Institution: Edinburgh Research Partnership in Engineering – ERPE (Heriot-Watt/Edinburgh)

Unit of Assessment: B15: General Engineering

Title of case study: New Standards to Extend the Life of Concrete Infrastructure with Fibre Reinforced Polymer

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

ERPE research, since 2001, into the application of Fibre Reinforced Polymer (FRP) composites for strengthening existing civil engineering structures continues to impact design guidelines for preserving and updating the worldwide ageing infrastructure. The lifetime extension of existing infrastructure and buildings is a priority: the UK Government plans to invest up to £250bn over 10 years to return UK infrastructure to 'world class' performance. 75% of developed world infrastructure investment covers retrofitting and repair rather than new-build. FRP strengthening is now the method of choice for seismic retrofit, capacity enhancement, structural repair and rehabilitation of concrete and masonry structures.

ERPE research to enhance strength and structural integrity has been used in the development of, or been incorporated into, at least 12 design guides codes and standards worldwide in at least 5 countries including Australia, Canada, China etc.

2. Underpinning research (indicative maximum 500 words)

Since 2001, ERPE academics have actively studied fibre reinforced polymers (FRPs) for construction: Professors Bisby, Cairns, and Rotter, and Senior Lecturer Stratford (all in post throughout period) with Reader Chen (to 2012) and May (to 2011) have carried out research across the full breadth of FRP composites in construction, ranging from investigation of fundamental mechanics to the development of practical models that have been implemented in design guidance across the world.

The important ERPE research contribution to international codes and standards includes:

- **Adhesive Joint Analysis.**
  A vital component in all FRP strengthening applications is the adhesive joint between the FRP and the substrate material. The ERPE group has made significant contributions to understanding the mechanics of this adhesive joint to concrete, masonry and metallic structures [6]. For example, the group's work has produced internationally adopted models for FRP bonded to concrete, FRP bonded to metallic structures, and the impacts of elevated temperature on bond. Chen's bond model work in particular is seminal and is universally cited by researchers. The work was the first to demonstrate that the interaction of adjacent cracks has an important effect on the interfacial bond strength, which explains the phenomenon that the FRP strain at intermediate crack induced debonding in an FRP-strengthened reinforced concrete (RC) beam is significantly larger than that obtained from isolated bond pull-off tests. This has formed the basis for design guidelines [2] and further development.
- **Strengthening Concrete Structures using FRP Composites.**
  Examples of the Group's work on FRP strengthening of concrete structures include the development of models that allow concrete structures to be strengthened for flexure [3], shear [1], and confinement [4] which have been adopted in design practice. Work on the mechanics of FRP confining reinforcement for concrete columns has led to changes in the fundamental understanding of how this form of strengthening works (and fails); this has also been adopted in design codes. ERPE has performed pioneering work on advanced numerical simulation of FRP strengthened concrete structures, which has been well received internationally and resulted in invited keynote presentations at international conferences such as FRPRCS-9 (Sydney), CICE 2010 (Beijing), and ACMBS-VI 2012 (Kingston, Canada).
- **FRP strengthening for extreme events.**
  The Group has established the performance of FRP strengthening in fire, application of strengthening to previously fire-damaged structures [4], and developed fire protection systems

for FRP strengthening. This work has allowed more widespread use of FRP strengthening in building structures and in new applications. For example, ERPE was the first to investigate the performance of FRP strengthened slabs in a real fire (EPSRC EP/E025315/1). Recent work also includes strengthening of concrete structures for blast – producing the first FRP-to-concrete bond model which considered the strain rates effect. The work was undertaken by Chen, Stratford, Lu, and 3 PhD students [5], with group members invited to deliver keynotes.

- **Strengthening metallic structures using FRP composites.**
  The concept of FRP strengthening has been transferred from concrete to metallic structures. ERPE has addressed the fundamental differences between these types of strengthening, examining flexural [6], shear and fatigue strengthening, and strengthening for buckling-critical thin-walled structures such as thin shells and plate girders. The internationally-leading CIRIA (2004) UK design guidance report C595 on "Strengthening metallic structures using externally bonded fibre-reinforced polymers" was produced, and incorporates, for example, ERPE's adhesive stress distribution reported in [6] as the main analysis method.

