Institution: University of Warwick		
Unit of Assessment: B12 – Engineering		
Title of case study: Influencing policy and practice on Fibre-Polymer Composites (FPCs) in civil engineering in the US and Europe		
Period when the underpinning research was undertaken: 2000-2020		
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:**
James Toby Mottram	Professor	1987 – Present
Period when the claimed impact occurred: 1 August 2013 to 31 December 2020		
Is this case study continued from a case study submitted in 2014? N		

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

Professor J. Toby Mottram's pioneering research with Fibre Polymer-Composites (FPCs) has made a key contribution to the safe design of many civil engineering structures, from pedestrian bridges and walkways to waste-water cooling towers and oil rig maintenance platforms. Mottram's research with FPC bolted connections and other structural FPC components has led to new guidelines, including for durability, being incorporated into national and international policy and practice. The European and US bodies overseeing design codes for FPCs describe his research input as 'irreplaceable' and 'instrumental'. Since 2018, entire US product ranges have been evaluated for the first time with Warwick's FPC bearing strength test method. In the UK, Warwick expertise has been factored into two nationally-applied documents: a 2018 practice-focused guide that has been used in over 20 FPC structures costing circa GBP2,750,000, including historic twin aqueducts in Standedge, West Yorkshire; and in 2020, a Highways England-issued design manual for FPC bridges and highways.

2. Underpinning research (indicative maximum 500 words)

Fibre-Polymer Composites (FPCs) are construction materials comprising a polymer resin (often a thermoset) based matrix reinforced with fibres of glass and/or aramid (kelvar®) and/or carbon and/or basalt. Various composite processing methods (e.g. pultrusion and resin infusion) produce shapes and systems by wetting-out the fibres, consolidating the two phases (for negligible porosity), and curing the matrix. Advantages offered by FPC components in civil engineering are light-weighting, design flexibility, lower life cycle costs and durability – requiring minimum maintenance. The overall material property portfolio of FPCs provides engineering, environmental, economic and social benefits for low-carbon infrastructure.

Designers routinely use national or international industry design standards (known as codes) specific to construction material structures, which offer several benefits: reduced cost and material usage; need for less specialist design know-now; and confidence that safety-critical structures are unlikely to fail and are more environmentally-friendly. However, design code development is a lengthy process, with completion lead-times of up to 20 years. As FPC shapes and systems started to gain prominence in the 1990s, its limit state design code development is at least two decades behind achieving equivalent reliability to materials with historical precedence: steel, concrete and timber. To increase the complexity of designing with FPCs, the failure modes are different and can be brittle. Transferring actions safely into and out of FPC structures and systems therefore poses severe challenges to code writers.

Over the 20-year census period Professor Mottram has published 19 relevant peer-reviewed journal and 3 conference papers that inform design standard writing; all of these are referenced in one or more of **[5.1, 5.2c & 5.3b]**. Through experimentation and computational modelling, Warwick's primary objective has been to publish reliable knowledge and test results and to provide key insights into the underpinning understanding of the behaviour of FPCs for civil engineering works **[3.1-3.7]**.

Pioneering research from **[3.1]** and **[3.2]** helped specify the provisions in **[5.1]** and **[5.3b]** for the strength calculations of FPC bolted connections, failing in bearing. **[3.1]** is for the necessity of test procedure C (in ASTM D953-19 **[5.4]**) and **[3.2]** verifies that when a thread is in bearing the reduction factor of strength without thread can be specified as 0.6. In **[3.3]**, the Hart-Smith procedure is clearly demonstrated to be appropriate for calculating the net-tension strength in multi-row bolted connections and this refined and optimum design provision is offered in an appendix in **[5.3b]**. **[3.4]** uses **[3.3]** to develop the mandatory (lower-bound) non-optimum strength formula in **[5.3b]** for net-tension strengths in multi-row bolted connections.

