The Institution of Structural Engineers

JANUARY 1999

Guide to

The structural use of adhesives

Published for the Institution of Structural Engineers

The Institution of Structural Engineers

Guide to

The structural use of adhesives

JANUARY 1999

The Institution of Structural Engineers
11 UPPER BELGRAVE STREET SW1X 8BH

Constitution of Task Group

D McQuillan, BSc(Eng), CEng, FIStructE, FICE, FIEI, FIHT (Kirk McClure Morton), *Chairman*
A Bush (The Welding Institute)
S B Desai, OBE, BE, PhD, CEng, FIStructE, MICE (Department of the Environment, Transport and the Regions)
S A Hurley, BSc, PhD (Taywood Engineering Ltd)
A R Hutchinson, BSc, PhD, CEng, MICE (Oxford Brookes University)
G C Mays, BSc, PhD, CEng, MIStructE, FICE (Cranfield University (RMCS))
C J Mettem, MTech, CEng, MIMechE, FIWSc (TRADA Technology)
D R Morris, BSc, MSc, PhD, DIC, CEng, MIStructE, MICE (Brown & Root)
C J Newman, BSc, (Building Research Establishment) (Until September 1997)
J S Robinson, BSc, CEng, FICE, MIStructE (Allott & Lomax)
N Thorpe, BSc(Hons), CEng, MICE (Health & Safety Executive)

Corresponding members
K Crews, BE(Hons), MEng(res), AIMSc, MIEAust, CPEng (University of Technology, Sydney)
F K Garas, BSc(Eng), PhD, CEng, FIStructE, FICE (*formerly* Taylor Woodrow Construction Ltd)
J F Orr, BSc, PhD, CEng, FIMechE (The Queens University of Belfast)

Consultant to the Task Group
J L Clarke, MA, PhD, CEng, MIStructE, MICE (The Concrete Society, *formerly* Sir William Halcrow & Partners)

Secretary to the Task Group
S M Doran, BSc(Eng), AKC, PhD, CEng, MICE, FRSA (The Institution of Structural Engineers)

Published by SETO, 11 Upper Belgrave Street, London SW1X 8BH

First published 1999

ISBN 1 874266 43 3

Contents

Foreword 5

Acknowledgements 5

1 Glossary 7

2 Introduction and scope 9
- 2.1 Introduction 9
- 2.2 Status of the report 9
- 2.3 Scope 9
- 2.4 Overview of applications 9
- 2.5 Advantages and disadvantages of adhesives 10
- 2.6 Design life 11
- 2.7 Economics 11
- 2.8 Health and Safety considerations 11
- 2.9 Relevant Standards 12
- 2.10 References 12

3 Adhesive bonding technology 13
- 3.1 Fundamental concepts 13
- 3.2 Types of adhesive 13
  - *3.2.1 Introduction* *13*
  - *3.2.2 Epoxy resin adhesives* *13*
  - *3.2.3 Polyurethane adhesives* *13*
  - *3.2.4 Acrylic adhesives* *13*
  - *3.2.5 Polyester adhesives* *13*
  - *3.2.6 Resorcinol-formaldehyde (RF) and phenol-resorcinol-formaldehyde (PRF) adhesives* *14*
  - *3.2.7 Phenol-formaldehyde (PF) adhesives* *14*
  - *3.2.8 Melamine-urea-formaldehyde (MUF) adhesives* *14*
  - *3.2.9 Casein adhesives* *14*
  - *3.2.10 Polyvinyl acetate and elastomeric adhesives* . .*14*
  - *3.2.11 Adhesive tapes* *14*
- 3.3 Outline of adhesive properties 14
- 3.4 Adhesion 14
- 3.5 Health and Safety considerations 16
- 3.6 References 16

4 Behaviour of adhesive joints 17
- 4.1 Introduction 17
- 4.2 Current design standards 17
- 4.3 Safety factors 17
- 4.4 Basis of design 18
- 4.5 Design methods 19
- 4.6 Fatigue loading 19
- 4.7 Environmental effects 20
- 4.8 Fire 20
- 4.9 Proprietary systems 20
- 4.10 Summary of design method for simple joints in shear 20
- 4.11 References 22

5 Behaviour of combined adhesive/mechanical joints . .23
- 5.1 Introduction and review of combined behaviour 23
- 5.2 Situations in which combined joints may be beneficial 23
- 5.3 Situations in which combined joints will be ineffective 23
- 5.4 References 24

6 Fabrication of joints 25
- 6.1 Quality assurance 25
- 6.2 Selection of adhesive 25
- 6.3 Surface preparation 25
- 6.4 Evaluation of surface condition 25
- 6.5 Mixing and application of adhesive 27
- 6.6 Environmental conditions 27
- 6.7 Assembly and visual inspection 28
- 6.8 Support systems 288
- 6.9 Proof testing 28
  - *6.9.1 Introduction* *28*
  - *6.9.2 Standard control samples* *28*
  - *6.9.3 Non-destructive tests on connections* *29*
  - *6.9.4 Testing prototype connections* *29*
  - *6.9.5 Testing connections on site* *29*
- 6.10 References 29

7 Connections between various materials 31
- 7.1 Introduction 31
- 7.2 Concrete 31
  - *7.2.1 Surface preparation* *31*
  - *7.2.2 Selection of adhesive* *31*
  - *7.2.3 Assembly* *32*
- 7.3 Steel 32
  - *7.3.1 Surface preparation* *32*
  - *7.3.2 Selection of adhesive* *32*
- 7.4 Zinc coated steel 32
  - *7.4.1 Surface preparation* *32*
  - *7.4.2 Selection of adhesive* *33*
- 7.5 Stainless steels 33
  - *7.5.1 Surface preparation* *33*
  - *7.5.2 Selection of adhesive* *33*
- 7.6 Aluminium 33
  - *7.6.1 Surface preparation* *33*
  - *7.6.2 Selection of adhesive* *33*
- 7.7 Timber 33
  - *7.7.1 General* *33*
  - *7.7.2 Surface preparation* *33*
  - *7.7.3 Selection of adhesive* *33*
  - *7.7.4 Assembly* *33*
- 7.8 Reinforced plastics or fibre-reinforced polymer composites 35
  - *7.8.1 Surface preparation* *35*
  - *7.8.2 Selection of adhesive* *35*
  - *7.8.3 Assembly* *36*
- 7.9 Glass 36
  - *7.9.1 Surface preparation* *36*
  - *7.9.2 Selection of adhesive* *36*
- 7.10 Connections between different materials 36

7.11 References 37

8 Applications in new construction 37
8.1 Introduction 37
8.2 Buildings 37
8.2.1 Concrete 37
8.2.2 Timber 37
8.2.3 Steel 38
8.2.4 Stainless steels 38
8.2.5 Fibre-reinforced polymer composites 38
8.2.6 Glazing and structural glass 38
8.2.7 Cladding 38
8.2.8 Sandwich panels 39
8.2.9 Stone 39
8.2.10 Masonry 39
8.3 Bridges 39
8.3.1 Concrete 39
8.3.2 Steel 39
8.3.3 Timber 39
8.3.4 Fibre-reinforced polymer composites 40
8.3.5 Composite steel and concrete 40
8.3.6 Aluminium 40
8.3.7 Prestressing tendon anchorages 40
8.4 Tunnels 40
8.5 Foundations 40
8.6 Geotechnical applications 40
8.7 Offshore platforms 40
8.8 Railways 40
8.9 Miscellaneous applications 40
8.10 References 41

9 Examples of repairs, refurbishment and upgrading 43
9.1 Introduction 43
9.2 Buildings 43
9.2.1 Concrete 43
9.2.2 Masonry 43
9.2.3 Timber 44
9.3 Bridges 44
9.3.1 Concrete 44
9.3.2 Masonry 45
9.3.3 Steel 45
9.3.4 Cast iron 45
9.3.5 Timber 45
9.4 Other structures 45
9.5 References 45

10 Future development 47
10.1 Introduction 47
10.2 New construction 47
10.2.1 Steel structures 47
10.2.2 Steel-concrete composite structures 47
10.2.3 Timber structures 47
10.2.4 Aluminium structures 47
10.2.5 Glass structures 47
10.3 Repair techniques and applications 47
10.3.1 Concrete structures 47
10.3.2 Timber structures 47
10.3.3 Masonry structures 47
10.4 Testing 47
10.5 Education and training needs 47
10.6 References 48

Appendix A Organisations providing specialist advice on adhesive technology 49
Appendix B British and international standards 50
Appendix C Health and Safety regulations 51
Appendix D Acknowledgement of illustrations 51

Foreword

The use of adhesives in structural and semi-structural applications is increasing. Although a significant amount of 'stand-alone' information exists there is a definite lack of guidance, and it is difficult for practitioners to determine the suitability, or otherwise, of adhesives for potential applications.

The 10th SCOSS Report had some misgivings in respect of inappropriate use of adhesives and also felt that opportunities for use could be restricted due to a lack of knowledge. The Task Group has therefore attempted to pull together the available knowledge of materials and techniques involved, in a coherent way, to allow Structural Engineers, with little or no knowledge of adhesives, to:

- be aware of the range of applications.
- carry out, where appropriate, preliminary designs and prepare outline specifications

Hopefully the Guide will also be of use to manufactures, suppliers and contractors.

The Guide is therefore not a textbook or a definitive design guide – hence the very extensive reference lists contained. The Task Group took a fundamental decision not to focus on the chemistry involved because such specific and detailed information is readily available from suppliers.

Throughout the Task Group has attempted to highlight Health and Safety aspects, and the importance of workmanship and quality control issues.

The Task Group held a workshop in September 1997 at which the draft was presented to a wide range of practitioners. The feedback received was very supportive and endorsed the need for such guidance.

Finally, my thanks go to all the members of the Task Group for their enthusiasm and hard work. It has been a privilege to be associated with them in the production of this Guide. Special thanks go to John Clarke who, as Consultant to the Task Group, did most of the drafting and editing and to Sue Doran who served the Task Group so efficiently.

Don McQuillan
Task Group Chairman
December 1998

Acknowledgements

The preparation of this report was partly funded by the Department of the Environment, Transport and the Regions under the 'Partners in Technology' Programme.

The Task Group gratefully acknowledges the assistance of all those who contributed to the drafting of this report by commenting on drafts, attending the workshop held at the Institution in September 1997 or supplying data and illustrations. Detailed acknowledgement of the providers of the illustrations is given in Appendix D.

1 Glossary

As many of the readers of this Guide will be unfamiliar with adhesive technology, a number of the terms used are defined. A more extensive glossary has been prepared by ASTM[1.1] and there is a draft European standard which gives terms and definitions for adhesives[1.2].

Adherend
A member of a bonded joint.

Adhesion
The attraction between surfaces whereby, when they are brought into contact, work must be done to separate them.

Adhesive
A polymeric material which is capable of holding two materials together by surface attachment.

Bond
The adhesion of one surface to another, with the use of an adhesive or bonding agent.

Combined joint
A joint where the surfaces are held together by both adhesive and mechanical means.

Composite or composite material
A combination of high modulus, high strength and high aspect ratio fibre reinforcing material encapsulated by and acting in concert with a polymeric matrix.

Coupling agent (or adhesion promoter)
A chemical additive which promotes a strong and possibly more durable interfacial bond.

Cure
To change the properties of an adhesive irreversibly by chemical reaction into a more stable condition and to develop the desired properties.

Filler
A relatively inert substance added to an adhesive to alter its physical, mechanical, thermal or other properties or to lower the cost.

Glass transition temperature (T_g)
The approximate midpoint of the temperature range over which a polymeric adhesive changes from a relatively stiff and brittle material to a viscous material.

Grout
A heavily filled resin based material, the primary purpose of which is to fill a void, but which is capable of transmitting some stress.

Hardener
The curing agent or catalyst which promotes chemical cross-linking with the resin in two component adhesive systems.

Mechanical connection
The use of bolts, nails or similar means to join two structural elements.

Mould release agent
A substance applied to mould surfaces to prevent adhesion so as to facilitate release of moulded items.

Open time
The maximum allowable period between the mixing of the adhesive and the closure of the joint.

Peel ply
The outside layer of a reinforced plastic material which is removed to achieve improved bonding.

Polymeric
Adjective describing a material (most commonly organic) composed of molecules characterised by the repetition of one or more types of monomeric units.

Pot life or usable life
The period of time during which a multi-part adhesive can be used after mixing the components. (NOTE: The pot life varies with the volume and temperature of the mixed adhesive and the ambient temperature. The term 'pot life' is also used for the application of hot-melt adhesives for the period for which an adhesive, ready for use, remains usable when kept at normal operating temperature.)

Prepreg
Reinforcing fibres in sheet or roll form impregnated with resin and stored for use.

Primer
Material used to protect a surface prior to the application of the adhesive, improve adhesion and/or improve the durability or to stabilise/protect the substrate.

Pultrusion
A continuous process for the manufacture of composite profiles by pulling layers of fibres, impregnated with a thermoset resin, through a heated die, thus forming the ultimate shape of the profile.

Resin
The reactive polymer base in adhesive and prepreg matrix systems.

Roughness
Micro-roughness represents the fine structure of a surface with dimensions less than 0.1μm. Macro-roughness represents the coarser structure of a surface, with dimensions greater than this.

Safe working temperature
The temperature (generally 10 – 20°C below the glass transition temperature, see earlier) below which the properties of the adhesive in service may be assumed to be unaffected.

Sealant
A material that seals the gap between two elements, prevents the passage of fluids and will accommodate relative movement, but will not transmit any significant stresses.

Shelf life
The period for which the components of the adhesive may be stored, under the conditions specified by the manufacturer, without being degraded.

Sound
Adjective describing a surface as being free from weak and loosely attached layers.

PREVIOUS PAGE IS BLANK

Substrate
The material of the adherend adjacent to the adhesive layer.

Thermoplastic
A polymeric material that repeatedly can be softened by heating and hardened by cooling through a temperature range characteristic of the material.

Thermoset
A resin that is substantially infusible and insoluble after being cured.

Wettability
The ability of a liquid to spread on a specific solid surface.

Wetting
The formation of a thin layer of liquid spreading uniformly over a surface without breaking into droplets.

References

1.1 ASTM D907-96a. *Standard terminology of adhesives.* West Conshohocken: American Society for Testing and Materials

1.2 EN 923: 1998: *Adhesives — terms and definitions.* London: BSI, 1998

2 Introduction and scope

2.1 Introduction

Adhesives have been used for many years in the aerospace and automotive industries. A great deal of research has been carried out on the behaviour of adhesively bonded joints of the type used by those industries. There are obvious advantages to be gained from the transfer of appropriate technology to the Construction Industry, with the possibility of new design approaches, improved structural efficiency and safety of construction. However, there is a lack of appropriate guidance for structural engineers. Concern had been expressed by the Standing Committee on Structural Safety[2.1] that adhesives may be being used inappropriately or opportunities for development were being lost.

This Guide is intended for Structural Engineers with little or no knowledge of adhesives and the behaviour of adhesive joints. It aims to provide the engineer with a basic knowledge of the materials and techniques involved, to outline the range of applications for structural adhesives and to indicate how simple joints may be designed. It is not intended to be a text book; extensive references are provided throughout to other appropriate sources of information.

2.2 Status of the report

The Institution of Structural Engineers has produced this report as a guide and, as such, it is only intended for use as a guide. It is not intended to provide the definitive approach in any situation, as in all circumstances the party best placed to decide on the appropriate course of action will be the Structural Engineer undertaking the particular project.

2.3 Scope

This Guide is concerned with the use of adhesives with a polymeric matrix used in structural applications; cementitious materials are not considered. The Guide does not specifically cover the use of sealant materials in applications such as structural glazing. This is covered in another Institution of Structural Engineers publication[2.2].

The intended readership of this Guide are engineers concerned with the structural design of buildings and other structures, both onshore and offshore, and it should be used in conjunction with the appropriate structural design codes. It is also intended for use by engineers concerned with the repair, strengthening and upgrading of structures.

The intention of this Guide is to provide Structural Engineers with sufficient information which, when coupled with their own expertise, will enable them to carry out a preliminary design and to prepare an outline specification using structural adhesives. For more detailed information on the behaviour of adhesive joints reference should be made to one of the standard books on the subject, such as Adams, Comyn and Wake[2.3]. In addition, for specific applications it will generally be necessary to obtain specialist advice from suppliers. The Guide does not consider the chemistry of adhesives in any significant detail. Extensive references are given so that the reader may obtain additional information if required. It does not list specific products but deals only with generic types of adhesives. Similarly, it does not specify the particular chemicals to be used in degreasing and the like; throughout it is assumed that such materials and associated techniques will be selected in conjunction with the recommendations of the manufacturer of the adhesive.

Adhesive connections may be divided, very broadly, into three categories, namely structural, semi-structural and non-structural. For the purposes of this Guide, they may be considered to be as follows:

- structural: the bonded joint carries all the load in a particular direction, at service load or at both service and ultimate loads; failure in the bond line leads to a significant change in the behaviour of the structure or in its loadcarrying capacity.
- semi-structural: the bonded joint is required chiefly to distribute the loads, the main loadcarrying being by some other mechanism; failure in the bond line may result in some change of behaviour under service loads but the ultimate strength will not be affected.
- non-structural: the bonded joint is subjected to a nominal stress; the consequences of failure in the bond line are structurally insignificant (though failure can still lead to a risk of serious injury).

This Guide is concerned chiefly with the use of adhesives in structural and semi-structural applications though many of the topics covered, such as Health and Safety aspects, apply equally well to all adhesive connections. It is important to note that the three connection categories are very general and it may not be clear exactly into which category a particular application falls. For example, a connection may rely on adhesives to carry all the shear loads and yet may carry direct tensile forces by mechanical means. (An example is the Advanced Composites Construction System, see Section 8.3.4).

A clear distinction must be made between the situation in which the adhesive forms an integral part of the structural material, such as plywood or glued laminated timber (glulam), and adhesive connections between structural elements. In the former case the selection of the adhesive is made by the manufacturer of the product. The engineer designs on the basis of properties of the manufactured product and will not be concerned with the behaviour of the adhesive. In the latter case the engineer will be required to design the connection, and hence specify the required properties of the adhesive. A key aspect in the design of the adhesive joint is the bond between the adherend and the adhesive; this is discussed further in Section 3.4.

The importance of workmanship is emphasised throughout the Guide; it is better to apply a reasonable adhesive correctly rather than the best adhesive badly.

