Institution: University of Bath		
Unit of Assessment: B12 Engineering		
Title of case study: Extending the life of our aging concrete infrastructure		
Period when the underpinning research was undertaken: 2001 - 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Antony Darby	Reader, previously Senior Lecturer, Lecturer	September 1999 - present
Tim Ibell	Professor, previously Senior Lecturer, Lecturer	October 1997 - August 2017; September 2018 – present
John Orr	Lecturer	January 2013 - September 2017
Period when the claimed impact occurred: 2013 - 31 July 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Research within the Building Research Establishment Centre for Innovative Construction Materials (BRE-CICM) at the University of Bath has allowed the life of concrete structures to be prolonged through developing (a) reliable methods for assessing existing load capacity and (b) the means to increase or restore load capacity where necessary. This has prevented buildings and bridges (managed, for example, by large asset owners such as Highways England and Network Rail) from being condemned as unfit for purpose, "*the cost of which would run into many millions of pounds each year*" and preventing disruption to infrastructure users. The underpinning research led to the researchers being commissioned to write guidance documents that are routinely used by infrastructure owners and consulting engineers worldwide. This guidance has also been taken up by material supplier Sika AG as part of design software which has global reach and impact. Over the course of the last six years it can be confidently stated that this has resulted in "*many millions of pounds of savings to building and infrastructure owners worldwide*".

2. Underpinning research

Many existing aging concrete structures and infrastructure are both deteriorating and being asked to take higher loads than originally designed for, or used in new ways, such as allowing change of building use. Traditional methods of assessment are often inadequate and retrofit methods disruptive, costly and in many cases impractical.

Use of advanced composite materials, which are lightweight, strong, stiff and durable provide a solution to the above problems. Based upon experimentation and fundamental structural mechanics, our research has studied how various reinforced concrete elements and systems can be properly assessed and, if necessary, retrofitted using these materials through a deeper understanding of the original existing structural behaviour and load capacity coupled with the interaction between concrete and advanced composites.

Structural Strengthening Research – restoring load capacity

Column strengthening: As part of EPSRC funded project EP/E039901/1, between 2008 and 2012, Darby and Ibell studied the effect of Fibre Reinforced Polymer (FRP) confinement on non-circular columns, particularly when loading is non-concentric and columns are of realistic size (Fig. 1). The majority of previous work in the field was on small scale columns which do not reveal size effects, and furthermore, focussed on circular columns (which make up the minority of all columns used in structures) under concentric loading (which is rarely if ever the real situation).


Fig. 1 FRP reinforcement

Shear strengthening: Starting in 2001, Darby and Ibell developed a method for strengthening beams and slabs against shear failure, known as 'deep embedment shear strengthening' [1]. This involves FRP rods glued into holes drilled through the beam or slab to act as additional internal shear reinforcement. This addresses problems related to access to sides/webs of beams and premature debonding of surface mounted FRP and the previous inability to connect compression zone to tension zone in beams – a fundamental assumption in conventional 'truss analogy' design. This also protects the FRP from fire and vandalism, provides a pseudo-ductile failure behaviour and causes minimal disruption to traffic flow in the case of bridge strengthening. This research has been supported by EPSRC GR/S18144/01 and via Marie Curie ITN 'ENDURE'.

Flexural strengthening: Near Surface Mounted Reinforcement (NSMR) uses FRP glued into slots cut into cover concrete to increase flexural capacity of beams and slabs. Our research developed an anchorage model which accounts for various failure modes and geometric configurations of the strengthening system (slot dimensions, adhesive thickness, bar size, shape and type) [2]. Darby and Ibell also studied the effect of flexural cracking on allowing FRP to develop its full capacity. Previously cracking was seen as detrimental but our research demonstrated that it is a necessary requirement for FRP flexural strengthening to be effective. This resulted in a step change in how strengthening prestressed concrete elements was considered [3]. Finally, the effect of redistribution of moments in FRP strengthened indeterminate structures was studied. This demonstrated that redistribution of moments into (but not out of) strengthened zones was possible. This work began was supported by EPSRC grant EP/K019015/1 [4].

