in Proceedings 8th International Conference on Advanced Composites in Construction (ACIC 2017), 5-7 September 2017, NetComposites Ltd., Chesterfield, UK, (2017), p11-16.

Fibre Reinforced Polymer Structures: Design Guidance or Guidance for Designers

J .Toby Mottram
School of Engineering,
Warwick University, Coventry,
CV4 7AL, UK

ABSTRACT

Presented in this paper is a status on the preparation for us having codified design guidance for new-build structures with Fibre Reinforced Polymers (FRPs). After a summary of the history to where we are today with progress on national and international projects, the paper explores the reasons why it takes many years before design rules in a consensus-based standard appear in print. The reasons are for a complex interaction of the availability of reliable and relevant technical data/information and of the human resources to process data that constructs robust and reliable design procedures for safety critical structures. To be positive, the structural reliability tools needed to develop a standard are at hand and progress has been strong into identifying what are, and what are not, known gaps in knowledge. We can expect before 2020 to witness the publication of the first design standard in America for pultruded shapes. It is likely to be another 10 or more years before we see the appearance of a structural Eurocode for FRP materials because of the extra complexity of involving components made by several composite processing methods, and specifically those of free-form shell structure, with or without sandwich construction. In the meantime, rather than using codified design guidance, we will need to rely on peer reviewed sources to promote and activate practice by offering robust and relevant guidance for designers.

INTRODUCTION

We start this paper by giving a historical perspective towards the preparation and implementation of national or international codified design standards for structures having components that are of Fibre Reinforced Polymer (FRP) shapes and systems. New-build structures can be either of all-FRP or in the form of hybrid combinations with components of traditional structural materials. The latter are to be designed using their specific standards, such as available in the Eurocode suite. This paper does not scope standards for the developed applications of FRPs to retrofitting of existing non-FRP structures or as non-metallic reinforcement in concretes [1].

To the author's knowledge there have been two parallel efforts in the USA and Europe to have brand new standards based on the limit state design philosophy. Let's now introduce the Load and Resistance Factor Design (LRFD) project in North American for a design standard specific to FRP shapes made by the pultrusion composite processing method. Its scope is for building structures with the possibility (which is not in the scope) of being applicable for bridge structures too. Its commencement was promoted by Richard Chalmers (of Chambers Engineering P.C.) when, before 2000, he set-out in [2] and [3] the justification for why detailed development of a pre-standard is warranted, and should be commenced at an accelerated pace ("yes", more than 20 years ago). A useful source for background guidance information was already available, by way of the American Society of Civil Engineers (ASCE) Manual No. 63 [4]. In 2003, Ellingwood [5] introduced to the community that the structural reliability tools needed to develop a standard are at hand, and that the main obstacle was the known rudimentary statistical databases for calibration of the (strength (or resistance in Eurocodes)) formulae.

It was in 2006 that the author received communications on a project call to create a drafting team to prepare the pre-standard *Load and Resistance Factor Design (LRFD) of Pultruded Fiber-Reinforced Polymer (FRP) Structures*. Funded by three American pultrusion manufacturers (Strongwell, Creative Pultrusions Inc. and Bedford), and under the aegis of the Pultrusion Industry Council (PIC) of the American Composites Manufacturers Association (ACMA), a three year funded project started in 2007. The deliverable was a pre-standard that was finalised in November 2010 [6].

One very important finding from this funded drafting exercise is that test results (for structures, sub-assemblies (connections and joints) and, even, at the material level) were rudimentary and Bruce Ellingwood took account of this statistical uncertainty when using structural reliability tools to calibrate the various resistance factors in the LRFD pre-standard [6] (which are equivalent, but not the same, as the inverse of the Eurocode partial factors for a material property).

This project, for pultruded structures, continues to be for a world-first codified standard, and the Fiber Composites and Polymers Standards Committee (FCAPS of ASCE) are close to concluding the next stage of preparation after carrying out 35 ballots that are transforming the pre-standard into its standard. To accompany this structural design standard, PIC and ACMA have prepared, and published in 2012, comprehensive information for the fabrication and installation of structures of pultruded shapes [7].

