Institution: University of Greenwich

Unit of Assessment: (UoA 15) - General Engineering

Title of case study: Fire Safety Engineering Group (FSEG) fire and evacuation research

1. Summary of the impact

The Fire Safety Engineering Groups (FSEG's) research related to fire dynamics, fire modelling, human behaviour and evacuation modelling is saving lives because it is used to design safer aircraft, ships and buildings. Its Economic impact stems from licensing the SMARTFIRE and EXODUS software to over 300 organisations in 32 countries and commercial applications of the software which enable the realisation of cutting-edge designs and enabling the continual safe use of heritage structures such as the Statue of Liberty. Impact on Practitioners is a result of changes to international maritime guidelines based in FSEG research and the wide scale use of the SMARTFIRE and EXODUS software by engineers around the world. Society impact results from its research featuring in a number of popular documentary programmes attracting audiences measured in the millions.

2. Underpinning research

Research into fire dynamics/fire modelling and human behaviour/evacuation modelling at the University of Greenwich started in 1986 and 1991 respectively with a focus on understanding fire and human behaviour in aircraft accidents. In the later 1980s, FSEG fire modelling research was focused on aircraft fire modelling related to the Manchester airport Boeing 737 fire. The work was funded jointly by the UK CAA and the EPSRC. This research utilised commercial Computational Fluid Dynamics (CFD) software to develop one of the first CFD fire models to utilise body fitted co-ordinates in order to accommodate the curved configuration of the aircraft fuselage. Work in fire modelling expanded to include the simulation of fire suppression using sprinklers and water mist. This research focused on developing CFD fire models within commercial third party general purpose CFD simulation software such as PHOENICS and CFX. Limitations of general purpose CFD software, such as its user unfriendliness and limited capabilities to simulate combustion and toxic gas generation led FSEG to begin research, with support from the EPSRC [3a], into the development of a fire specific CFD fire simulation software tool that could be used by fire engineers, the SMARTFIRE CFD fire simulation software [3.1]. SMARTFIRE is an unstructured mesh CFD fire simulation code written in C++ which has been in a constant state of development since its beginnings in 1997. Since 1997 FSEG, with support from industrial funding [3b, 3c] and research grants [3d-3i] has expanded the fire modelling capabilities of SMARTFIRE to include advanced combustion models, toxic gas models, flame spread models and advanced smoke models [3.2-3.4]. The software is used in applications from the built environment to maritime and aviation environments.

FSEG evacuation research started several years after the fire research and was initially concerned with developing a modelling tool that could predict the behaviour of passengers subjected to a post-crash aircraft fire. This early work led to the development of the world's first microscopic evacuation model that coupled fine grained spatial resolution, human behaviour, toxicological models and fire hazard data generated from fire models – this early prototype would later become the airEXODUS evacuation software [3.5]. The research was supported through a series of research grants from the EPSRC [3d] and UK CAA [3e] aimed at developing the prototype into a practical engineering tool that could couple the impact of fire to human behaviour during evacuation. The EPSRC project and the CAA project were aimed at improving the understanding of human behaviour in aviation accidents. The CAA funded project [3e] supported the development of the world's first practical engineering tool to simulate aircraft evacuation – airEXODUS [3.5]. Research continued to be funded through a series of EU funded research projects [3f, 3g] which built on the link between the CFD fire modelling capability of SMARTFIRE and the human behaviour and evacuation modelling capability of the airEXODUS software and expanded the modelling capability of both software tools through the development of advanced combustion models to accommodate modern construction materials and advanced behaviour models to accommodate the interaction of passengers with crew. From 1994, FSEG research into human behaviour expanded to include the built environment. The agent based modelling concept using a fine spatial mesh that was used to simulate aircraft evacuation was adapted to simulate evacuation of people from building environments involving fire. This required the modelling approach to be extended to represent

stairs, the behaviour of people on stairs and various mathematical approaches to represent route finding, interaction with signage, group behaviour, and behaviour in smoke filled environments [3.6]. This research was funded through a variety of grants including [3b, 3c and 3h].

