Institution: Lancaster University		
Unit of Assessment: 12, Engineering		
Title of case study: Lancaster research into composite structures informs new structural design guides and their use by the civil engineering industry.		
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:**
Dr Geoffrey Turvey	Senior Lecturer	01/03/1972-present
Period when the claimed impact occurred: 2016-2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Research headed by Dr Turvey at Lancaster University defines best practice for the design of glass fibre-reinforced polymer (GFRP) composite materials, beams, columns and bolted and bonded joints used in civil engineering structures. The research has impacted the development of the UK's Construction Industry Research and Information Association's (CIRIA) and the European Composite Industry Association's (EuCIA) design guides [C779 (2018) and JCR (2016)] for GFRP composite bridges and structures. These design guides have significantly influenced the development of Highways England's document 'CD 368 – Design of Fibre Reinforced Polymer Bridges and Highway Structures (2020)' which replaces the Highways Agency's outdated 'Design Manual for Roads and Bridges BD 90/05' (2005).

The design guides are used by international companies, e.g. Atkins, WSP, Jacobs, Network Rail (UK) and COWI (London/Denmark) to design and construct GFRP composite bridges and structures in the UK. They also assist the companies' design engineers to exploit GFRP's advantageous properties over more traditional materials such as concrete and steel, i.e. high corrosion resistance, high electrical and thermal insulation, low self-weight and low transportation, construction and maintenance costs, to extend in-service structural life.

Note: FRP is a general term which refers to all long fibre-reinforced polymer composite materials. In this case study it means glass fibre-reinforced and/or carbon fibre-reinforced polymer composite materials

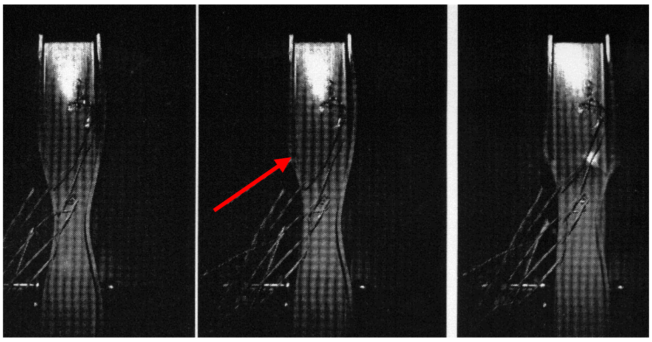
2. Underpinning research

GFRP composites are heterogeneous, anisotropic, elastic-brittle materials which may be tailored to address their advantageous properties. Several manufacturing processes, e.g. pultrusion, resin transfer moulding etc. are used to make GFRP structural profiles and flat sheet for bridges and structures. The ability to tailor material properties and manufacturing processes offers the opportunity to produce optimal GFRP structural profiles. However, on a size-for-size basis their flexural and shear stiffnesses are lower than those of steel and aluminium structural profiles. These factors have increased significantly the research required and the time to develop serviceability and ultimate limit state design guidance for GFRP composite bridges and structures. Thus, whereas limit state design guidance for steel and concrete structures has been available in the form of Eurocodes for three decades, this remains a future objective for GFRP composite structures. Nevertheless, recently the situation in the UK has changed significantly, as the potential advantages of using GFRP composites in infrastructure are recognised more widely and important research developments are being incorporated into limit state design guides such as C779 (2018) and JCR (2016) – precursors to future GFRP composite British Standards/Eurocodes for bridges and structures.

Between 2000 and 2020 Turvey has contributed significantly (37 journal and 35 conference papers) to the research required for limit state design guides for GFRP composite bridges and structures. In 2013, he became a member of a design committee, sponsored by Composites UK Ltd, to develop the world's first design guide for FRP composite bridges. The guide was published by the Construction Industry Research and Information Association (CIRIA) as 'Report C779: Fibre-Reinforced Polymer Bridges-Guidance for Designers' [5.1a]. Turvey was only one of three academic co-authors of C779 (the others being J. Toby Mottram and Wendel Sebastian) and has contributed significantly to its contents, specifically Chapter 5 "Structural Analysis". This chapter cites eight of his post-2000 papers, including research on the characterization of the rotational stiffness and strength of web-flange junctions of pultruded GFRP profiles via web bending tests [3.3], flexure of pultruded GFRP beams with semi-rigid end connections and tearing failure of web-flange junctions in pultruded GFRP profiles. At 36 pages long, this chapter accounts for approximately a third of the main body of the C779 report.

