Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 999 (1997)

Artikel: Design guidance for joints using polymeric composite materials

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DOI: https://doi.org/10.5169/seals-987

Design Guidance for Joints Using Polymeric Composite Materials

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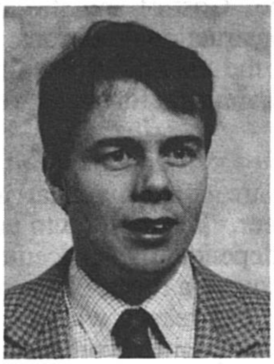

Toby Mottram, born 1958, received his engineering degrees in 1979 and 1984. He has researched polymeric composite materials and structures since 1979. At Warwick University since 1987, his research has focused on framed construction. He is Chairman of DG XII COST C1 material working group.

Summary

A review is presented on design guidance sources for structural joints between members of polymeric composite, and of other materials. Testing, analysis and design for the various types of structural connection are considered. Two principal findings are that; design procedures are more complex than for conventional structural materials; standard joint details are needed to provide end-users with confidence on performance.

1. Introduction

Growth and interest in polymeric composite materials in the building and construction industry occurred initially during the 1960s and 70s. Materials consisted of glass fibre and room temperature curing polyesters, often referred to as glass reinforced polyesters. These were manufactured into curved panels and vessels using contact moulding techniques (Hollaway 1993). Fibre reinforcement was often discontinuous chopped strand mat, at a relatively low volume fraction. To obtain satisfactory strength and stiffness the correct structural form had to be used, and joints, if present, did not transmit appreciable forces (i.e. their purpose was to provide a weather seal).

In the last fifteen years there has been further interest in the use of polymeric composites as different manufacturing processes are exploited (Hollaway 1993, Clarke 1996). Amongst these attractive processes are pultrusion, filament winding, resin transfer moulding, and prepreg moulding. Each process uses different fibre systems with continuous reinforcement, at a relatively high volume fraction, to produce specific structural members and components. Mechanical properties of polymeric composite materials using these processes are therefore higher than those by contact moulding. One advantage of composites over conventional construction materials is the versatility of the different manufacturing processes. In the rest of the paper FRP will be used as shorthand for polymeric composite materials.

Key advantages of FRP are, free-form and tailored design characteristics, high strength-to-weight ratios, and a high degree of corrosion resistance. These are some of the reasons why their use in construction has received increasing attention (Mottram 1995). However, despite the wide use of FRPs in the aerospace industries the civil engineering sector has been slow to take up these materials. There are many in the construction sector who do not have the confidence to use FRPs because of concerns on basic issues relating to the material itself, such as mechanical properties and modes of failure, durability and fire resistance. However, many of these issues are not such a serious problem as to prevent FRPs from being used, and to educate the construction industry these have in detail been addressed in recent publications (Hollaway 1993, Clarke 1996). There does however remain the problem of cost and this is likely to persist until there is well-established practice and more experience. Cost of any structure is always a major consideration when choosing between different construction solutions. FRPs are expensive materials (on a weight basis) and because of this the reinforcement in more than 90% of applications is glass. The general points given herein are therefore most relevant to joints using glass FRPs.

Those engaged in developing FRPs and structures are conscious that jointing has a special significance and poses a major challenge to the engineer. This has led to pultruders (Anon 1989, 1993, 1995) and others (Clarke 1996) to write, independently, procedures for the structural design of connections. Each design guidance source covers a range of connection types from the list in Table 1. The diversity of guidance available is one reason why this review is timely and within the scope of the activities of the Polymeric Composites working group (1995-); part of the European DG XII project COST C1, 'Semi-rigid behaviour of Civil Engineering Structural Connections' (1991-1999). It is worth noting that none of the sources discussed has any national or international legal standing; there is the expectation that what exists today will form the nucleus for regulatory standards by the next century.

2. Connections

2.1 Classification

The choice of manufacturing processes and the wide range of available fibre reinforcement/polymer resin systems means that the range of structural forms is larger than with concrete, steel and timber (Hollaway 1993, Clarke 1996). Table 1 gives a hierarchic classification of connection types having a potential in construction. As a result of this, there is naturally a larger scope for connection types. The main focus is on FRP to FRP connections because these have received most attention. Some of the design guidance is also appropriate for connections of FRP and steel, FRP and timber, FRP and concrete.

Mechanical joints	Bonded joints	Combined joints	JOINT CATEGORIES
Bolted (shear loaded) Bolted (axially loaded) Riveted (shear loaded) Riveted (axially loaded) Clamped Contact (keyed, hooked) Embedded fasteners	Adhesively bonded Laminated Moulded Cast-in Bonded insert	Bonded-bolted Bonded-riveted	JOINING TECHNIQUES
Lap Strap Tee Angle Others	Lap Strap Scarf Butt Tee Angle Others	Lap Strap Tee Others	JOINT CONFIGURATION

Table 1 Classification of connection types (from Clarke 1996)

Classification is also dependent on the function of the joint in the structure. Connections are therefore further classified (Clarke 1996) into;

primary structural

secondary structural
non-structural.