It is strongly advised that consultation with specialists in the field of adhesive bonding is undertaken before any detailed design is carried out. A list of some of the organisations which can provide specialist advice is given in Appendix A.

2.4 Overview of applications

It has been estimated that the largest use of structural adhesives in civil engineering, more than 75%, is in repairs. However, for many engineers the most familiar use of structural adhesives is likely to be for connecting dowel bars into concrete or into masonry or else in the form of resin anchors. These applications are largely outside the scope of this Guide, but are considered briefly in Section 4.9.

As far as the various construction materials are concerned, the largest use of adhesives for structural applications is with timber, either in the form of fabricated products, such as plywood and glued laminated timber (glulam), or for connections between members. Examples of applications include footbridges and long-span roof structures for buildings.

Fig 1. Sydney Opera House

Adhesives are also extensively used in glazing where they have an important structural role. For concrete the main uses of adhesives are in the joints between precast units, such as in glued segmental bridges. Fig 1 shows the Sydney Opera House, the precast concrete segments of which were bonded together. A growing area of use is for strengthening and upgrading using bonded steel or fibre-reinforced polymer composite plates.

There has been limited use of adhesives with steel structures, though there is considerable potential for applications in the near future.

Fibre-reinforced polymer composites are used extensively for structural applications in boats and other marine applications and also in the aerospace and motor industries. They are starting to be used offshore, because of their low weight and good durability, and for special structures on land. In many applications of these materials, adhesive bonding is the most effective method of forming connections. Fibre composites are starting to be used in a wide range of strengthening techniques for concrete, timber, masonry and other structures.

As indicated above, some applications for structural adhesives are well established, with the appropriate guidance readily available, while other applications are still being developed. Table 1 gives an overview of the situation. More detailed information on current applications is given in Chapter 8 for new construction and Chapter 9 for repairs, refurbishment and upgrading. Possible future developments in applications for structural adhesives are given in Chapter 10. Where emerging technology is used particular care is essential and in appropriate cases the engineer may need to warn the client accordingly.

Table 1 Overview of applications showing degree of acceptance by the Construction Industry

Status	Application
Established technology	Anchors and fixings, including dowels in concrete and timber Ground anchors Replacement wall ties Timber composites Timber-timber connections Steel plate bonding Precast concrete segmental construction Fibre composites Glazing Cladding panels
Technology becoming established	Carbon fibre plate bonding Timber repair techniques
Emerging technology	Steel-steel connections Other structural metals, e.g. stainless steel Structural glass Timber-FRP composites

2.5 Advantages and disadvantages of adhesive connections

The advantages and disadvantages of using adhesives follow. They are presented in no particular order as the relative significance of any factor will depend on the particular application being considered. In some cases a particular factor may not apply at all. Where appropriate, the advantages and disadvantages of adhesives are compared with the more traditional forms of connection.

Advantages

- no damage to parent material (cf. drilling for bolts, etc.)
- no damage to exposed surfaces (cf. spot-welding)
- good aesthetics
- fewer pieces required to form connection (cf. bolts, washers, etc.)
- smaller additional pieces, e.g. gusset plates, required to form connection (cf. bolted connections and similar where minimum edge distances may determine plate dimensions)
- fluid- and weathertight joint
- improved resistance to corrosion
- high effective stiffness of joint (cf. bolted connections which may slip)
- improved fatigue performance, because of reduction in stress concentrations
- high, uniform strength and stiffness along joint
- tolerant to dimensional inaccuracies
- dissimilar materials can be joined readily; elimination of bimetallic corrosion
- good noise and vibration damping
- efficient method of joining thin materials
- potential for simpler, faster fabrication

Disadvantages

- lack of experience of use when compared with traditional materials and methods
- properties will vary between different suppliers and are constantly being 'improved'
- surface treatment required
- requires a high level of supervision by experienced staff
- generally requires a carefully controlled environment during assembly and curing of a joint, which is often difficult to achieve (particularly important for site assembly)
- possible Health and Safety implications (though this will also apply to techniques such as welding)
- time taken for connection to achieve full loadcarrying capacity (cf. bolting or welding)
- completed connection not easily inspected
- strength limited under certain directions of loading; joints must be suitably designed
- connection can not be disassembled (cf. bolts)
- adhesive properties affected by temperature and humidity (cf. bolts)
- possible complete loss of performance in fire
- lack of long-term experience in some applications
- creep effects may be significant, particularly at elevated temperatures
- lack of agreed design guidance (applies to some materials only)

As may be inferred from the preceding lists, there will be situations in which it will be more appropriate to use traditional connection techniques, or a combination of techniques such as using adhesives in a bolted connection. The latter is discussed in Chapter 5. The aim of this Guide is to present the properties of adhesives and bonded connections so that the designer can make the appropriate choices. The decision as to whether to use adhesives or not needs to be taken early in the design process as it can have a significant influence on the geometry of the connections. The decision will also have a significant influence on the methodology of erection or construction of a structure and hence on the cost.

2.6 Design life

The design life of an adhesive connection in a new structure will generally be required to be the same as that of the total structure. Some guidance is given in the draft ENV 1991–1[2.4], which divides structures into various classes, as shown in Table 2. All the figures given are 'boxed' values, i.e. they can be amended by the relevant National Application Document. In the UK, design codes such as BS 8110[2.5] do not actually specify an intended life for buildings. For highway bridges in the UK the specified design life is 120 years[2.6].

There is limited experience of the long-term behaviour of adhesives. This has led to recommended minimum lives for adhesive repairs of 30 years[2.7]. There is experience of the use of adhesives in the aircraft industry for a number of years, but the design considerations are somewhat different from those in civil engineering structures. The lack of knowledge of the long-term behaviour of adhesives in appropriate situations is a limitation which could prohibit the use of structural adhesives in many applications. As systems for monitoring the condition of adhesive connections are developed, confidence in their long-term behaviour will improve.

However, there may be some applications in which a component is removed and replaced on a regular basis during the life of the structure, such as bearings in bridges. In others it may be possible to inspect joints between structural members at intervals during the life of the structure, and carry out any necessary repairs. Finally there could be applications in temporary works, where a long life is not a requirement. In these cases the use of adhesives may be a practical solution, despite concerns over the limited design life.

2.7 Economics

The economics of the use of an adhesive rather than a mechanical connection will depend on the particular circumstances being considered. Many factors will be involved, some of which have been outlined in the lists of advantages and disadvantages in Section 2.5. It will be necessary to consider cost comparisons both in the short term and also in the long term. The latter may be difficult to quantify as the lifetime behaviour can only be estimated fairly crudely.

In glued segmental construction, the rapid gain in strength of adhesives in the joints, in comparison to the longer time taken by cement-based products, leads to significant savings in the total construction time.

For repairs, factors such as the cost of access and possession time will have to be taken into account. For example, work on the upgrading of a major highway in New York City had to be carried out at night as there was a requirement for the road to be fully open during the day. The penalty for failure to reopen the carriageway in the morning was $30 000 per hour, with a penalty of $20 000 per day for over-run of the complete project.

Similarly high costs are incurred by the closure of railways. It has been reported that the cost of closure of the Central Line on the London Underground amounts to £0.25M per day in lost revenue.

Unfortunately, for most of the applications given in later Chapters, the reported economic considerations are largely qualitative, but they can be used for guidance when attempting to determine the economics of a particular application.

Marble cladding panels, which had come loose from the facade of a 31-storey building in Houston, USA, have been refixed using a polyurethane adhesive. The work was carried out without the need to remove the panels from the building, reducing the cost of the repair from $6M to $0.5M[2.8].

In Florida the beam–column connections in a parking garage have been strengthened by bonding carbon fibre sheet material to the sides of the beams[2.9]. It was estimated that the adhesively bonded repair was 35% cheaper than the conventional method, which would have involved dowelling in additional steel reinforcement and encasing the joint with additional concrete.

Table 2 Design working life classification in draft ENV 1991–1[2.4]

Class	Required design working life (years)	Example
1	1–5	Temporary structures
2	25	Replaceable structural parts, e.g. gantry girders, bearings
3	50	Building structures and other common structures
4	100	Monumental building structures, bridges, and other civil engineering structures

A small concrete underpass beneath a major road near Great Missenden in Buckinghamshire was repaired with carbon fibre composite strips of the type previously developed in Switzerland[2.10]. The alternative to a plate bonded repair in this situation would have been complete reconstruction, which would have resulted in significant road closures and the consequent disruption to traffic.

In Canada, carbon fibre-reinforced polymer composite sheet material was applied to the soffits and the sides of a bridge in Edmonton, to improve the shear resistance[2.11]. The cost was reported as $70 500 for strengthening the complete bridge. The paper makes some comparisons with a conventional external stirrup system, which was estimated to cost some $100 000. Thus the bonded solution showed approximately a 30% saving in costs, due chiefly to the fact that the work was carried out below the bridge avoiding the traffic closures that would have been required for the conventional system.

2.8 Health and Safety considerations

This Guide is intended for use by Structural Engineers, who should be aware of their duties under the various Health and Safety regulations. These include *The Management of the Health and Safety at Work Regulations* 1992 and *The Construction (Design and Management) Regulations* 1994 (CDM). In particular the engineer should take into account the changes to the assessment of the risks involved with the design and construction process when adhesives are used in place of conventional joining techniques. Thus the risks associated with adhesives will have to be included in the CDM Health and Safety Plan, which must be produced at the design stage and developed by the principal contractor (as defined by the CDM Regulations) as the work proceeds. This plan forms the basis for the Health and Safety File which must be handed over to the client on the completion of the works so that it can be available to anyone involved in future maintenance or construction work. The Health and Safety File should include details of the use of adhesive joints in the structure together with any inspection and testing regime that is considered appropriate.

Reference is made throughout this Guide to the Health and Safety requirements for the use of the adhesive materials themselves and the associated surface preparation processes. Health and Safety data sheets should be obtained from the manufacturers and should be followed at all times.

A list of some of the relevant Health and Safety regulations is given in Appendix C.

2.9 Relevant Standards

Throughout this Guide, reference is made to appropriate British and other Standards. For convenience they are brought together in Appendix B as well as at the end of the appropriate chapters in the text. It should be noted that British Standards are in the process of being superseded by European Standards though the latter will still be issued by BSI; the Structural Engineer should always ensure that the most recent relevant Standard is being used.

2.10 References

2.1 Standing Committee on Structural Safety. *SCOSS Tenth report*. London: SETO, 1994

2.2 Institution of Structural Engineers, *The structural use of glass in buildings*. London, SETO (to be published 1999)

2.3 Adams, R. D., Comyn, J., Wake, W.C.: *Structural adhesive joints in engineering*, 2nd edn. London: Chapman and Hall, 1997

2.4 DD ENV 1991-1: 1996: *Basis of design and actions on structures* (Eurocode1). London: BSI, 1996

2.5 BS 8110: *Structural use of concrete*. London: BSI

2.6 BS 5400: *Steel, concrete and composite bridges*. London: BSI

2.7 Rendel, Palmer and Tritton. *Adhesive bonding in a civil engineering environment*. Report to Scottish Development Agency, December 1983

2.8 Kraker, J. M.: 'Fix salvages unglued panels, saving tower owner $5.5 million'. *Engineering News Record*, 10 March 1997, p9

2.9 Kliger, H.: 'Repair of parking structures'. *FRP International*, **IV** (4), Autumn 1996, p3-4

2.10 Anon: 'Passing the plate'. *New Civil Engineer*, 13 February 1997, p9

2.11 Anon: 'Packing more road into parkway'. *Engineering News Record*, 12 May 1997, p30-31

3 Adhesive bonding technology

3.1 Fundamental concepts

A number of different aspects must be taken into account when considering the use of an adhesive to form a structural connection. These include:

- design of the geometry of the joint (see Section 4.4)
- selection of the adhesive itself, taking into account the materials to be joined, the stresses to be carried and the environmental conditions both during application, curing and in service (see Section 3.2 and Chapter 7)
- preparation of the surfaces to be joined (see Chapter 7)
- workmanship (see Chapter 6)
- Health and Safety and environmental considerations, both during assembly and throughout the life of the structure (see Sections 3.5 and 6.1)

Throughout it is essential to consider an adhesive connection as a total system. Failure to take sufficient account of one particular aspect of the design or of the fabrication of the connection may result in total failure.

Some general considerations are given in the following Sections; more detailed coverage may be found in standard references[3.1–3.4] and information relevant to specific materials is given elsewhere in this Guide.

3.2 Types of adhesive

3.2.1 Introduction

This Section is intended to give a brief overview of the various types of adhesives that are suitable for structural applications. It is assumed throughout that the adhesives are correctly formulated appropriate to their intended use and have been obtained from a reliable, quality assured, source. Further general information on adhesives for engineering applications can be found in Mays and Hutchinson[3.5] and Lees[3.6], while TRADA provide information on adhesives for timber[3.7]. Silicones, which are used extensively for lightly loaded bonded glazing have not been included in this Section. Further information on this application may be found in the Institution of Structural Engineers guide on structural glass[3.8].

Adhesives are categorised as thermoplastic or thermoset, depending on their chemical makeup and the effect of temperature in their hardened state. They are available in a wide variety of forms, including liquids and pastes, in one- or two-part formulations. In the latter, a hardener, or catalyst is mixed with the resin to initiate curing. Heat may or may not be required.

While adhesives are generally classified under the names given later, they are complex blends of many components, including fillers and plasticisers, which are added to the basic formulation to make them suitable for particular applications. Thus the following Sections should be seen as describing families of adhesives rather than specific materials. Indicative values for the properties of structural adhesives are given in Section 3.3. Data for specific products must be obtained from manufacturers; because of the rapid developments in materials, it is essential that any data sheets used are current.

3.2.2 Epoxy resin adhesives

Epoxy adhesives can be formulated in a wide range of forms to give a broad range of properties after curing. Hence they are suitable for bonding a wide range of materials in a range of applications. They possess good gap filling properties, depending on the formulation and the filler content, they generally exhibit low creep and resist environmental effects well. Their range of operating temperatures and the limited cure shrinkage make them particularly suitable for structural applications.

Numerous formulations are available, which may be suitable for cold curing or may need the addition of heat during the curing period. The adhesive can be supplied in liquid or paste form, generally as two components though single component products are available. The latter, however, require a high cure temperature.

Epoxies are very strong and durable. Structural materials for which they are suitable include steel, concrete, many plastics, etc. They are commonly used for repairs to timber involving steel and other inserts. They have been used for bonding wood, but only in special cases due to their high price.

It should be noted that, though not dealt with in EN 1995[3.9], the use of epoxy resins is not explicitly rejected. This is in keeping with modern codes for timber which aim to be less prescriptive and are geared more towards stating performance requirements.

3.2.3 Polyurethane adhesives

Polyurethane adhesives are very versatile, with many possible applications. They exhibit good durability, with an adequate resistance to water and a high tolerance to oils and chemicals. However, they are slightly weaker than epoxies and more susceptible to creep and moisture effects. Their operation temperature, up to say 60°C for some formulations, makes them suitable for many structural and semi-structural applications in which the bonded materials are kept reasonably dry.

They are generally supplied in a two-component form, though single-part formulations, which rely on moisture as the catalyst, are available. One-part products are used extensively in sandwich panel applications. Two-part products are used in timber joints and repairs, but are sensitive to the moisture content of the timber.

Structural materials for which polyurethane adhesives are suitable include timber and natural stone. Because they are not resistant to attack by alkalis, polyurethane adhesives are not generally suitable for use with concrete unless correctly formulated. However, they have been used for bonding rail base plates to concrete track bed.

In Scandinavia, polyurethanes are favoured over epoxies for perceived Health and Safety reasons.

3.2.4 Acrylic adhesives

Acrylic adhesives cover a range of materials with a variety of curing mechanisms. For structural applications toughened acrylics are generally used, which bond readily to various adherends with minimal surface preparation. The adhesives are generally supplied in two-component parts.

Thermoplastic acrylics are liable to exhibit significant creep, particularly at elevated temperatures.

Applications for which acrylic adhesives are suitable include sandwich and cladding panels. They are particularly suitable for applications in which thin bond lines are achievable, e.g. metal to metal or with plastics.

3.2.5 Polyester adhesives

Polyester adhesives are used in applications in which a rapid gain in strength is required, such as in resin anchors. Formulations are available which allow curing to take place at sub-zero temperatures. However, their use as structural adhesives in many situations will be limited by their poor creep and shrinkage behaviour, their lack of tolerance to damp or wet conditions and their relatively high intrinsic cure shrinkage.

3.2.6 Resorcinol-formaldehyde (RF) and phenol-resorcinol-formaldehyde (PRF) adhesives

These are a range of adhesives suitable for use with timber, covered by both British and European Standards[3.10, 3.11]. Curing may be at room temperature or at elevated temperatures. The adhesives are very strong and durable; they are fully water-, boil- and weather-resistant and will withstand salt-water exposure. They are widely used in laminated timber, finger-jointing of members, etc., both indoors and outside. Best performance is obtained with thin adhesive layers. Hence the materials are not suitable for gap filling applications.

RFs are rarely used alone because of their relatively high cost[3.12].

3.2.7 Phenol-formaldehyde (PF) adhesives

These are hot-cured adhesives which are typically used in hot-press fabrication of structural plywood and similar materials. They have the same durability properties as RF- and PRF-adhesives. If PFs are to cure at room temperature (cold setting) then strong acids are required which are liable to damage wood, which limits their use for structural purposes. They are unlikely to be used other than in factory conditions.

3.2.8 Melamine-urea-formaldehyde (MUF) and urea-formaldehyde (UF) adhesives

These are timber adhesives which have intermediate water-resistance and hence are mainly suitable for protected conditions, or where the member is protected from the worst effects of the weather. They may be cured at a range of temperatures from 10°C upwards. Unless suitably filled, they should be used in applications in which the bond-line is thinner than 0.1mm.

3.2.9 Casein adhesives

These are derived from milk and are less water-resistant than urea-formaldehydes, but have been found to be suitable for loadbearing use in fully protected indoor timber structures. They are susceptible to bacteriological and fungal attack.

