Institution: Queen's University Belfast

Unit of Assessment: 14 Civil and Construction Engineering

Title of case study: £ millions saved by London Underground and Bridge Owners through research by QUB team

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

£80m has been saved since 2008 by London Underground (LU) and yet more by bridge owners in the UK as a direct result of using the Arching Action (AA) enhancements in strength predicted by our research. The associated disruption would have resulted in enormous congestion, losses economically of £ billions and negative social impact. Multi-million $ savings have also accrued in North America from the use of corrosion free deck bridges, which have minimum maintenance, as has our innovative flexible concrete arch (patented 2004) which has been used for over 40 FlexiArch bridges (£15m in contracts) since 2008.

2. Underpinning research (indicative maximum 500 words)

Background. Reinforced concrete slabs in structures have much higher strengths than predicted by flexural design methods which are widely used in practice. Depending on the degree of lateral restraint the strength enhancement due to AA can range from a few percent to over three times the predicted flexural strength. Likewise Arches have enormous reserves of strength whilst being aesthetically pleasing and highly durable.

As the leading AA research team in the UK and acknowledged internationally (see Wikipedia article in this area) much of the research undertaken by Adrian Long (since 1971), Barry Rankin (since 1989), A Mufti (ISIS Canada since 2000 and part-time QUB since 2012), David Cleland (since 1983), Desmond Robinson (since 1985), Su Taylor (since 2004) and Danny McPolin (since 2008) in conjunction with Jim Kirkpatrick (ex-Bridge Engineer, DRD Roads Service) and Abhey Gupta (Macrete Ireland Ltd) – is targeted at mastering the fundamentals so that reliable systems are developed for use in the construction industry.

Arching Action. The interaction between arching and flexural action is very complex and required much experimental work and parallel analytical studies to derive viable prediction methods which have provided solutions for flat slab structures, bridge deck slabs, cellular offshore concrete structures and composite floor slabs. Greatly improved prediction methods have been developed which have been simplified by our team for inclusion in (BD81/02(2002)) for use by designers (so that they could assess the strength of laterally restrained slabs in practice). This has permitted a 70% reduction in the amount of reinforcement in bridge deck slabs. However recognising that most of the research had been published in highly technical journals Long (Ref. 1) highlighted the potential benefits to practitioners at a lecture in the Institution of Civil Engineers in 1994,. A number of innovative advances were highlighted by Long which led to an increase in awareness in the UK of the potential benefits of AA through the use of high strength/fibre reinforced concrete, centrally located conventional steel reinforcement and corrosion free fibre reinforced polymer (FRP) bars in deck slabs. They also led to an upsurge in experimental and analytical research in this area at Queen's University (Ref. 2) which was backed up by full-scale testing on site. Highly rated papers in the Journal of the ICE were published in 1997 (Ref. 2) and 2001 (Ref. 3,4), (including two Telford Premium Awards by ICE). A regular stream of PhDs have been awarded at QUB and numerous Journal papers published in this important area of research, eg 2007 paper in a US Journal (Ref. 5).

In Canada researchers (Mufti et al) also identified the innovative advances due to Arching Action and focused on the development of corrosion-free deck slabs for steel-concrete composite bridges and demonstrated to industry in Canada that such systems were not only viable but required minimal maintenance. As in Canada the quest for maintenance-free bridges, based on the benefits of arching action, has been a central focus at Queen's. Thus Mufti, then President of ISIS Canada in Winnipeg, accepted the invitation to contribute part-time at QUB because of his ongoing

involvement in AA research and his overlapping research interests with the Belfast team.

Flexible Concrete Arch. In 1994 Professor Long recognised that maintenance free bridges could be based on the arch form of construction. Few arch bridges had been built since the early 1900's even though they are aesthetic, strong, durable and require little maintenance. However, the centring and preparation of the voussoirs by stone masons incurred cost and time penalties which made them non-competitive with RC, PC or steel alternatives. Subsequent research at Queen's could not be published until the innovative flexible concrete arch system was patented (Long AE, Int. Patent No W.O.2004/044332A1). Macrete Ireland were licensed to manufacture the 'FlexiArch' and since 2008 over 40 bridges have been installed in the UK/Ireland. Extensive research has been carried out in parallel and this has included model tests in the laboratory, full-scale testing at Macrete, field testing and analytical research using a range of approaches (Ref. 6).