Other examples of the group's contributions include:
- FRP strengthening applied to masonry arch bridges (Chen, Stratford).
- The dynamics and durability of lightweight FRP footbridges (Stratford).
- Short fibre reinforced concrete structures (Bisby, Chen, Stratford).
- Internal FRP reinforcement for concrete structures (Bisby, Stratford).
- Fibre reinforced mortars for fire-safe strengthening of concrete/masonry (Bisby, Stratford).

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

References identified with * are those which best indicate the quality of the underpinning research.

[1]* Chen, J.F. and Teng, J.G., "Shear capacity of FRP strengthened RC beams: FRP debonding", Construction and Building Materials, Vol.17, No.1, 27-41, 2003. DOI:10.1016/S0950-0618(02)00091-0. 203 Google Scholar (GS) citations.
This is the most cited paper in Elsevier civil engineering journals 2003-2004. This paper together with its companion paper [Chen and Teng DOI:10.1061/(ASCE)0733-9445(2003)129:5(615)], developed two rational shear strength models based on the fundamental failure mechanisms which were directly adopted as provisions in the Australian design guidelines and were partially adopted in the Concrete Society design guidelines TR55 (2004, 2012).

[2]* Teng, J.G., Chen, J.F., Smith, S.T. and Lam, L., "Behaviour and strength of FRP-strengthened RC structures: a state-of-the-art review", Proceedings of the Institution of Civil Engineers - Structures and Buildings, Vol.156, No. SB1, pp 51-62, 2003. DOI:10.1680/stbu.2003.156.1.51. 119 GS citations.
This most cited paper, among all 917 papers published in this journal since 1992, was awarded the ICE Howard Medal 2004 and forms the framework for many design guidelines such as the Chinese code GB-50608 & Hong Kong guidelines.

[3]* Teng, J.G., Smith, S.T., Yao, J. and Chen, J.F., "Intermediate crack-induced debonding in RC beams and slabs", Construction and Building Materials, Vol.17, No.6-7, pp447-462, 2003. DOI:10.1016/S0950-0618(03)00043-6. 254 GS citations.
The 2nd most cited of 3196 papers published in this Journal since 1995 when its Science Citation Index data became available. It forms the basis for the design methods adopted by ACI, Australian and Chinese design guidelines.

[4] Bisby L.A., Chen J.F., Stratford T.J., Cueva N. and Crossling K., "Strengthening fire-damaged concrete by confinement with fibre-reinforced polymer wraps", Engineering Structures, 33(12):3381-3391, 2011. DOI:10.1016/j.engstruct.2011.07.002.
As well as being the first demonstration of FRP applied to fire-damaged concrete, the ERPE work on confined concrete (this and other papers) has led to design models in e.g. Concrete Society TR55.

[5] Bisby L. and Stratford T., "Design for fire of concrete elements strengthened or reinforced with fibre-reinforced polymer: state of the art and opportunities from performance-based approaches", Canadian Journal of Civil Engineering, Vol. 40: 1-10, 2013. DOI:10.1139/cjce-2012-0506.

Describes the basis of worldwide research and design standards on FRP strengthening in fire (e.g. ACI-440.2R-08, clause 1.3; Concrete Society TR55, clause 5.7.1).

[6] Stratford T.J. and Cadei J.M.C., "Elastic analysis of adhesion stresses for the design of a strengthening plate bonded to a beam", Construction and Building Materials, 20, 34-45, 2006. DOI:10.1016/j.conbuildmat.2005.06.041. 85 GS citations.

The 4th most cited paper among 2636 papers published in the journal since 2005, adopted in CIRIA (2004) report.

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

"The work of the team within the ERPE on structural applications of FRP composites has had a very significant international impact over many years. It has been adopted in design standards and guides around the world, and the qualities and capabilities of the team are widely recognised. In particular, they are right at the forefront of work on fire performance of FRP materials, and have made highly influential contributions in the fields of adhesive joint analysis, strengthening for square columns and web strengthening for steel girders." Director of Engineering, Parsons Brinkerhoff [S1].

The ERPE research has significant and ongoing impact on industrial practice worldwide, chiefly through adoption into many published international design guidelines and standards to enable infrastructure design with FRP materials, while enhancing public safety.

