Institution: University of Bath

Unit of Assessment: 16: Architecture, Built Environment and Planning

Title of case study: Prolonging the Life of our Concrete Infrastructure

1. Summary of the impact

Research within the Building Research Establishment's sponsored **Centre for Innovative Construction Materials** (CICM) at the University of Bath has allowed the life of concrete structures to be extended through developing (a) proper methods for assessing existing capacity and (b) the means to increase capacity where necessary. This has prevented buildings and bridges (managed, for example, by large asset owners such as the Highways Agency and Network Rail) from being condemned as unfit for purpose, resulting in vast savings in reconstruction costs and preventing disruption to infrastructure users. The work has led to the researchers being commissioned to write guidance documents that are routinely used by infrastructure owners and consulting engineers worldwide. Over the course of the last eight years this has resulted in several £millions of savings to infrastructure owners and the UK economy.

2. Underpinning research

Staff Involved: Tim Ibell (1997 to date: Senior Lecturer, Professor) and Antony Darby (1999 to date: Lecturer, Senior Lecturer, Reader) with Jon Shave (2000-03: PhD student), Pierfrancesco Valerio (2003-06: Research Officer) have spent the last thirteen years at the University of Bath working in the field of *assessment* and *strengthening* of concrete infrastructure.

Assessment

Between 2000 and 2003, Ibell led EPSRC project GR/N07059/01[1] (with Shave) investigating the shear capacity of bridges with insufficiently anchored reinforcement. This problem was associated with bridges built prior to 1972, designed to standards considered insufficient today. Existing assessment guidance led to these bridges being condemned. However, this 'Federation Internationale du Beton' award winning research developed a plasticity approach as the basis of a simplified assessment procedure which showed that in many situations the capacity of these poorly detailed structures was, in fact, sufficient [2].

More recently (2003-2006) an EPSRC project GR/S18144/01[3] led by Ibell and Darby (with Valerio) has provided a shear assessment methodology for bridges constructed using prestressed beams, laterally post-tensioned together, which form part of the UK rail network. Existing assessment methods for these bridges ignored the effect of lateral prestress on capacity. The research showed that this prestress increased capacity by over 40%, even if much of the prestress was lost. A plasticity approach was developed to allow realistic assessment of these bridges [4].

Strengthening

As part of the same EPSRC project [3], Darby and Ibell developed a strengthening method for when these bridges were found to have inadequate capacity. The method, termed deep embedment strengthening, involves Fibre Reinforced Polymer (FRP) rods glued into holes drilled through the beams to act as additional shear reinforcement [5]. This 'Institution of Civil Engineers' award winning method is ideal for structures where the sides of beams are inaccessible, preventing use of conventional externally applied FRP. The technique is more efficient and ductile than alternative methods and can be applied to slabs as well as beams.

Further research led by Darby and Ibell from 2000-present, has examined other issues related to FRP strengthening of concrete structures such as the effect of curved soffits, the presence of live load, the effect of concrete cracking and moment redistribution in FRP strengthened structures [6][7][8]. This work was incorporated into the second edition of the Concrete Society's Technical Report (TR) 55 (published in 2004), the UK guidance on strengthening concrete structures.

Following publication of TR55 further projects commenced to address the gaps which limited the use of FRP strengthening. This led, between 2007 and 2010, to Darby and Ibell examining FRP wrapping of rectangular columns (EPSRC grant EP/E039901/1) [9], the first time that such columns had been examined at large-scale, under combined axial and bending loads. The technique was shown to be effective and a mechanics based model was developed.

3. References to the research

[1] EPSRC Grant GR/N07059/01 Effects of inadequately anchored reinforcement on the integrity of existing concrete bridges

[2] Shave, J.D., Ibell, T.J. and Denton, S.R., 2007. Shear assessment of reinforced concrete bridges with short anchorage lengths, *The Structural Engineer*, 85, pp. 30-37. http://www.istructe.org/journal/volumes/volume-85-(published-in-2007)/issues/issue-5/articles/shear-assessment-of-reinforced-concrete-bridges-wi

[3] EPSRC Grant GR/S18144/01 Realistic shear assessment and novel strengthening of existing concrete bridges

[4] Valerio, P., Ibell, T. and Darby, A., 2011. Shear assessment of prestressed concrete bridges, *Proc. of ICE Bridge Eng.,* 164(4), pp. 195-210 (DOI:10.1680/bren.2011.164.4.195)

[5] Valerio, P., Ibell, T. and Darby, A., 2009. Deep embedment of FRP for the shear strengthening of concrete. *Proc. of ICE, Structures and Buildings*, 162 (5), pp. 311-321. (*Winner of the ICE Bill Curtin Medal)* (DOI: 10.1680/stbu.2009.162.5.311)