Test results using full-sized joint sub-assemblies in **[3.5]** prove that by following the design provisions in **[5.1]** and **[5.3b],** beam-to-column joints having FPC web cleats can possess the required rotational capacity prior to damage onset that enables the detailing to be classified as simple (i.e. pinned), with a limitation on the value of serviceability limit state deflection. Underpinning research from **[3.6]** ensures that in **[5.1]** strength calculations for elastic instabilities account for the influence of geometrical imperfections from FPC processing. **[3.7]** demonstrated that the long-term changes (after 50 years) in mechanical properties of FPCs, owing to temperature and moisture, cannot be modelled computationally. This is important evidence establishing the design approach adopted in **[5.1]** that long-term strengths are calculated using the Eurocode 0 methodology of specifying conversion factors that are applied to short-term mechanical properties. Bolted connection **[3.1-3.5]** and durability **[3.7]** underpinning research received funding from EPSRC **[G1 & G2]**; the case for support to each grant outlined that resulting research would be exploited to address gaps in FPC design standards/guidance. It was because of known gaps in knowledge and understanding for code writing that these grants were prepared.

3. References to the research (indicative maximum of six references) **Warwick = Bold**

All research papers were published in peer-reviewed journals

[3.1] Mottram, J. T. and **Zafari, B.** (2011) *Pin-bearing strengths for design of bolted connections in pultruded structures*. Structures and Buildings, 164 (5). pp. 291–305. doi: 10.1680/stbu.2011.164.5.291

[3.2] Matharu, N. S. and **Mottram, J. T.** (2017) *Plain and threaded bearing strengths for the design of bolted connections with pultruded FRP material*. Engineering Structures, 152. pp. 878-887. doi: 10.1016/j.engstruct.2017.10.003

[3.3] Mottram, J. T. (2010) *Prediction of net-tension strength for multirow bolted connections of pultruded material using the Hart-Smith semiempirical modeling approach*. Journal of Composites for Construction, 14 (1). pp. 105-114. doi: 10.1061/(ASCE)CC.1943-5614.0000043

[3.4] Mottram, J. T. (2013) *Rationale for simplifying the strength formulae for the design of multi-row bolted connections failing in net tension.* In: Sixth International Conference for Advanced Composites in Construction (ACIC 2013), Queen's University of Belfast, pp 383-392. http://wrap.warwick.ac.uk/58210/

[3.5] Qureshi, J. and **Mottram, J. T.** (2014) *Response of beam-to-column web cleated joints for FRP pultruded members*. Journal of Composites for Construction, 18 (2). pp. 1-11. doi: 10.1061/(ASCE)CC.1943-5614.0000392

[3.6] Nguyen, T. T., Chan, T. M. and **Mottram, J. T.** (2013) *Influence of boundary conditions and geometric imperfections on lateral–torsional buckling resistance of a pultruded FRP I-beam by FEA*. Composite Structures, 100. pp. 233-242. doi: 10.1016/j.compstruct.2012.12.023

[3.7] Grammatikos, S. A., **Zafari, B.**, Evernden, M. C., **Mottram, J. T.** and Mitchels, J. M. (2015) *Moisture uptake characteristics of a pultruded fibre reinforced polymer flat sheet subjected to hot/wet aging*. Polymer Degradation and Stability, 121. pp. 407-419. doi: 10.1016/j.polymdegradstab.2015.10.001

Grants

[G1] Mottram, J. T., Connections and Joints for Buildings and Bridges of Fibre Reinforced Polymer. **Sponsor:** EPSRC [EP/H042628/1] **Duration:** Oct 2010 – Mar 2014 **Award**: GBP445,030

[G2] Mottram, J. T. (PI), Gosling, P. D., Pearce, C., Sebastian, W. M., Kilsby, C., Purnell, P., Evernden, M. and Kaczmarczyk, L., Providing Confidence in Durable Composites (DURACOMP). **Sponsor:** EPSRC [EP/K026925/1] **Duration:** Jun 2013 – Aug 2016 **Award**: GBP1,396,722