Historical context in Europe is different, because there have been independent national projects with publications in 1996 in the UK [8], in 2007 in Italy [9] and in 2014 in Germany [10]. Moreover, in 2106, we received the Joint Research Centre (JRC) Science and Policy Report [11] from a pan-European country project under the aegis of the Structural Eurocode committee CEN/TC250. CEN is the Comité Européen de Normalisation or the European Committee for Standardization, which is a public standards organization whose mission is to foster the economy of the European Union in global trading. It is noteworthy that this JRC project had its promotional publication for commencement back in 2007 [12]. The world-first source of guidance is the EUROCOMP Design Code and Handbook [8], which is not a recognized design code, and scopes structural elements made by four composite processing methods. Only the German output [10] is recognised as a national standard, and along with the Italian guide (which is not recognized) [9] is restricted to FRP components made by pultrusion.

The most important European publication to date has to be the 2016 JRC Science and Policy report [11] for the *Prospect for New Guidance in the Design of FRP*. Its preparation was without any specific project funding. It scopes FRP components made by a number of processing methods and thereby along with pultruded shapes involves free-form shells, with or without sandwich construction. The report has the same format and style as the materials' Part 1-1 for concrete, steel, composite steel and concrete, timber, masonry and aluminium in the Eurocode suite. Its preparation by Working Group 4 (WG4) of CEN/TC250 draws on knowledge and understanding from the earlier publications [4, 5, 7-10, 13], a significant project in The Netherlands for updating CUR 96 [14], and the expertise of specialists working with FRPs from 20 European countries. The author is the UK's representative on CEN/TC250/WG4, via the British Standards Institution committee B/525 for Building and Civil Engineering Structures. After a pan-European consultation review process during 2016, WG4 have updated the report [11] using 789 feedback comments. The 2017 version will have been considered at the CEN/TC250 meeting at Naples on 10-11 May 2017 for the project to be given approval to proceed to the next stage of three that are for a Eurocode standard. The second stage is to prepare a CEN Technical Specifications, which was previously known as an ENV. After a successful ballot (closed July 3rd) this stage can receive funding through CEN/TC250 and the M/515 Mandate that provides funds for amending existing Eurocodes and extending the scope of structural Eurocodes.

In the late 1990s there was a related project [15] that led to the first CEN standard, which has the scope of laying down specifications for pultruded shapes, for example, in terms of their minimum mechanical properties, immediately after processing [13]. In the UK another independent project provides the design manual BD 90/05 [16] that, in 2005, presents the requirements for the design of highway bridges and structures with FRP materials and for re-decking existing bridges. This is the only design document to hand that is specific to bridge structures in Europe.

To complete the historical summary, there is an on-going project with the trade organization Composites UK, whose Construction Sector Group is preparing *FRP Bridges – Guidance for Designers*. Although not a standard, this soon to be published peer-reviewed source (with CIRIA), is having content at the same engineering/technical level as the well-known practitioner manuals from the Institution of Structural Engineers, UK. Preparatory work for this unfunded project by an ad-hoc group of industry and academic devotees and experts was started in 2011.

In what follows this paper explains and, equally, justifies, why the process to prepare appropriate codified design rules and get them universally recognised is inherently slow (the 2010 suite of

Eurocodes took 30 years). With the know-how, information and understanding we have in 2017 it is realistic for stakeholders to expect for structures having FRP components that we can in 2017 have publications that offer robust, state-of-the-art guidance for designers, but not design guidance with mandatory rules.

PREPARING STANDARDS FOR FRP MATERIALS

So why does it take a long time to prepare and have a universally accepted design standard for a new structural material? From personal experience of supporting the preparation of parts in a number of FRP 'standard' project since 1994 [6], [8] and [11] the reasons are many, are complex, interact, and for FRP materials can be seen to be focused around the rudimentary statistical data and rudimentary technical know-how owing, in part, to their relatively short construction history (of < 50 years) combined with a continual development in what structural shapes and systems are processed and used in civil engineering works.