Quality of Research. This has been recognised through 9 awards/medals to members of the team and contributed to Professor Long receiving the highly prestigious Ewing Gold Medal of the ICE/Royal Society in 2009 and the Institution of Civil Engineers Gold Medal (ICE's premier award) in 2011.

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

Selected Publications

1. Long AE, Kirkpatrick J and Rankin GIB, 'Enhancing influences of compressive membrane action in Bridge Decks', Bridge Modification 94, Proceedings of Seminar, ICE, London, March 1994, pp 217-227.
2. *Rankin GIB and Long AE, 'Arching action strength enhancement in laterally restrained slab strips', Proc ICE, Structures and Buildings, Vol 122, Issue 4, Nov 1997, pp 461-467. (Awarded Telford Premium by ICE in Nov 1998).
3. Peel-Cross J, Rankin GIB, Gilbert SG and Long AE, 'Compressive membrane action in composite floor slabs in the Cardington LBTF', Proc ICE, Structures and Buildings, Vol 146, Issue 2, May 2001, pp 217-226. (Awarded Telford Premium by ICE in Nov 2002).
4. Taylor SE, Rankin GIB and Cleland DJ, 'Arching action in high strength concrete slabs', Proc ICE, Structures and Buildings, Vol 146, Issue 4, Nov 2001, pp 353-312.
5. *Taylor SE, Rankin B, Cleland DJ and Kirkpatrick J, 'Serviceability of bridge deck slabs with arching action', ACI, Structural Journal, Vol 104, Issue 2, Jan-Feb 2007, pp 39-48.
6. *Long AE, Kirkpatrick J, Gupta A, Nanukuttan S and McPolin D, 'Rapid construction of arch bridges using the innovative FlexiArch', Proc ICE, Bridge Engineering, Vol 166, Issue 3, Sept 2013, DOI: 10.1680/bren.11.00036.

External funding for Arching Action research

1994-96 (GR/J51351/01) Influence of in-plane effects on composite slabs, EPSRC £95k.
1995-98 (GR/K57138/01) High strength concrete in bridge deck slabs, EPSRC £152k + £100k from DRD Roads Service (NI).
2009-11 Monitoring FRP reinforcement in a concrete bridge deck, UK Bridge Owners Forum £120k + £100k from DRD Roads Service (NI).

External funding for FlexiArch research

Three Knowledge Transfer Partnerships with Macrete on various aspects of the FlexiArch; 2004-6 £105k, 2007-9 £119k, 2010-12 £125k
Major Technology Strategy Board (TSB) project on Low energy concrete with Macrete and Creagh Concrete with input by Network Rail and Arup, 2008-11 £2,100k
A number of smaller grants from Concrete Bridge Development Group, Leverhulme Trust, ICE R&D Fund and RAEng Global Research Award over period 2005-12, total £65k.
In parallel Macrete have been awarded three Invest NI grants with a total value of £1,300k (including contributions of over £900k by Macrete) over the periods 2004-7, 2008-11 and 2011-14. This facilitated invaluable full scale tests where the QUB team coordinated testing/monitoring, the analysis of data and prepared the reports.

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

London Underground (LU). In the early 1990s, LU were confronted with a major dilemma. Having assessed over 1200 platforms on the underground system they found that when flexural methods of design were applied most platforms were found to be structurally deficient. Thus a major repair/replacement programme appeared to be inevitable (LU estimated replacement cost of a typical platform was £1.6 million). However, structural engineering staff of LU had become aware of our research through Journal papers (Ref 1) and of the potential benefits of arching action in cellular structures. By adopting our research findings, unique new design guidelines for LU platforms were drawn up in the late 1990's but it was only in 2005 that these were approved for use in the LU system. Taking into consideration the benefits of arching action in their assessment programme allowed 95% of their platforms to be retained and since 2008, LU staff have estimated that over £80m has been saved (cost of structural repair/replacement). Here it should be noted that by avoiding the repair/replacement of the vast majority of their platforms the enormous disruption to the transport system in London has not occurred which would have been an additional drain on the UK economy as well as being socially unacceptable. Bearing in mind that over 1 billion people use the LU system each year the cost (due to the loss of productivity) of the associated congestion has been acknowledged by LU staff to be '£billions not £millions' (see Section 5).