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

Worldwide civil engineering structures are most commonly designed in accordance with codes of practice, with the European (the Eurocode suite) and North American (American Society of Civil Engineers, or ASCE; American Concrete Institute, or ACI) codes being the practitioner gold-standards. Typically these codes are controlled by a committee of experts and informed by the community-at-large, with one UK industry practitioner commenting they offer a "*consistent baseline for designers*", and enable the choice of appropriate materials, joints and connections "*together with safe and economic design*" **[5.5a]**. For fibre polymer composites (FPCs, also known as fibre reinforced polymers, or FRPs), the UK Composites Leadership Forum Construction Sector Group (CSG) estimated the global FPC construction market to be worth USD15,900,000,000 in 2020. This reveals a sizeable potential for exploitation once design codes are in place.

Professor Mottram is a member of both the Fiber Composites and Polymers Standards (FCAPS) committee of ASCE for development of a US FPC standard (based on **[5.3b]**), as well as Working Group 4 (WG4) for Fibre Reinforced Polymer Structures, as part of the wider CEN Technical Committee for Structural Eurocodes (CEN/TC 250). In addition, he is an expert member of the British Standards Institution (BSI) Technical Committee B/525 Building and Civil Engineering Structures that is responsible for providing the UK input to structural Eurocodes. His far-reaching and international contributions have allowed Warwick research **[3.1-3.7]** to feature throughout FPC standards and design documents, with key examples outlined below:

Europe and UK policy and practice – In 2007 the JRC publication EN EUR 22864 first presented the justification for new standards regarding the use of FPC composites in civil engineering. Following a resolution in 2009, Professor Mottram was appointed to WG4, and in 2018 as one of six experts on M515 mandate Project Team (WG4.T2), as part of CEN/TC 250. The first generation of Eurocodes became mandatory for UK design in 2010, with the second generation (of which FPC structures is to be a Technical Specification) set to be published in February 2027.

A working group drives the development of Eurocodes through three Stages: (S1) publication of a CEN/TC 250 agreed Science and Policy Report **[5.1]**; (S2) publication of an agreed Technical Specification (prCEN/TS 19101 for Fibre Polymer Composite structures); and (S3) trial use of the Technical Standard to determine how it shall be converted into the Eurocode. Based on existing research **[3.1, 3.3 & 3.6]** Professor Mottram co-authored sections 8.0-8.3 on bolted connections in the two S1 reports (published in 2016 and 2018 – **[5.1]**), described as "*particularly challenging, not least, because there are many connection details and always a number of failure modes to consider*" **[5.6]**. In 2018, Professor Mottram was appointed to new project team (WG4.T2) overseeing the conversion of the S1 Science and Policy Reports into a S2 Technical Specification (TS). This led to a 230-page draft TS under review/inquiry during 2020, and into 2021 **[5.6]**.

With Eurocodes often having a lead time of 20 years, the Science and Policy report **[5.1]** and draft TS mark inextricable milestones for FPC civil engineering policy in the EU. Warwick has made "*an effective and essential contribution*" to these, with significant contributions specifically in the field of bolted joints and limit states design of FPC structures. The Convenor of WG4 expanded: "*There is no single other expert within Europe that could have been a member of WG4.T2 to replace the experience and expertise that Prof. Mottram is able to provide*" **[5.6]**. As chair of BSI mirror group BS/525/-/4 (with five industry and two academic members), Prof Mottram further reviews and leads progress towards the FPC Eurocode from inside the UK **[5.5a]**.