Another important reason for slow progress is that the drafters working on design rules are not full-time and usually take on the work as enthusiastic volunteers. This has to been seen as a major handicap, since to be a 100% effective code writer needs time to contemplate, to evaluate and analysis data/information, and to formulate rules that can be quantified and verified. Drafters need also to have a comprehensive understanding of the state-of-the-art for all the standards' content and should be equally comfortable with the manufacturing and execution of FRP structures. For FRP materials the biggest unknown is to have data/information for the state of FRP structures and FRP components at the end of their design working lives (50 years can be appropriate). There are other significant gaps in knowledge linked to the structural engineering of connections and joints (as introduced in [17], and to the strengths and stiffnesses of sandwich panels. The necessary comprehensive understanding is unlikely to be satisfied with the demands of the day job, and those drafters who approach possessing the skills/know-how sets are too valuable to industry to have time to draft codes. To make progress requires teamwork and members on a drafting project (as with CEN/TC250/WG4) scoping the entirety of the knowledge and understanding needed. The need in drafting for 'engineering judgment' remains paramount [18], and the author knows that it takes years to assimilate knowledge and understanding, and to apply these appropriately with confidence.

Professor Roger P. Johnson in his 2006 Gold Medal Address to the Institution of Structural Engineers [18] observed, in the 1960s, that only a tiny fraction of the published research on structures had then been applied in practice. This led to him listing 'eight reasons why 80% of published research is useless'. Here the word 'useless' means only that the research results could not have an impact in being 'useful' as a basis for preparing codified design rules that are fit for purpose.

Today, academics actively doing structural engineering research with traditional materials, such as steels and timbers, can use Eurocode 0 [19] and other supporting information for a framework to 'eradicate' the eight reasons, and thereby carry-out quality research that can readily be transferred into practice. But this has not been the case, as Johnson observed 50 years ago, and the eradication of 'useless research' is a bigger challenge when the structural material is new, it has no recognised design rules, and it has its roots outside of the construction industry. This is certainly true for FRP materials, but to be positive is getting less so for FRPs in construction.

From Johnson's [18] list of eight reasons those of most relevance to informing the preparation of design rules are:

- no clear definition of the domain of applicability of the work;
- no critical review of previous research relevant to that domain;
- test results that omit crucial data on properties of specimens;
- test specimens with materials having strengths different to typical design strength;
- theory that fails to allow for imperfections that can occur in practice.

.
This leads to a third reason why standard writing takes a long time to come to fruition. For FRP materials there is no official national or international design standard on which one can build valuable information from historical precedence of practice and to have a template for the specification of targeted and beneficial Research and Development (R&D). This weakness can be highlighted as being more important against us having effective code preparation because there are not appropriate

sets of standards for either materials specification or characterisation of coupon level mechanical and sub-assembly properties over the design working lives of FRP structures.

The environment is made even more difficulty, because as Horne [20] observed a well-planned and ordered progression through a rational sequence of basis research on to the strategic development of increasingly ambitious practical applications requires collaborative industry support. He says that experience of R&D in practice is a great more complex and hesitant, and they go hand in hand. Their achievement of their effective interplay has to be the researcher's main inspiration. Research groups, however, usually decide for themselves what they would like to work on without knowing if it will be 'useful' or 'useless', and this can lead to disappointments for code drafter when the outcomes are useless only because there have been minor digressions to one of more of Johnson's eight reasons for it classified as 'useless' research. The author has journal papers [21] that have to be classified into this 'disappointing' pool of research contributions. The third reason maybe summarized by the catch 22 of "to be able to write a codified standard (say for a Eurocode) the FRP R&D community needs (matured) practice to learn lessons from, and to have practice at this level we need the standard to overcome cost and an inherent reluctance to choose FRP as the structural material".

Regarding higher education researches, which are disseminated with the aim of informing code development the reviewers of peer-reviewed journal papers could improve matters by being more critical of defects [18]; of course this can only be successful if the referees themselves are conversant with what code writers want, and often they do not. Another problem is that word limits imposed by editors often force journal papers to omit salient, essential data/technical information. Two actions to elevate this impediment to the effective transfer into practice will be to allow an increased word count (at editor's digression) when the answer is 'yes' to a new review question of 'Is the manuscript having information/data that is for design standard development/preparation". Professor Johnson's remedy to ensuring that none of his eight reasons can be responsible for published information being deemed 'useless' is to cross-refer to a full report, made freely available on the web. But the challenge here is that academic researchers are time poor and there's no metric gain from spending time, they do not have, on dissemination in a full report that will attract no citations, etc. An up-to-date alternative will be to use the Internet either by complying with funders', such as Research Councils (RCs), obligation to make source data accessible to all or by the researcher using web pages to mount information with an appropriate format, but not a full report, for others, such as code writers, to easily access and work with. It is not unreasonable to go further, because of the great importance of having the information complete, to recommend that, specific for this dissemination, there are small RC funds (say £10-30k) that can be apply for.

