Institution: Lancaster University

Unit of Assessment: UoA 15: (General Engineering, Main Panel B, Sub-Panel 15)

Title of case study: Lancaster's research on pultruded glass fibre reinforced polymer composite joints and structures – its impact on current and emerging design codes

1. Summary of the impact

The key impact is in the definition of best practice for the design of joints, components and structures comprised of glass fibre reinforced polymers (GFRP, also known as fibreglass). The primary beneficiaries are (i) professional civil and structural engineering designers of GFRP structures; (ii) pultruders and composites fabricators due to continually expanding use of GFRPs in construction; and (iii) the general public through the provision of sustainable structures.

In particular, Lancaster's research on pultruded GFRP materials and structures has contributed to the *EUROCOMP Design Code and Handbook* (1996), the world's first limit state design code for GFRP structures. This code has influenced GFRP structural design globally ever since, both pre and post-2008. Additionally, post-2008, EUROCOMP has triggered and influenced development of new European and Japanese design codes, in turn impacting designers, fabricators and the public in those geographical regions. Lancaster's research has influenced the US Load and Resistance Factor (LRFD) Prestandard (2010) and ASCE's Manual No.102 on bolted and bonded joints (2011) two codes and guidelines that will accelerate the US's application of composites in construction.

Thus, the use of Lancaster's research in these codes and guidelines has supported the construction of fibreglass-based civil structures across the globe as well as the delivery of individuals with the analysis and design skills needed by the composites industry.

2. Underpinning research

GFRP dominates fibre reinforced polymer (FRP) composite construction, not least because GFRP structural components (beams, columns etc) are manufactured economically by pultrusion.

In the early 1990s, structural engineers' lack of knowledge and understanding of: (i) the load-resistance characteristics of pultruded GFRP, (ii) the validity and limitations of *conventional* design and analysis procedures for FRP structures and (iii) the lack of design codes continued to retard the use of FRP in infrastructure. Consequently Dr Geoff Turvey, a Senior Lecturer in Engineering who has led Lancaster's pultruded GFRP research since its inception, decided in 1993 to focus Lancaster's on-going GFRP research in four areas: material property characterisation, bolted joints, structural components (beams, columns etc) and full-scale structures (frames, trusses etc), and produce outputs, particularly in the form of design guidance, for the benefit of practicing civil and structural engineers. Examples of significant insights and findings from two of the areas are:-

<u>Bolted Joints</u>

- Provision of an understanding of the relationships between joint geometries and their failure modes [see **Ref. 1** in §3 below].
- The creation of design charts (with confidence limits), including the effect of bolt torque on joint strength [**Ref. 1**].
- Design guidance on the reduction in joint strength due to off-axis loading.
- Ranking of the impact on joint strength of: load orientation, hole clearance, temperature and moisture and their quantification in terms strength reduction factors [**Ref. 2**].
- Experimental determination of rotational stiffness and strength of beam-to-column and column-to-base joints [**Ref. 3**].
- The first state-of-the-art review of bolted tension and flexural joints in pultruded GFRP structures.

<u>Beams</u>

- Establishment of the validity & accuracy of analytical & numerical tools for predicting experiment-al lateral buckling loads [**Ref. 4**] and the effect of load position (relative to the centroid).
- Formulation and experimental verification of new deformation equations and performance indices for the design of both unstiffened and carbon fibre reinforced polymer (CFRP) stiffened beams [**Ref. 5**] and sway columns.
- Numerical analysis study of the benefits of CFRP stiffening for enhancing lateral buckling loads of single and two-span beams.

In 1993 Lancaster's research reputation on pultruded GFRP joints & structures, and its relationship with the UK's leading pultruder (now Exel Composites UK Ltd), led to Turvey joining the Committee which developed and wrote the world's *first* limit state design code for FRP structures. The resultant *EUROCOMP Design Code & Handbook*, developed during the EUREKA-sponsored EUROCOMP project, was first published in 1996. As well as sitting on the Committee that oversaw the code compilation, he also input knowledge from his contemporaneous research on pultruded FRP structures [**Refs. 1, 4**] and contributed to the Handbook with a research Case Study on material stiffness and strength properties, beam flexural analysis and testing and the UK's *first* analysis and testing to failure of a portal frame [**Ref. 6**]. His continuing research on pultruded GFRP bolted joints and beams has also influenced two US design codes and guidelines, namely the US Load & Resistance Factor Prestandard (2010) [**Refs. 1, 2, 4, 5**] and the ASCE's Manual No. 102 (2011) [**Refs. 3, 6**].

