Institution: University of Ulster

Unit of Assessment: 16 Architecture, Built Environment and Planning

Title of case study: Innovative Safe Structures in Buildings: STRUCTURES

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

The development of standards and design guides at a European level for composite concrete floors with cellular steel beams has been informed by research undertaken in the Fire Safety Engineering Research and Technology centre (FireSERT), Built Environment Research Institute. Central to the impact is the establishment of technical rules for the fire safe design of buildings constructed with the use of cellular beams. Research at the University of Ulster has demonstrated that the use of unprotected cellular beams can reduce the cost of fire protection. This research was corroborated by a major fire test conducted at an international scientific conference hosted by FireSERT in February 2010. Design guidance for innovative safe structures in fire scenarios have been published in leading journals with high impact factors.

2. Underpinning research (indicative maximum 500 words)

The underpinning research has been developed over a significant period of time with the initial studies funded by EPSRC grants in the late 1990s. In particular the research grant "Performance in fire of restrained columns in steel framed construction" (award of £125K, 1996-1999 to O'Connor (left University 2001) and Nadjai (in post continuously since 1995 and professor from 2004)) was the first substantive research in this area. In 2001, Nadjai advanced this research with further work on the development of innovative structural and economic solutions in steel structural elements and steel cellular beams in buildings.

Stemming from this body of work, Nadjai with Ali (in post from 1996, professor since 2009) highlighted that the structural fire engineering European design code (prEN1993-1-2/prEN1994-1-2 and British Standard BS5950 Part 8) did not contain rules or guidance on the fire resistance of composite floors employing cellular steel beams (http://www.iom3.org/news/cellular-composite-floor-beams-fire-high-temperature published by the Materials World Magazine). This gap in the knowledge base concerning structural fire design for cellular beams has major implications for the construction industry and raises issues in relation to not only the use of a specific product but the wider application of structural steel elements in buildings. Furthermore, in industry there has been much debate concerning the requirements for intumescent coatings. The outcome of this research has been to highlight the need for a uniform European design approach to address the implications arising from the gap in the knowledge base.

Research over the ensuing ten year period (2001-2011) by Nadjai and colleagues has sought to address these issues by focussing on the failure mechanism of the fire resistance of long span cellular beams (grants 3a, 3b, 3c). The first of these research awards (grant 3a) Fire Resistance of Long Span Cellular Beams Made of Roller Profiles (FICEB) funded by CEC Research Fund for Coal and Steel (total value £1.6M) http://www.build.ie/construction_news.asp?newsid=107400 involved the collaboration of major industrial steel manufacturers ASD Westok Ltd (UK) and Arcelor Mittal (Luxembourg), regulators the Steel Construction Institute (SCI-UK) and the Centre Technique Industrial de la Construction Metallique (CTICM- France) and an academic partner the University of Liege. The significance of this research, as discussed in Section 4, was the development of standards and design guides, through the establishment of European codes for the fire safe design of buildings constructed using cellular beams. While grant 3a was concerned with natural fire, the second award (grant 3b) considered the fire resistance of cellular beams, both protected and unprotected, in a furnace fire situation. The results from this aspect of the research have informed British standards for cellular beams in relation to the restraint effect (the effect of the surrounding elements not subject to fire). The third of these, grant 3c, brought together the European codes and British standards regarding resistance of buildings to fire and facilitated dissemination to key stake-holders.

A distinct characteristic of the underpinning research has been the ability to complement laboratory based research by field testing http://www.theengineer.co.uk/Articles/301348/Fiery+research.htm. Innovation is evident in the conducting, by a research team led by Nadjai in February 2010, of a large real scale 3D compartment fire test for a typical office construction (references 3.1, 3.2 and 3.3). The tests were designed to investigate the failure mechanism of long cellular beams, the membrane actions of composite structures and to propose robust design solutions. The scale of the fire test was unique with an invited international audience of scientists and companies sponsoring the event (http://www.firesert.ulster.ac.uk/FSIW/pdf/final-programme.pdf).

The underpinning research on concrete and steel beams and columns by Nadjai and colleagues in FireSERT (references 3.4 – 3.6, grant 3d) has resulted in extensive international collaboration, one example being that with the Korean Ministry of Knowledge Economy (grant 3e) in a research project on the investigation of fire protection requirements which currently do not exist in Korean regulation (Choi lecturer in post since 2008 with Nadjai).The outcome of this research is providing a set of practical design recommendations to satisfy the requirements of fire safe engineering, transferring knowledge from Ulster with specific application in Korea.