[6] Ibell, T. J., Darby, A. P. and Denton, S., 2009. Research issues related to the appropriate use of FRP in concrete structures. *Construction and Building Materials*, 23 (4), pp. 1521-1528. (DOI: 10.1016/j.conbuildmat.2008.05.011)

[7] Darby, A. P., Denton, S. R. and Ibell, T. J., 2009. Influence of changes in cross section on the effectiveness of externally bonded FRP strengthening. *Journal of Composites for Construction*, 13 (3), pp. 208-216. (DOI: 10.1061/(ASCE)CC.1943-5614.0000005)

[8] Darby, A., Ibell, T., Clarke, J., Denton, S., Farmer, N. and Luke, S., 2004. Strengthening concrete structures using fibre composites. *Proc. of ICE Bridge Eng.*, 157 (BE3), pp. 123-129. (DOI: 10.1680/bren.2004.157.3.123)

[9] EPSRC Grant EP/E039901/1 Modelling of realistically sized and loaded FRP confined rectangular reinforced concrete columns

4. Details of the impact

The Highways Agency (the UK's largest bridge owning authority) and Network Rail are responsible for maintaining almost 12,000 concrete bridges, constructed as far back as the 1920s. The underpinning research has directly fed into various design and maintenance guidance documents which have allowed the aging stock of bridges and structures to remain in service throughout the UK and worldwide during the REF period and into the future.

Design Guides and Standards

Bath's research on strengthening structures using FRPs established the team's credentials to lead the writing of the UK's guidance on strengthening concrete structures using advanced composites, the Concrete Society's TR55 (2nd ed. 2004). The findings of Bath's strengthening research are incorporated into the document, forming essential clauses associated with maintaining structural integrity, which must be complied with when considering any FRP strengthening scheme. This edition is recognised as a leading document in the field and its reach has been Worldwide.

The Technical Advisor of the Concrete Society comments with regard to TR55: "We have had enquiries about it from Australia, New Zealand, Hong Kong and Singapore. Clearly it is highly thought of in Singapore. Material supplier, Fyfe Asia, specifically asked to be involved with both the Second Edition and the present project [the third edition of TR55]. It is used in preference to the ACI documents in regions of the world where the design codes are based on British Standards rather than American Concrete Institute. In the UK, it is of course the document of choice for Highways Agency, Network Rail and London Underground." [1]

For example, TR55 was consulted when designing the strengthening of the West Gate Bridge cantilevers in Australia (completed in 2011), as part of a $240M upgrading scheme [2]. It has also informed key design clauses in the American Design Standard (2008), ACI 440.2R-08 [3] as evidenced by direct reference to TR55. The success and significance of this document has been recognised by both the Concrete Society and industry, leading to commissioning of a third edition, again led by the Bath team [4]. This third edition (2012) contains additions based on Bath's more recent research (deep embedment shear strengthening and column strengthening). This allowed the first use of Bath's deep embedded bar technique to increase the load capacity of a coffered floor slab in a data storage centre in London in 2012 (a £315k contract), the only feasible method to carry out the strengthening [5].

Additionally, the Highways Agency (HA) requires designers using FRP to strengthen HA infrastructure to comply with their document, BD85/08, which was revised in 2008 to incorporate the approaches that Bath had developed for TR55 in 2004 (http://www.dft.gov.uk/ha/standards/dmrb/vol1/section3/bd8508.pdf). The techniques developed by Bath for dealing with inadequately anchored reinforcement were also incorporated into a recent revision of the Highways Agency bridge assessment document, BD44, to be published in 2014. This document too must be complied with by designers when dealing with HA structures.

Engineering Consultants

The research on *assessment* of inadequately anchored reinforcement was carried out in collaboration with the HA and Parsons Brinckerhoff, a leading engineering consultant. One of the Bath researchers involved in the work (Shave) is now employed by Parsons Brinckerhoff and he exploits the technique for the benefit of their clients. During structural assessment, they regularly encounter situations where anchorage of reinforcement is short/unknown. The techniques developed by Bath allow them to assess the adequacy of these structures.