Thus LU would have had to accept the prospect of enormous disruption to their system had their staff not been able to take into account the benefits of AA.

Bridge Deck Slabs, UK and North America. Our research has impacted on policy which allows bridge designers/assessors to take account of the benefits of AA, e.g. less deck reinforcement, not having to replace decks found to be unsatisfactory using flexural analysis and indirect savings as disruption/congestion is minimal. Consequential savings are likely to be of the order of tens of £ millions over the past 5 years, however the overall benefits have not been quantified by the UK Highways Agency.

In N America the considerable benefits of corrosion free deck bridges has been embraced in most Canadian Provinces and in a number of northern states of USA arising from the parallel research by Mufti and his research team. Over 50, (mostly multi-span) bridges have been constructed and ISIS have estimated that long term savings of hundreds of $ millions have/will accrue through minimal maintenance, dramatically reduced life cycle costs and losses to the economy resulting from disruption/congestion associated with repair/replacement. The system is now being utilised for highly prestigious projects such as the Winnipeg Floodway – a major $ 700m project in Manitoba where 6 multi-span bridges were built in 2009.

Since 1994 the QUB team and Mufti's researchers have derived mutual benefit from their overlapping AA research. In the USA and Canada AA research has impacted on bridge construction since the late 1990's and, as far as REF2014 is concerned, through the past 5-6 years.

'FlexiArch'. As already highlighted in Section 2, conventional arches are expensive to build and take much longer to construct than beam and slab bridges made up of prefabricated components. To counter this, an innovative flexible concrete arch was devised and patented in 2004. As this does not require expensive centring the arch can be quickly constructed (days rather than months for a conventional arch) and by using precast concrete voussoirs it can be manufactured at a relatively low cost. All the basic features of a conventional arch are retained and in 2005 Macrete Ireland Ltd (Toomebridge) were licensed and since 2008 over 40 bridges ranging in span from 4m to 15m have been installed in UK/Ireland. Its potential was anticipated in 2006 at an International conference when Brian Bell, Network Rail, acknowledged that the FlexiArch would allow highly durable arches (seldom used since 1900) to compete with other rapid methods of construction (crucial for railways).

This innovative system has received 9 awards including the Best Engineering Excellence Award of

RAEng (2009) and the UK National Construct Award for Innovation and its adoption twice (in 2009 and again in 2013). Commercially the 'FlexiArch' has had a very significant impact in a severely depressed market, and since 2008 an extra 50 person years of employment have been generated at Macrete. In addition, the 'FlexiArch' system has been a key element in winning the associated construction contracts, valued at £15m. A number of leading precast contractors in Europe, N America and Australasia have approached Macrete to acquire a sub-licence for the FlexiArch in their regions – these would greatly enhance the future use/impact of the FlexiArch. More details of the system are given in Ref (6).

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

- **Arching Action**
  - London Underground (LU), Benefits for Cellular Concrete Structures/Railway platforms taken into account by Structural Engineering staff at LU (Letter of confirmation has been provided by LU)
  - Wikipedia – 'Arching or Compressive Membrane Action in Reinforced Concrete Slabs' gives an invaluable overview of the benefits of research in this area for bridge decks and cellular structures

- **'FlexiArch' System**
  - www.macrete.com (FlexiArch)
  - YOUTUBE – FlexiArch – Construction of 14m span 'FlexiArch' bridge at Sheinton in Shropshire (2010) and refurbishment of Ashton bridge in Manchester (our entry won the UK National Construct Award in 2013)
  - Macrete (A letter confirming number of FlexiArch bridges installed and their total contract value has been provided by the Managing Director)
  - Network Rail (A letter confirming that the FlexiArch could allow arches to be re-established as the prime method of construction for short span bridges (a position they enjoyed prior to 1900) has been provided by the Head of Civil Engineering R & D)