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

The quality of the underpinning research is reflected by an extensive portfolio of research papers in leading journals, with high impact factors, concerned with fire testing and structures.

3.1 Nadjai, A, Bailey, CG, Vassart, O, Han, S, Zhao, B, Hawes, M, Franssen, J-M and Simms, I (2011) *Full-scale fire test on a composite floor slab incorporating long span cellular steel beams.* The Structural Engineer, 89 (21). pp. 18-25. http://eprints.ulster.ac.uk/20470/1/8772-89-21%5BstructE%5D.pdf

3.2 Nadjai, A, Goodfellow, N, Kong Fah T, Ali, F and Choi, S (2010) *Analysis of Composite Floor Cellular Steel Beams in Fire.* Journal of Stuctural Fire Engineering, 1 (3). pp. 161-175. 10.1260/2040-2317.1.3.161

3.3 Vassart, O, Bailey, CG, Hawes, M, Nadjai, A, Simms, WI, Zhao, B, Gernay, T and Franssen, J-M (2011) *Large Scale Fire Test of Unprotected Cellular Beam Acting in Membrane Action.* Structural Fire Engineering, 2 (4). pp. 259-267. http://eprints.ulster.ac.uk/20784/1/Nadjai-%5Blarge_scale_fire_test%5D.pdf

3.4 Rafi, M, Nadjai, A and Ali, F (2008) *Finite Element Modeling of Carbon Fiber-Reinforced Polymer Reinforced Concrete Beams under Elevated Temperatures.* ACI (Structural Journal), 105 (6). pp. 701-710. URL: http://www.concrete.org/PUBS/JOURNALS/AbstractDetails.asp?ID=20098

3.5 Ali, F, Nadjai, A and Choi, S (2010) *Numerical and experimental investigation of the behavior of high strength concrete columns in fire.* Engineering Structures, 32 (5). pp. 1236-1243. 10.1016/j.engstruct.2009.12.049

3.6 Scullion, T, Ali, F and Nadjai, A (2011) *Experimental study on performance of elliptical section steel columns, under hydrocarbon fire.* Journal of Constructional Steel Research, 67 (6). pp. 986-991. doi:10.1016/j.jcsr.2011.01.010

The research has been underpinned by several significant research grants achieved from prestigious sources including EPSRC, the EU, the Korean government and the private sector.

3a Nadjai
Fire resistance of long span cellular beams made of roller profiles (FICEB)
CEC Coal and Steel
01/07/2007 to 30/06/2010
£107,650

3b Nadjai and Ali
Performance of cellular composite floor beams under severe fire conditions
EPSRC
01/05/2008 to 31/12/2011
£404,764

3c Nadjai
MACS+: Membrane action in fire design of composite slab with solid and cellular steel beams
CEC Coal and Steel
01/07/2011 to 31/12/2012
£23,671

3d Ali and Nadjai
Behaviour of axially restrained steel columns elliptical sections subjected to severe fire
EPSRC
01/03/2011 to 28/02/2013
£229,586

3e Choi and Nadjai
Development of advanced PBD method for structural fire protection using innovative insulation material
Korean Ministry of Knowledge Economy
01/11/2008 to 31/12/2014
£139,606

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

The impact of the underpinning research on cellular beams is apparent in the construction sector. *Significance* is in terms of the development of a new design concept applicable in all European countries, influencing regulations concerning the sustainability of buildings and cost savings in relation to fire protection. *Reach* extends beyond industry and the construction profession with benefits to wider society in terms of safer building structures in the event of fire.

Contribution to the regulatory environment is evidenced in two principal ways namely development of the European Fire Design Guidance and improvement to the British Standards BS476: Part 20-22 and BS5950 Part 8: Fire Design. Concerning European Design Guidance, the underpinning research, in particular the results from the major fire test (February 2010) and findings from the fire resistance of long span cellular beams project have directly led to the development of a new design code for single cellular beams submitted to fire and extended design guidance concerning the whole floor structure (http://bookshop.europa.eu/en/fire-resistance-of-long-span-cellular-beam-made-of-rolled-profiles-ficeb--pbKINA25122/?CatalogCategoryID=w2wKABst3XAAAAEjfJEY4e5L). The *significance* of the design guidance to industry is highlighted by Arcelor Mittal (corroborating statement 1, source 5.1) with this company confirming benefits in relation to fire protection and more economic designs. Likewise, the findings of the research are directly applicable to manufacturers. For example, ASD Westok identified the impact upon market share and cost savings to the company (corroborating statement 2, source 5.2) while Kingfell (corroborating statement 3, source 5.3) has indicated improvement of the structural performance in fire.