Beyond FPC Eurocode development, Warwick and Professor Mottram have had a wider and important influence on UK industry. *Fibre-reinforced polymer bridges – Guidance for designers* (CIRIA, 2018) **[5.2c]** was prepared by the Construction Sector Group (CSG) of Composites UK, with Professor Mottram as one of two co-editors and writing 40% of the document including sections on connections and joints, structural analysis and FPC durability (drawing on **[3.1, 3.3-3.4, 3.6 & 3.7]**). Despite its recency, this industry focused guide (https://tinyurl.com/yy79wl4b) has been downloaded more than 2,350 times and has seen use by top UK engineering firms (Jacobs, NOV Fibre Glass Systems, and others) in the design of 20+ projects **[5.2a, 5.2b]**. Named examples include the Poole Park Sluice Gate Bridge, Doctors Footbridge and the Bridge St Footbridge both in Lancashire, the Roxwell Bridge in Essex, and 2 twin aqueducts in Standedge **[5.5a, 5.5b]**. As a conservative estimate, the total design and construction costs of these projects is a minimum of GBP2,750,000 (costs "in excess" of GBP900,000 from Jacobs, and using GBP118,000 acquisition costs for the other 16 projects – a figure taken from G*uidance for designers* itself which covers design and installation for a typical 30m^2 footbridge. The Standedge aqueducts were factored into this 16 despite being substantially larger engineering efforts, indicating a suitable minimum estimate) **[5.2c, 5.5a]**.

North American policy and practice – Between 2007 and 2010, three North American pultruders funded (USD1,500,000) a project to draft an ASCE pre-standard **[5.3b]**. Professor Mottram was on the project team and led (with Professor Larry Bank, then University of Wisconsin-Madison) the writing of Chapter 8 for Bolted Connections, having mandatory design provisions (18 pages) and a commentary (28 pages). Before the pre-standard, there were no previous procedures to work with. Since 2011, the committee Fiber Composites and Polymers Standards (FCAPS) (at the American Society of Civil Engineers) has worked on converting the pre-standard to an American National Standards Institute (ANSI) standard through a balloting process. Updating the standard involves new Warwick research **[G1]** for design of bolted connections **[3.1-3.4 & 3.5]**, covering essential knowledge gaps for: developing a standard test (procedure C in ASTM D953) for determination of bearing strength **[3.1]**; having a single (simple) closed form expression **[3.4]** for calculating the strength of multi-rowed bolted connections failing in the net-tension mode **[3.3]**; and the design of beam-to-column joints (for serviceability limit state rotation capacity) **[3.5]**.

Between August 2013 and February 2020 the developing ASCE standard underwent 42 rounds of balloting with 42 votes, with Professor Mottram participating in each round and his research being an important reference material in the standard's commentary. The Chair of ASCE FCAPS added: "*Toby's work on the FCAPS Committee has been instrumental in formulating particularly the Connections Chapter*", with an instrumental contribution also provided in the balloting process for approving "*the design provision for the strength of bolted connections failing with the bearing mode of failure*" **[5.3a]**.

Beyond use generally in the US pultrusion industry for reference citations and requirements for FPCs, the Director of Marketing and Product Development at Creative Pultrusions stated that since August 2013 the US company used the LRFD Pre-standard "*extensively for the design of FRP structures and products*". These include pedestrian bridges, access structures, docks, maintenance platforms, crossarms, utility poles and various other custom engineered structures– permitting the company "*to significantly increase market share while growing sales and profitability*" **[5.7a]**. On its international applicability, Creative Pultrusions Inc. (in collaboration with Lionweld Kennedy Flooring Ltd.) expanded station platforms in the UK for Network Rail through use of the pre-standard, and more broadly, "*Toby's work has permitted us to supply engineered solutions in Canada and Europe adding [to] our average yearly growth rate*" **[5.7a]**.

