lecturers: Gillie; Pankaj; Stratford; and Welch, and Lecturer Carvel (all in post throughout) with, from 2013, Professor Simeoni and Lecturer Hadden. Professor Drysdale retired in 2006 and Lecturer Rein left in 2012.

Fire safety engineering research has been a globally unique strength in ERPE for more than three decades. Beginning with the seminal work on Fire Dynamics, which remains the most important research output and compilation in this field (3rd edition [1], 2011), this topic has remained a major research thrust within ERPE over the last decade and the most important science-based fire safety solutions in the period for REF underlying research include:

Detection, Containment and Suppression of Fires.

The interdisciplinary underpinning research has involved theoretical, experimental, and computational investigations of compartment fire ignition, spread and eventual development to flashover and post-flashover phases, including structural response to fire. A wide range of associated issues have been addressed by the ERPE team, such as detection and suppression at incipient and early development phases and organising fire service intervention for containment, evacuation, fire-fighting, structural response to fire, and forensic assessment of damage including structural integrity after the fire. A key focus during the REF period has been to create an integrated approach to addressing fire safety problems in modern buildings. An exemplar is the 'FireGrid – Integrated Emergency Response System' project (UK DTI/BIS and the Building Research Establishment (BRE), 2005-2009, £2.3M). This included fundamental and applied research on combustion, flammability, fire dynamics, computational fluid dynamics, sensor-steered computational fire simulation, coupled thermal-structural finite element modelling, wireless sensing and communication, and grid computing. The coupled understanding of fire dynamics and structural response developed within ERPE has been applied by leading consultancies such as Arup (Fire Engineering Practice), Section 4.

Performance-based Building Design.

Fire safety researchers in ERPE lead the global community in research promoting holistic, performance-based design of buildings for fire, considering full-structural response and treating fire as a design load. This work commenced with validated, quantifiable modelling of the structural response of the Cardington Fire tests in the mid 1990s [2] and has subsequently transformed industry thinking, practice and regulation around structural design for fire globally. For instance, ongoing Arup-funded research in this area performed within ERPE [3 - 6] has led to the development and implementation of validated computational techniques to describe both fire

dynamics and structural response modelling leading to new methodologies and regulatory frameworks to engineer buildings for fire which continue to revolutionise the fire safety industry. Lane (PhD 1997), Director of Technology Practices (incl. Fire Engineering) at Arup and ERPE visiting professor, was awarded the Royal Academy of Engineering (RAEng) Silver Medal in 2008 for her pioneering work in this area, which was and continues to be underpinned by Arup's ongoing fruitful collaboration with Edinburgh [2, 3]. Approvals by building control and fire services of the first major multi-storey steel-framed office building design by Arup (Lane, Lamont (PhD 2001) in partnership with ERPE researchers [2, 3]), in which fire protection to the structure was based on direct estimation of performance, led to a quantifiably safe building and a significant saving in the cost of fire protection (Plantation Place, London, 2004). Further, ERPE staff were invited by US National Institutes for Standardisation and Technology (NIST) to present their findings (2002-2004); included in the NIST final report on the 9/11 attacks (http://www.nist.gov/customcf/get_pdf.cfm?pub_id=101279). Usmani and Torero also provided analysis to support the (multiple £billions) litigations on the 9/11 collapses requiring the development of validated computational models [4] for the spread of fires in Building 7 of the World Trade Center (WTC) site.

Numerous subsequent successes in this area and ongoing collaboration with industry led to the formation of Edinburgh's BRE Research Centre for Fire Safety Engineering in 2004 with an externally-funded BRE/RAEng Research Chair, £1.3M, and the further hiring of 5 academics (3 of whom are externally funded by industry).

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

References identified with * are those which best indicate the quality of the underpinning research.

[1] Drysdale, D.D., "An Introduction to Fire Dynamics", 3rd ed., John Wiley & Sons, 576pp, 2011, ISBN 978-0-470-31903-1. Available on request.

This handbook provides a reference to all significant fire research, from ERPE as well as many other worldwide researchers and practitioners. All chapters are authored by ERPE staff and they summarise and cite many ERPE advances. More than 3500 copies have been sold since 2008, including 2500 sales since the 2011 launch of the 3rd edition.

