JOINING FIBRE-REINFORCED PLASTICS

Edited by F.L. MATTHEWS

ELSEVIER APPLIED SCIENCE

JOINING FIBRE-REINFORCED PLASTICS

Edited by

F. L. MATTHEWS

Director, Centre for Composite Materials,
Imperial College of Science and Technology,
London, UK

ELSEVIER APPLIED SCIENCE
LONDON and NEW YORK

ELSEVIER APPLIED SCIENCE PUBLISHERS LTD
Crown House, Linton Road, Barking, Essex IG11 8JU, England

Sole Distributor in the USA and Canada
ELSEVIER SCIENCE PUBLISHING CO., INC.
52 Vanderbilt Avenue, New York, NY 10017, USA

WITH 17 TABLES AND 189 ILLUSTRATIONS

British Library Cataloguing in Publication Data

Joining fibre-reinforced plastics.
1. Fiber reinforced plastics—Joints
I. Matthews, F. L.
668.4'94 TP1177.5.F5

Library of Congress Cataloging in Publication Data

Joining fibre-reinforced plastics.

Bibliography: p.
Includes index.
1. Fiber reinforced plastics—Joints. I. Matthews, F. L.
TA455.P55J65 1986 620.1'923 86-11648

ISBN 1-85166-019-4

Printed in Great Britain by Galliard (Printers) Ltd, Great Yarmouth

Preface

The performance of a structure, or component, is critically dependent upon the behaviour of any joints it contains. All too often a weight or strength advantage, brought about by clever design or use of materials, is lost because the characteristics of the associated joints were not properly understood.

As fibre-reinforced composite materials have become more widely used, so the need for reliable, efficient, load-carrying joints has become apparent. In recent years, a very large number of articles on most aspects of joints in composites has appeared in the literature.

It seemed timely, therefore, to gather together the major features of joints' behaviour in one publication. I wish to thank my colleagues (Terry Collings, Ken Liechti, Steve Johnson, Dave Dillard, Bob Adams, and John Hart-Smith) for allowing themselves to be persuaded to participate in this endeavour; without their collaboration there would be no book. A special word of thanks is also due to Hal Brinson, who, although himself unable to contribute, found the authors for Chapter 4.

We believe that this text will be useful to research workers in universities and other establishments, and to engineers and designers in all branches of industry using fibre-reinforced plastics for load-bearing structures.

F. L. MATTHEWS

Contents

Chapter 1

Introduction

F. L. MATTHEWS
Centre for Composite Materials,
Imperial College of Science and Technology,
London, UK

1.1. INTRODUCTION

Ideally, a structure would be designed without joints, the latter being a source of weakness and/or excess weight. In practice limitations on component size imposed by manufacturing processes, and the requirements of inspection, accessibility, repair and transportation/assembly, mean that some load-carrying joints are inevitable in all large structures.

The designer has essentially two basic techniques at his disposal for joining components of fibre-reinforced plastics, mechanical fastening and adhesive bonding. The advantages and disadvantages of these approaches may be summarised as follows:

Mechanically Fastened Joints

Advantages:

(i) No surface preparation of components required.
(ii) Disassembly possible without component damage.
(iii) No abnormal inspection problems.

Disadvantages:

(i) Holes cause unavoidable stress concentrations.
(ii) Can incur a large weight penalty.

Bonded Joints

Advantages:

(i) Stress concentration can be minimised.
(ii) Incur a small weight penalty.

Disadvantages:

(i) Disassembly impossible without component damage.
(ii) Can be severely weakened by environmental effects.
(iii) Require surface preparation.
(iv) Integrity difficult to confirm by inspection.

It is well known that, for metals, fatigue is the major cause of structural failure and many fatigue failures are associated with some type of joint.[1] Although the fatigue-to-static strength ratio is on the whole better for composites than metals, it is still necessary to have a detailed understanding of the behaviour of joints in composites. The reasons for this are associated with the basic characteristics of metals and composites.

Because of their ductile nature an accurate stress analysis is usually not required for metals, and design procedures for joints are reasonably straightforward and well-established. The essential features of lap joints, the usual type of load-carrying joint and the subject of this book, mean that the structural elements being joined will be subjected to high in-plane direct and shear stresses and relatively high through-thickness direct and shear stresses. Fibre-reinforced plastics (FRP) composites have a relatively low in-plane shear strength, and are particularly weak in through-thickness shear and tensile modes. Hence a comprehensive stress analysis is required to provide an understanding of the factors controlling joint strength, to give guidance on the strengths to be expected from a particular design, and to assist in producing improved joint designs with consequent gains in efficiency.