From 1999 FSEG fire and evacuation research expanded to include maritime environments. The ship environment while similar to that of buildings poses additional challenges, such as a heeled deck, the impact of lifejackets on human performance, and the behaviour of passengers in these environments with smoke resulting from fires. Here, the coupling of SMARTFIRE with maritimeEXODUS enabled fire to be reliably represented within a ship evacuation scenario for the first time [3i]. This work was supported by a major EU FP5 project [3i] that not only enabled data to be collected relating to the time required by passengers on ships at sea to respond to the evacuation alarm and begin the evacuation process [3.7], an essential parameter in evacuation modelling, but also data related to passenger performance in dynamic situations involving roll and the impact of smoke on passenger performance in heel and roll situations. Data generated from this work was used in the development of maritimeEXODUS and the interaction of passenger movement in smoke filled corridors subjected to heel.

3. References to the research (REF1 submitted staff in **bold**, and Galea, Gwynne, Filippidis, Patel, Knight and Lawrence are being submitted to other UOA's).

3.1 S Taylor, E Galea, M Patel, M Petridis, B Knight, J Ewer. SMARTFIRE: An Integrated Computational Fluid Dynamics Code and Expert System for Fire Field Modelling. Proceedings of the 5th International Symposium IAFSS, Melbourne, Australia 1997, Ed: Y. Hasemi, pp. 1285-1296. With Galea being a Prof and FSEG group leader, Patel (Reader), Ewer (Post Doc) and Taylor (PhD student) being members of FSEG and other authors being in the same School.

3.2 **Z. Wang**, F.Jia, E.R.Galea, M.K.Patel and J.Ewer, Predicting HCl concentrations in fire enclosures using an HCl decay model coupled to a CFD-based fire field model, Fire and Materials, 31, pp443-461, 2007, DOI: http://dx.doi.org/10.1002/fam.942. All authors were members of FSEG, with Galea being a Prof and group leader, Patel is a Reader, Wang and Jia were Post Docs.

3.3 Jia F, Patel M, Galea E, Grandison A, Ewer J, "CFD Fire Simulation of the Swissair Flight 111 In-Flight Fire – Part 2: Fire Spread analysis", The Aeronautical Journal. Vol 110, Number 1107, pp 303-314, 2006. All authors were members of FSEG, with Galea being a Prof and group leader, Patel is a Reader, Jia, Grandison and Ewer were Post Docs. This paper won the gold medal from the Royal Aeronautical Journal – in 2007.

3.4 Galea, E.R., Filippidis, L., **Wang, Z.,** and Ewer, J., "Fire and evacuation analysis in BWB aircraft configurations: computer simulations and large-scale evacuation experiment", The Aeronautical Journal, volume 114, Number 1154, pp 271-277, April 2010. All authors were members of FSEG, with Galea being a Prof and group leader, Filippidis, Wang and Jia were research assistants. This paper won the bronze medal from the Royal Aeronautical Journal in 2011.

3.5 Owen, M., Galea, E. R., Lawrence, P. J., & Filippidis, L. (1998). The numerical simulation of aircraft evacuation and its application to aircraft design and certification. *Aeronautical Journal*, *102*(1016), 301–312. Retrieved from http://cat.inist.fr/?aModele=afficheN&cpsidt=2335655
All authors were members of FSEG, with Galea being a Prof and group leader, Lawrence is a Reader, Filippidis and Owen were research assistants. This paper won the best paper award from the Royal Aeronautical Journal – The Hodgson Prize in 1999.

3.6 **Xie, H.,** Filippidis, L., Gwynne, S., Galea, E. R., Blackshields, D., & Lawrence, P. J. (2007). Signage Legibility Distances as a Function of Observation Angle. *Journal of Fire Protection Engineering*, *17*(1), 41–64. http://dx.doi.org/10.1177/1042391507064025.
All authors were members of FSEG, with Galea being a Prof and group leader, Lawrence is a Reader, Gwynne and Xie are Post-Docs, Filippidis and Blackshields are research assistants. Xie was a doctoral student who now has a PhD and based part of his doctoral thesis on this work.

3.7 Galea, E. R., **Deere, S.,** Sharp, G., Filippidis, L., Lawrence, P. J., & Gwynne, S. (2007). Recommendations on the nature of the passenger response time distribution to be used in the MSC 1033 assembly time analysis based on data derived from sea trials. *International Journal of Maritime Engineering*, *149*(A1), 15–29. Retrieved from http://gala.gre.ac.uk/id/eprint/1076
All authors were members of FSEG, with Galea being a Prof and group leader, Lawrence was a Reader, Gwynne was a Post-Doc, Filippidis and Sharp were research assistants and Deere was a doctoral student who now has a PhD and based part of his doctoral thesis on this work.