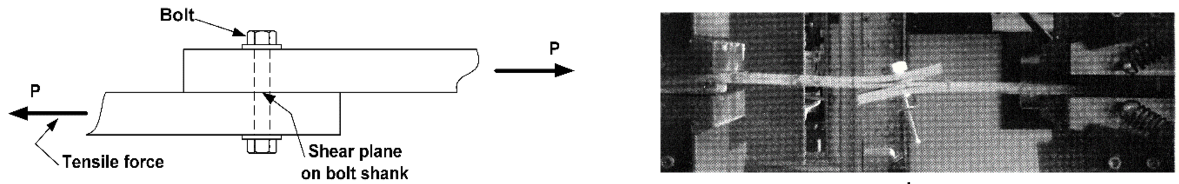
The European Composites Industry Association (EuCIA) has been tasked by the EU to develop a Eurocode for FRP structures. The first output towards this goal was JCR (2016) [5.8]. JCR cites five of Turvey's papers. These include [3.1] in the section on beam design and [3.4], [3.5] plus two others in the section on GFRP bolted joint design.

Figures 1 and 2 provide small <u>snapshots</u> of experimental research on buckling collapse of axially compressed short wide-flange (WF) GFRP columns and tensile failure of GFRP single-lap, single-bolt joints. Both figures have been taken from taken from Turvey, G. 'Testing of pultruded fibre-reinforced polymer (GFRP) composite materials and structures' in Jiping Bai (Ed.) ***Advanced fibre-reinforced polymer (FRP) composites for structural applications,*** (2013), Woodhead Publishing Ltd, pp.440-508. Further information is presented below of Turvey's research on GFRP beams, columns, joints and characteristic material properties, which contribute to the design of GFRP composite structures



a b c

Figure 1. Three high speed video images showing axially compressed short WF columns: (a) local buckling of web and flanges, (b) initial failure at left web-flange junction (red arrow) and (c) subsequent failure at opposite right web-flange junction [Note: Time interval between states (b) and (c) was 0.001 seconds.]



a b

Figure 2. (a) Technical drawing showing single- lap, single-bolt tension joint and (b) tensile failure of joint showing significant rotation of the bolt and flexure of the laps and their internal delamination.

Turvey's publications include one of the first research reviews on bolted GFRP joints. Equations for the flexural design of GFRP beams with semi-rigid end connections have also been developed. Additionally, for the first time, serviceability limit state design equations have been derived for bending of unstiffened and carbon fibre-reinforced polymer (CFRP) stiffened pultruded GFRP beams with and without bolted end connections [3.1]. Furthermore, advanced understanding of the buckling, post-buckling and initial failure of axially-loaded GFRP columns has been reported in [3.2]. High speed video imaging pin-pointed the initial failure location of the column's web-flange junctions (see Figure 1). In [3.3], Turvey was the first to quantify the stiffness and strength of web-flange junctions of WF GFRP profiles using a novel test rig. These junctions are their weak zones due to fibre waviness arising during the pultrusion process. Moreover, the first investigations of hot and wet environmental conditions on the stiffness and strength of bolted GFRP tension joints are reported in [3.4] and [3.5]. In another paper, the longitudinal/transverse and tensile/compressive ultimate stresses, elastic moduli, major/minor Poisson's ratios and ultimate strains (many not provided in pultruders' design manuals) are reported for GFRP WF, channel and angle profiles [3.6]. They are used to determine *characteristic* ultimate stresses and elastic moduli of the GFRP profiles and are compared to the pultruders' design manual minimum values. The characteristic ultimate stresses are shown to depend on profile size and shape whereas the characteristic elastic moduli are independent of these attributes. Turvey was also the first to provide experimental verification of new performance indices for the design of CFRP stiffened GFRP beams. In addition to [3.1] – [3.6], other seminal research has quantified the effects of: (i) load orientation, (ii) hole clearance, and (iii) temperature/moisture on the characteristic strengths and knock-down factors of bolted GFRP tension joints. These strengths and factors are fundamental for limit state and permissible stress design respectively of these joints. Furthermore, Turvey's experimental research has also quantified the rotational stiffnesses and strengths of pultruded GFRP bolted beam-to-column and column-to-base joints, both necessary for column buckling/collapse design.

3. References to the research

[3.1]. **G.J. Turvey** (2006) Structural analysis of CFRP-plated pultruded GRP beams, *Proceedings of the Institution of Civil Engineers: Structures and Buildings*, 159, (SB2), 65-75.
[3.2]. **G.J. Turvey** and Y. Zhang (2006) A computational and experimental analysis of the buckling, postbuckling and initial failure of pultruded GRP columns, *Computers & Structures,* 84, 1527-1537. ***102 citations (Scopus)***.
[3.3]. **G.J. Turvey** and Y. Zhang (2006) Characterisation of the rotational stiffness and the strength of web-flange junctions of pultruded GRP WF-sections via web bending tests, *Composites Part A: Applied Science and Manufacturing,* 37, 152-164.
[3.4]. **G.J. Turvey** and P. Wang (2007) Thermal preconditioning study of bolted tension joints in pultruded GRP plate, *Composite Structures,* 77 (4), 509-513.
[3.5]. **G.J. Turvey** and P. Wang (2007) Failure of pultruded GRP single-bolt tension joints under hot-wet conditions, *Composite Structures*, 77 (4), 514-520.
[3.6]. **G.J. Turvey** and Y. Zhang (2018) Mechanical properties of pultruded GFRP WF, channel and angle profiles for limit state/permissible stress design, *Composites Part B*, 148, 260-271. REF2 Output.