We are principally concerned with primary structural where the joint is expected to provide major strength and stiffness to an assembly for the whole life of the structure. The failure of these connections will have a substantial effect on the performance of the whole structure. Such connections will carry the highest requirement for strength, stiffness and durability. Design guidance must be adequate for connections to be safe and reliable over their whole design life.

When the large choice of connection types (Table 1) is linked with the enormous range of FRP mechanical properties it is not surprising that we find design guidance is often limited in scope and, if general, it has only been partially assessed by testing. This is an important observation which engineers need to understand before they apply any guidance appropriate to the specified materials and structural form.

2.2 Research

Prior to the late 1980s the majority of FRP structures had components manufactured by contact moulding. Jointing was generally non-structural or maybe secondary structural. The need to understand the structural behaviour of these connections was limited and they did not receive much attention. Only a handful of technical papers on FRP joints were published prior to this time (Heger 1984, Mottram 1995).

The interest in structural members made by pultrusion saw the need for research on the performance of primary structural connections. Studies made by academics include extensive laboratory testing and numerical simulation. The objective has been to provide data for the development of design guidance. Between 1980 and 1989 a single conference paper was published. The number of publications has increased significantly in the 1990s with to date over 30 conference and 20 journal papers. Most of the research has been with bolted joints (lap and tee joint classification). Much of the recent work has not yet been used by those involved in writing design guidance.

Hutchinson (1997) has prepared a state-of-art report to review all aspects of joining FRPs in construction. Chapter 5 on 'Joint Design Approaches' has a section where Hutchinson compares recent recommended fastener distances for pultruded lap-joints with those previously known (Anon 1989, Clarke 1996). One interesting feature of the report is that Chapter 8 gives case studies of joints. It was expected that the case studies would refer to the design guidance in Chapter 5. However, Hutchinson found that full details on how each joint was designed were absent when the structure was reported; this a consequence of the commercial nature of these new construction technologies.

3. Design Guidance for Joints

3.1 Europe

The two sources of design guidance (Anon 1995, Clarke 1996) use the limit state approach (Head 1994). They are different and specific details are not within the scope of the paper.

In 1995 the pultruders Fiberline Composites A/S released their design manual (Anon 1995). The limit state approach adopted by the Company uses partial safety factors for material strengths and stiffnesses in order to conform the dimensioning to Danish Standard 456. A design procedure is presented for flat panels (thickness 3 to 20 mm) fastened by steel bolts (M6 to M48) in a lap-joint configuration. Loading is in the plane of joint. Simple design equations are given to determine the joint's ultimate resistance. Of the five different modes of failure used in the design procedure two have new theoretical models that, to the author's knowledge, have not been reported elsewhere. The manual presents tables of design values (load capacity (kN)) in the longitudinal and transverse material directions to enable engineers to design their own bolted connections of the types listed in Table 1. A number of worked examples (e.g. lap, tee, angle joints) illustrate how the tables can be used.

Testing was conducted to determine the characteristic material strengths needed in the design equations. The Fiberline Design Manual does not provide reference to any joint test results. There are no recommendations for jointing by adhesive bonding.

The first independent, practical source of guidance on structural connections is given in the EUROCOMP Design Code (Clarke 1996). Chapter 5 deals with the problem of designing efficient, safe and reliable connections. It is recognised that FRPs differ from conventional materials in that adhesive bonding is used to form primary structural joints. Many of the fundamental principles used to develop the procedures was due to technology transfer from aerospace companies in America.

The code provides guidance for inplane loaded joints where the joined members are flat panels. The guidance is for general application. At the ultimate limit state a simplified approach is given for bolted and bonded joints. A more rigorous design procedure is provided for bonded joints. The equivalent procedure for bolted joints relies on proprietary finite element software (BOLTIC 1996) and is detailed in the background part of the book. It does not appear in the code because the EUROCOMP partners felt that it had not been sufficiently proven. Both rigorous design approaches use analyses that allow the joint response to be semi-rigid.

All design procedures have to consider the problem of predicting, to acceptable accuracy, the effect on joint resistance of local stress fields. These occur for example in a panel in the region adjacent to the boundary between a bolt and FRP material. A solution is by finite element analysis (BOLTIC 1996). Such a problem is not as serious when the panel is of steel because yielding relieves such stress 'hot spots'. This single factor ensures that design for FRP connections requires special attention and is one reason why good design guidance remains limited. It also means that compliance testing of a new connection design will remain important, and it will often be a necessary stage in the design process. The code recommends this approach.

Partial safety factors listed for the design approaches are based on the collective experience of the EUROCOMP code writers. The code provides guidance to check serviceability of connections.