Australian Standard HB 305 (2008). "Design handbook for RC structures retrofitted with FRP and metal plates: beams and slabs [S2]." This new standard, the first of its kind in Australia, makes extensive use of our research. ERPE work adopted in this document includes:

- the concept on how the side plates resist shear forces in RC beam was adopted in Chapter 3 (Generic stress resultants and capacities).
- Bond strength model for externally bonded FRP to concrete, IC debonding model, [3], two shear strength models (for FRP rupture failure and FRP debonding failure [2,3]), were adopted into Chapter 4.

American Concrete Institute (ACI) (2008). "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures." Report ACI 440.2R-08 [S3]. Both this and the earlier (2002) edition made use of ERPE work, including:

- the proposed "development length" model was included in Clause 13.1.3.
- A revised form of ERPE's IC debonding model [3] in Clause 10.1.1.
- Strengthening limits for both ambient and fire resistance design are based on ERPE's work.

UK Concrete Society (2012). "Design guidance for strengthening concrete structures using fibre composite materials." Technical Report 55, 3rd Edition. TR55 is the design standard for FRP strengthening in the UK, and is used internationally. ERPE's work adopted in this extensively re-written and updated edition includes:

- Our improved, rational model for confinement of square and rectangular columns forms part of Chapter 8.
- Our world-first work on Fibre-reinforced cementitious mortar (FRCM) systems is recommended in Chapter 9.
- All provisions related to fire (new in the 3rd edition) are based on ERPE's work (Chapters 3, 5).
- The strain distribution factor [3] is adopted in Chapter 7.

China Planning Press (2010). "Technical code for infrastructure application of FRP composites." GB-50608. ERPE work adopted in this new Chinese standard [S4] and now in use in the industry includes:

- proposed debonding failure framework [3] was adopted in Chapter 4.
- A revised form of ERPE's IC debonding strength model [3] was adopted in Clause 4.2.7.
- The adopted shear strength models (Clause 4.3.5) were developed based on [1].

Hong Kong design guidance (2012). "Guide for the strengthening of concrete structures using FRP composite." New design guidance based in part on ERPE work:

- proposed classification of debonding failure modes (DoI:10.1680/stbu.2009.162.5.335) was adopted by this guidance (Section 4.3).
- The adopted IC debonding strength model (Clause 4.4.3.5) was developed based on Chen, Teng and Chinese collaborators, while the width effect factor (Eq. 4.8) was directly adopted from Chen and Teng's proposal.
- The whole chapter on shear strengthening design (Chapter 5) was based on Chen, Teng in Hong Kong and Chinese collaborators.
- ERPE work on behaviour of FRP strengthened slabs in a real fire (DoI:10.1260/136943309790327743) provided basis for some of the provisions (Chapter 9).

Canadian Standards Association (CSA). S806 (2012). "Design and construction of building components with fibre-reinforced polymers." Our work forms the basis of the detailed fire resistance FRP design guidance contained in Annex R, which is new to the 2012 edition of this code and authored by Bisby:

- *"Bisby is the undisputed global research leader in the area of fire resistance of FRP strengthened and/or reinforced concrete structures. Bisby and his ERPE colleagues are responsible for developing the research outputs which form the basis of essentially all current structural fire safety design guidance for these types of applications globally, including in the USA (ACI 440) and Canada (CSA S806)."* Chair of CSA Committees S806, S807 and S808 [S5].

Other ERPE impact is included in these design codes and guidance documents, which are in current use today:

- USA ACI 440.3R-12 Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures.
- USA ACI 440.5M-08 Specification for Construction with Fiber-Reinforced Polymer Reinforcing Bars.
- USA ACI 440.6M-08 Specification for Carbon and Glass Fiber-Reinforced Polymer Bar Materials for Concrete Reinforcement.
- The International Federation for Structural Concrete (fédération internationale du béton) fib (2012). "Externally bonded FRP reinforcement for RC structures." Bulletin 14, Lausanne, Switzerland.

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

[S1] Director of Engineering at Parsons Brinkerhoff. Impact of ERPE research in CIRIA (2004) and Concrete Society (2012) UK design guides. See comments included in Section 4.

[S2] Author Australian Standard (AS) HB 305 (2008). "Design handbook for RC structures retrofitted with FRP ......"

[S3] Chair of ACI-440D sub-committee (2008). "His guide made extensive use of ERPE research…"

[S4] Editor China Planning Press (2010). "Technical code for infrastructure application….."

[S5] Chair of Canadian Standards Association (CSA) S806, S807 and S808 standards committees CSA S806 (2012), see comments included in Section 4.