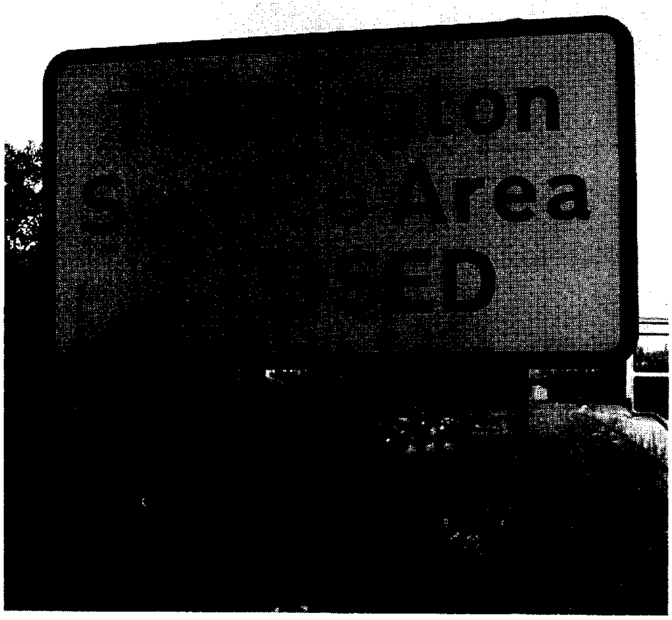


Fig 2. Double-sided tapes used for fixing signs

3.2.10 Polyvinyl acetate and elastomeric adhesives

These are limited to non-loadbearing uses indoors, such as attaching laminates to woods. They have limited resistance to moisture. Cross-linking polyvinyl acetate adhesives are much stronger and more durable, but are still restricted to non-structural use.

3.2.11 Adhesive tapes

Double-sided adhesive tapes are particularly suitable for bonding materials with a very smooth surface finish. The tapes are contact adhesives, bonding under relatively light pressure, leading to rapid assembly; 50% of the ultimate bond strength can be achieved after 10 minutes at normal room temperatures. They can be used to bond materials with very different coefficients of thermal expansion, such as polycarbonate sheet to a metal framework, the thermal movements being accommodated by the high strain capacity of the tape. With the correct choice of tape, the operating temperature can be as high as 65°C or down to well below zero.

A major use is in the automotive and aircraft industries. However, one widespread structural application is bonding traffic signs to the supporting framework as in Fig 2. In addition, double sided tapes are used to fit cladding and ceiling units and have applications in glazing, connecting glass to the supporting framework.

3.3 Outline of adhesive properties

Table 3 gives some typical properties of adhesives that may be used for structural applications. They should only be taken as indicative; detailed information for design purposes should be obtained, wherever possible, from the appropriate manufacturer, though not all manufacturers may be able to provide the required values. Where manufacturers are unable to provide the appropriate data, values will have to be obtained from technical literature or from standard text books. The choice of appropriate factors of safety is discussed in Chapter 4. Fig 3 shows some test methods commonly used to determine the properties of adhesives. It should be noted that appropriate factors of safety will be applied to some of these values to give design strengths, see Sections 4.3 and 4.10. Values for the commonly used timber adhesives have not been included as they are generally assumed to be stronger than the timber itself.

The values in Table 3 may be compared with the values in Table 4 for common structural materials. For the metals in Table 4, the values quoted for the shear and tensile strengths are at yield; their ultimate values will be significantly higher.

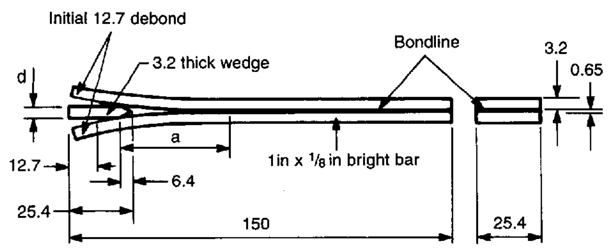
Table 5 gives indicative characteristics of some structural adhesives, which may be used to determine the suitability of a particular type of resin for a particular application. It must be noted that the comparisons are with other adhesives and not with the structural materials with which they will be used. In addition, it must be borne in mind that, because of the wide range of formulations available, there can be exceptions to the stated characteristics in certain circumstances.

3.4 Adhesion

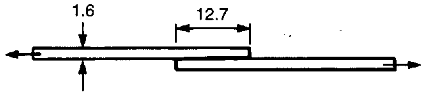
Adhesion is the attraction between surfaces whereby, when they are brought into contact, work must be done in order to separate them. Thus adhesion is associated with intermolecular forces acting across the interface. The basic requirements for good adhesion are:

- intimate contact between adhesive and substrate
- absence of weak layers or contamination at the interface.

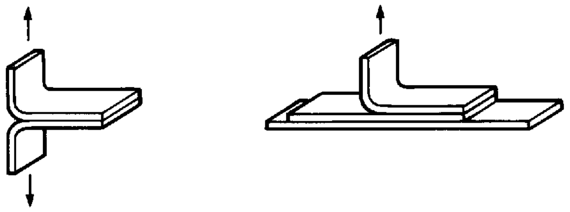
There are various mechanisms by which forces are carried across the interface between the adhesive and the substrate, namely adsorption, mechanical interlocking and diffusion bonding.



(i) Wedge cleavage specimen



(ii) Shear test specimen



(iii) T – and L – Peel test configurations

Fig 3. Standard adhesive tests

In the adsorption mechanism, molecules of the adhesive are adsorbed onto the surface of the substrate because of the natural forces of attraction between the materials. Chemical bonding may occasionally take place. Mechanical interlocking of the adhesive and the substrate will improve the adhesion; with porous surfaces such as concrete and masonry the adhesive will penetrate into the substrate. In the diffusion process, some of the adhesive material penetrates the surface of the substrate, combining with the material to form a compound.

It is important that the adhesive, and any primer that is required, thoroughly wets the surface of the substrate and flows into any irregularities. For wetting to occur, the surface tension of the liquid adhesive must be lower than the surface energy of the substrate. Metals, when suitably cleaned, have high surface energies and are readily wetted. For materials such as reinforced thermoset plastics the surface energy is similar to the surface tensions of adhesives and wetting can still be achieved. For low surface energy materials such as thermoplastics wetting may be a problem unless some modification can be made to the surface.

From the above it is clear that surface preparation prior to the application of the adhesive will play a crucial role in the behaviour of the connection. This is dealt with in detail in general terms in Chapter 6 and in more detail in Chapter 7. It should be noted that the purpose of surface preparation is not just to obtain initial adhesion, but to provide a surface which will remain stable for a long period of time, particularly in the presence of water. A good standard of surface preparation is therefore essential to promote long-term durability.

The role of any primer that is used is to coat the substrate with a material that has a strong link with both the substrate and the adhesive. With porous surfaces, the primer will penetrate the surface providing a mechanical link. With non-porous surfaces some chemical bonding may occur. The selection of an appropriate primer will depend on the nature of the substrate and of the adhesive and hence is likely to be

Table 3 Typical properties of some structural adhesives

Property	Epoxy	Polyurethane	Acrylic	Polyester
Shear strength (N/mm^2)	15–35	15–25	15–25	??
Shear modulus (kN/mm^2)	0.5–2	0.1–0.2	0.01–0.02	??
Shear failure strain (%)	5–50	50–200	50–200	??
Tensile strength (N/mm^2)	20–40	15–25	15–35	10–25
Tensile modulus (kN/mm^2)	1–10	-0.5	-0.5	??
Tensile failure strain (%)	1–4	10	50	6
Glass transition (°C)	35–100*	35–80	-100	30–70*
Poisson's ratio	0.3–0.4	0.4	0.43	??
Thermal expansion (10^{-6}/°C)	30–70	40	50	30–70

* If post-cured

Table 4 Typical properties of some common structural materials

Property	Steel	Concrete	Timber	Aluminium alloys
Shear strength (N/mm^2)	120	1-3	5–16	150
Tensile strength (N/mm^2)	250	1-5	8–40	240
Tensile modulus (kN/mm^2)	200	N.A.	4–17	70
Tensile failure strain (%)	5	0.01	0.9–5	7–15
Poisson's ratio	27	0.15	0.3–0.7	0.3
Thermal expansion (10^{-6}/°C)	12	8–12	2–10	23

Table 5 Indicative characteristics of some structural adhesives

Characteristics	Epoxy	Polyurethane	Acrylic	Polyester	RF & PRF	PF
Creep resistance	Excellent	Poor	Poor	Fair	??	??
Moisture resistance	Excellent	Fair	Good	Fair	Excellent	Excellent
Heat resistance	Good	Fair	Fair	Good	??	??
Cold or hot cure	Both	Cold	Cold	Cold	Both	Hot
Cure time	Medium/long	Medium/short	Short	Short	??	Short
Gap filling	Yes	Yes	No	Yes	Yes	??

unique for any particular application.

Where the surface is prepared in the factory but the adhesive is applied on site, the primer may be required to protect the surface during transport.

3.5 Health and Safety considerations

The manufacturer's Health and Safety data sheets must always be obtained and read before use. They should be used as the basis of any COSHH (Control of Substances Hazardous to Health) assessment. Adhesives should always be used in accordance with the manufacturer's recommendations, taking the necessary precautions such as the use of protective clothing during mixing and application. Similarly, when preparing the surface prior to the application of some adhesives, provision must be made for adequate extraction of noxious fumes, dust, etc. and a suitable supply of fresh air.

Mixing should always be in accordance with the manufacturer's instructions, particularly with regard to the quantity of adhesive mixed at any one time, as exothermic reactions can lead to excessive temperature rises.

In addition to considering the Health and Safety aspects of fabricating the adhesive connection, it is also necessary to consider the long-term behaviour including the possibility and consequences of failure.

3.6 References

3.1 Feldman, D.: *Polymeric building materials*. New York: Elsevier Science, 1989

3.2 Kinloch, A. J.: *Adhesion and adhesives: science and technology*. London: Chapman and Hall, 1987

3.3 Panek, J. R. and Cook, J. P.: *Construction sealants and adhesives*, 2nd edn. New York: Wiley, 1984

3.4 Wake, W. C.: *Adhesion and the formulation of adhesives*. London: Applied Science, 1976

3.5 Mays, G. C., Hutchinson, A. R.: *Adhesives in civil engineering*. Cambridge: Cambridge University Press, 1992

3.6 Lees, W. A. ed.: *Adhesives and the engineer*. London: Mechanical Engineering Publications Limited, 1989

3.7 TRADA: *Adhesives for wood and wood products – BS EN Standards*. Wood information, Section 2/3, Sheet 35, High Wycombe: Timber Research and Development Association, 1993

3.8 Institution of Structural Engineers. *The structural use of glass in buildings*. London, SETO (to be published 1999)

3.9 DD ENV 1995-1-1: 1994: *Design of timber structures. General rules for building*. London: BSI, 1994

3.10 BS 1204: 1993: *Specification for type M R phenolic and aminoplastic synthetic resin adhesives for wood*. London: BSI, 1993

3.11 EN 301: 1992: *Adhesives, phenolic and aminoplastic, for load-bearing timber structures: classification and performance requirements*. London: BSI, 1992

3.12 Raknes, E.: 'Adhesives'. In: Blass, H. J. *et al.*: *Timber engineering*, STEP 1, lecture A12. Almere: The Netherlands: 1995

4 Behaviour of adhesive joints

4.1 Introduction

This Chapter considers the design of joints in which the load is carried by the adhesive only. The behaviour of joints in which the load is carried by a combination of adhesive and mechanical means is covered in Chapter 5. Only the behaviour of the adhesive itself is discussed here, it being assumed that the adhesion to the adherends is adequate. Further information on the general properties of adhesives in engineering applications may be found in Chapter 3. Definitions of the terms used to describe modes of failure in adhesive joints are defined in BS EN ISO 10365[4.1]. Detailed information of adhesive joints may be found in Adams, Comyn and Wake[4.2]. The selection of adhesives suitable for use with various common structural engineering materials is covered in Chapter 7.

4.2 Current design standards

There are no National or International standards dealing specifically with the design of adhesive joints. Advice on the design of adhesively bonded joints is given in the EUROCOMP Design Code and Handbook[4.3]. Though this document deals only with fibre composite materials, the principles involved should be equally applicable to other materials. The Highways Agency advice document gives guidance on the design of steel plate bonding[4.4]. Some advice on the design of bonded connections in timber is given in BS 5268: *Part 2*[4.5] and in the draft EN 1995[4.6]. The design of finger joints is covered in BS EN 385[4.7].

4.3 Safety factors

The safety factors used in the design of an adhesively bonded joint must take into account both the uncertainties associated with the joint as fabricated and also the changes in material properties with time, as follows:

- uncertainties concerning the assumed stress distribution in the joint, particularly with complex loadings or combined mechanical and adhesive connections
- uncertainties over the magnitude and direction of loads applied to the joint
- effects of workmanship
- changes in properties of the adhesive
- changes at the interface affecting the adhesion
- possible changes in the adherend, e.g. due to moisture changes in timber.

Simple joints have been well studied experimentally, but generally at small scale. There may be scale effects when considering structural engineering applications, but the joints are likely to be more efficient as the effects of local stress concentrations at the ends will be less dominant. Hence there can be a high level of confidence in the methods of analysis used, resulting in the need to apply a relatively low factor of safety. With more complex joints it may be necessary to apply greater factors to account for uncertainties.

The determination of the forces applied to the joint will be part of the overall structural analysis, with partial safety factors being applied to the loads. In BS 5400 a partial safety factor, γ_{f3}, is incorporated, which in the case of *Part 4* for concrete bridges allows for non-linear resistance of concrete by taking the form of a function of the method of analysis. It is therefore applied to the calculated forces, whereas in *Part 3* for steel bridges this factor is constant and is applied directly to the calculated resistance. For a variety of reasons, other design Codes do not use a separate partial safety factor for this effect.

All materials used should be in accordance with recognised Standards to reduce uncertainties to acceptable levels. The effects of workmanship are difficult to quantify but some indication can be obtained by means of testing representative samples, see Section 6.9. Obviously the simplest way to reduce uncertainty is to use suitably qualified staff to carry out the work, in accordance with detailed and proven method statements and specifications. Variability will be reduced by careful control of the bonding process with regular inspection accompanied by the maintenance of detailed records.

The long-term behaviour of the adhesive and the durability of the adhesive/parent material assembly may be more difficult to quantify. While there is some information on the long-term strength retention of adhesives, this will generally be from unstressed samples[4.8]. In service the adhesive will be stressed, which will have some additional influence on the long-term properties (see Section 4.7). In any case, the properties obtained from relatively short-term exposure tests will have to be extrapolated to the design life of the structure.

Adhesives properties are significantly affected by the ambient temperature. Hence higher factors of safety will be required if the adhesive is used at temperatures higher than that at which the properties were determined. No adjustment will be required when the ambient temperature is lower than the test temperature.

Changes at the interface and in the adherend will be more difficult to quantify. It will be best to eliminate changes wherever possible. For example, the provision of a generous fillet to the adhesive will help to seal the joint and prevent the ingress of moisture.

Taking all these considerations into account it can be seen that it will be necessary to set conservative safety factors to be applied to the material properties to determine design values when considering the design of any adhesive joint. The EUROCOMP Design Code[4.3] suggests a range of partial safety factors which reflect the various components that go into

Table 6 Recommended values for partial safety factors to be applied to adhesive properties[4.2]

Source of the adhesive properties	γ_{m1}
Typical or textbook values (for appropriate adherends)	1.5
Values obtained by testing	1.25
Method of adhesive application	γ_{m2}
Manual application, no adhesive thickness control	1.5
Manual application, adhesive thickness controlled	1.25
Established application procedure with repeatable and controlled process parameters	1.0
Type of loading	γ_{m3}
Long-term loading	1.5
Short-term loading	1.0
Environmental conditions	γ_{m4}
Service conditions outside test conditions	2.0
Adhesive properties determined for the service conditions	1.0
Fatigue loading	γ_{m5}
Loading basically static	1.0
Adhesive subjected to significant fatigue loading	See Table 7

determining the overall factor that should be applied to the adhesive. In designing the joint, the partial safety factor, γ_m, by which the adhesive properties should be divided to give design values, is given by:

$$\gamma_m = \gamma_{m1}\,\gamma_{m2}\,\gamma_{m3}\,\gamma_{m4}\,\gamma_{m5}$$

where Table 6 gives recommended values for each of the factors. They are based on the assumption that the safety factor will be applied to characteristic values for the material properties.

Where manufacturers supply information about minimum properties, the factor of 1.25 applied to the 'Values obtained by testing' in the Table may be reduced slightly, to 1.2.

However, it should be noted that quoted values will generally apply to standard test conditions. If the in-service temperature differs significantly from that at which the tests were carried out, an additional factor is applied, see 'Environmental conditions' in the Table.

For connections designed by testing, γ_m should not be taken as less than 2.0. For connections subjected to long-term loading, the overall γ_m should not be less than 4.0.

It should be noted that other industries use lower factors of safety for adhesive connections, see Section 6.9.4, but these are for very different applications, and are made under very different conditions, and hence are not appropriate for this Guide.

4.4 Basis of design

There are many aspects to be considered in the design of an adhesive joint, which include the geometry of the bonded area, the selection of a suitable adhesive with the appropriate properties and a consideration of the stresses to which the adhesive will be subjected while in service. Mays and Hutchinson[4.8] have identified a number of general principles to be adopted when designing a joint as follows:

- provide the maximum bond area
- stress the adhesive in the direction of maximum strength of the adherend (i.e. in shear or compression)
- avoid stress concentrations
- make the adhesive layer as uniform as possible to avoid stress concentrations
- maintain a continuous bond line.

The overall geometry of the joint is very important when considering the second point. The objective must be not only loading in the direction of maximum strength but also to minimise the loads in the weak directions, e.g. those causing peeling stresses. This is best illustrated by a number of 'good' and 'bad' joints shown in Fig 4 taken from Lees[4.9].

In the simple single lap joint (Fig 5) the lines of action of the forces in the two members are not coincident and hence bending is induced into the joint, leading to unwanted peel stresses at the ends in addition to the local stress concentrations due to the geometric discontinuities. In a double lap joint or a double strap joint, see Fig 6, the lines coincide resulting in pure shear and reducing the peel stresses. In addition the available bond area is doubled, reducing the length of the joint.

In all adhesive connections, peak stresses exist at the ends of the adhesive layer. Their magnitude depends on the relative stiffnesses of the adhesive and the adherends. The stresses are illustrated in Fig 7 which shows a photoelastic test on a single lap joint. The increased fringe orders at the ends of the adherends show the stress concentrations. In addition the bending deformation, characteristic of single lap joints, is visible. Fig 8 shows the shear stress distribution in the adhesive layer of an externally reinforced concrete beam; the stresses at the end of the plate are significantly higher than the average stress.