Additional quality indicator:
EPSRC GR/R28386/01, Dr. G.J. Turvey. Awarded 1st October 2001 to 31st March 2005, £251,505.00 [3.2, 3.3].

4. Details of the impact

The research outputs described above are a selection of those that underpin the development of the aforementioned up-to-date Limit State design guides for GFRP bridges and structures, i.e. C779 (2018) and JCR (2016), which replace outdated guides. Further evidence of the research's impact is given by leading international civil engineering consultancies positively acknowledging the use and importance of these new design guides for the design and construction of GFRP footbridges and structures. They confirm that GFRP structures are: environmentally more sustainable, structurally more efficient, materially more durable, lighter to transport to site and quicker to erect than those made of more traditional materials.

4.1. CIRIA Report C779

The report was first presented to the engineering community in November 2018 in London, and again in June 2019 in Manchester. Turvey attended the London presentation and was impressed that the number of practicing civil/structural engineers, architects, and materials suppliers greatly outnumbered the academics in attendance. Following its announcement on CIRIA's website, C779 has attracted significant worldwide attention. By July 2020 it had been downloaded more than 2,350 times by civil engineering design and construction companies, and individuals [5.1b, 5.4].

Atkins (Swansea, UK & Epsom, Surrey):
Atkins, a member of the SNC-Lavalin Group, is one of the world's most respected design, engineering and project management consultancies. Their Technical Authority (Transportation) Engineer confirms that C779 has had a "*very positive impact*" on the Engineering industry. As the use of FRP is still relatively new in bridge design, "*the publication of this code allows us to*

reference the relevant parts of this industry standard, which gives further confidence to our clients". The code has "*therefore acted an enabler to get this new material applied into practice"* and is being currently used by his company to design 20 FRP bridges over the UK's new East-West railway [5.2a, 5.2b]. He also confirms that C779 has enabled the Highways Agency's 'Design Manual for Roads and Bridges BD 90/05 (2005)' to be replaced by Highways England's CD 368 (2020) [5.2a].

WSP (London, UK):

WSP are involved in numerous bridge design projects. Their Technical Director confirms that CIRIA C779 has been "*a key advance in the documents available for FRP bridge design"* as there "*was no similar document available in the UK before this covering how to design FRP bridges and calculate structural resistance*".

WSP are currently using C779 in the in the design and construction of the following FRP bridges: [5.3]

1. Springkells (Aspatria, Cumbria): 9.5m span highway bridge over a railway.
2. Saxe Street (Teignmouth, Devon): 15m span footbridge over a railway.
3. Eatons (Poole, Dorset): 20m span footbridge.
4. Widewater (West Sussex): 20m span footbridge.

Network Rail (London, UK):

The Operations Manager for Composites UK (the trade association for the UK composites industry) has confirmed that Network Rail is using C779 to design 10 non-station and 2 station FRP footbridges over the Bicester to Bletchley line (part of the new East-West Rail project) [5.4]. These footbridges are part of the 20 FRP footbridges aforementioned under Atkins [5.2b]. The Standedge Aqueduct also forms part of this project and Composites UK confirm that C779 has also been used in this design. The steel aqueduct will be replaced by two 10.2m span FRP aqueducts, which allow the river Colne to flow over the railway. Network Rail's involvement is due to the aqueduct crossing a railway. The use of twin FRP aqueducts facilitates maintenance by closing one aqueduct for inspection/maintenance whilst the river flows along the other aqueduct. [5.4]

North West Rail [part of Network Rail] also indicated to Composites UK that, following a "*Whole Life Cost*" exercise for different materials used in bridge construction, it was decided to use FRP footbridges for the East-West Rail project. Design and supply of the FRP decks is based on: 1. American Association of State Highway and Transportation Official's prefabricated bridge specification, 2. Eurocomp Design Code and Handbook (Turvey was on the committee which developed and wrote this code, and contributed a Case Study) and 3. CIRIA's C779: FRP Bridges – Guidance for Designers [5.4].