Experimentally determined behaviour of both small and full-size joints is also required to complement the theoretical work. Knowledge of failure modes, at macroscopic and microscopic levels, is essential if theoretical models are to be refined. One of the problems with composites is the very large number of materials that can be evolved by changing fibre, matrix, fibre orientation, lay-up, stacking sequence, etc. In view of the prohibitive cost of testing all possible combinations a general predictive method is clearly needed. Although, at present, no universal technique exists, reliable methods are being used in a number of (restricted) cases.

In the present text, lap joints are emphasised only to limit the scope and not because other types of joint are considered to be unimportant. For example, flange joints play a vital role in chemical plant where pipes are joined to vessels, and in turbojets where casing segments join. When such components are manufactured from FRP, difficulties will be encountered which are again associated with the anisotropic nature of the material.[2] Likewise, special joints which are neither lap nor flange type may be needed for particular situations. A good example of this is the root attachment of helicopter rotor blades which can be effected by wrapping continuous fibres around a pin.[3] Another example of composites in joining is the use of FRP, with either thermosetting or thermoplastics matrices, to manufacture rivets.[4] The object here is to reduce galvanic corrosion problems associated with aluminium alloy, steel and stainless steel fasteners in carbon fibre composites.

In the current book, then, single, double, scarf and stepped lap joints will be discussed, although the emphasis will change from chapter to chapter. For bonded joints all types will be examined, although most consideration will be given to single and double laps, whereas for mechanical joints attention will be focused almost exclusively on double lap configurations.

1.2. MECHANICALLY FASTENED JOINTS

1.2.1. Experimentally determined strength

The general behaviour of mechanically fastened joints can be conveniently discussed, as in Chapter 2, under three broad headings: fastener type; materials; geometric factors.

Although mechanically fastened joints in FRP exhibit the same failure modes as in metals, the mechanisms by which damage initiates and propagates is fundamentally different and extremely complex.[5] The dependence of damage development and associated strength on through-thickness restraint means that torque-tightened bolts are superior to rivets which, in turn, are superior to other forms of mechanical fastening.

The influence on failure of the relative values of fibre and matrix failure strain explains, in part, the strength differences between CFRP (carbon or graphite fibre-reinforced epoxy resin), GFRP (glass fibre-reinforced epoxy), KFRP ('Kevlar' fibre-reinforced epoxy), and GRP (glass fibre-reinforced polyester resin). Lay-up and stacking sequence are also important since they determine the stress distribution around the fastener hole.

Joint behaviour, and particularly the failure mode, is also dependent on joint geometry, i.e. width in single-hole joints or pitch in multi-hole joints; end (or edge) distance; hole diameter; laminate thickness.

In addition to the above, joint performance is also determined by several other factors including: hole quality; the fit of the fastener in the hole (i.e. the relative diameters of fastener and hole); and the fit of the fastener in the washer (for bolted joints). The latter effect can be particularly important in fatigue.[5]

1.2.2. Stress analysis and strength prediction

Until quite recently far more theoretical work had been undertaken for bonded than for mechanically fastened joints.[6,7] This was largely for historical reasons. Bonded joints in metals had received fairly extensive analytical treatment in the 1940s and 1950s, and this foundation was rapidly extended when composites came into large-scale use in the late 1960s. Mechanically fastened joints in metals, on the other hand, had received very little analytical consideration and this, coupled with an initial reluctance to make such joints in composites, meant that the topic got off to a slow start. Developments have, however, been rapid in the past few years as both continuum methods and finite element techniques have been brought to bear on the problem. Both these approaches, together with methods of strength prediction, are discussed in Chapter 3.

Many of the classical continuum analyses are based on the fundamental work of Bickley[8] for isotropic materials. A rigorous approach demands the inclusion of anisotropic elasticity, friction at the fastener/hole interface, finite plate dimensions, fastener flexibility and fastener/hole tolerance. Such analyses are two-dimensional and hence strictly apply only to pin-loaded holes. It is clear that the length of contact arc on the pin surface, and the regions of slip and non-slip within this arc, should be determined from the analysis, not assumed at the outset. Also, the commonly made assumption that pin bearing pressure is distributed in a cosinusoidal fashion is seen to be seriously in error in certain circumstances.