These peaks are taken into account in the design approach

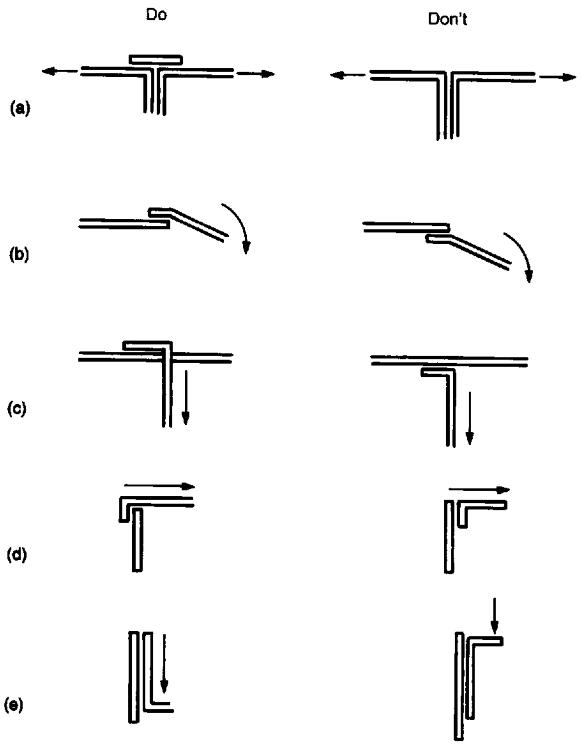


Fig 4. Acceptable and unacceptable joints

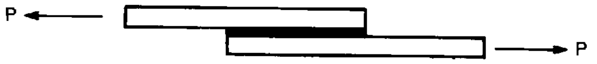


Fig 5. Single lap joint

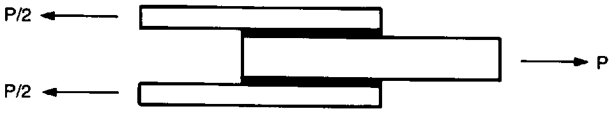


Fig 6. Double lap joint

Fig 7. Photoelastic test on single lap joint

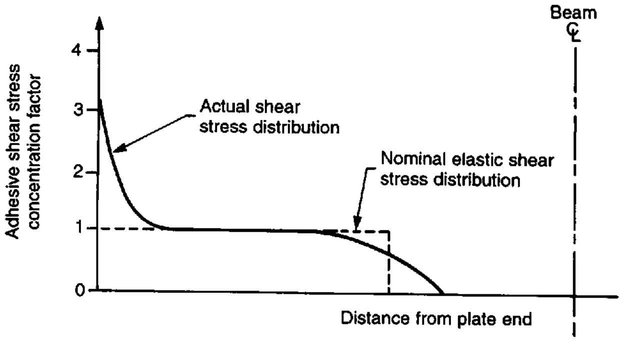


Fig 8. Stress distribution in adhesive

described later, in Sections 4.5 and 4.10.

A butt joint is an ineffective form of connection because of the available area to be bonded, see Fig 9. Alternative approaches are scarf joints or stepped joints as shown in Fig 10 and 11 Both will require the ends of the members to be joined to be machined to the required profile.

Finger joints, as shown in Fig 12, are widely used in timber. Guidance on their fabrication and performance is given in BS EN 385 and EN 387[4.7, 4.10].

For more complicated connections such as angle joints or tee joints, additional angles will be required to be bonded to the main members to give the joint sufficient strength, see Figs 13 and 14 respectively.

The peak stresses at the ends of the adhesive layer should be reduced where possible by applying a suitable chamfer to the ends of the units to be joined and also to the adhesive, as shown in Fig 15. The chamfer on the adhesive will, in addition, help to seal the joint and prevent the ingress of moisture.

Although the peak stresses can be reduced substantially they cannot be eliminated. They will tend to initiate failure and hence increasing the length of a joint beyond a certain point will not increase the loadcarrying capacity. The basic principle of the design, to resist static loads, is that there should be an adequate region at a low level of stress in the middle of the joint.

4.5 Design methods

Methods of design, for simple joints, are given in the EUROCOMP Design Guide and Handbook[4.3]. A simple approach for lap and strap joints is given in Section 4.10 of this Guide which may be used to determine the required bond area. A more rigorous design method for lap and strap joints is also given in the EUROCOMP book.

Alternatively, more sophisticated analysis may be carried out, by using finite elements or similar approaches, which will lead to a more realistic indication of the stress distribution in the joint which will result in a more economic design. A number of standard analysis packages specifically aimed at adhesive joints are available[4.11–4.14].

Whichever form of analysis is carried out, it is necessary to ensure that the stresses in the adhesive do not exceed the strength of the material to which it is applied.

For joints that are standard in a particular form of construction, design by testing may be an appropriate route, as outlined in Section 6.9.4.

Fig 9. Butt joint

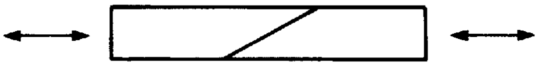


Fig 10. Scarf joint

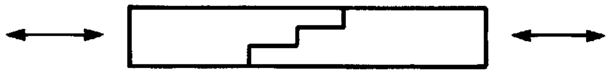


Fig 11. Stepped joint

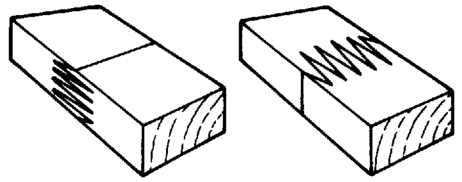


Fig 12. Finger joints

4.6 Fatigue loading

Fatigue loading may be a major consideration in some joints[4.15]. The performance of a joint subjected to fatigue will be related to the configuration of the joint and the range of stresses that occur in the regions of peak stress. Ideally the range of stress variation should be kept below the 'endurance limit', i.e. it should be sufficiently low for fatigue not to be a problem. Typical fatigue curves, determined from different types of adhesively bonded specimens, are shown in Fig 16.

Fig 17 shows a comparison between the fatigue behaviour of adhesively bonded joints with that of riveted joints; the adhesive joints have a significantly better response, because of the more even distribution of stress.

Where possible, the fatigue performance of the adhesive should be determined by means of tests, under environmental conditions similar to those that will be experienced in the joint. In the absence of test data, the EUROCOMP Code[4.3] suggests that the partial safety factors given in Table 6 should be multiplied by an additional factor γ_{m5}, which depends on the level of inspection of the joint in service, as given in

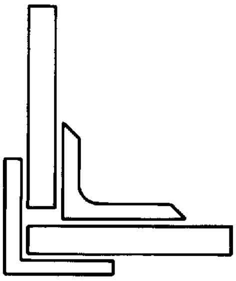


Fig 13. Angle joint

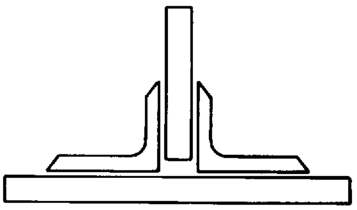


Fig 14. Tee joint

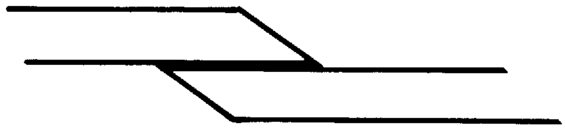


Fig 15. End chamfers

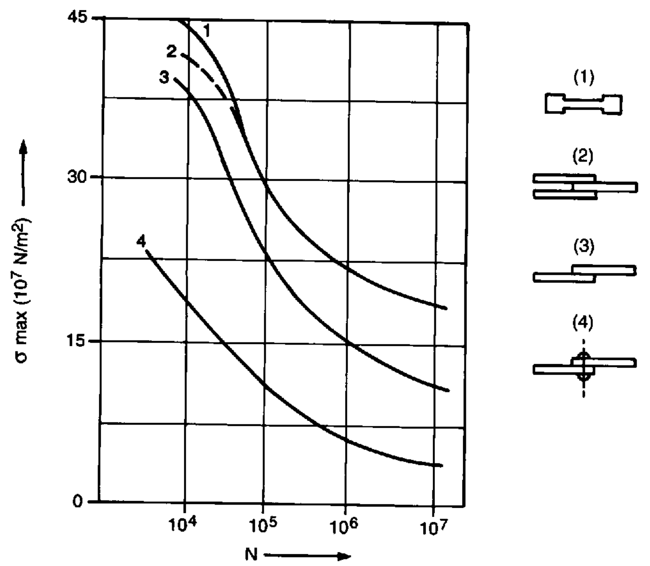


Fig 16. Fatigue curve for bonded specimens

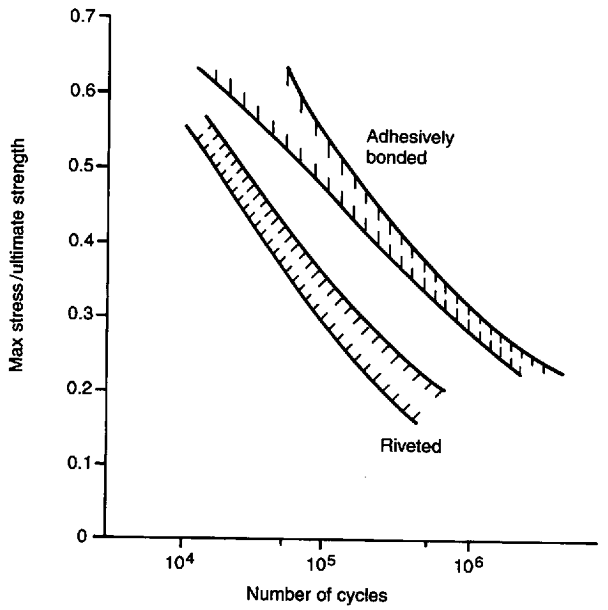


Fig 17. Fatigue strength of riveted and adhesively bonded joints

Table 7 Partial coefficient, γ_{m5}, for fatigue strength[4.3]

Degree of inspection	Fail-safe joints	Non fail-safe joints
Periodic inspection, good access	1.5	2.0
Periodic inspection, poor access	2.0	2.5
No inspection/maintenance	2.5	3.0

Table 7. (Note: In the EUROCOMP Code the factor is referred to as γ_{m4}, which may cause some confusion). Further information on non-destructive testing, which should form part of any inspection process, is given in Section 6.9.3.

The values in Table 7 are for fibre composite materials but may be taken as being appropriate for adhesives, in the absence of other guidance. 'Fail-safe' joints are such that failure does not result in failure of the structure, or large sections of it. 'Non-fail-safe' joints are those for which failure will result in failure of the structure, or large sections of it.

In addition to checking the behaviour of the adhesive under fatigue loading, it will be necessary to consider the fatigue behaviour of the substrate material. The latter may be the governing factor in some circumstances; the Highways Agency Bridge Advice document BA 30/94[4.4] controls the fatigue behaviour of plate bonding applications by limiting the cyclic stresses that may be applied to the reinforcing steel.

It should be noted that cyclic strains applied to an adhesive during the curing period, for example from traffic loading on a bridge under repair, are likely to lead to a small reduction in the strength of the fully cured material.

4.7 Environmental effects

The environmental conditions that influence the creep and fatigue performance of adhesive joints are the temperature, humidity and the level of applied stress. It will therefore be necessary to select an adhesive that is appropriate for the in-service environment of the joint; guidance is given in Section 3.3. The temperature of the adhesive joint in service must be below the safe working temperature, as given by the adhesive manufacturer, taken as 10 or 20°C below the glass transition temperature, T_g. High ambient temperatures will increase the tendency for the adhesive to creep. As a general recommendation, the sustained stress in an adhesive bonded joint should be kept below 25% of the short-term strength of the joint for the normal design life of the structure, as indicated in Section 4.3, in which it is stated that the overall material partial safety factor should not be less than 4.0.

4.8 Fire

For the design of adhesive joints in fire, it will obviously be necessary to consider the behaviour of the adherends as well as the behaviour of the adhesive itself.

It will be necessary to carry out an analysis of the flow of heat through the adherends and into the adhesive, working from a standard time:temperature curve such as that given in BS 476[4.16], for the required fire endurance. The temperature of the adhesive layer must not exceed the safe working temperature. Above this temperature the resin will start to soften and the loadcarrying capacity of the joint will be reduced significantly.

The temperatures in the adherends under the fire loading may be such that their properties are reduced. It will be necessary to determine the capacity of the joint with these reduced properties. However, this may not necessarily be a design limitation as the partial safety factors applied to both the materials and to the applied loads are reduced in fire, which is seen as an accidental load. For example, guidance for the design of concrete structures in fire is given in BS 8110 *Part 2*[4.17].

For standard adhesive joints, fire testing of representative specimens may be a more appropriate method for determining the fire resistance.

Where fire is a major design consideration, a pure adhesive joint will not be appropriate, unless the design of the joint is such that the adhesive can be effectively insulated. It will be necessary to design a combined joint, with the mechanical connection required to carry all the load in fire, taking into account the reduced partial safety factors mentioned above, and assuming that the adhesive is no longer effective.

4.9 Proprietary systems

Proprietary systems, such as resin anchors for fixing into concrete or masonry, and the fixing of dowels and starter bars using adhesives, are outside the scope of this Guide. However, the factors that affect the adhesive in a structural connection between two elements will equally affect the resin in a proprietary anchor. Hence the designer should be satisfied that the system is installed and used strictly in accordance with the manufacturer's recommendations. Particular attention should be paid to factors such as the magnitude and direction of loading, the working temperature and the ambient humidity.

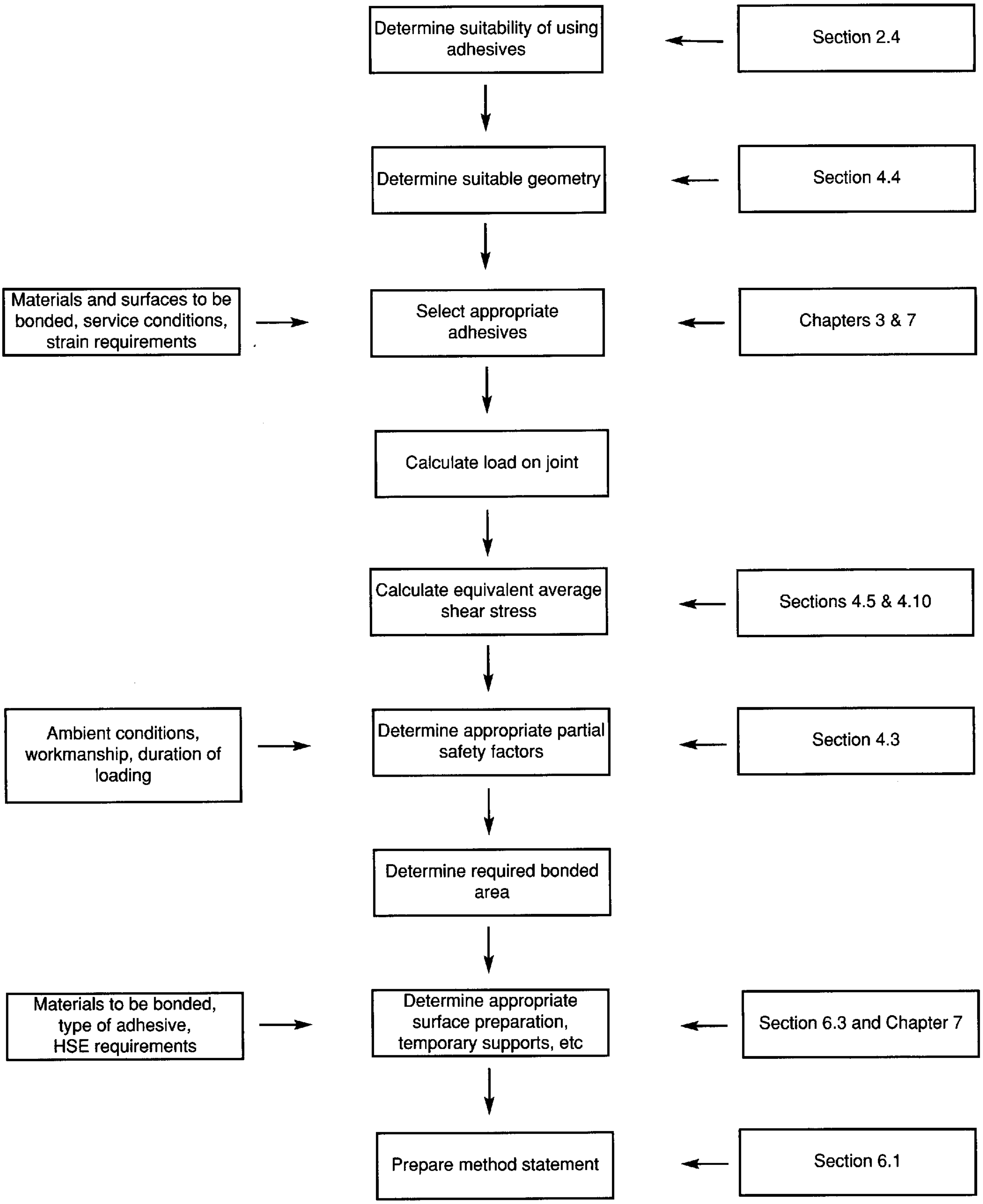


Fig 18. Flow chart for the design of an adhesive joint

4.10 Summary of design method for simple joints in shear

In the absence of a more detailed approach, the steps in the design approach for simple joints in shear at the ultimate limit state will be as follows. The process is also shown in the flow chart in Fig 18.

- determine the shear load to be carried by the joint under the appropriate loads applied to the structure, multiplied by the appropriate load factors γ_f
- assume a uniform distribution of stress in the adhesive layer and hence determine the required adhesive stress
- multiply this stress by a factor of 5 to allow for differences between the assumed uniform stress distribution and the actual distribution to obtain a design stress due to the applied load
- determine the ultimate shear stress for the adhesive from test specimens or from manufacturer's literature as appropriate
- divide this value by the appropriate partial safety factors as given in Table 6 to obtain the design shear capacity of the adhesive
- compare the design shear stress with the design shear capacity to determine the required bond area.