During 2018, the Chair of ASTM Subcommittee: D20.18 engaged the expertise of Professor Mottram in revising D953 to specify an industrial standardised test method (via Procedure C) to measure the bearing strengths in polymer resin-based materials. Previously, D953 was only for thermoplastics, with the 2018 revisions scoping both thermosets and their FPCs – such as those produced by the pultrusion **[5.4, 5.7b]**. Because of the suitability and flexibility of Procedure C as highlighted in **[5.3b]**, D20.18 founded the procedure (which "*Professor's Mottram's expertise was vital in developing*" **[5.7b]**) on the Warwick compression loading method **[3.1-3.2]**. Regarding use of D953, the Engineering Director of Bedford Reinforced Plastics (BRP) elaborated: "*BRP have already used the ASTM D953 test procedure to evaluate our entire range of pultruded structural shapes. Products tested using this method are sold to all of our clients throughout the USA and internationally*." Applications of these shapes are seen in stair towers, walkways, pedestrian bridges, pipe supports, cooling towers etc. for use in a wide range of markets such as wastewater/water treatment, oil & gas, mining and chemical processing **[5.7b]**.

Due to delays from the COVID pandemic, the ANSI standard is provisionally set for publication in August 2021 and will be adopted into the International Code Council's (ICC) International Building Code (IBC) **[5.3a]**. For impact on the FCAPS Committee directly, actual publication beyond 2020 is incidental to the instrumental contributions from Warwick through balloting from August 2013 and 2020 – with balloting being the formal policy-driven process which make ANSI standards a reality. For realised impact on US civil engineering, the Pre-standard in its current form and the *ASTM D953–19* test method have both had a marked effect on companies such as Creative Pultrusions and Bedford Reinforced Plastics – facilitating sales and collaborations internationally.

Further uptake of guidance and standards – In February 2020 *CD 368 Design of fibre reinforced polymer bridges and highway structures* **[5.8]** was issued by Highways England, with involvement from the Welsh Government, Transport Scotland and the Northern Ireland Department for Infrastructure. The design manual "includes additional information taken from the draft Eurocode (JRC report) **[5.1]** and recently released CIRIA C779 FRP Bridges: Guidance for designers **[5.2c]**… and reflects current best practice" **[5.8]**. This demonstrates that two distinct sets of FPC guidance with strong contributions of Warwick expertise have been factored into a nationally-applied document that forms part of the works specification. Unsolicited uptake such as this is defining of a far-reaching, pervasive influence in the sector, and lends weight to Warwick contributions to FPC civil engineering being made "*at the highest level and with absolute reliability*" **[5.6]**.

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

[5.1] *Prospect for New Guidance in the Design of FRP Structures* (European Composite Industry 2018), https://tinyurl.com/y3rabpdf
[5.2a] Covering statement from Chair of the Composites UK CSG; **[b]** Composites UK press release 02.07.20, https://tinyurl.com/yy96tgxb **[c]** *Fibre Reinforced Polymer Bridges – Guidance for Designers*, Composites UK: Construction Sector Group (CIRIA, 2018), https://tinyurl.com/yy79wl4b
[5.3a] Covering statement from Chair of the ASCE FCAPS committee; **[b]** *Pre-Standard for Load and Resistance Factor Design (LRFD) of Pultruded Fiber Polymer (FPC) Structures (Final)* (American Composites Manufacturer Association 2010)
[5.4] ASTM D953 – 19, '*Standard Test Method for Pin-Bearing Strength of Plastics'*, https://www.astm.org/Standards/D953.htm
[5.5] Statements of 5.2c usage; **[a]** from the Associate Director of Bridges, Jacobs; **[b]** from the MD of Structural Evolution Ltd. (formerly the Senior Engineering Manager of NOV Fiber Glass Systems)
[5.6] Statement from the Convenor of WG4 of CEN/TC 250
[5.7] Statements of corroboration of US impact: **[a]** from the Director of Marketing and Product Development at Creative Pultrusions Inc.; **[b]** from the Engineering Director at Bedford Reinforced Plastics.
[5.8] *CD 368 Design of Fibre Reinforced Polymer Bridges and Highway Structures* (Highways England, 2020), https://tinyurl.com/y3z6cb4z