If the failure process is to be accurately modelled a three-dimensional method, which includes the two-phase nature of composites, is required. Currently this means using finite element techniques. To include all the effects mentioned above, together with through-thickness stresses and the influence of bolt tightening, is a formidable and expensive task which has not apparently been attempted to date. However, the simplified three-dimensional analyses that have been undertaken show encouraging correlation between stress distributions and observed failure modes.

No universally applicable method of strength prediction is available. Although for some failure modes two-dimensional methods give good results, their success appears to be specific to the particular material under investigation.

1.3. BONDED JOINTS

1.3.1. Experimentally determined strength

The vital difference between bonded and mechanically fastened joints in FRP is in the respective dimensions of the load transfer elements: fractions of a millimetre for the adhesive layer, several millimetres for the fasteners. The very thin adhesive layer gives rise to special difficulties, as indicated by Brinson.[9]

As with mechanically fastened joints, a thorough understanding of the initiation and progress of the failure process is vital if analytical models and widely applicable predictive methods are to be derived. Because they allow a detailed description of the failure behaviour, the methods of fracture mechanics are emphasised in Chapter 4.

Because of the mixed-mode nature of debonding, it is suggested that three different specimen geometries be used to determine fracture properties. The double cantilever beam is used when Mode I effects are relevant, the cracked lap shear specimen for mixed Mode I and Mode II effects, and the end-notched flexure specimen for purely Mode II. Single lap shear specimens, commonly used for testing, are useful only for purposes of ranking, but not of rational design.

Detailed information of failure can only be obtained from refined methods of measuring displacements and strains. No single technique is suitable and a combination of pointwise methods, using transducers, and whole field methods, using Moiré interferometry, is needed.

Since the matrix of FRP laminates may be much weaker than current structural adhesives, failure may occur within the composite by delamination or interply fracture, rather than debonding. The exact nature of failure will therefore depend on the surface ply orientation, stacking sequence, joint geometry and loading, in addition to the matrix and adhesive.

1.3.2. Stress analysis and strength prediction

As stated in Section 1.2.2, continuum methods of stress analysis of bonded lap joints in composites are derived from investigations of similar joints between metal adherends. In these analyses a longitudinal section of the joint is considered, giving therefore a two-dimensional, or in the simplest cases one-dimensional, stress distribution. The latter approach, which ignores through-thickness stresses, produces a physically infeasible, i.e. non-zero, adhesive shear stress at the ends of the overlap. Nevertheless, such an approach is useful for parametric studies and can provide valuable general guidance for design purposes.[7]

The inclusion of through-thickness stresses, adherend anisotropy and stacking sequence, non-linear behaviour and geometric refinements (double lap, scarf and stepped lap configurations) introduce additional complexity into the analysis. In some instances it may be difficult to obtain a solution to the governing equations.

When real effects, such as the spew-fillet at the edges of the adhesive, are to be considered, finite element methods must be used if an accurate stress distribution is required. The thin adhesive layer causes particular difficulties for finite element modelling, especially if through-thickness effects are to be included. A satisfactory element mesh within the adhesive can lead to a very large number of elements in the whole joint; there is a clear need for special elements to represent the adhesive layer. The number of elements will probably become unacceptably large when the necessary modelling of the adherends on a ply-by-ply basis is also included.

Comparison with measured strengths shows that it is essential to include the non-linear shear stress–strain behaviour of the adhesive, if meaningful predictions of strength are to be achieved. One difficulty, still to be satisfactorily resolved, is the accurate measurement of such properties.

The above, and other related factors, are discussed in Chapter 5.

1.4. DESIGN

The ultimate objective of the experimental and theoretical investigations described above is to produce information that can be used for design purposes. At any moment in time, design methods will rarely include the most advanced state of current knowledge. This is inevitable since industry has to meet deadlines and to achieve this may have to accept a slightly less efficient product. Such a situation need not worry us provided the results of the latest research work are incorporated into the design process at the earliest opportunity.

The final chapters of the current text address the design of mechanically fastened (Chapter 6) and bonded (Chapter 7) joints. The approach described reflects present-day practice in the aerospace industry which, of necessity, designs to higher safety standards than industry in general. The methods should, therefore, be applicable to all structural joints, no matter what the field of application.