Guidance on design is also given in Section 4.5.

4.11 References

4.1 BS EN ISO 10365: 1995. *Adhesives. Designation of main failure patterns.* London: BSI, 1995

4.2 Adams, R. D., Comyn, J., Wake, K. C.: *Structural adhesive joints in engineering*, 2nd edn. London: Chapman and Hall, 1997

4.3 Clarke, J. L. ed.: *Structural design of polymer composites — EUROCOMP design code and handbook.* London: Spon, 1996

4.4 BA30/94: *Strengthening of concrete highway bridges using externally bonded plates.* Department of Transport and others Advice Note BA30/94. London: HMSO, 1994

4.5 BS 5268: Part 2: 1996. *Structural use of timber.* Part 2: *Code of practice for permissible stress design, materials and workmanship.* London: BSI, 1996

4.6 prENV 1995-1-1: 'Design of timber structures. Annex A: Glued in steel rods'. London: BSI, 1994 & 1998

4.7 BS EN 385:1995. *Finger jointed structural timber. Performance requirements and minimum production requirements.* London: BSI, 1995

4.8 Mays, G. C., Hutchinson, A. R.: *Adhesives in civil engineering.* Cambridge: Cambridge University Press, 1992

4.9 Lees, W. A. ed.: *Adhesives and the engineer.* London: Mechanical Engineering Publications Limited, 1989

4.10 prEN 387: 'Glued laminated timber – production requirements for large finger joints. Performance requirements and minimum production requirements'. London: BSI, 1991

4.11 ESDU: Report No. 78042, *Shear stresses in the adhesives in bonded joints.* London: Engineering Science Data Unit, 1978

4.12 ESDU: Report No. 79016 (with Amendment A), *Inelastic shear stresses and strains in the adhesives bonding lap joints in tension or shear.* London: Engineering Science Data Unit, 1997

4.13 ESDU: Report No. 80039 (with Amendments A and B), *Elastic adhesive stresses in multistep lap joints loaded in tension.* London: Engineering Science Data Unit, 1995

4.14 ESDU: Report No. 92041, *Stress analysis of single lap bonded joints.* London: Engineering Science Data Unit, 1997

4.15 Mays. G. C.: *Fatigue and creep performance of epoxy resin adhesive joints.* Crowthorne: Transport and Road Research Laboratory, Contractor Report 224, 1990

4.16 BS 476: Part 20: *Fire tests on building materials and structures.* Part 20: *Method for determination of the fire resistance of elements of construction (general principles).* London: BSI, 1987

4.17 BS 8110: Part 2: 1985: *Structural use of concrete.* Part 2: *Code of practice for special circumstances.* London: BSI, 1985

5 Behaviour of combined adhesive/mechanical joints

5.1 Introduction and review of combined behaviour

There are situations in which it may appear to be beneficial to use adhesives to improve the performance of a mechanical connection or to use mechanical means to improve an adhesive connection. For example, a bolted connection will have a high ultimate capacity once all the bolts are acting in bearing. However, to achieve this, some slip between the joined members will be necessary, which may not be acceptable under service conditions. Hence the use of an adhesive to provide a more reliable behaviour than friction to enhance the serviceability behaviour would appear to be an attractive option.

Work has been carried out on connections in steel structures using a combination of bonding and bolting[5.1]. They lead to the conclusion that initially the load is transferred by bond but, once the adhesive fails, all the load is carried by the bolts; the strengths of the adhesive and the bolts are not additive. This would appear to be a general conclusion; because of the large bonded area, the effective stiffness of the adhesive will generally be greater than that of the bolts or other mechanical connectors. Hence the adhesive carries the majority of the load under normal conditions while the bolts will carry the loads once the capacity of the adhesive has been exceeded.

Similarly, where bolts, nails or similar are used to hold the two parts of a bonded connection together while the adhesive cures one might be tempted to assume that the two are complementary. However, the design methods for timber connections generally ignore the contribution of nails and screws passing through the joint[5.2] even though they may carry stresses perpendicular to the joint and hence enhance the actual behaviour. The one exception is that specially formulated adhesives, with a more compatible stiffness, are used in North America to fix timber in floors, walls and roofs, in conjunction with nails. Here design methods have been developed which take into account the contribution of both the nails and the adhesive.

The conclusion from the above, which holds good for other materials such as fibre composites, is that the strengths of the adhesive and the mechanical connectors should not be considered as additive. However, there are situations where combined joints may be beneficial, as outlined in the following Section.

5.2 Situations in which combined joints may be beneficial

The primary reason for using a combination of mechanical and adhesive connection will be where the joint is subjected to loads in various directions. For example, the shear may be carried by the adhesive but direct tensions, that would tend to open up the joint, will be best carried by mechanical means.

At the ends of adhesively bonded lap joints relatively high peel stresses are developed. Mechanical fasteners in these locations can be used to carry the transverse loads and hence reduce the peel stresses from the bolted connections. Fig 19 shows part of the elevation of Bures Bridge, a cast iron structure that was strengthened with bonded steel plates, as described in Section 9.3.4. Bolts and clamps were used to hold the plates in position. Fig 20 shows measured stresses from a plated cast iron test beam, demonstrating the effect of the adhesive on the stresses in the plate. It should be noted that, as mechanical fasteners will generally only be provided over a limited length of the joint, they could not be relied upon in the event of failure of the adhesive.

With certain materials, there is considerable scope for the development of special forms of connection which utilise adhesives to carry the shear stresses and mechanical interlock to carry the loads in the transverse direction. One example of this is the connection in the Advanced Composite Construction System which consists of pultruded fibre composite elements joined by a bonded dumbbell-shaped insert as shown in Fig 21. Examples of the application of this system for the construction of buildings and bridges are given in Sections 8.2.5 and 8.3.4 respectively.

It has been shown that the introduction of an adhesive into a bolted connection can significantly increase the fatigue life[5.3]. One practical implication of this is that fewer bolts would be required to ensure a given fatigue life. Thus the overall size of the connection could be reduced without lowering the fatigue life.

A purely adhesive solution may not be suitable for joints in structures for which fire is a design consideration; mechanical fasteners, such as bolts, could be used in this case to carry the loads in fire, on the assumption that the adhesive would fail.

5.3 Situations in which combined joints will be ineffective

If a stiff connection is needed in a structure that will be required to operate at high temperatures, the use of a combined adhesive/mechanical joint will be unsatisfactory as the adhesive will soften, leading to a reduced joint stiffness.

The use of adhesive in a combined joint will generally lead to a stiffer connection which may thus attract more load to itself and to neighbouring members. This will change the overall behaviour of the structure and could cause problems elsewhere.

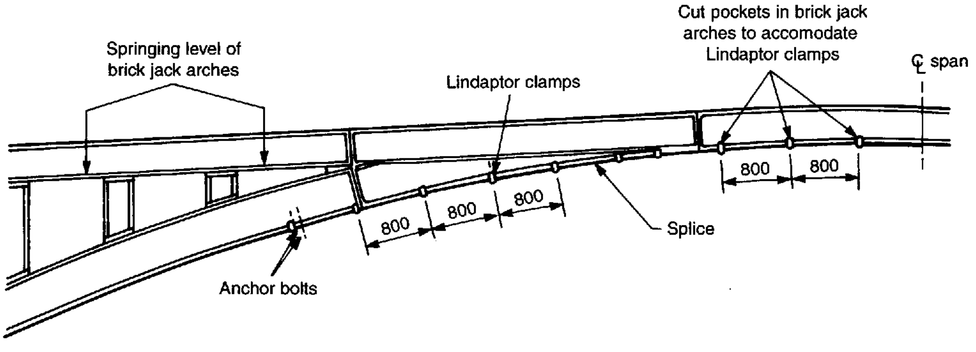


Fig 19. Elevation of Bures Bridge

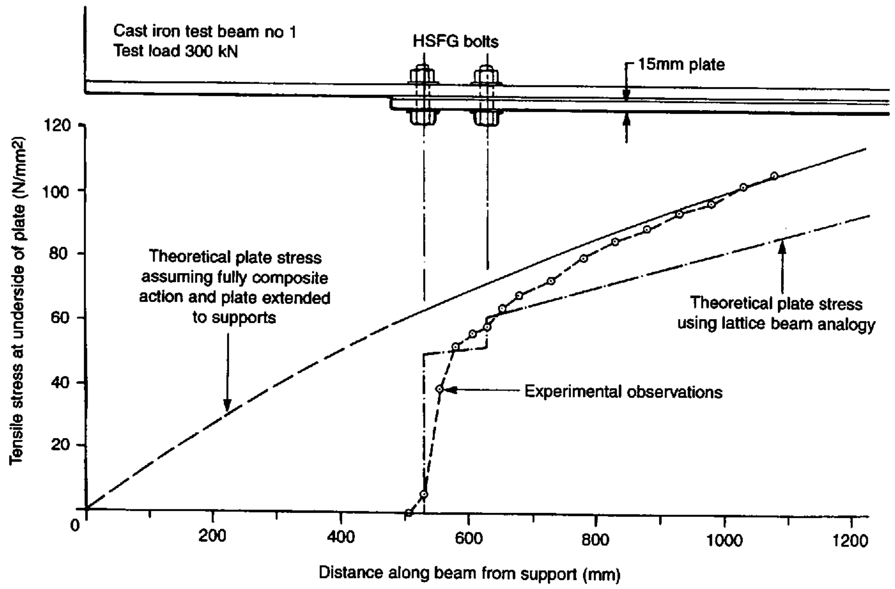


Fig 20. Tensile stresses in bonded-bolted connection

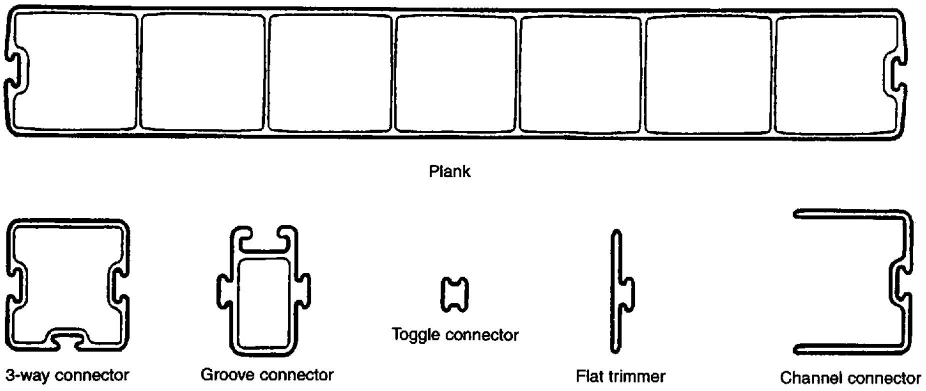


Fig 21. Details of the Advanced Composite Construction System

Combined joints, or purely bonded joints, will be inappropriate in situations in which good electrical continuity is required, such as process plant which must be earthed; adhesives filled with suitable metals, which would provide electrical continuity, are available but are very expensive.

5.4 References

5.1 Albrecht, P., Sahli, A. H.: 'Static strength of bolted and adhesively bonded joints for steel structures'. In: Johnson, W.S. ed.: *Adhesively bonded joints: testing, analysis and design,* ASTM STP 981. Philadelphia: American Society for Testing and Materials, 1988, p229-251

5.2 TRADA: *Structural glued joints in timber.* Wood information, Section 2/3, Sheet 31, High Wycombe: Timber Research and Development Association, 1992

5.3 Albrecht, P., Sahli, A. H.: 'Fatigue strength of bolted and adhesive bonded structural steel joints'. In: *Fatigue in mechanically fastened composite and metallic joints,* ASTM STP 927. Philadelphia: American Society for Testing and Materials, 1986, p72-94

6 Fabrication of joints

6.1 Quality assurance

A full method statement should be prepared by the Structural Engineer, in consultation with the adhesive supplier and/or contractor, dealing with all the factors required to form a satisfactory bonded connection. This should include:

- selection of appropriate materials, including both the adhesive to be used and any materials used in the preparation of the surfaces to be bonded, such as degreasing agents and primers
- preparation of the surfaces to be joined
- method of mixing and application of the adhesive
- appropriate levels of competence for the staff carrying out the work and levels of supervision required (see also Section 10.5)
- control of environment, or specified limits on ambient conditions, for storage of materials, during surface preparation and during application and curing of the adhesive
- requirements for any temporary props, clamps or other supports
- requirements for inspection and testing
- any Health and Safety requirements, over and above those specified by the manufacturers of the adhesive and any other materials used

A flow chart giving the various steps in the process of preparing and assembling the joint is given in Fig 22.

It is particularly important that adhesive connections should be made by adequately trained staff. The method statement should state clearly who is responsible for ensuring that correct procedures have been carried out under the required conditions. It may be appropriate to make trial connections, under realistic conditions, which can be tested to demonstrate the competence of the staff involved and the appropriateness of the chosen procedures, see Section 6.9.

6.2 Selection of adhesive

The selection of the adhesive to be used in a particular application will be governed by the following factors:

- the materials to be joined and the nature of their surfaces
- the type and magnitude of the loading to be applied to the joint
- the thickness of the adhesive in the completed joint
- the environment at the time that the joint is formed
- the environment during the life of the structure
- any special requirements, such as speed of fabrication or gap filling
- any special Health and Safety restrictions

General information on adhesives is given in Chapter 3. Details of the types of adhesives appropriate to various materials, loading conditions, environments, etc., are outlined in Chapter 7. A number of adhesive selection software packages are available, though these should be used with caution as they may be biased towards a particular manufacturer's products[6.1, 6.2].

6.3 Surface preparation

To ensure that the adhesive connection behaves efficiently, it is essential that the surfaces of the elements to be connected are adequately prepared, to ensure both initial adhesion and long-term joint durability. This is particularly the case when the joint is located in an aggressive environment. It is important to understand that many adhesives are blamed for 'not sticking' when the main cause of the problem is usually inadequate surface preparation.

Table 8 Target joint thicknesses for various materials to be joined

Material	Target joint thickness (mm)
Concrete	1 - 5
Timber	
in the factory	0.2 - 1.5
in repairs	1 - 5
Metals	0.2 - 2
Reinforced plastics	0.2 - 2
Glass	0.2 - 1.5

The various tasks may be outlined as follows:

- removal of contaminants, rust, paint, grease, oils or any weak layers (e.g. concrete laitance) that will reduce the adhesion to the adherend
- removal of mould release agents or other similar materials used in the fabrication process
- removal of any dust and neutralising of any chemicals used for cleaning the surface
- drying of substrates such as concrete, timber and polymer composites
- assessing the quality and roughness of the surface finish
- priming the surface ready for the application of the adhesive, where necessary

The preparation of the surface should be such as to produce a uniform thickness of the adhesive layer. The thickness of the joint that should be aimed for in the preparation of the surfaces will depend on the materials being joined. Target joint thicknesses are given in Table 8.

Suitable methods of surface preparation are given in Chapter 7 for all common construction materials. In addition, advice should be sought from the manufacturer of the adhesive to be used. For materials not given in Chapter 7 it will be necessary to carry out large-scale trials to demonstrate the suitability of the selected method of surface preparation.

A considerable amount of information of the effects of surface preparation was assembled in a recent DTI project on the performance of adhesive joints[6.3]. Some comparisons of the effects of surface preparation on the short- and long-term shear strength of joints are given in Chapter 7.

6.4 Evaluation of surface condition

Prior to bonding, the surface should be visually inspected to check that any contaminants have been removed and that the surface would appear to be uniform. Where appropriate, such as when bonding to concrete or timber, it will be necessary to ensure that the exposed substrate is sound. If it is not sound, substandard areas will have to be repaired or the whole surface preparation taken to a sufficient depth such that the substandard area is removed.

A simple way to check the preparation of a non-absorbent surface prior to applying the adhesive is to carry out a surface wetting or water-break test. In this, a few drops of distilled water are placed on the surface; if the drops spread out over

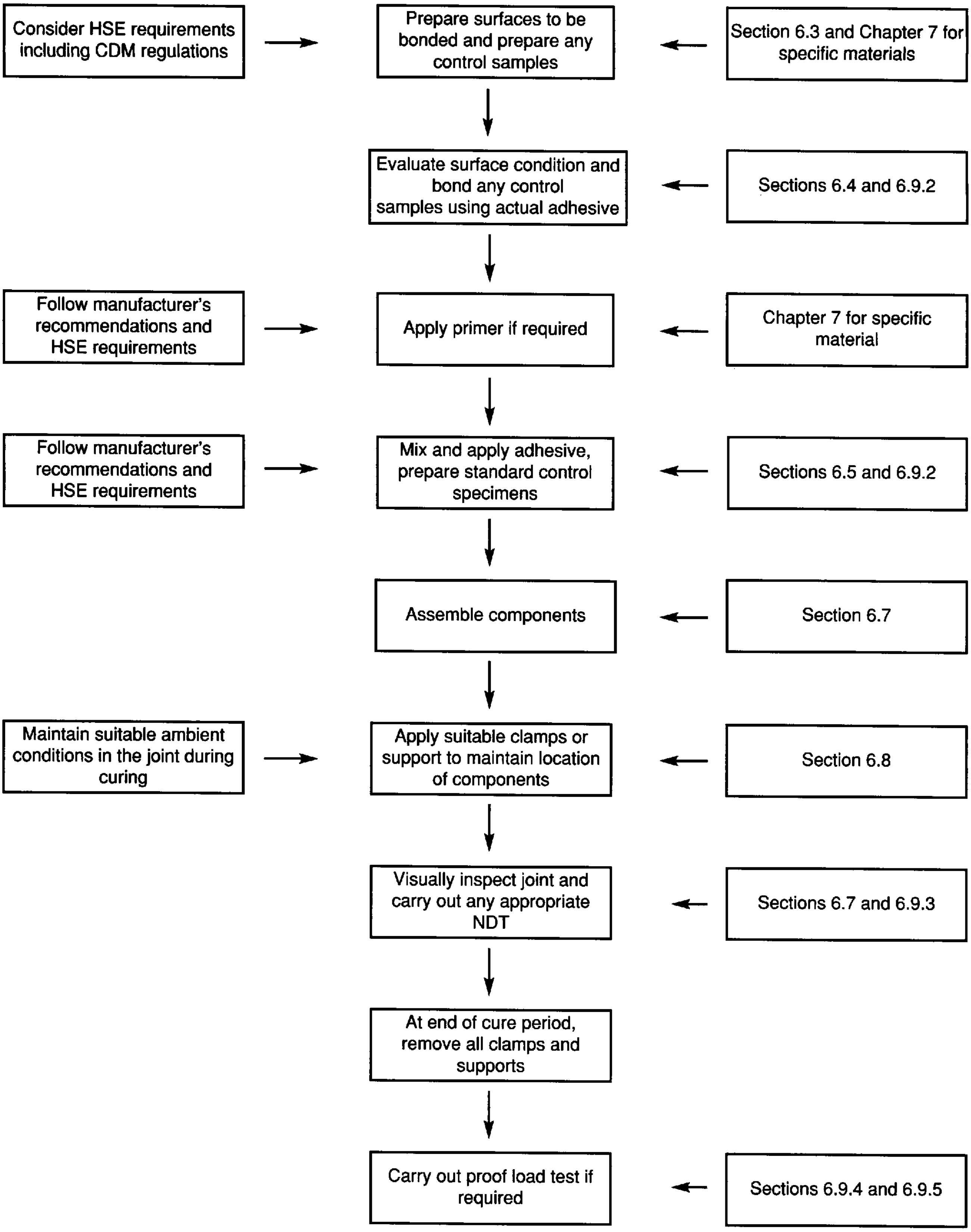


Fig 22. Flow chart for the preparation and assembly of adhesive joints

the surface then the preparation is adequate and the adhesive will similarly wet the surface.