These observations do not detract from the worthiness of the many incremental research studies (see [20] for nearly 2500 publications with pultruded FRP shapes and systems) that do add value to what is known, and are informing what characterization work is needed to take the rudimentary statistical data and rudimentary technical know-how to the next level of appropriateness. The truth is that for the purpose of calibrating (strength) formulae to go into a design standard (see [6] or [11]) a majority of published test results will be judged to be 'useless'. Again to be positive, the ASCE LRFD pre-standard [6] and the JRC Science and Policy Report [11] can now, despite limitations, be used as important templates to direct and target R&D work that will generate useful data/technical information to inform the preparation of design rules. To aid this important form of progress, we can expect a step change to happen when FCAPS completes its transformation work and the ASCE LRFD standard for bolted structures of pultruded shapes is finally published.

Although the appearance of the ASCE LRFD standard (before 2020) will be a key milestone towards us having recognized design guidance, its scope is narrow by being limited to one composite processing method. It would be inappropriate to think that an FRP Eurocode could be ready within 10 years of 2017, especially since it is known that there is much less data, information and know-how for free-from FRP components/structures [11] than there are for pultruded shapes and systems [20]. To plug the gap, while work progresses on preparing an FRP structural Eurocode, there's a strong need now for publications that provide guidance for designers. Specific to FRP bridge engineering, this gap will shortly be plugged by the Composite UK project for the 'step-change' document *FRP Bridges – Guidance for Designer*. The date of publication might well be known when this paper is delivered at ACIC 2017 between 5 and 7 September 2017.

CONCLUSIONS

One conclusion from a presentation that summarizes progress towards us having national or international codified design standards for (building and bridge) structures having Fibre Reinforced Polymer (FRP) shapes and systems is that the processes and stages leading to publication will take a relatively long time, say 10 or more years. From personal experience of supporting the preparation to parts in three 'standard' projects since 1994 the author knows the reasons why are many. An underlying key reason for why this must be so with the new structural material of FRP is the complex and difficult requirements to formulating verifiable design rules suitable for safety critical structures. One major obstacle to making quicker progress is that the statistical data and/or technical information needed to inform the reliable formulation of a specific rule is often either not known or is simply lacking in completeness. Another important reason is that the code drafters working on the content are not full-time and usually take on their standard's work as volunteers. A further handicap to making quicker progress is the fact that, in 2017, there is no official national or international design standard that would ensure we had, for example, sound and reliable knowledge from historical precedence. Moreover, the existence of a published standard would provide the community with an essential template for executing targeted and beneficial R&D to inform further code development or refinement.

To be positive, much progress has been achieved, especially over the last decade (see [6] and [11]), and we can expect, before 2020, to have the first national standard for pultruded shapes, published by the American Society of Civil Engineers. Because a structural Eurocode for FRP materials is to scope components made by several composite processing methods, the author believes it will take another 10 or more years to write, and to receive CEN approval for publication. In the meantime we should be content to rely on state-of-the-art publications that are strong in giving guidance for designers, such as *FRP bridges – Guidance for Designers*, from the Construction Sector Group with Composites UK. In this way the FRP construction community can provide stakeholders with robust guidance that creates the confidence and know-how to design and execute with FRP shapes and systems on new-build civil engineering projects.