COWI (London, UK & Lyngby, Denmark):

Figure 3: Futura FRP Station Footbridge, reproduced with kind permission from Marks Barfield Architects and COWI

COWI is a multinational consultancy group and is among the leading consultants within complex infrastructure design. The Director of COWI (UK Bridge) highlights that C779 is "*very useful*" and provides industry practitioners with "*much of the FRP design information they need in one place".* COWI is currently using C779 to develop the design of a new typology of FRP station footbridge "Futura" (see Figure 3, left) for Network Rail in conjunction with the National Composites Centre (NCC) [5.5a]. The Chief Executive of the NCC describes this bridge as "*ground-breaking*" and outlines the huge benefits the use of FRP materials offer, including the "*cost-effective nature of their construction and installation*", that they are a "*more sustainable solution"* and that they are "*intrinsically safer*" than more traditional materials [5.5b]. The Principal Engineer for Network Rail also adds that these benefits and the corrosion resistant nature of composites will mean "*less disruption and impact on passengers when we're installing and maintaining our assets*" [5.5b].The Project Director of Marks Barfield Architects, the originators of the Futura FRP station footbridge concept, indicates that from its inception the footbridge offers the benefits of large scale pre-fabrication and cutting-edge innovative use of GFRP composite materials [5.5b]. COWI also state that they are using JCR (2016), discussed subsequently, as a standard and design approach for their bridges [5.5a].

Jacobs (Manchester, UK)
Jacobs is a multinational company with 52,000 employees worldwide. Their Associate Director of Bridges reports the use of C779 and CD 368 in the design of several FRP footbridges: (i) Lower Otter River Project (comprising three 25m spans), (ii) Raglan Road Footbridge in Lancashire (one 30m span over the railway), (iii) Level crossing replacement footbridge (Network Rail, Winstantow) (one 25m span over a railway) and (iv) Rowell Road Bridge (Essex) (5m span over a stream) [5.6].

4.2. JCR (2016) Design Guide [5.8]
In 2018, JCR (2016) underwent very minor updating and was re-named EuCIA (2018). In addition, in April 2020 a Technical Specification, (derived from JCR (2016) and EuCIA (2018)), was approved by WG4 of CEN TC 250 (the EU's body for approving Eurocodes) and should become a new Eurocode for FRP structures within two to three years. As discussed above, COWI has confirmed that they are using JCR (2016) as a standard and design approach for their bridges [5.5a].

4.3 CD 368 – Design of Fibre Reinforced Polymer Bridges and Structures
Prior to C779, only the Highways Agency's *outdated* 'Design Manual for Roads and Bridges BD90/05' (2005) existed. No other UK design guides for FRP bridges were available. In February 2020, Highways England published CD 368. The importance of JCR (2016) and C779 (2018) in the development of CD 368 can be evidenced by [5.2a], [5.7] and page 3 of [5.9]. The General Manager of Lifespan Structures Ltd (London, UK) confirms that they have already used CD 368 in the design of several completed FRP footbridges, with spans ranging from 6m to 12m. Both Lifespan Structures and Jacobs have confirmed that they are also using this code in the design of several ongoing projects [5.7, 5.6].

5. Sources to corroborate the impact

[5.1]. (a) CIRIA Report C779 'Fibre-reinforced Polymer Bridges-Guidance for Designers' (November 2018). Corroborates Turvey as an author of the report and a member of the FRP Bridges Committee (pp. iv, v). Turvey's post-2000 research is cited 8 times (including [3.3] on p.65). (b) Email from Composites UK Ltd dated 5th March 2020 corroborating over 2000 downloads of [5.1] in 2018 and 2019. Please see [5.4] for further increase by July 2020.

[5.2]. (a) Letter from the Technical Authority (Transportation) Engineer, Atkins and co-editor of CIRIA C779, corroborating C779's use in the design of 20 FRP railway bridges. Dated 13th November 2020. (b) Email from the same contact corroborating that footbridges for the new East-West Rail Project (as described in [5.4]) are those being designed by Atkins. Dated 24th November 2020.

[5.3]. Email from the Technical Director of WSP corroborating the benefit of C779 in the design of 4 FRP bridges. Dated 24th November 2020.

[5.4]. E-mail from Operations Director at Composites UK confirming the use of C779 in the design of footbridges for the East-West Rail Project and the 2350 downloads of C779. Dated 2nd July 2020.

[5.5]. (a) Statement from the Director of COWI (UK Bridge) confirming the impact of C779 and use in the design of the new bridge design for Network Rail dated 12th November 2020 and (b), Press release from the National Composites Centre regarding the Futura Bridge dated 16th September 2020.

[5.6]. E-mail from Jacobs' Associate Director of Bridges dated 15th December 2020, confirming use of C779 and CD 368 in their designs.

[5.7]. Email from the General Manager of Lifespan Structures Ltd confirming the use of CD 368 in their designs. Dated 22nd November 2020.

[5.8]. Prospect for New Guidance in the Design of FRP, (JCR, EUR 27666. 2016).

[5.9]. 'CD 368 Design of Fibre Reinforced Polymer Bridges and Highway Structures' (Highways England, 2020). The importance of JCR (2016) and C779 (2018) is acknowledged on p. 3.