Because there is no universally applicable failure theory for composites, the design of mechanically fastened joints is best treated from a general point of view which does not need to be changed as different materials are considered. One benefit of this approach is to allow definition of a minimum programme of tests to characterise adequately joints in any composite. In describing the behaviour of single fastener joints, and the influence of material variables, there will be some overlap with Chapter 2. However, this is necessary in order to develop a generalised approach to multi-row joints and obtain a measure for structural efficiency.

A major problem with bonded joints is the sensitivity of the adhesive to moisture. The design of joints should therefore ensure that such degradation is precluded by correct choice of adhesive. Joint geometry can be related to applied load intensity and undesirable effects such as 'peel' (through-thickness tensile) stresses can be minimised by suitable tapering the adherends. Adequate understanding of joint behaviour allows us to specify acceptable repair methods, a topic which is assuming ever-increasing importance.

REFERENCES

1. Kirkby, W. T. Report No. AGARD-AG-176 (Ed. H. Liebowitz), 1974, Advisory Group for Aerospace Research & Development, Paris, France.
2. Matthews, F. L., Foulkes, D. M., Godwin, E. W. and Kilty, P. F., *Proc. 14th Reinforced Plastics Congress*, 1984, The British Plastics Federation, London, UK.
3. Stratton, W. K., Scarpati, T. S. and Class, C. A., *Proc. 4th Army Materials Technology Conference, Advances in Joining Technology* (Eds J. J. Burke, A. E. Gorum and A. Tarpinian), 1975, Brook Hill Publishers, Chestnut Hill, Mass., USA.
4. Tanis, C. and Poullos, M., Jr, *Fibrous Composites in Structural Design* (Eds E. M. Lenoe, D. W. Oplinger and J. J. Burke), 1980, Plenum Press, New York, USA.
5. Smith, P. A., PhD Thesis, 1985, Cambridge University, Cambridge, UK.
6. Godwin, E. W. and Matthews, F. L., *Composites*, 1980, **11**, 155.
7. Matthews, F. L., Kilty, P. F. and Godwin, E. W., *Composites*, 1982, **13**, 29.
8. Bickley, W. G., *Phil. Trans. Roy. Soc.*, 1928, **A227**, 399.
9. Brinson, H. F., *Appl. Mech. Rev.*, 1985, **38**, iii.

Chapter 2

Experimentally Determined Strength of Mechanically Fastened Joints

T. A. COLLINGS

Royal Aircraft Establishment, Farnborough, Hampshire, UK

2.1. INTRODUCTION

The use of mechanically fastened joints in fibre-reinforced plastics (FRP) is a logical carry-over from the fastening technique used for structures made from isotropic materials where a wealth of experience and understanding already exists. The enthusiasm of designers to use mechanical joints for composites has in the past been lukewarm due partly to a lack of confidence in the ability of composites to suffer holes and cut outs, and partly to designers extending joining techniques used for isotropic materials to composites without understanding the anisotropic nature and failure mechanisms of composites. This is not the case today because of a new approach in composite thinking and the development of new design philosophies based on an understanding of the mechanisms of failure of FRP.

It is true that FRP components can be considerably weakened by the introduction of holes; this is attributable in part to the large stress concentrations that occur in the region of such discontinuities, and partly to a lack of plasticity. This is evident if we look at the value of the tensile elastic stress concentration due to a circular hole in a unidirectional infinite sheet, which can be as large as 8 in contrast to the value of 3 normally associated with isotropic materials. Furthermore, because most isotropic materials exhibit some degree of plasticity, yielding can occur at regions of high stress and the effect of stress concentrations on the final net failing stress is small. This is not the case for unidirectional FRP, which is essentially elastic to failure, so the effect of stress concentration is to give rise to a low net tensile stress. It is not surprising therefore that the efficiency of mechanical joints in unidirectional FRP is very low indeed. If, however, the degree of anisotropy is reduced in the vicinity of a hole some 'softening' or pseudo-plastic behaviour can be introduced, and an increase in efficiency brought about. Indeed such joint softening can be readily achieved (see ref. 1) by the incorporation of fibres oriented in different directions in the vicinity around a hole.