Turvey was lead author on all research outputs listed in Section 3. In his research, he was supported by research students (for all of whom he was Director of Studies), research assistants (supported by grants on which he was PI) and UK / visiting academics (especially Profs Narita and Kobayashi, Japan, Prof Wei Wenhui, China and Prof Kadkhodayan, Iran). Collaboration and resource (incl. financial support) have also been provided by Dr. J. Hartley (Exel Composites UK, Ltd), D. Witcher (Strongwell, USA until October 2012), Dr. G. Sims (NPL), J. Quinn (James Quinn Associates Ltd), Dr. R.A. Downey (Engineered Composites Ltd), M. Singleton (StartLink Systems Ltd). S. Kaethner (Ove Arup & Partners) and Profs. A. Alderson, W. Cantwell, R. Day, and P. Withers (all of the North West Composites Centre, of which Turvey was a member).

3. References to the research

1. C. Cooper, **G.J. Turvey** 'Effects of joint geometry and bolt torque on the structural performance of single bolt tension joints in pultruded GRP sheet material', *Composite Structures*, Vol.32, Nos.1-4, 1995, pp.217-226.
2. **G.J. Turvey**, P. Wang 'Failure of pultruded GRP single-bolt tension joints under hot-wet conditions', *Composite Structures*, Vol.77, No.4, 2007, pp.514-520.
3. **G.J. Turvey**, C. Cooper 'Semi-rigid column-base connections in pultruded GRP frame structures', *Computers and Structures*, Vol.76, Nos.1-3, 2000, pp.77-88.
4. R.J. Brooks, **G.J. Turvey** 'Lateral buckling of pultruded GRP I-section cantilevers', *Composite Structures*, Vol.32, Nos.1-4, 1995, pp.203-215.
5. **G.J. Turvey** 'Structural analysis of CFRP-plated pultruded GRP beams', *Proceedings of the Institution of Civil Engineers: Structures and Buildings*, Vol.159, No.SB2, 2006, pp.65-75.
6. **G.J. Turvey** 'Testing of a pultruded GRP pinned base rectangular portal frame for the EUROCOMP project', *EUROCOMP Design Code and Handbook (J.L. Clarke ed.), E & F.N.Spon, 1996, pp.719-741.*

Notes:-

(a) Refs. 1, 2 & 5 are the three that best indicate the quality of the underpinning research.
(b) Refs. 1, 2, 4 and 5 plus 10 other papers (not listed above) are cited in the *Commentary* on Chapters 5 and 8 of the LRFD Prestandard (2010).
(c) All of the research outputs cited above were subjected to rigorous peer review.
(d) Ref. 5 was returned as part of Lancaster's RAE2008 submission under UoA25. The outcome of that exercise was that 100% of the research outputs submitted to UoA25 by Lancaster Engineering were rated at 2* or better.

Key peer-reviewed EPSRC grants that supported this research include the following, all led by Turvey as PI: 'Characterisation of beam-to-column and column-to-base joint behaviour & its application to pultruded GRP frame structures' (1994-7, £124k); 'Structural integrity of bolted joints for pultruded GRP profiles' (2000-02, £127k); 'Structural integrity evaluation of buckling-triggered failure in pultruded GRP and HF profiles' (2001-05, £251k). Other support was derived from the NWDA-funded 'North West Composites Centre' (2006-09, [Total value of the grant to the partner universities (Bolton, Lancaster, Liverpool and Manchester) was £2,100,000, Turvey again PI].

4. Details of the impact

The key impact is on professionals and practitioners through the use of research in the development of design standards and codes, so defining best practice – specifically in the design of joints, components and structures comprised of GFRPs. Secondary impacts arise in the economic domain *via* increased uptake of GFRPs in construction, glassfibre producers, and in the environmental domain by provision of sustainable structures.