[2]* Usmani, A.S., Rotter, J.M., Lamont, S., Sanad, A.M. and Gillie, M., "Fundamental principles of structural behaviour under thermal effects", Fire Safety Journal, 36(8): 721–744, 2001. DOI:10.1016/S0379-7112(01)00037-6. 102 Google Scholar (GS) citations.

Validated novel approaches to computational modelling of the reaction of structures to fire, and paved the way for validated modelling of the assessment of full-structure response to fire. A seminal work in the field of performance-based structural fire design, recognized in the NIST reports on the 9/11 collapses of the World Trade Centre (WTC) towers.

[3] Lamont, S., Lane, B., Jowsey, A., Torero, J.L., Usmani, A.S. and Flint, G., "Innovative Structural Engineering for Tall Buildings in Fire", Structural Engineering International, 16(2): 142-147, 2007. DOI:10.2749/101686606777962549.

Novel, performance-based approaches to engineering structures for fire which have subsequently revolutionised structural fire engineering globally, have created an entirely new class of engineering consultancy, and have allowed the development and implementation of architectural and engineering designs which would not be permitted under existing prescriptive rules (buildings listed in Section 4).

[4]* Usmani, A.S., Chung, Y.C. and Torero, J.L., "How Did the WTC Collapse: A New Theory", Fire Safety Journal, 38(6): 501-591, 2003. (http://hdl.handle.net/1842/1216). 74 GS citations.

The most downloaded paper in the history of the University of Edinburgh's online research archive (ERA), with more than 3900 downloads. Cemented ERPE as leaders in the area of performance-based structural fire engineering and forensics, particularly for coupled thermal-mechanical full-structure finite-element modelling to support failure analysis.

[5]* Rein, G., Torero, J.L., et. al., "Round-robin study of a priori modelling predictions of the Dalmarnock Fire Test One", Fire Safety Journal, 44(4): 590-602, 2009.

DOI:10.1016/j.firesaf.2008.12.008. 27 GS citations.

Instrumental in the organisation of two large studies by the Fire Service in France, and is currently under discussion in the European Committee on Standardisation (CEN) TC127 and International Standards Organisation (ISO) TC92. This is noted in the official documentation of the industry standard Fire Dynamics Simulator (FDS), 7/e (2012). Demonstrated that available fire modelling tools are unfit for purpose leading to investigation on safe design of tall buildings (EP/J001937/1).

[6] Law, A., Stern-Gottfried, J., Gillie, M. and Rein, G., "Influence of travelling fires on a concrete frame", Engineering Structures, 33: 1635-1642, 2011. DOI:10.1016/j.engstruct.2011.01.034.

Demonstrated a novel methodology to consider the structural impacts of travelling fires in buildings. The resulting methodology has been applied on at least 6 Arup projects 2011-2013, and won a best-paper prize and the Lloyd's "Science of Risk" prize for Law's 2012 PhD thesis. A further consequence is that fire regulators in London now require consideration of travelling fires in performance-based fire design for high rise buildings.

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

ERPE research during the 1990s, validating large scale computational modelling of structures in realistic credible fires, has profoundly influenced the use of performance-based design procedures to engineer modern buildings for fire, both from life safety and property protection perspectives. Coupled with research to understand the causes and mechanisms of the fire-induced collapses of the WTC towers in 2001 [4] (and other subsequent collapses), has catalyzed changes in tall building design practice globally. Whereas traditionally buildings have been designed for fire safety based on outdated – and in many cases irrational – prescriptive requirements, ERPE research during the past two decades [1 - 6] has provided the foundational scientific understanding needed to perform a quantified assessment of the fire safety of building designs. Torero was selected to chair the fire safety committee of the Council on Tall Buildings and Urban Habitat (CTBUH) (2009-present) leading also to the project "Real Fires for the Safe Design of Tall Buildings" (EP/J001937/1, £819k) with BRE, Corus, Buro Happold, Arup etc. ERPE research has thus assisted the design and construction of increasingly optimised, sustainable, and economical buildings globally with significant changes in building design and regulation.