The Regional Associate of Parsons Brinckerhoff states: "The research carried out at Bath University on the shear assessment of concrete bridges with short anchorage details has resulted in significant economic and operational benefits related to the management of concrete bridges. The particular issue identified in the research has cropped up in around 5 of the bridges that Parsons Brinckerhoff has assessed since 2008 for Local Authority clients responsible for maintaining the local road network. Without the findings of Bath's research, these structures would have needed very expensive replacement or strengthening works amounting to hundreds of thousands of pounds. However, we were able to advise the clients on suitable management strategies including refined assessment methodologies based on the direct application of the research, and this has allowed these structures to remain in service. In addition, through effective dissemination of the research, the benefits have been realised to a greater extent across the industry, including the incorporation of the methodology into the standard for assessment of concrete highway structures, BD44." [6]

The Concrete Society's TR55 document allows consultants to propose efficient, cost effective *FRP strengthening* schemes where, otherwise, strengthening would be unfeasible or prohibitively expensive. For example, consultants Tony Gee and Partners, in the last two years alone, have carried out approximately 16 FRP strengthening schemes, designed according to TR55.

The Executive Director, Tony Gee and Partners comments: "The publication of TR55 and subsequent update, have given clients the confidence to specify the use of FRP materials. The research carried out at Bath and elsewhere, together with contributions made by many respected designers, provides evidence that the procedures in the document are robust, efficient and safe. We no longer have to justify the robustness of the technique to clients, who are delighted that we are able to preserve structures that would otherwise need to be replaced at major additional costs. We have even used the document to promote the technique overseas, building a portfolio of over 200 FRP strengthened structures." [7]

Apart from preventing needless demolition of structures, whose replacement cost would run into £millions (replacement of a two lane concrete motorway bridge costs £1.5M-£2M), large savings (hundreds of £thousands) are made, compared to conventional strengthening methods, due to improved construction speed, site safety, and reduced road closure costs. Another example of the impact of this work is a £160,000 strengthening scheme in 2010 by engineering consultants Mouchel for Minsterley Bridge, a Grade II listed concrete arch bridge which provides the primary means of access to Minsterley. Research carried out at Bath on curved soffit strengthening was used directly in the scheme, as too was TR55 [8]. This allowed removal of a 7.5 tonne load restriction, providing full lorry access for the benefit of local business.

Bath's FRP strengthening research has also been disseminated since 2003 through our undergraduate 'Advanced Composites in Construction' taught unit. Graduates have used these techniques in practice. For example, in 2009, Graduate Engineers at Integral Structural Design designed extensive FRP strengthening as part of the refurbishment of Temple Circus in Bristol, providing floor slab cut-outs for stairs and services, extending the usable life of the building [9].

Infrastructure owners

Bath's research, via TR55 and BD85/08, has fed into five major composite strengthening schemes on HA owned concrete bridges since 2008, costing between £100,000 and £600,000 each. The Bath research incorporated into TR55 has also benefited Network Rail, who state that they make savings well in excess of 30% (typically saving £200,000 per bridge) by adopting FRP strengthening schemes, compared to conventional techniques. They estimate that, over the last 5 years, the savings have totalled in excess of £5 million [10]. While not all are concrete structures, this indicates the scale of economic savings on bridges that have been made possible using the techniques developed and disseminated by the Bath team.

Network Rail was closely involved in the project on assessment and strengthening of laterally prestressed beam bridges. The work reassured Network Rail that the affected bridges were not in danger and they have therefore not been prioritised for further investigation, allowing financial and manpower resources to be directed towards more critical structures.

Society and the economy

The economic cost associated with lane closures due to bridge maintenance, as calculated according to Highways Agency BA 28/92, is usually the highest cost associated with such works (typically £10,000-£50,000 per lane, per day). Although difficult to quantify, considering the number of bridges strengthened or assessed by the HA, Local Authorities and Network Rail since 2008, the economic savings as a result of Bath's research is clearly several £million.

5. Sources to corroborate the impact

[1] Technical Advisor of the Concrete Society, email 12/04/2011.

[2] Section Manager: Bridges - Roads and Rail, SKM consulting, email 6/10/2012.

[3] American Concrete Institute, 2008, ACI 440.2R-08: Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures.

[4] Concrete Society, 2012, Technical Report 55 - Design Guidance for Strengthening Concrete Structures Using Fibre Composite Materials – third edition, Blackwater, Surrey.

[5] Technical Manager, fibrwrap UK Offices, email 31/01/2013.

[6] Regional Associate of Parsons Brinckerhoff, email 8/04/2011.

[7] Executive Director, Tony Gee and Partners, email 7/04/2011.

[8] Canning, L. 2011, Minsterley Bridge Strengthening Using Novel Materials, *Proceedings of Advanced Composites in Construction Conference*, Warwick, 6-8 Sept, pp.21-29.

[9] Engineer, Integral Structural Design, Bath, email 2/10/2009.

[10] Bell, B. 2009, Fibre-reinforced polymer in railway civil engineering, *Proc. of the ICE, Eng. and Computational Mechanics*, 162(EM3), pp. 119-126. (DOI: 10.1680/eacm.2009.162.3.119).