Alternatively the surface condition may be evaluated indirectly by using the same surface preparation technique to prepare control samples, which may then be bonded and tested, as indicated in Section 6.9.2.

For concrete, BS 1881: Part 207[6.4] gives a method for pull-off testing which may be used to give a measure of the surface quality. Guidance for steel is given in BS 7079[6.5]; though specifically intended for paints, the approach is equally valid for adhesives.

6.5 Mixing and application of adhesive

The storage of materials prior to mixing and the actual mixing of the adhesive should be strictly in accordance with the manufacturer's instructions. In particular, the amounts of materials mixed at any one time should not exceed the amounts specified by the manufacturer, as larger volumes will lead to higher temperatures being generated, resulting in a reduced pot life. Thus pre-batched quantities of resins and hardeners should be used to minimise mixing problems. In addition, the recommended method of mixing, e.g. the use of a power driven mixer, see Fig 23, should be used wherever possible.

Some two-component adhesives are supplied in cartridges for use in applicator guns, which may be manual or air-powered. The two components are extruded through a mixing nozzle, which ensures that they are thoroughly mixed, in the correct proportions, see Fig 24.

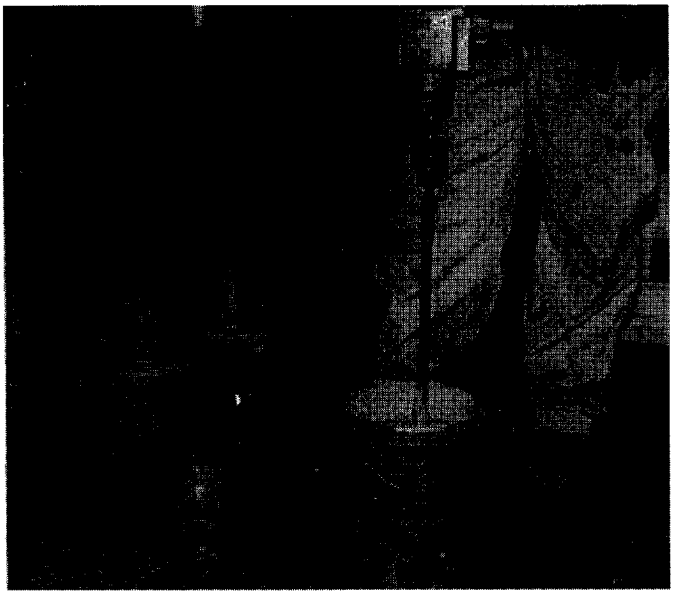


Fig 23. Mixing adhesive using power drill attachment

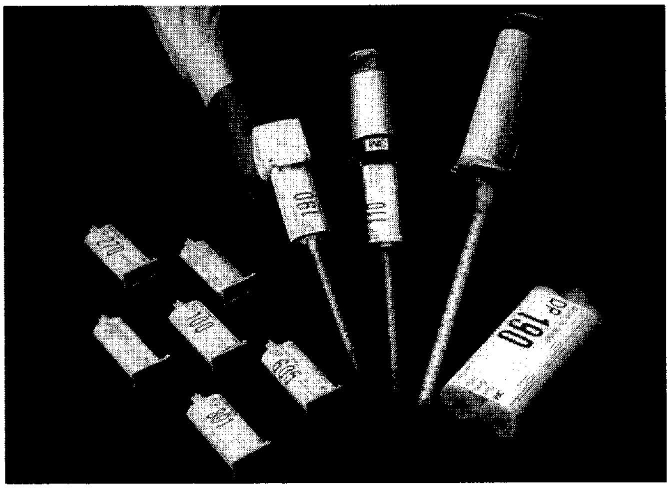


Fig 24. Applicator guns for adhesives

Application of the adhesive on to the substrate should also be in accordance with the manufacturer's recommendations. Fig 25 shows adhesive being applied to a plate. The volume of adhesive mixed at a given time must be such that it may be applied and the surfaces brought together before the pot life of the adhesive has been exceeded. Any excess adhesive remaining at the end of the specified pot life must be discarded.

In general, standard control samples should be prepared to check the properties of the adhesive, see Section 6.9.2.

Fig 26 shows adhesive tape being fitted to a metal framework to support mirror-finished ceiling tiles in an American airport building.

6.6 Environmental conditions

It will generally be necessary to control the environment surrounding the adhesively bonded connection during the preparation of the surface, the application of the adhesive and the subsequent curing period. Control during surface preparation will generally consist of a system to extract dust and fumes from the work area and the exclusion of any material that might contaminate the prepared surface. The latter may be something as simple as moisture; it may be necessary to warm the surface to prevent condensation. Some guidance, for steel substrates, is given in Part B4 of BS 7079[6.5].

During curing of the adhesive it may be necessary to maintain the temperature in the glue line at an appropriate level for a specified period of time, in accordance with the requirements of the manufacturer of the adhesive. Lower glue-line temperatures will result in longer cure times. However, it is particularly important that the maximum temperature specified by the manufacturer is not exceeded during the curing period as this may result in a joint with poor long-term prop-

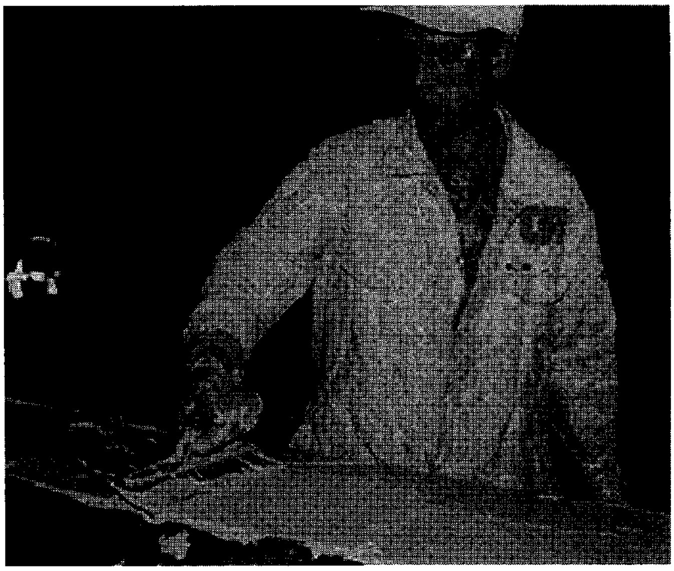


Fig 25. Adhesives being applied to a plate

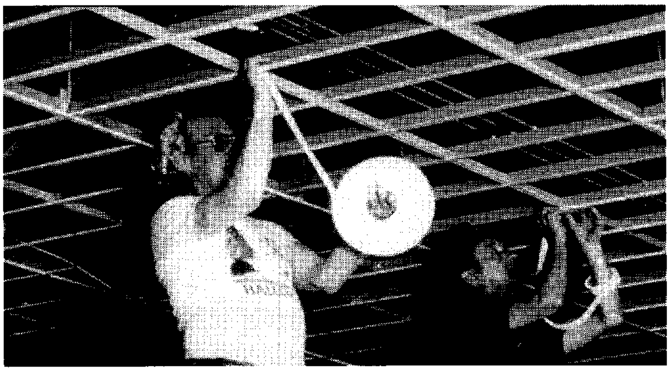


Fig 26. Application of adhesive tapes

erties. Similarly, the temperature should not drop below the minimum specified by the manufacturer; this may result in an adhesive which appears to be satisfactory but in fact has a low strength.

While maintaining environmental conditions will be relatively straightforward if the joint is being made in the workshop, it will be more difficult on site. Here it may be necessary to create a controlled zone around the joint, by means of a temporary enclosure which can be fitted with the necessary heating equipment, etc.

As part of the quality assurance scheme, see Section 6.1, records of temperature and, where appropriate, humidity should be maintained throughout the period of work.

The environmental conditions which may be required with particular materials and adhesives are outlined in Chapter 7.

6.7 Assembly and visual inspection

The adhesive should be applied to the substrate and the components brought together in such a manner that forming the joint leads to a uniform adhesive layer over the whole area. For example, the applied adhesive should be slightly domed in the middle, so that it will be squeezed towards the edges of the joint. In some cases a 'carrier', which consists of a thin layer of woven material, may be used to reduce trapped air in the adhesive. Immediately after assembly, the joint should be inspected. The aim is to ensure that there is a continuous and uniform layer of adhesive visible all round the joint. In some situations the uniformity of the adhesive layer over the area can be checked by tapping the bonded material once the joint has been formed.

In lap joints the adhesive should be formed into a fillet, which leads to extra protection against moisture ingress to the joint.

Care must be taken to ensure that the surfaces are brought together within the period specified by the manufacturer of the adhesive.

Fig 27 shows bonded external reinforcement being positioned.

6.8 Support systems

Where the adhesive in the joint may be subjected to a shear or tensile load before it has fully cured, the joint should be fixed by means of suitable clamps, props, etc., until the adhesive has reached an adequate strength. This may be of the order of 12 hours after making the joint; information on the rate of gain in strength under the appropriate temperature should be obtained from the manufacturer.

As indicated in Section 4.6, cyclic strains applied to an adhesive during the curing period are likely to lead to a small reduction in the strength of the fully cured material. Thus any support system should be designed so as to eliminate such stresses. However, in repairs it may be difficult to avoid some stress variation in the cured adhesive, for example from traffic loading on a bridge. In this situation, an allowance for the resulting reduction in strength must be made in the design process.

It is important that the load applied by any support or clamping system is such that it does not cause local damage to the adherend. This is particularly important for fibre composite materials, which have a low interlaminar tensile strength.

For a joint subjected to a significant compressive load, shims may be required to prevent the adhesive being squeezed out. To avoid the creation of hard points in the completed joint, which could lead to stress concentrations, the shims should generally be removed once the adhesive has cured, unless the stiffness of the shim material is less than that of the fully cured adhesive.

In combined joints, such as bolted/bonded joints as discussed in Chapter 5, the clamping may provide part of the loadcarrying capacity of the joint at a later stage. The same will apply in connections involving combined mechanical interlocking and bonding.

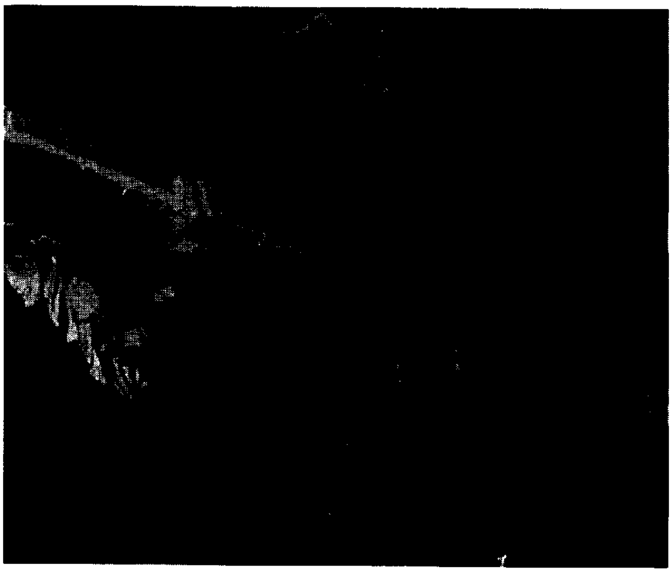


Fig 27. Positioning of external reinforcement

6.9 Proof testing

6.9.1 Introduction

Testing will generally be required as part of the quality control process and will consist of some, or all, of the following:

- tests on standard control samples
- non-destructive tests on connections
- tests on prototype connections
- tests on selected connections on site

The amount and complexity of testing that is to be carried out should be agreed between the engineer and the contractor. The extent of the testing required will depend on the significance of the structure and the degree to which the behaviour of the structure is influenced by the behaviour of the adhesive in the connection. It will also depend on previous experience of the materials being used and of the type of connection being considered. Testing of specially prepared specimens can also be used as a method of determining the competence of the staff carrying out the work.

It is important that, before undertaking any programme of testing, a clear test plan should be drawn up and agreed by all concerned. It will be necessary to make clear distinction between those tests that are part of the manufacturing process of components, such as glulam beams, and those that are concerned with the construction, i.e. adhesive connections between components, either in the factory or on site.

6.9.2 Standard control samples

Tests should be carried out on standard test samples, in accordance with agreed National or International Standards to confirm the properties of the materials used. This will apply to both manufactured components, e.g. glulam beams, as well as adhesives; the latter should be tested in accordance with the relevant Standards. Where the structure will be subjected to abnormal environmental conditions, such as elevated temperatures, high moisture or cyclic conditions, consideration should be given to carrying out control sample tests under appropriate conditions rather than those specified in the agreed Standard.

Tests should be carried out to check that the adhesive itself conforms with the specification[6.6]. Shear tests, using appropriate adherends correctly prepared, can be used to demonstrate the properties of the adhesive[6.7, 6.8].

Tests may be carried out for the following purposes:

- to check the adhesive properties when mixed and cured under actual conditions of use, using standard adherends prepared in a standard manner
- to check the adhesion, using adherends of the same material as those in the actual structure, prepared in the same manner and under the same conditions. This is an indirect method of evaluating the surface condition, see Section 6.4.

For manufactured components, proof testing of standard control samples should form part of the Quality Assurance scheme for the manufacturing process.

EN 1504[6.9] will be a product standard for materials involved in the repair and protection of concrete. It will concentrate on laboratory tests required for repair materials, including materials for structural bonding.

BA 30/94[6.10] gives guidance on the material testing required for steel plate bonding to concrete bridges.

6.9.3 Non-destructive tests on connections

Various non-destructive tests may be used to inspect a completed adhesively bonded connection[6.11]. The most commonly used methods, such as ultrasonic techniques or pulse thermography, are able to detect voids and areas of cracking in the adhesive. They may also be able to identify areas of disbonding between the adhesive and the adherend. For thin materials, such as bonded steel plates, tapping the surface can give an indication of voids in the adhesive. However, there are currently no non-destructive methods that are capable of detecting poor adhesion, which might lead to failure of the joint in the long term. Techniques are being developed that propagate ultrasound along the length of the adhesive joint, rather than through the joint, which have the potential to inspect the bond line. This latter type of test may be more appropriate to connections in structures, in which the thickness of the elements being joined will generally be significantly greater than in applications in the automotive or aerospace industries.

It has been suggested that, where there may be doubts about the long-term behaviour, non-destructive tests should be used during periodic inspections to assess the durability of adhesive connections, particularly those in aggressive situations[6.12]. The aim would be to correlate the *in situ* performance of the adhesive with that in bonded joints under standard conditions of exposure.

This is obviously an area that needs considerable development; simple, non-destructive tests that could be used to check the in-service behaviour of connections would significantly increase confidence in the structural use of adhesives.

6.9.4 Testing prototype connections

Testing of connections will be required when a new technique is being developed or where new materials are being used. Testing may also be required when the staff carrying out the work are unfamiliar with the materials or the techniques being used.

The draft EN 1990[6.13] has an extensive Annex, *Design assisted by testing*, which gives guidance on the evaluation of the test results and the derivation of appropriate design strengths. In some other industries in which adhesive connections are used, design by testing is the preferred option. For example, in space satellites standard types of connection are widely used. The strength of a particular connection is determined from a minimum of 10 specimens, the data being used to calibrate analytical approaches which can then be used to extend the results to other similar connections. A low factor of safety can then be used for the adhesive connection, typically 1.5. However, it should be stressed that all assembly is carried out in conditions of cleanliness far removed from those found in the Construction Industry and hence higher factors should always be used in construction, see Section 4.3.

Because the efficiency of the connection will generally depend to a large extent on the workmanship, care should be taken to ensure that the process of forming the connection is representative of that which will be found in practice, including surface preparation and curing of the adhesive.

Generally testing should be carried out on full-scale connections. Tests on limited parts of connections, or on scale models of connections, may be carried out where experience has shown that the results may be related to the full connection with reasonable accuracy.

If the testing is part of a development programme, consideration should be given to testing a range of skill levels and a range of variations in making the connection, such as different ambient conditions.

Wherever possible, prototype specimens should be subjected to long-term loading, in a representative environment, so that the effects of creep and other similar phenomena on the behaviour of the joint may be determined.

Testing of the connection is unlikely to be covered by current National or International Standards. Hence the test method should be carefully chosen so that it adequately represents the loadings that will be applied in service. Where appropriate, the testing should be carried out at realistic ambient conditions. The number of connections to be tested under a particular loading will depend on the scatter of results obtained; sufficient tests will be required so that statistical methods can be used to set a level of confidence to the results obtained.

6.9.5 Testing connections on site

It may be appropriate to test representative connections on site. Where the connection forms part of a strengthening system, it may be appropriate to load test the complete structure. In general the structure should be loaded to slightly above its service load; guidance, for concrete structures, is given in BS 8110: Part 2[6.14]. Draft guidance on the load testing of bridges is being prepared by the Highways Agency.

Where the connection is a prototype, and does not form a part of the completed structure, it may be appropriate to load it to the design ultimate load. This will give confidence that the connections in the actual structure are capable of performing satisfactorily. Unless a linear behaviour up to collapse of the connection can be assumed, such tests give little indication of the ultimate margin of safety. However, they confirm that a premature failure will not occur.