REFERENCES

1. Bank, L. C. *Composites for Construction - Structural Design with FRP Materials*, John Wiley and Sons, New Jersey, (2006).
2. Chambers, R. E., 21st Century Composites Require ASCE Standards and SDS: Materials for the 21st Century, *presented at the 1993 Annual Convention and Exposition - Plastics Composites for 21st Century Infrastructure Session*, American Society of Civil Engineers, New York, Dallas, Texas, October 24-28, 1993.
3. Chambers, R. E., ASCE Design Standard for Pultruded Fiber-Reinforced-Plastic (FRP) Structures,' *Journal of Composites for Construction*, **1(1)**, 26-38 (1997).
4. Anonymous. *Structural Plastics Design Manual.* American Society of Civil Engineers Manuals and Reports on Engineering Practice, No. 63, American Society of Civil Engineers, New York, NY (1984).
5. Ellingwood, B. R., Toward Load and Resistance Factor Design for Fiber-Reinforced Polymer Composite Structures,' *Journal of Structural Engineering*, **129(4)**, 449-458 (2003).
6. Anonymous. *Pre-Standard for Load and Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer (FRP) structures (Final)*, American Society of Civil Engineers, Reston, VA (2010).
7. Anonymous. *Code of Standard Practice for Fabrication and Installation of Pultruded FRP Structures*, ANSI standard, American Composites Manufacturers Association, 1st Edition, Arlington, VA (2012).
8. Clarke, J. L., (Ed.), *Structural Design of Polymer Composites - EUROCOMP Design Code and Handbook*, E. & F.N. Spon, London, (1996).
9. Anonymous, *Guide for the Design and Construction of Structures made of FRP Pultruded Elements*, Advisory Committee on Technical Recommendations for Construction, National Research of Italy, CNR-DT 2005/2007, Rome, CNR, (2008). (English Version) http://www.cnr.it/documenti/norme/IstruzioniCNR_DT205_2007_eng.pdf (12 June 2017)
10. BÜV-Empfehlung. *Tragende Kunststoffbauteile im Bauwesen [TKB] – Entwurf*, Bemessung und Konstruktion,' Springer, Wisebaden, (2014). (in German)

11. Ascione, L., Caron, J-F., Godonou, P., van IJselmuijden, K., Knippers, J., Mottram, T., Oppe, M., Gantriis Sorensen, M., Taby J. and Tromp, L., *Prospect for New Guidance in the Design of FRP*, Support to the implementation and further development of the Eurocodes, JRC Science and Policy Report, Policy Framework Existing Regulations and Standards, Prospect for CEN Guidance, European Commission, Joint Research Centre Institute for the Protection and Security of the Citizen, JRC99714, EUR 27666 EN, European Union, Luxembourg, (2016). http://eurocodes.jrc.ec.europa.eu/showpublication.php?id=539# (12 June 2017)
12. Gutiérrez, E., Dimova, S. and Pinto, A., *Purpose and Justification for New Codes and Standards Regarding the use of Fibre-Reinforced Polymer Composites in Civil Engineering*, Support to the implementation, harmonization and further development of the Eurocodes, EUR 22864 EN, JRC European Commission, (2007). http://eurocodes.jrc.ec.europa.eu/doc/EUR22864EN (12 June 2017)
13. BS EN 13706:2002. *Reinforced Plastic Composites - Specification for Pultruded Profiles*, British Standards Institution, London, UK, (2002).
14. CUR Commission C124, *Recommendation 96 Fibre-Reinforced Polymers in Civil Load Bearing Structures*, CUR Gouda, The Netherlands, (2003).
15. Sims, G. D., Pulling Together on European Standards for Pultruded Profiles,' *presented at Fourth EPTA World Pultrusion Conference*, European Pultrusion Technology Association, The Netherlands, 1998.
16. Anonymous. *Design of FRP Bridges and Highway Structures, Design Manual for Roads and Bridges. Vol. 1 Highway Structures: Approval Procedures and General Design, Section 3 General Design, Part 17, Design Manual for Roads and Bridges*, BD 90/05. The Highways Agency, Scottish Executive, Welsh Assembly Government (Llywodraeth Cynulliad Cymru), The Department for Regional Development Northern Ireland, (2005).
17. Mottram, J. T., Design Guidance for Bolted Connections in Structures of Pultruded Shapes: Gaps in Knowledge presented at the *17th International Conference on Composite Materials (ICCM17)*, Edinburgh 27-31 July 2009, Paper A1:6.
18. Johnson, R. P., Bridging Gaps, *The Structural Engineer*, **84(23)**, 58-64 (2006).
19. BS EN 1990:2002. *Basis of Structural Design*, British Standards Institution, London, UK (2002).
20. Horne, M. J., *Research and Development*, *Chapter 8 in Structural Engineering – History and Development*, R. J. W. Milne (Ed.), E & FN Spon, Edmundsbury, (1997).
21. Mottram, J. T., Literature Database on R&D with Pultruded Fibre Reinforced Polymers, University of Warwick. http://www.eng.warwick.ac.uk/staff/jtm/pfrp_latest.pdf (12 June 2017)