Changes to Building Design and Regulation.
Research outputs [1 - 6], in conjunction with the design work of ERPE's industry partners have led to profound changes in regulatory approaches for fire safety globally. The research has catalyzed the development of the fire sections of the Structural Eurocodes (BS EN 1991-1-2, 1992-1-2, 1993-1-2, 1994-1-2) during the period 1995-2002. Further the ideas behind these new regulatory approaches are now being adopted elsewhere, including in the USA by the American Institute for Steel Construction. Collaborations with industry have been fostered from the early development of this research area within ERPE. Direct involvement of industry leaders in key projects (particularly with Lane, Law and Lamont) [S1, S2] has regularly led to adoption of methodologies and tools developed in research within practical design situations. Members of the ERPE fire research group have been involved in translating research into practice through direct participation in building and fire code committees globally, including those of: The American Concrete Institute (ACI, 216); British Standards Institute (BSI, B/525) and European Committee on Standardization (CEN, TC 250); the International Council on Tall Buildings and Urban Habitat (CTBUH, Fire & Safety Working Group); Canadian Standards Association (CSA, S806, S807); National Fire Protection Association (NFPA); and Society of Fire Protection Engineers (SFPE).

A New Class of Design Consultancy.
Since 2008 ERPE's research in this area has created an entirely new class of design consultancy which continues to be applied to great advantage (e.g. Arup, Buro Happold, etc) in UK buildings and elsewhere. Numerous UK buildings have been engineered using performance-based structural fire engineering techniques developed within ERPE [1, 2, 3]. Heron Tower, London (2012) is a particularly good example of the profound impact of ERPE research in real building design. ERPE worked through collaborative research funded by Arup to develop new knowledge and modelling

approaches for predicting fire dynamics in large multi-storey open plan compartments with central atria, as well as advanced computational approaches and procedures for coupled thermal-structural finite element modelling of steel-framed buildings in realistic, multi-floor fire scenarios. The resulting research outcomes led to the first regulatory approval of a tall building fire strategy based on a multiple floor design fire (globally), in addition to enhanced robustness, significantly reduced material and construction costs, and increased safety. Without this research Heron Tower could never have been approved or built.

> *"Research within ERPE has turned on its head the conventional wisdom on how to protect buildings during fires, and the resulting design tools and methodologies are now being used in some of the world's most iconic new structures including Heron Tower, The Shard, and others. The work allows fire protection measures to be targeted at the total response of a structure, taking account of all of the necessary factors; this has helped to establish structural fire engineering as a mainstream skill and has also created an entirely new class of engineering consultancy and exciting business opportunities for Arup and others."* Director of Technology Practices, Arup [S1]

From 2010, BRE Trust [S3] supported the development of novel design methodologies for alleviating travelling fires in modern open-plan buildings [6]. These offer a paradigm shift in the structural engineering of modern buildings, and have led to revolutionary changes in the assumed design fires. These have been implemented by Arup [6] in at least 6 current design projects (e.g. see: Arup, "Structural Fire Analysis: Design Fire Scenarios", 60 Ludgate Hill, May 2012. This report details use of travelling fire analysis developed at Edinburgh in performance-based design of a multi-storey building). ERPE research has thus profoundly altered the way in which iconic buildings are structurally engineered [S4] and will continue to influence optimization and enhanced safety and sustainability of urban environments worldwide.

Industrial R&D and Research Consultancy.
ERPE researchers' innovation in the area of fire safety engineering has led to our involvement in numerous research consultancy projects between 2008 and 2013, including industrial R&D (with Arup, Rockwool, Ruredil, International Paint, Corus), academic research consultancy to support the design consultants of the world's most sought after architects (Arup, Pelli Clark Pelli (USA), and Foster + Partners (UK) [S5]) and litigation/expert witness involvement (e.g. WTC, IFIC Forensics).

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

[S1] Director Technology Practices, Arup (including Fire Engineering), see comments included in Section 4.

[S2] Arup Fire Engineering can verify that" through collaboration with ERPE Arup have developed new knowledge and modelling approaches for fire prediction in large multi-storey buildings…."

[S3] Director Fire Sciences and Building Products, BRE Global Ltd., states that "BRE have collaborated with ERPE to understand better the evolution of travelling fires in buildings…."

[S4] Sustainability Manager, The British Constructional Steelwork Association Ltd., indicates that "ERPE research has profoundly altered the way iconic buildings are structurally engineered…."

[S5] Partner, Foster + Partners, have "used ERPE staff as consultants in fire safety engineering…"

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