It is clear from the experimental evidence available that mechanical joints in FRP are indeed promising; however, because of the large number of variables involved, complete characterisation of all joint materials, joint types and failure mechanisms is difficult. The approach set out in this chapter is to demonstrate the behaviour of some types of joints, materials and fasteners, and where possible to infer the influence of important parameters and to highlight design philosophies.

2.2. FAILURE MODES

Mechanically fastened joints in composites display the same failure modes as do metals; i.e. failure can take place in tension or shear or bearing. Because of the nature of FRP two other modes of failure are possible, namely cleavage and pull-out. Figure 1 shows the location of each of the modes. The failure mechanisms of FRP, unlike those of metals, are complex and varied, and will be dependent upon many factors such as fibre type, orientation, surface treatment and matrix, etc. It follows that a knowledge of a wide range of variables is needed if favourable joint conditions are to be achieved and unwanted failure modes avoided.

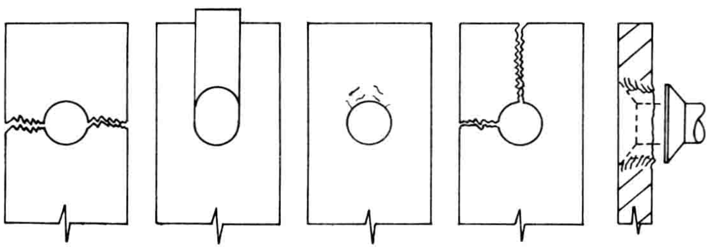

FIG. 1. Modes of failure for mechanical joints in FRP.

Failure of laminates made from unidirectional rovings, in which at least 10% of the fibres are aligned in the direction of the load, will now be considered since this fibre arrangement is usually required to perform at high stresses and at near-optimum strength.

2.2.1. Tension failure

As with conventional materials, the tensile load required to fail a laminate through a section at which holes occur (net section) is less than at a section at which there are no holes (gross section). The stresses at these sections, at failure, are given respectively by

$$\sigma_N = \frac{P}{(w - nd)t} \tag{2.1}$$

and

$$\sigma_G = \frac{P}{wt} \tag{2.2}$$

where P is the failing load of the member, w the joint width at the net section, n the number of holes of diameter d occurring at that section, and t the joint thickness. The tensile strength efficiency achieved at these sections, expressed in the form of average net and gross stress concentrations, is given by

$$k_{\mathrm{N}} = \frac{\sigma_{\infty}}{\sigma_{\mathrm{N}}} \tag{2.3}$$

and

$$k_{\mathrm{G}} = \frac{\sigma_{\infty}}{\sigma_{\mathrm{G}}} \tag{2.4}$$

where σ_{∞} is the theoretical ultimate tensile strength of a plain laminate.

Since FRP materials are essentially elastic to failure, they cannot take advantage of plastic behaviour and yielding at the hole edge; therefore the effect of stress concentration is to give rise to a correspondingly low net failing stress. Because the value of the net failing stress will depend upon the degree of anisotropy in the region of a hole, fibre orientation will feature strongly in the way failure occurs and in the magnitude of the ultimate failing stress. Figures 2 and 3 show typical tensile failures for different lay-ups of carbon fibre-reinforced plastic (CFRP)[1] and glass fibre-reinforced plastic (GFRP)[2] using unidirectional rovings.

When a CFRP laminate is subjected to a tensile load the fibres parallel to the loading axis will carry most of the load; tensile fracture of a laminate will be governed by failure of these fibres. The process by which tensile failure of the net section can occur for loaded holes can be explained by a mechanism postulated by Potter[3] for a holed laminate being loaded remotely from the hole. Failure occurs at the net section, being initiated by and propagated from the stress concentration at the edge of the hole at a location 90° to the loading axis. This means that all load-carrying axial fibres must have failed sequentially in such a way that failure of one fibre inevitably led to the failure of its immediate neighbours. Since the tensile strength of a loaded hole is almost completely controlled by axial fibres, it is this sequential fibre failure process which will also govern laminate failure. Acoustic emission work on CFRP by Collings and Mead[4] has shown that for a $0/\pm 45°$ laminate, geometrically constrained to fail in tension, at sufficiently low shear and bearing stresses to reduce other possible acoustic emission sources, fibre failure first occurs at approximately 85% of the net strength, after which a stable situation is reached. No further fibre failure occurs until about 95% of net strength