The narrative of this impact begins when, as a result of his expertise in pultruded GFRP joints and structures, Turvey was invited to join the Committee tasked with the development of the *first* limit state code for the design of FRP composite structures in construction (under the EU funded joint UK-Finland-Sweden-France EUREKA Project No. 418). Turvey participated in meetings which considered, developed and improved drafts and approved the final version of the code and also contributed a case study. The latter included material property characterisation data, beam flexural testing and analysis, and the UK's *first* failure test and analysis (using specially developed equations) of a pultruded GFRP portal frame – all arising from research by Turvey [see **Ref. 6** in §3 above].

The significance of the resultant *EUROCOMP Design Code and Handbook* [see source of **Ref. 6** in §3] is that, for many years, it was the only *limit state design* code for FRP composite structures. Since its publication in 1996, EUROCOMP has been used to design the UK's FRP infrastructure, *particularly the majority of its FRP bridges*, which benefit the public with essential and sustainable communication links. Indeed, it is specifically taken into account in the Highways Agencies' Design Manual for Roads and Bridges [see reference **EP1** in the evidence portfolio of §5 below].

Post-2008 UK consultants Tony Gee & Partners [**EP2**], Sinclair Knight Merz, Gurit and Optima Projects (in association with Network Rail) have used EUROCOMP to design FRP bridges at Standen Hey, Moss Canal, Calder Railway Viaduct, Foryd (first two-span lift bridge) and Dawlish Railway Station (GFRP copy of Grade II listed footbridge). James Quinn Associates Ltd, cite EUROCOMP as the primary literature source in all of their design and analysis reports on FRP structures – including one for the GFRP formwork for diving boards for the 2012 Olympics Aquatics Centre. These consultancies state that EUROCOMP's partial factors for GFRP materials and design guidance on bolted/bonded joints are particularly useful.

The reach of EUROCOMP's impact extends beyond the UK. In Saudi Arabia, Gurit used it in the design of 160000 m^2 of sandwich panels for Haramain Station's roof (construction 2009-14, part of the Haramain High Speed Rail Project expected to carry 3 million passengers p.a. including Hajj and Umrah pilgrims) and cladding panels for the top 200 m of the world's tallest clock tower, the 76 storey, 601 m high Makkah Clock Royal Tower (completed 2012). In Switzerland it has been used to design the sandwich canopy over the Novartis Building entrance in Basel.

Further reach is evidenced by information from EUROCOMP being included in or influencing the development of other national design codes & guidelines, including those in Italy (2008) [**EP3a,b**], Germany (2010) [**EP4**], Japan (2011) [**EP5a,b**] and Holland (The *Dutch Civil Engineering Centre for Execution of Research & Regulation (CUR) Recommendation 96*, 2003, under revision 2012) and used in the design of over 60 bridges (including Lotharingen (2009), Oosterwolde (2010) and Geestmerambacht (2012)) [**EP6**]. The *Handbook* is used to induct young engineers at Royal Haskoning DHV in FRP materials/processes [**EP6**]. These examples show EUROCOMP's wide-ranging impact and, by direct implication, that of Lancaster's pultruded structures research.

Additional evidence of the impact and reach of Turvey's pultruded GFRP bolted joints and structures research is its citation and use in US design guidance / codes. The *American Society of Civil Engineers (ASCE) Manuals and Reports on Engineering Practice No. 102* (2011) on bolted/bonded joints cites research conducted at Lancaster in Chapters 2, 7, 8 and 9. Much of Chapter 8, (i.e. deformation equations and performance indices for beams and sway columns with semi-rigid end connections and all of the tables) is reproduced directly from Turvey's pultruded GFRP papers [**EP7**]

Prior to final drafting of the US Load and Resistance Factor Design (LRFD) Prestandard (published Nov 2010), trial designs of FRP structures were undertaken by leading US consultants (Robert Silman & Associates, Severud, Walter P. Moore, Arup, Gilsanz, Murray & Steficek, Hardesty Hanover, Magnusson Klememic Associates and Alfred Benesch) to check its acceptability and utility. These organisations will have appreciated the impact and reach of Lancaster's pultruded GFRP bolted joint and beam research through its citation and discussion in the Prestandard's *Commentaries* on Chapter 5 (*Design of Members for Flexure and Shear*) and Chapter 8 (*Design of Bolted Connections*) [**EP8, EP9, EP10**]. When the Prestandard is published as an ASCE / ANSI (American National Standards Institute) standard in 2013 / 2014, even greater impact and reach of Lancaster's research contributions will ensue amongst the US structural engineering community.