Bridge Assessment Research – reliably assessing existing load capacity
Orr, Darby and Ibell were commissioned in 2015 – 2017, by Balfour Beatty/Mott MacDonald, on behalf of Highways England, to investigate anchorage of prestressing tendons in half-joints on prestressed concrete highway bridge structures. This is a very common construction technique, but one which has led to significant reinforcement corrosion problems and loss of concrete cover in the critical prestressed tendon anchorage zones. This work demonstrated that even after loss of concrete cover and prestress to the main tendons, significant anchorage capacity remained which could, and should, be taken into account in design [5]. This capacity was previously neglected in bridge assessment leading to unnecessary remedial work or load restrictions. This work built on earlier research at Bath, which showed that concrete bridges containing curtailed steel reinforcing bars close to supports could be assessed appropriately using a plasticity-based approach, thereby avoiding unnecessary demolition or strengthening [6].

3. References to the research

[1] Valerio, P, Ibell, T & Darby, A 2009, 'Deep embedment of FRP for concrete shear strengthening', *Proceedings of the Institution of Civil Engineers-Structures and Buildings*, vol. 162, no. 5, SB 800079, pp. 311-321. https://doi.org/10.1680/stbu.2009.162.5.311

[2] Kalupahana, WK, Ibell, T & Darby, A 2013, 'Bond characteristics of near surface mounted CFRP bars', *Construction and Building Materials*, vol. 43, pp. 58-68. https://doi.org/10.1016/j.conbuildmat.2013.01.021

[3] Darby, AP, Denton, SR & Ibell, TJ 2009, 'Influence of changes in cross section on the effectiveness of externally bonded FRP strengthening', *Journal of Composites for Construction*, vol. 13, no. 3, pp. 208-216. https://doi.org/10.1061/(asce)cc.1943-5614.0000005

[4] Tajaddini, A, Ibell, T, Darby, A, Evernden, M & Silva, P 2016, 'Quantifying moment redistribution in FRP-strengthened RC beams', *Proceedings of the Institution of Civil Engineers: Structures and Buildings*, vol. 169, no. 11, pp. 853-862. https://doi.org/10.1680/jstbu.15.00126

[5] Orr, J, Darby, A, Ibell, T, Thoday, N & Valerio, P 2017, 'Anchorage and residual bond characteristics of 7-wire strand', *Engineering Structures*, vol. 138, pp. 1-16. https://doi.org/10.1016/j.engstruct.2017.01.061

[6] Shave, J, Ibell, T & Denton, S 2007, 'Shear assessment of reinforced concrete bridges with short anchorage lengths', *The Structural Engineer*, vol. 85, no. 5, pp. 30-37. [Available on request]

4. Details of the impact

Impact 1 – New design guidance: Our research has led to the introduction of guidance documents which are used by designers to underpin their assessment, retrofit designs and interventions. Our work has underpinned the 2012 edition of the UK guidance document, TR55 [A]; specifically, the findings of the University of Bath's strengthening research is incorporated into the TR55 guidance, forming essential clauses associated with maintaining structural integrity, which must be complied with when considering any FRP strengthening scheme, whether axial, shear of flexural strengthening. This edition is recognised as a leading document in the field and its reach has been Worldwide, particularly in countries where structural design guidance is based upon Eurocodes (EU, Africa, Asia, Middle East). This has led to the saving of at least many 100s of buildings and structures from being demolished or requiring more costly and invasive interventions over the census period, both within the UK and internationally.

Our work has also been incorporated into the new Highways England Design Manual for Roads and Bridges, CS455 [B], in March 2020, but was used prior to this for ongoing bridge assessment since 2017. In both cases, this has resulted in major savings to cost of interventions and reduced environmental impact to both construction and infrastructure users (e.g. maintained or increased traffic flow, providing societal benefit). As a direct example of the impact, within the census period, Highways England alone has commissioned four major structural strengthening schemes, all designed to TR55, using methodology informed by our research [C]:

1) Hawley Lane South Bridge (Fig. 2), carrying the M3 Motorway over a county road (2014). The flexural strengthening design of RC solid slabs.

2) Ashridge Farm Bridge, carrying the A34 Trunk road over a farm access (2015). The strengthening of RC abutments.

3) Peover Eye Bridge, carrying the M6 Motorway over the Peover stream (2016). The flexural strengthening design of RC voided slabs.

Fig.2 Hawley Bridge

4) Tickeridge Farm Accommodation Bridges (originally constructed between 1958 and 1962), carrying a farming road over the M5 (2017). NSM flexural strengthening design of RC abutments.