EXAMPLE RESEARCH GRANTS:

3a. E. R. Galea. R+D of the SMARTFIRE Fire Simulation Environment. EPSRC Grant (GR/L56749/01). 1997-2000. £171k.
3b. E. R. Galea. Evacuation analysis of cable fire scenarios. Borealis project, 2001-2002. £30k.
3c. E. R. Galea. Toxicity from cable combustion in fires. Borealis, 2003-2005. £55k.
3d. E. R. Galea. *Fire and evacuation in aircraft environments.* EPSRC Grant (GR/K38250). 1996-1998. £41k.
3e. E. R. Galea. *airEXODUS development.* UK CAA Grant (7D/S/923/1and2). 1997-1999. £113k.
3f. E. R. Galea. *VELA - Very Efficient Large Aircraft.* EU FP5 (G4RD-CT2002-00842). 2002-2004. £130k (UoG component).
3g. E. R. Galea. *NACRE* (Project concerned with fire+evacuation analysis of Blended Wing Body aircraft). EU FP6 (project 516068). Apr 2005 – Mar 2009. €590,000.
3h. E. R. Galea. *HEED Consortium (led by FSEG and Professor Galea involving Universities of Ulster and Liverpool. Project concerned the evacuation of the World Trade Centre).* EPSRC (GR/S74201/01 and EP/D507790). Sept 2004 – Oct 2007. £1.5 million.
3i. E. R. Galea. EU FP5 Fire Exit (contract GRD2-2001-50055). 2001-2005. £325k.

The quality of this research is demonstrated through the award of national and international prizes:

- 2011, Royal Aeronautical Society's Bronze Award for a paper published in 2010, "Fire and Evacuation analysis in BWB aircraft configurations: computer simulations and large-scale evacuation experiment", which appeared in the Aeronautical Journal,
- 2007, Royal Aeronautical Society's Gold Award and George Taylor Prize for the best paper published in 2006, "CFD Fire Simulation of the Swissair Flight 111 In-Flight Fire – Part 2: Fire Spread analysis", which appeared in the Aeronautical Journal.
- 2003/2004 European IST prize by the European Council of Applied Sciences, Technology and Engineering (Euro-CASE) for the development of the EXODUS suite of software.
- 2003 Royal Aeronautical Society Hodgson Prize for best paper on a safety topic for a publication Prof Galea co-authored, entitled, "Examining the effect of exit separation on aircraft evacuation performance during 90 sec certification trials", which appeared in the Aeronautical Journal 2002.
- 2002 Queen's Anniversary Prize, citation:

"The University is a recognised world leader in the area of evacuation model development. Use of its software technology by businesses and public authorities greatly enhances public safety and its specialised training offers vital expertise to the user community worldwide."

- The 2001 RINA/LR Safer Ships Award (Royal Institution of Naval Architects/Lloyds Register).

4. Details of the impact

1) Economic Impact: During the assessment period, Greenwich University Enterprises Limited (GUEL), the commercial arm of the University of Greenwich, has generated over £837k from licensing the EXODUS software to 250 licensees in 32 countries and £230k licensing the SMARTFIRE software to 64 organisations in 16 countries. These licensees, ranging from engineering consultancies, regulatory authorities and national laboratories, use the software to explore the evacuation safety of complex structures, ensuring that they are safe and fit for purpose thereby generating considerable consultancy income. Example projects that have used the EXODUS software include the Airbus A330-X, A340 and the initial design of the Airbus A380 [5.1]. FSEG and the airEXODUS software were used in the preliminary design of the multi-billion euro A380 where it was used to assist AIRBUS in selecting a configuration for the largest passenger aircraft in the world that would meet international regulatory requirements for evacuation. Towards the end of the design programme, Airbus again used FSEG and airEXODUS to de-risk the A380 full-scale evacuation certification trial, saving the manufacturer potentially millions of euro by identifying possible problems that may occur during the certification trial and ensuring that the A380 was a safe aircraft [5.1]. The A380 comfortably passed the evacuation certification trial and is an aviation success story flying with the worlds leading airlines. airEXODUS was also recently (2010) used by JET AVIATION to demonstrate that a private VIP configured B747 and by Mitsubishi (2008) in the design of their new regional jet, would satisfy international evacuation certification requirements [5.2]. Thus airEXODUS is used to save aircraft manufacturers tens of millions of dollars/euros in wasted development costs and lost sales revenues by ensuring that the aircraft will pass the certification trial and thereby also ensures that the design is safe for the travelling public [5.1, 5.2].