When considering testing connections on site, it should be borne in mind that it is likely to be costly and time-consuming. It is thus unlikely that site testing would generally be a regular requirement, though some suppliers of resin bonded dowel bar systems do provide a service.

6.10 References

6.1 PAL – *Adhesive selection software*. Eastleigh: Permabond UK

6.2 EASel – *Engineers adhesive selector*. Abington/Eastleigh: TWI/Permabond UK, 1998

6.3 *The performance of adhesive joints; Project 3, Environmental durability of adhesive bonds, Project 4, Characterisation of surface condition*. London: Department of Trade and Industry, Various reports dated 1993-1996

6.4 BS 1881: Part 207: 1992: *Testing concrete:* Part 207: *Recommendations for the assessment of concrete strength by near-to-surface tests*. London: BSI, 1992

6.5 BS 7079: *Preparation of steel substrates before application of paint and related products*. London: BSI.

6.6 BS EN 302: *Adhesives for load-bearing timber structures: test methods*. London: BSI

6.7 BS 5350: *Methods of test for adhesives: GroupC: adhesively bonded joints: mechanical tests:* Part C5:

1990 (1997): *Determination of bond strength in longitudinal shear;* Part C15: 1990 (1997): *Determination of bond strength in compressive shear.* London: BSI

6.8 ASTM C882-91: *Test method for bond strength of epoxy-resin systems used with concrete by slant shear.* West Conshohocken: American Society for Testing and Materials, 1991

6.9 prEN 1504: 'Products and systems for the protection and repair of concrete structure'. Part 1, *General scope and definitions;* Part 2, *Surface protection;* Part 3, *Structural and non-structural repair;* Part 4, *Structural bonding;* Part 5, *Concrete injection;* Part 6, *Grouting to anchor reinforcement or to fill external voids;* Part 7, *Reinforcement corrosion prevention;* Part 8, *Quality control and evaluation of conformity;* Part 9, *General principles for use of products and systems;* Part 10, *Site application of products and systems and quality control of the works.* London: BSI

6.10 BA30/94: *Strengthening of concrete highway bridges using externally bonded plates.* Department of Transport, and others, Advice Note. London: HMSO, 1994

6.11 Munns, I.: 'Adhesive bond inspection using non-destructive testing'. *Materials World,* November 1995, p527-529

6.12 Davies, C. M.: 'The durability of adhesive bonds in structural applications'. In: Armer, G. S. T., Clarke, J. L., Garas, F. K.: *The life of structures; physical testing.* London: Butterworths, 1989, p272-280

6.13 ENV 1991: *Basis of design and actions on structures* (Eurocode 1). London: BSI

6.14 BS 8110: Part 2: 1985: *Structural use of concrete.* Part 2, *Code of practice for special circumstances.* London: BSI, 1985

7 Connections between various materials

7.1 Introduction

This Chapter covers the various specific requirements when using adhesives with various structural materials, including an outline of the required properties, and indicates any special techniques that are required, such as surface preparation. Each structural material is considered in turn. More detailed information and guidance will be provided by the manufacturer of the selected adhesive, which should be followed at all times. Hussey and Wilson[7.1] have prepared a guide giving details of a wide range of adhesives, data sheets, trade names, etc.

In some cases the adhesive will be used to form the connection between two elements of the same material, but in others it will be used to join two different materials. In this latter case, the selection of the adhesive is likely to be something of a compromise; this is considered in Section 7.10.

Of particular concern in the selection of a suitable adhesive for a particular application will be its strain to failure, which must be greater than that of the adherend. Thus an adhesive with a relatively low strain will be sufficient for concrete, provided that it has an adequate strength, but one with a much higher strain is required when bonding composites.

This Chapter gives details of the surface preparation that will be required for various common structural materials. The guidance given only covers the main steps in the process. As has been emphasised earlier, correct surface preparation is essential for the satisfactory long-term performance of the joint. It is therefore important that any detailed requirements specified by the manufacturer of the adhesive should be satisfied.

Suitable types of adhesive are indicated for each structural material. It will be necessary to obtain detailed guidance on the most suitable formulation from the manufacturer.

General requirements for the fabrication of joints, including quality assurance, proof testing and other matters, are given in Chapter 6. Where necessary, aspects of the assembly that are of particular importance for the material being considered are also included.

7.2 Concrete

7.2.1 Surface preparation

Concrete has a cement-rich skin or laitance on the surface, particularly the upper surface as cast. Faces that have been cast against a mould are likely to be contaminated by the residues of mould release oils. In addition, chemical curing agents are widely applied to surfaces, particularly the top surface of floor slabs. These various surface contaminants must be removed, along with the laitance, to ensure good adhesion with the adhesive. Finally surface treatments may be applied to the surface of exposed concrete to restrict the ingress of aggressive chemicals. These may not be detrimental to the performance of the adhesive, but advice should always be sought from the manufacturer.

Before carrying out any surface preparation, it may be necessary to check the integrity of the concrete, by coring or by carrying out suitable non-destructive tests, to determine if there is any delamination or other near-surface defects that may affect the strength of the adhesive joint. This is likely to be particularly applicable to repair. It is important that the preparation process selected is such that it removes the surface layer to expose small particles of aggregate without causing micro-cracks or other damage in the layer below, which would lead to a plane of weakness and hence a reduction in the strength of the adhesive connection. The surface should not be polished or unnecessarily roughened.

The various steps in the process of surface preparation should be as follows:

- remove any damaged or substandard concrete, e.g. honeycombed areas, and reinstate with good quality material
- remove laitance by shot- or grit-blasting or water jetting (the use of bush-hammering or needle-gunning is not recommended as it carries a significant risk of damage to the underlying concrete)
- remove dust and debris by brushing, by oil-free air blast or preferably by vacuum cleaner
- if necessary, clean, with a suitable uncontaminated solvent, to remove any remaining contaminant
- if necessary, dry the surface to be bonded
- apply a levelling layer and fill any holes in the substrate, if necessary
- apply a suitable primer, if required by the adhesive manufacturer.

After preparation, the suitability of the surface should be checked by means of pull-off or twist-off tests. These consist of small steel plates bonded to the surface and loaded, in pure tension or torsion, until failure occurs. Though the stresses in neither test are truly representative of those in the adhesive joint they do give a good indication of the likely behaviour. Further guidance on the use of epoxy adhesives and a standard form of specification may be found in ACI 503R and 503.1[7.2, 7.3]. A general method for assessing the bond strength of epoxy adhesive is given in ASTM C882[7.4].

Fig 28 shows a concrete surface being grit-blasted and Fig 29 shows schematically a cross-section through a concrete surface before and after preparation, showing the removal of the weak, cement-rich, surface layer to expose the firm layer below.

7.2.2 Selection of adhesive

The adhesives most commonly used with concrete are epoxies, while fixings and anchors often use polyesters. Because of the highly alkaline nature of concrete, polyurethane-based

Fig 28. Grit-blasting concrete

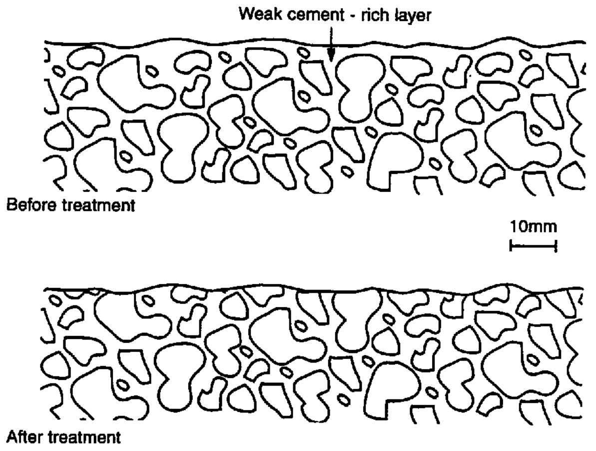


Fig 29. Concrete surface before and after preparation

materials are generally not suitable for structural connections, though they are often used in non-structural applications such as floor toppings. Advice should be obtained from the manufacturer.

7.2.3 Assembly

With highly porous concretes a large proportion of the adhesive may be absorbed, leaving too little in the joint. In this situation, the concrete should be given two coats of adhesive, the second being applied while the first is still tacky[7.2].

Because of the likely weight of the units being joined, they should be rigidly supported during the curing of the adhesive to eliminate any relative movement at the joint and to avoid significant stresses in the adhesive.

7.3 Steel and cast iron

7.3.1 Surface preparation

The purpose of the surface treatment is to remove any weak or loosely bonded oxide layers. There are many different techniques used in manufacturing industry for surface treatment but many of them, such as those involving dipping or the use of fluids at high temperature, are not suitable for use in structural applications.

The various steps in the process of surface preparation should be as follows:

- degrease with suitable solvent
- abrade the surface to remove mill-scale and metal oxides by wire brushing, using an abrasive disc or, preferably, by grit-blasting; very high pressure water-jetting may also be used
- remove dust and debris by brushing, by oil-free air blast or preferably by vacuum cleaner
- dry the surface
- apply a suitable primer, if required by the adhesive manufacturer, or if there is to be a delay before the application of the adhesive.

Further guidance may be found in BS 7079[7.5], BS EN 12768[7.6] and ASTM D2651[7.7].

Fig 30 shows the effect of three different surface treatments on the roughness of a mild steel surface. Clearly the choice of the grit size in the two grit-blasting treatments has a significant effect on the final surface profile. The choice of surface treatment has a significant effect on both the short-term strength and also the long-term strength, as illustrated in Table 9 which shows shear strengths for 3 treatments and 3 different adhesives.

7.3.2 Selection of adhesive

The most suitable adhesives for fully structural applications will be epoxies. For semi-structural applications in which high strength is not required, acrylic or polyurethane adhesives may be appropriate, though not in applications of high humidity or those in which creep can have a significant effect. Advice should be sought from the manufacturer.

Table 9, based on data from Project 3 of reference 7.8, shows the effect of the choice of the adhesive on the initial shear strength and also the long-term strength, after 60 weeks in water at 60°C. The properties are shown for 3 particular adhesives with different surface treatments. The values given are indicative of the differences between the various combinations considered and should not be used for design purposes.

7.4 Zinc-coated steel

7.4.1 Surface preparation

Galvanising and similar processes for applying a layer of zinc to the surface of the steel produce a material less prone to rusting in most environments. A number of surface finishes can be obtained, some of which are more suitable for adhesive bonding than others. With the correct surface preparation the adhesive-zinc interface will be stronger than the steel-zinc interface.

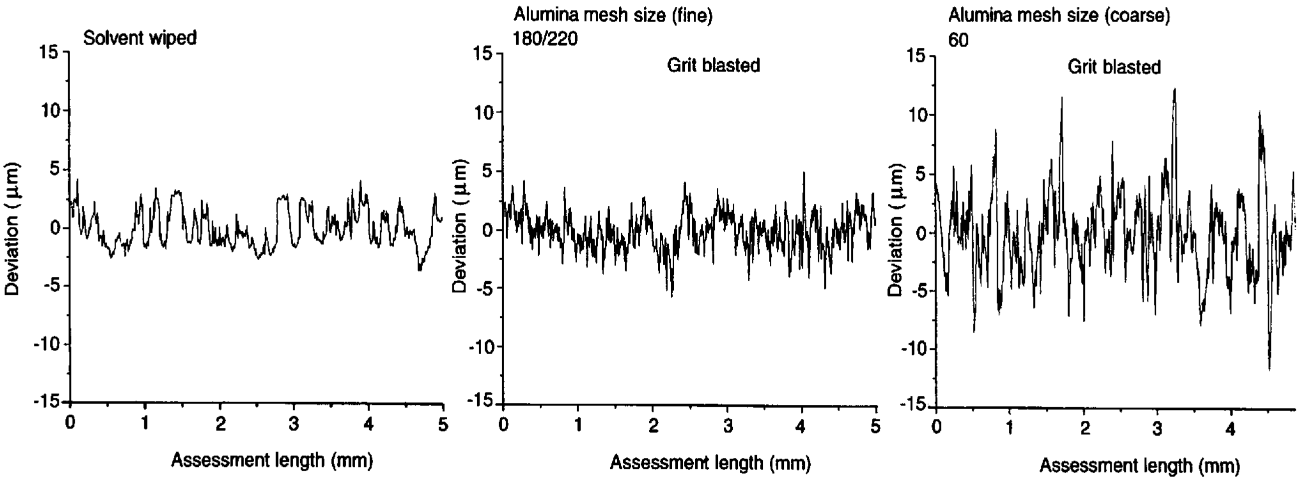


Fig 30. Effect of three different treatments on a steel surface

Table 9 Effect of choice of adhesive and surface treatment on short- and long-term shear strength for steel adherends[7.8]

Adhesive	Surface	Failure load on 20mm x 10mm single lap shear specimen with 1.2mm adherend thickness	
		Initial	After 60 weeks in water @ 60°C
Cold-cure epoxy	Degreased	2.70	Failed
	Grit-blast	4.70	2.10
	Grit-blast plus silane*	4.8	3.13
Hot-cure epoxy	Degrease	4.29	3.90
	Grit-blast	5.24	4.71
	Grit-blast plus silane*	5.16	5.16
Acrylic	Degrease	2.21	Failed
	Grit-blast	3.68	1.66
	Grit-blast plus silane*	4.40	2.68

* Coupling agent

The various steps in the preparation of the surface should be as follows:

- degrease to remove oils and lubricants used in any forming process
- lightly abrade — care must be taken to ensure that the method used does not break through the layer of zinc
- remove any dust by vacuum cleaner or air blast
- chemically etch
- dry the surface
- apply a suitable primer if required by the adhesive manufacturer.

There are a number of proprietary treatments available. It should be noted that some will only be appropriate for preparation in the factory while others will be suitable for site use. Advice should be obtained from the manufacturer.

Further guidance may be found in BS EN 12768[7.6].

7.4.2 Selection of adhesive

The most suitable adhesives will be epoxies. Acrylic adhesives are generally incompatible with the zinc surface and hence are not suitable.

7.5 Stainless steels

7.5.1 Surface preparation

Advice should be obtained from the manufacturer of the adhesive as to the most appropriate surface treatment. Typical steps in the preparation of the surface should be as follows:

- acid etch the surface
- remove the products of the etching process ('desmutting')
- apply a suitable primer

Ideally the treatment of the surface to be bonded should be carried out in the factory to obtain a good keying primed surface. However, a brush treatment may be applied on site.

An alternative preparation process, which may be more appropriate for site use, is as follows:

- degrease with solvent
- grit blast
- apply a chemical coupling agent (such as silane)

There are a number of proprietary treatments available. It should be noted that some will only be appropriate for preparation in the factory while others will be suitable for site use. Advice should be obtained from the manufacturer.

Further guidance may be found in BS EN 12768[7.6].

7.5.2 Selection of adhesive

Toughened epoxy adhesives are generally recommended for structural applications though acrylics may also be used.

7.6 Aluminium

7.6.1 Surface preparation

The various steps in the preparation of the surface should be as follows:

- degrease with a suitable solvent
- clean with suitable alkaline solution
- acid etch, followed by neutralisation
- apply a suitable primer if required by the adhesive manufacturer.

With sealed anodized aluminium components, such as those commonly used in buildings for cladding panels, bonding may be extremely difficult. It may be necessary to remove the surface layer.

Alternatively, the surface may be prepared by grit blasting, followed by a silane primer. This will be more appropriate for site use.

Table 10, based on data from Project 3 of reference 7.8, shows the effect of the choice of the method of surface preparation on the initial shear strength and also the long-term strength, after 60 weeks in water at 60°C. The properties are shown for one particular adhesive, a cold-cure epoxy and should be taken as being indicative only; they should not be used for design purposes.

Fig 31 shows the effect of three different surface treatments on the roughness of an aluminium surface. As for steel (see

Table 10 Effect of choice of surface treatment on short- and long-term shear strength, for cold-cure epoxy adhesive and aluminium adherends[7.8]

Surface treatment	Failure load on 20mm x 10mm single lap shear specimen with 1.6mm adherends	
	Initial	After 60 weeks in water @ 60°C
Degreased	2.91	1.34
Grit-blast	4.27	2.42
Grit-blast plus silane coupling agent	4.49	2.39

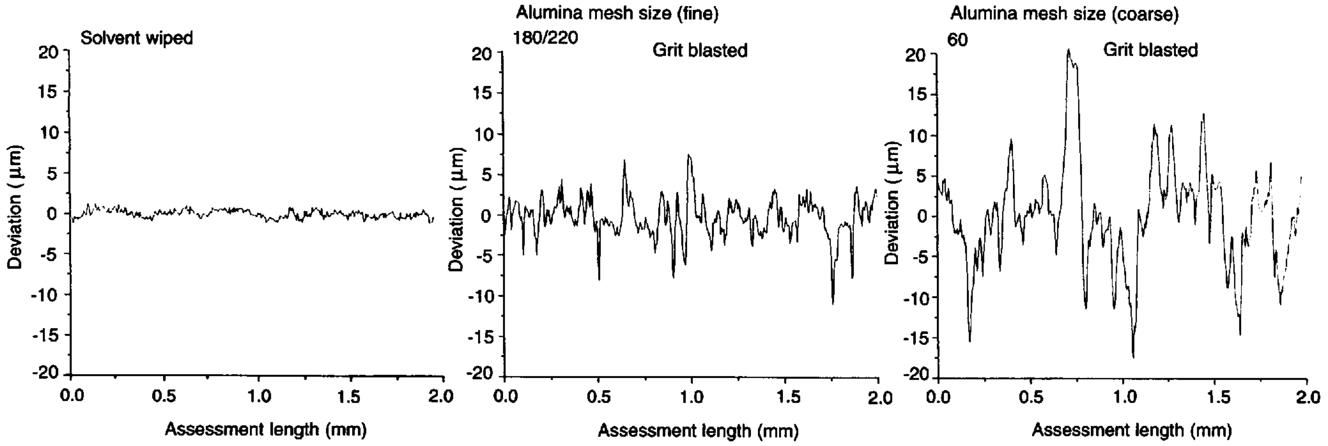


Fig 31. Effect of three different treatments on an aluminium surface

Section 7.3) the choice of the grit size has a significant effect on the final surface profile. However, for a given grit, the surface of the aluminium is far rougher than for the steel.