As an example of scale, the Hawley Bridge strengthening scheme cost GBP5,000,000 (using 1,000m of FRP rods and 5,000m FRP plate) [D]. As part of the tendering for these works, whole life cost analysis is always carried out. The capital cost of the Tickeridge Farm bridge strengthening works [E] was GBP796,759. Compared to the alternative conventional steel plate strengthening approach (which was also costed) the whole life cost saving was

GBP554,807. The approach enabled construction time to be decreased from 17 to 10 days, greatly reducing impact of diversions and associated carbon footprint. The resulting work extended the existing design life by another 40 years. What's more, compared to conventional steel retrofit solutions, FRP strengthening schemes result in a decrease of 70% CO_2e emissions, require 80% less energy and use 95% less water. [F]

Impact 2 – New design software: The new retrofit and assessment methods developed by the Bath team have been adopted by Sika AG in their design software [G] and others, globally. The scale of the reach and breadth of impact is best indicated via Sika AG's strengthening materials business: Sika AG are an international company with a GBP6,700,000,000 turnover in 2019 [H]. 20% of this is related to refurbishment, which includes strengthening using composites, supported by the software based on TR55. As they state in their letter [I]:

> "*This has had global reach, with over* ***6,000 downloads and activations of our software across Europe alone and another 8,000 across the rest of the world****; Africa, Asia, the Middle East and North America, where Sika also operate, having* ***active users in more than 100 countries***". "*Since introducing the software, we have seen a very dynamic growth in our business based on the wider understanding of the system within engineers community; this reflects in a >* ***30% increased total turnover*** *in CFRP systems for structural strengthening since 2015 in EMEA [Europe, Middle East and Africa] countries".*

Sika added that [I]:

> *"…implementation of this strengthening technique using our products has saved countless buildings, bridges and structures across the world from being demolished or requiring extensive structural interventions, the cost of which would run into* ***many millions of pounds each year***".

Examples includes the Rialto Bridge structural restoration in 2017 and structural strengthening of the world's largest archaeological museum, the Grand Egyptian museum, Giza, in 2019 [J].

Impact 3 - Bridge half-joint assessment impact:
The results of the research into assessment of bridge half-joints with reduced concrete cover to prestressing tendons due to corrosion has already found its way into design standards. In 2017, Highways England approved the rules for assessment, informed by our research, to be used in all the prestressed concrete bridges with half joints due for assessment in Area 10 and 13 in the UK (a total of almost 100 bridges of which 15 have already been assessed as of January 2020) [B]. As stated by the Highways England Structures Manager [C]:

> "*As a direct result of the research described in the paper* [5]*, which has provided the appropriate technical background based on rigorous and verifiable procedures to define the required level of safety, a number of bridges located in Cheshire, Greater Manchester, Merseyside, Lancashire and Cumbria on Highways England's Strategic Road Network have had their service lives extended by avoiding unnecessary assessment failures. This led to substantial operational and cost savings, as it ensured that measures such as road closures, monitoring, strengthening or replacement, ranging in cost from a* ***few hundred thousand to a few million pounds for each bridge,*** *are only implemented when really necessary, also minimizing the associated environmental impact of the works*".

5. Sources to corroborate the impact

[A] The Concrete Society. 2012. Technical Report 55: Design guidance for strengthening concrete structures using fibre composite materials. Third edition. (Amendment October 2013). ISBN 978-1-904482-70-3

[B] Highways England. 2020. Design manual for roads and bridges: CS455: The assessment of concrete highway bridges and structures (Specifically section 9.1).

[C] Email from Structures Manager, Highways England, 2 January 2020.

[D] Sika Ltd. 2015. Sika at work: Hawley bridge M3, Surrey. Available at: https://gbr.sika.com/dms/getdocument.get/fac8f42b-30fd-3b3e-b0d6-70ac3806eb48/Hawley%20Bridge%20M3,%20Surrey.pdf

[E] Email from Structures Manager, Highways England, 12 January 2020, including Options report.

[F] Zhou, H. 2013. The comparative life cycle assessment of structural retrofit techniques. Arizona State University. Available at: https://repository.asu.edu/items/17488

[G] Sika Group website, accessed 3 November 2020. Structural strengthening. Available at: https://www.sika.com/en/construction/structural-strengthening.html

[H] Sika business year 2019. Available at: https://www.sika.com/content/dam/dms/corporate/x/NEW-glo-annual-report-2019-sika-business-year-new.pdf

[I] Testimonial letter from Regional Business Development Manager, Engineered Refurbishment Europe, Middle East and Africa, Sika, 13 February 2020.

[J] Sika Group website, accessed 3 November 2020. Reference projects. Available at: https://www.sika.com/en/reference-projects.html