Reach is extensive, key beneficiaries of the guidance stemming from the underpinning research are structural designers using performance based fire design criteria, regulatory authorities at a UK and European level, fire-fighters and the general public who will benefit from safer structures and buildings. The *significance* of the New European Fire Design Guidance, (http://www.ife.org.uk/about/events) Innovative Construction Design for Fire Safety Engineering is emphasised through the development of a European Training Course sponsored by CEC Coal and Steel and supported by the Institution of Fire Engineers and industrial partners. Such proactive dissemination of the Guidance has successfully extended *reach* to constituent groups. For example, RPS Group (corroborating statement 4, source 5.4) provides evidence of the training aspect of the impact and highlights the significance of the workshop sponsored by the European Commission as part of the underpinning research in the grant MACS+: Membrane action in fire design of composite slab with solid and cellular steel beams (research grant 3c).

Further illustration of the benefit of the underpinning research to the construction sector is the findings from the EPSRC grant (grant 3b) concerning the specific impact of the restraint effect on surrounding structural elements during a fire compartmentation. This issue has become a major concern for buildings after 9/11 in which the restraint effect and fire severity ultimately led to the collapse of the World Trade Center Buildings in New York. The research findings from this grant have shown how building collapse can be avoided by taking into consideration the axial effect (the additional forces transferred from the cold surrounding structural elements to the element under fire) at the fire design stage and thereby having more robust structures. S*ignificance* arises from reduction in the cost of damages and *reach* relates to societal benefit across a range of stake-holders by improving safety to occupants/users in the event of fire occurring (http://www.westok.co.uk). As a consequence of the research (notably references 3.1 - 3.3, grants 3a and 3b) the prescriptive "rule" specified in BS5950 Part 8:1990 for beams with web openings requiring 20% extra coating thickness, compared with solid-web beams, was withdrawn from the Steel Construction Institute (SCI) approved document AD269. This significant change in the British Standard has been verified by the Steel Construction Institute (corroborating statement 5, source 5.5).

The benefits flowing from the new design guidance, developed from the underpinning research, is to ensure maximum operational use with regard to the life expectancy of the structure, irrespective of the building layout. Furthermore, the analytical techniques developed by FireSERT have been utilised at an international level as evidenced by Kingfell (corroborating statement 3, source 5.3) and Beyond Fire (source 5.6) in regard to best practice. Commercially there has been benefit to long span construction and an increased market share of steel beams. As an illustration of the commercial benefit, ASD Westok suggests a cost saving of circa £3 to 5 million per annum (corroborating statement 2, source 5.2). The *significance* extends beyond cost. For example, when cellular steel beams are used in multi-storey buildings the reduction in the total weight of the steelwork has the benefit of decreasing the depth of floors required to accommodate pipes, conduits and ducting thereby yielding significant benefit to the construction sector regarding the development of certain multi-storey buildings and the users of these buildings. Details of the application and benefit of this research on cellular beams to industry has been highlighted on the ASD Westok web site (http://www.westok.co.uk) with specific reference to the underpinning research at FireSERT (source 5.7). Wider community impact and interest is evidenced through extensive media reporting of the significance of the research and the safety of buildings in the event of fire (source 5.8).

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

Electronic copies of all sources including web links can be provided.

5.1 Corroborating statement 1 - Director, Arcelor Mittal

5.2 Corroborating statement 2, Technical Manager, ASD Westok

5.3 Corroborating statement 3, Chairman, Kingfell Ltd

5.4 Corroborating statement 4, Senior Engineer, RPS

5.5 Corroborating statement 5, Senior Engineer, SCI

5.6 Beyond Fire: http://www.beyond-fire.com/index_files/Page418.htm

5.7 ASD Westok Ltd: http://www.asdwestok.co.uk/Technical+Support/Fire+Engineering.htm

5.8 http://www.bbc.co.uk/news/uk-northern-ireland-20370563