A unique version of buildingEXODUS is being incorporated within the security system of the Pentagon as part of project Pentagon Shield. This makes use of special software features e.g. parallel computing implementation, CBRN toxicity model capability (based on the SMARTFIRE developments) to enable faster than real time determination of optimal evacuation routes for building occupants during an incident. Battelle/DoD/Hughes turned to FSEG and buildingEXODUS when US based evacuation software was found to be inadequate, potentially jeopardising a multi-million dollar project [5.3]. Up until quite recently, the SMARTFIRE-EXODUS coupling was the only modelling environment that could bring together the detailed interaction of people and fire. The EXODUS and SMARTIFRE software tools provide fire engineering firms a competitive edge when bidding for projects, allowing them to win important contracts, generating significant income for the companies. An example is the use of buildingEXODUS, under license, by Hughes Associates to undertake an assessment of the life safety and emergency management systems within the Statue of Liberty [5.3]. Following this assessment and remodelling work, the Statue of Liberty was reopened to the public by President Obama in 2009. Another example is the use of SMARTFIRE by Fire Engineering firm FDS on the Greenwich Reach project where it assisted FDS in delivering a project worth over £1 million to FDS [5.4].

2) Impacts on Practitioners and Professional Services: FSEG was the first to collect human factors data defining how quickly passengers respond to evacuation alarms on ships at sea during semi-unannounced drills [3.7]. This work demonstrated that the data used in the International Guidelines on Ship Evacuation Analysis in IMO MSC Circ 1033 was incorrect and could lead to an incorrect assessment of the suitability of a ship design for evacuation. The data and analysis was presented to and accepted by IMO at their Fire Protection subcommittee meeting (FP51) held in January 2007 and now forms part of the revised International Guidelines document, IMO MSC Circ 1238 [5.5]. The data incorporated in MSC Circ 1238 are used around the world in ship evacuation analysis to demonstrate that passenger ships can be safely evacuated [5.6]. As already stated under Economic impact, over the assessment period, the EXODUS and SMARTFIRE software has been used by over 300 licensees in 32 countries and so has become a standard engineering design tool for safety analysis, used by fire safety engineers around the world. The software is therefore having an impact on the engineering profession around the world [5.3 and 5.4].

3) Impacts on Society, Culture and Creativity: FSEG research into fire and evacuation has engaged the public, informing them of our research, educating them concerning risks associated with fire and evacuation and how they can minimise those risks, as well as informing future industrial partners and policy makers. This has been achieved through several high profile TV and Radio programmes which have featured our research such as the BBC 'Horizon' documentary based on FSEG fire and evacuation research, entitled, "How to Survive a Disaster" (first broadcast 10/03/09 on BBC1 [5.7] which attracted a 1.7 million viewer audience representing 7% of the audience that night [5.8]). The concepts presented in this programme were considered so important; the US news programme ABC Nightline featured a story on its nightly news programme broadcast on 22/12/09 which drew on much of the material presented in the Horizon programme [5.9]. Other programs include the Channel 4 documentary "Terror at Sea" (first broadcast 31/01/12 on Channel 4, [5.10]) which followed the sinking of the Costa Concordia. Prof Galea commented on evacuation issues associated with large cruise ships (the programme attracted a massive 3.4 million viewers (http://bit.ly/17BJjP1) which was followed up by an interview on BBC Radio 4 Today (4 March 2012, (http://bit.ly/GAKPrP).

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

5.1 Airbus Chief Engineer, France.
5.2 Mitsubishi Aircraft Corporation, Payload Manager, Japan.
5.3 Hughes Associates, Principal, USA.
5.4 FDS Managing Director, UK.
5.5 International Guideline Document, IMO MSC Circ 1238 - http://bit.ly/15W1tI9, Annex2, p6
5.6 Director Centre for International Cooperation, National Maritime Research Institute, Japan.
5.7 http://bbc.in/15noerY
5.8 http://bit.ly/17BHAJx
5.9 http://bit.ly/1h8jGwP
5.10 http://bit.ly/17BIXHU