Other indicators of the impact, reach and quality of Turvey's research in GFRPs include:-
In the late 1990s, as part of a DTI SMART award, Lancaster undertook initial experimental

research to characterise the structural response of beams and joints fabricated from the *StartLink* system of novel pultruded GFRP profiles for buildings. The research was presented at an international conference in 2001 (and documented in 9 internal LU reports to the originator of the *StartLink* system). In 2008, an improved system was launched as the *StartLink Lightweight Building System Consortium* with funding from the Technology Strategy Board's *Low Impact Building Innovation* programme to develop further the original *StartLink* system. The Consortium's project concluded in 2012 with the opening of an all-FRP house made of pultruded GFRP profiles and stiffened panels. The house meets Level 4 of the 2016 sustainability criteria of the UK Government's Code for Sustainable Homes. The original research at Lancaster has impacted positively on the new StartLink Lightweight Building System system by identifying the shortcomings of the original profiles, and highlighting where improvements were required.

Turvey was also involved in the development of the Construction Industry Research & Information Association (CIRIA) Report 564 (2002) on FRP in construction which, in addition to EUROCOMP, has impacted on the Highways Agencies' design manual [**EP1**] referred to above. This design manual has been consulted by all UK consultants engaged in FRP bridge design ever since, including the post-2008 REF period. Lancaster has also produced the *Structural Analysis* section for the UK's *Design Guidelines for FRP Bridges* (sponsored by the Network Group for Composites in Construction (NGCC) and scheduled for publication in December 2013 / 2014).

Lancaster's FRP research outputs are communicated regularly to FRP pultruders and composites fabricators including J. Hartley (Exel Composites UK Ltd) and D. Witcher (Strongwell) so that the leading EU and US pultruders may benefit. The latter has commented that Turvey's (and Mottram's) bolted joints research is *unequalled*. [**EP10**]

In summary, since its initial publication in 1996 (reprinted 2003 and now available online) the EUROCOMP code, underpinned by research by Turvey at Lancaster, has had a continuing and significant impact on the design of GFRP structures in the UK and overseas. This has continued throughout the post-2008 REF period, during which it has influenced recent code developments in Europe, the USA and Japan and the design and construction of GFRP structures worldwide.

5. Sources to corroborate the impact – Evidence Portfolio

[**EP1**] *Highways Agency Design Manual for Roads & Bridges BD90/05*, The Stationary Office, 2005

[**EP2**] Exemplar factual statement from Senior Engineer at Tony Gee & Partners, corroborating the use of the EUROCOMP code in building projects, especially bridges, in the UK.

[**EP3a**] *Guide for the Design and Construction of Structures made of FRP Pultruded Elements*, National Research Council of Italy, 2008; [**EP3b**] Statement from a member of the Task Group that prepared the technical sections of EP3a, confirming use of EUROCOMP in compilation of EP3a.

[**EP4**] *German Federation of Business Associations* (*BUV) Recommendation for Load-Bearing Components in Construction 08/2010*, 2010

[**EP5a**] *Guidelines for Design & Construction of FRP footbridges* (excerpts), Japan Society of Civil Engineers, 2011; [**EP5b**] Translation of EP5a, corroborating use of EUROCOMP in its compilation.

[**EP6**] Factual statement from Project Manager and Consultant in Fibre Reinforced Polymers, Royal HaskoningDHV, corroborating the use of EUROCOMP in Dutch bridge construction, Dutch FRP Design Recommendations, and in the training of young engineers at Royal HaskoningDHV.

[**EP7**] *ASCE Manuals and Reports on Engineering Practice No. 102: Design Guide for FRP Composite Connections*, ASCE, 2011. Corroboration of the citation and use therein of Lancaster's research may be obtained by consulting Chapters 2, 7, 8 & 9 as discussed in §4 above.

[**EP8**] *ASCE Pre-Standard for Load & Resistance Factor Design of Pultruded FRP Structures*, ASCE, 2010.

[**EP9**] Corroboration of the citation and discussion of Lancaster's research in the Commentary of the ASCE Prestandard, **EP8**, may be obtained from a member of the project team that prepared the Prestandard.

[**EP10**] Corroboration of the citation and discussion of Lancaster's research in the Commentary of **EP8** may be obtained from the Vice-President of Engineering, Enduro, Texas, who will also testify as to the wider impact that Lancaster's research has had on EU & US pultruders.