The EUROCOMP code does not formally cover tee joints (e.g. beam-to-column) that are routinely used in framed construction. One of the test reports by Mottram (Clarke 1996) does present test results that are used to make simple design guidance for nominally pinned beam-to-column connections. Details of the five connections tested are to be found in the MMFG design manual (Anon 1989). This research, and that on the development of practical tee joint connections for frames to be designed as semi-rigid is discussed by Mottram and Zheng (1997). Understanding of this connection type is still at a low level and so design guidance is limited to simple connections.

Followers of the use of FRPs in construction will undoubtably have knowledge of the advanced composite construction system developed by Maunsells and Partners, UK (Hollaway 1993). This innovative system has joints formed by the mechanical interlocking of pultruded sections. Adhesive bonding is often used to improve connection performance. For commercial reasons details of the jointing method are not available and design guidance on this method has not been developed by others. The Company has its own limit state design approach (Head 1994).

3.2 American

The first design manual for pultruded structurals was prepared in 1971 by the world's largest pultruder Morrison Molded Fiber Glass Co. A major revision was started in 1983 representing years of manufacturing experience, monitoring applications and extensive product testing. The current manual was released in 1989 and is periodically updated. This manual (Anon 1989) uses the American stress allowable design approach and gives guidance for designing simple frames (braced). Recommended details are given for pinned framed connections with the principal method of connection by bolts (FRP). The dimensions of the connection pieces mimic practice seen in steelwork. The manual also recommends that best joint performance is obtained by combined bolting and bonding. The manual does not give access to the Company's extensive product testing. Results by academics of tests on MMFG's connection details were first published in 1990 (see Mottram and Zheng 1997) and this research is continuing.

In 1984 the American Society of Civil Engineers (ASCE) published their Structural Plastics Design Manual because its members could see these emerging materials as amongst the most promising and potentially useful to the engineering profession. The design manual funded by industry and government was a necessary step in overcoming the major unresolved problems of using the materials. Of the 1176 pages comprising the manual just 25 are on joints or connections. Little design guidance is provided and that which is relies on recommendations developed for marine applications in the early 1960s. This deficiency of the manual is recognised and in the Foreword it states "The Connection's-Fastening Committee is in the process of preparing proposals for solicitation from interested parties that would undertake the development of a manual covering this subject." No such ASCE manual has been published and to the author's knowledge its preparation is not well advanced. Within the Materials Division there is a Technical Committee on Structural Composites and Plastics (known as SCAP) that is involved in promoting the preparations of ASCE prestandards and standards.

R.E.Chambers of Chambers Engineering, Canton, Ma, started in 1996 a project to prepare the ASCE/PIC Prestandard 'Load and Resistance Factor Design (LRFD) Standard for Structural Pultruded Fiber Reinforced Plastic (PFRP) Rods, Plates and Shapes'. This will, for mechanical fastened connections, give design guidance similar to Fiberline (Anon 1995). There will also be an introduction to tee joint details for framed construction based on the novel universal connector piece developed by Mosallam in America (Anon 1993, Mottram and Zheng 1997).

4. Conclusions

Analysis of the design guidance sources and background information would led to the following general conclusions:

i) Connections between polymeric composite materials are generally by adhesive bonding or mechanical fastening (usually bolted), and their design is significantly more difficult than for connections between other construction materials.
ii) Connections for plate-to-plate and plate-to-structure (e.g. bonding of thin laminates to existing concrete/masonry structures) are the joint types preferred because the moment transmitted is low.
iii) Technology transfer from the aerospace industry has enabled there to be standard test methods, rigorous analytical and design tools for the structural design of bonded and bolted plate-to-plate connections (e.g., lap and strap joints).

iv) There is an urgent need for the available design procedures to be verified by research to ensure the reliability of 'safe' connections. Rigorous design procedures for bonded and bolted connections do consider the joint to behave with semi-rigid action.
v) Mechanical interlocking joints (bonding an option) are used successfully in practice. Their performance and design guidance remain restricted to commercial organisations.
vi) Connections for framed structures are not found in aerospace applications and so engineers have had little experience of how to use them in practice. Research is on-going to develop pieces and details for simple and semi-rigid connections for frames of pultruded members. Design guidance is very limited.
vii) Lack of 'ductility' of FRPs, and of certain adhesive systems, means that local analysis of stresses is very important, and this aspect of FRP connections make reliable design guidance, particularly for long-term loadings, much more difficult to develop than for other materials.
viii) The majority of the testing and analysis has been for connections between members of FRPs (and often the same material) that are plate-to-plate (lap joints).
ix) Research is needed to establish the reliability of all connection types, with particular reference to the variability in stiffnesses and strengths, etc. Understanding is also needed to develop standard products and modular systems, such that FRP frames with integral semi-rigid joints can be designed with the same degree of confidence as for steel.
x) The details of bolted and bonded connections often mimic those in steel practice and these joints do not necessarily use polymeric composite properties efficiently. There is therefore a need to create second generation connection designs to promote better use of the material.
xi) Interested parties should take existing design guidance and other information and prepare standards of legal standing.

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