Further guidance on surface preparation may be found in BS EN 12768[7.6] and ASTM D2651[7.7].

7.6.2 Selection of adhesive

The most suitable adhesives for structural applications will be epoxies and acrylics.

7.7 Timber

7.7.1 General

Some limited guidance on bonded joints in timber is given in BS 5268: Part 2[7.9]. The fabrication of finger joints is covered in BS EN 385[7.10]. Advice on appropriate adhesives for the repair of timber is available from TRADA[7.11].

7.7.2 Surface preparation

With repairs it will be necessary to remove any damaged material and to eliminate any fungal or insect attack before preparing the surface to be bonded; additional treatment may be necessary after the repair has been carried out. Any chemical used to treat the parent material should be compatible with the adhesive, see Section 7.7.3.

The various steps in the process of surface preparation should be as follows:

- dry the surface region, generally to below 20% moisture content
- ensure that the surfaces are at a similar moisture content, which should be close to the in-service conditions
- use a plane or similar to obtain a flat, clean surface, with cutter marks not more than 0.03mm deep (not applicable to some repair techniques where a simple sawn surface will be sufficient)
- for sheet materials such as plywood, lightly sand the surface
- remove dust by air blast or vacuum
- apply the adhesive to the surface as soon as possible; for absorbent surfaces, apply a priming coat of adhesive and allow to cure fully before applying a second coat

7.7.3 Selection of adhesive

Timber is the material that has the longest history of the use of structural adhesives. Most untreated timber can be readily bonded using common adhesives, such as resorcinol-formaldehyde (RF), phenol-resorcinol-formaldehyde (PRF) or phenol-formaldehyde. For repairs, an epoxy adhesive will generally be most suitable.

Adhesives are classified in accordance with their durability in terms of their resistance to breakdown under various exposure conditions. BS 1204[7.13] gives four adhesive types as follows:

WBP:	Weather-proof and boil-proof
BR:	Boil-resistant
MR:	Moisture-resistant and moderately weather resistant
INT:	Interior

The adhesive formulation should be selected with reference to the particular service conditions, through reference to appropriate standards, such as EC5, BS 1204 and EN 301[7.12, 7.13, 7.14] as indicated in Table 11.

There will be restrictions if the material has been treated with a preservative or a flame retardant[7.15]. These require careful selection of the adhesive. The manufacturer's advice should be sought to ensure that the proposed adhesive is compatible with the timber treatment that has been used. All treatments will affect the efficiency of the adhesive to some extent. With certain timber treatments adhesive connections may not be appropriate.

Where the timber is to be treated after connection, the adhesive must be selected such that it is not affected by the treatment process. The adhesive should be fully cured before the timber is treated. Resorcinol and phenolic adhesives are not affected by even the severest timber treatments, but urea-formaldehyde adhesives may be affected.

Where the surfaces to be joined are irregular, resulting in a wide gap at certain locations, it will be necessary to ensure that the adhesive has adequate gap filling properties. These are defined in BS 1204 as resins which provide a satisfactory bond strength in bond lines of up to 1.3mm thickness.

7.7.4 Assembly

Assembly should take place as soon as possible after the surfaces have been prepared, at a maximum within 48 hours or as recommended by the adhesive manufacturer. The surfaces to be bonded should be brought together and a pressure applied by means of clamps or weights, such that the glueline is as thin as possible without squeezing out all the adhesive. This will generally be in the region of 0.7N/mm^2.

Pressure should be maintained during the curing period, as specified by the adhesive manufacturer, and steps taken to ensure that the joint is not moved during this time. Where the joint is likely to be stressed as soon as the clamps are

Table 11 Adhesive types in different climatic conditions

Temp	Climatic equivalent[a]	Examples	EN 301	EC5	BS 1204[b]
≥50°C	Not specified	Prolonged exposure to high temperature[c]	I	1, 2, 3	BP/WBP
	≥85% rh at 20°C	Full exposure to the weather	I	1, 2, 3	BP/WBP
≤50°C[d]	≤85% rh at 20°C	Heated and ventilated building. Exterior protected from the weather. Short periods of exposure to weather	II	1, 2	MR only if ≤50°C

Notes:
a. 85% rh at 20°C will result in a moisture content of approximately 20% in softwoods and most hardwoods, and a somewhat lower moisture content in wood-based panels
b. BS 1204 refers only to phenolic and aminoplastic adhesives
c. This temperature may occur in some areas of buildings not normally inhabited, e.g. enclosed hot roof spaces
d. This temperature is unlikely to be attained in normal buildings in the UK. A reasonable upper temperature limit for inhabited areas is estimated at about 30°C

removed, pressure should be maintained across the joint for at least twice the recommended period.

7.8 Reinforced plastics or fibre-reinforced polymer composites

7.8.1 Surface preparation

Adhesive bonding is the most inherently natural and efficient method of forming a connection between fibre-reinforced polymer composite elements. Detailed advice on appropriate connection techniques, including surface preparation, etc., is provided by the manufacturers, such as Strongwell (formerly MMFG) in the USA[7.16] and by Hutchinson[7.17].

In general terms the suggested procedure for the preparation of the surface is as follows:

- remove grease, dust and other surface contaminants
- remove release agents, resin-rich surface layers, tissues and random fibre materials by using an abrasive cloth or gentle blasting; care must be taken to ensure that the main fibres are not exposed or damaged
- remove any traces of solvents and dust

Where the area to be bonded can be identified prior to manufacture of the fibre-reinforced polymer composite, a peel-ply can be incorporated which, when removed, leaves a surface with the correct texture, with no further cleaning necessary.

Fig 32 shows a typical surface produced by a woven peel-ply.

With some materials, the three steps indicated above can be combined into a simple cleaning process, using a suitable agent to remove the resin-rich surface layer of the composite.

Fig 33, taken from Hutchinson[7.17], shows the effect of various surface treatments on the short-term strength of a single lap joint made with a 2mm-thick woven carbon fibre epoxy composite, using two types of adhesive.

Further guidance on surface preparation may be found in ASTM D2093[7.18] and BS EN 1840[7.19].

7.8.2 Selection of adhesive

Some information on the selection of suitable adhesives for use with reinforced plastics is given in the EUROCOMP Code and Handbook[7.20]. For general applications, epoxy-based adhesives are likely to be the most suitable. In dry conditions, polyurethanes may be used and acrylics will be suitable where creep is not a major design consideration.

Fig 33 shows that a heat-cure epoxy adhesive is less sensitive to surface preparation than a cold-cure adhesive.

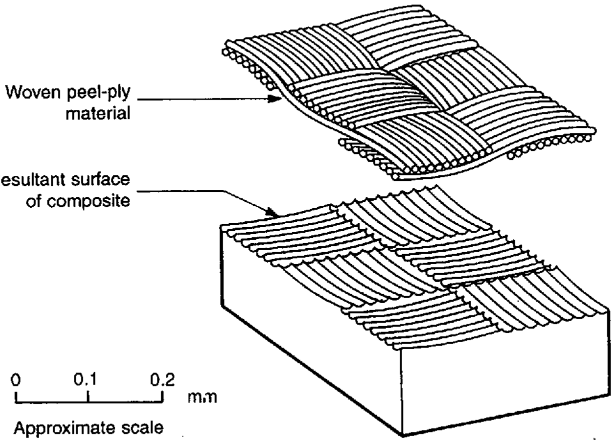
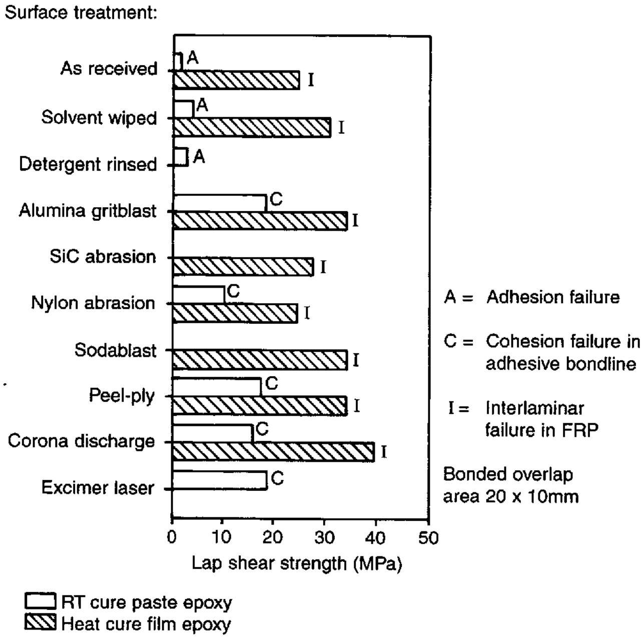


Fig 32. Typical surface topography arising from woven peel-ply material and composites



Note: relative insensitivity of heat cured adhesive!

Fig 33. Effect of surface treatment on the short-term strength of single lap shear joints in carbon-epoxy composite

7.8.3 Assembly

In some applications, the pieces to be joined may need to be clamped in position in such a manner that a compressive stress of about 0.1N/mm^2 is applied across the joint.

7.9 Glass

7.9.1 Surface preparation

Toughened glass has a surface that may be distorted by the toughening process; in addition the whole sheet may be distorted. Hence care must be taken in the selection of the elements to be joined so that a thin, uniform adhesive thickness can be achieved. The only surface treatment that should be required is the removal of any grease on the surface of the glass. There must be no grinding of the surface, as this may cause cracks which penetrate the surface compressive layer and cause the glass to shatter. Similarly, neither the adhesive nor any primer that is used should etch the surface as this would reduce the strength of the glass, even though it might improve the adhesion.

When structural bonding tape is to be used, the glass should be treated with a silane-based primer; formulations are available which can be used to both clean and prime the surface.

7.9.2 Selection of adhesive

The use of structural bonding tape is likely to be the most suitable either when joining glass to glass or glass to metals, such as supporting frames. As an alternative, a modified epoxy adhesive may be used.

It has been found[7.21] that structural silicone sealants are sufficient to carry short-term loads. However, they are not suitable for long-term loading in structural glass. They are not stiff enough to ensure good composite action between the glass elements being joined in fully structural applications.

7.10 Connections between different materials

It is often necessary to bond two different materials together, for example steel to concrete or steel to timber. When selecting the type of adhesive it may be necessary to come to some sort of a compromise between the properties ideally suited to bonding to the two materials separately. Alternatively, the adhesive can be made compatible with both materials by means of a suitable primer.

Table 12 lists dissimilar materials that are frequently bonded together.

There are some combinations of materials that are difficult to join with adhesives, such as those with very different coefficients of thermal expansion. One example would be steel and aluminium.

Table 12 Bonding of dissimilar materials

Material bonded on	Material of main structure	Application
Steel plate or rod	Concrete Timber Masonry	Repairs, dowel bars Repairs Reinstating wall ties
Fibre composites	Concrete Masonry/stone Timber	Repairs Repairs, flooring systems Repairs
Aluminium	Concrete	Cladding
Glass	Aluminium	Glazing and cladding

7.11 References

7.1 Hussey, R., Wilson, J.: *Structural adhesives – directory and databook*. London, Chapman and Hall, 1996

7.2 ACI 503R-93: *Use of epoxy compounds with concrete*. Detroit, American Concrete Institute, 1993

7.3 ACI 503.1-92: *Standard specification for bonding hardened concrete, steel, wood, brick and other materials to hardened concrete with a multi-component epoxy adhesive*, Detroit, American Concrete Institute, 1992

7.4 ASTM C882-91: *Test method for bond strength of epoxy-resin systems used with concrete by slant shear*. West Conshohocken: American Society for Testing and Materials, 1991

7.5 BS 7079: *Preparation of steel substrates before application of paints and related products*. London, BSI

7.6 BS prEN 12768: 'Structural adhesives – guidelines for surface preparation of metals'. London, BSI, 1997

7.7 ASTM D2651-90 (1995): *Standard guide for preparation of metal surfaces for adhesive bonding*. West Conshohocken: American Society for Testing and Materials, 1995

7.8 *The performance of adhesive joints;* Project 3, *Environmental durability of adhesive bonds*, Project 4, *Characterisation of surface condition*. London: Department of Trade and Industry, Various reports dated 1993-1996

7.9 BS 5268: Part 2: 1996: *Structural use of timber*. Part 2: *Code of practice for permissible stress design, materials and workmanship*. London: BSI, 1996

7.10 BS EN 385; *Finger jointed structural timber. Performance requirements and minimum production requirements*. London: BSI, 1995

7.11 TRADA: *Resin-bonded repair systems for structural timber*. Wood information, Section 4, Sheet 22. High Wycombe: Timber Research and Development Association, 1995

7.12 ENV 1995-1-1: 1994: *Design of timber structures: general rules and rules for buildings*. London: BSI, 1994

7.13 BS 1204: 1993: *Specification for type M R phenolic and aminoplastic synthetic resin adhesives for wood*. London: BSI, 1993

7.14 EN 301: 1992: *Adhesives, phenolic and aminoplastic, for load-bearing timber structures: classification and performance requirements*. London: BSI, 1992

7.15 TRADA: *Adhesives for wood and wood products – BS EN Standards*. Wood information, Section 2/3, Sheet 35, High Wycombe: Timber Research and Development Association, 1993

7.16 *Design manual, Extren structural shapes*. Bristol, Virginia: Strongwell, 1989

7.17 Hutchinson, A. R.: *Joining of fibre reinforced polymer composite materials*. CIRIA Report 46. London: CIRIA, 1997

7.18 ASTM D2093-93. *Practice for preparation of surfaces of plastics prior to adhesive bonding*. West Conshohocken: American Society for Testing and Materials

7.19 BS EN pr1840: *Structural adhesives – guidelines for the surface preparation of plastics*. London: BSI, 1995

7.20 Clarke, J. L. ed.: *Structural design of polymer composites – EUROCOMP design code and handbook*. London: Spon, 1996

7.21 Pye, A .J., Ledbetter, S. R.: 'The engineering of composite glass beams'. In: *Proceedings of International Conference on Building Envelope Systems & Technology*. Bath, April, 1997

8 Applications in new construction

8.1 Introduction

Adhesives are used in two distinct areas of application in new construction. The first is in factory-built products or components, such as glued laminated timber, and the second is in onsite connections between structural members, such as precast concrete units. The performance requirements for the adhesives in the two types of application are somewhat different, as outlined later. In addition, as discussed elsewhere in this Guide, the possible levels of inspection and testing of the adhesive in the two types of application are somewhat different.

As discussed in Section 2.6, the design life of the adhesive in new structures will generally be required to be the same as that of the total structure. For buildings this is likely to be about 60 years. For highway bridges in the UK the specified design life is 120 years. However, for adhesive repairs the recommended life is in the region of 30 years[8.1]. Failure of a structural adhesive in any application will lead to a significant change in the behaviour of the structure, either at service loads or at ultimate. Thus the most appropriate applications are likely to be where it is possible to inspect joints between structural members at intervals during the life of the structure, and carry out any necessary repairs.

It will probably not be possible to inspect and repair factory-built products but their suitability for particular applications will have to be determined in the light of experience.

These considerations will have a considerable influence on the choice of adhesives in a particular application.

8.2 Buildings

8.2.1 Concrete

Adhesives have been used in the connections between precast concrete units, for example at Coventry Cathedral and on the Exeter University Chemistry Building, to connect very slender column units. In both cases the joints were in compression, adhesives being used to keep the joint thickness to a minimum. A similar approach was adopted for connecting columns at Somerville College, Oxford, where, with accurate casting, a joint thickness of less than 0.5mm was achieved.

Adhesives were used in the connections between the precast units forming the roof of the Sydney Opera House[8.2] as shown in Fig 34. Although prestress was applied across the joints, adhesives were chosen in preference to conventional mortar because very thin bond lines could be obtained, which were watertight, and the erection sequence could be markedly speeded up because of the rate at which the adhesive gained strength. It was estimated that about 6 months of construction time was saved in all.

8.2.2 Timber

The strength of timber depends largely on the influence of strength-reducing characteristics, such as knots. Clear timber is at least twice as strong as average quality sawn timber. There are many different forms of timber composites. These consist of small elements from which the major defects have been removed, which are then adhesively bonded together to form a composite material, which has a higher strength than the parent timber. Details of the manufacturing processes involved, properties, design methods, etc., are given in a TRADA design guide[8.3]. The most common timber composite is plywood, which is used in structural applications, either in its own right or as a component of a prefabricated joist, as described later.

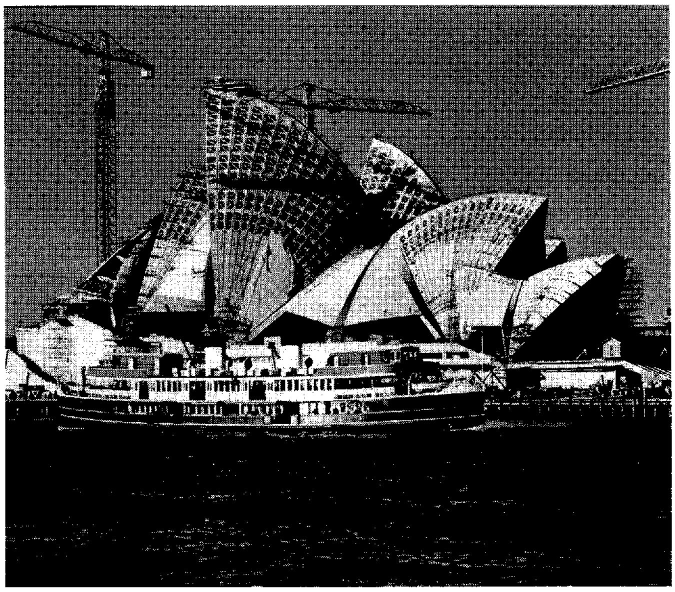


Fig 34. Roof of the Sydney Opera House during construction

Glulam (glued laminated timber) consists of small cross-section rectangular pieces of timber of uniform characteristics bonded together. The grain of all the pieces is parallel to the longitudinal axis, unlike plywood where the grain runs alternately parallel to and at right angles to the axis. Glulam has been used for the construction of timber portals and long-span roof structures for a number of years[8.4, 8.5]. Manufacturers supply a range of standard sizes of straight glulam elements for use as beams or columns. Beams may be fabricated straight or curved; lengths up to 35m are now commonplace. Performance requirements for glulam are covered by BS EN 386[8.6].

Examples of the use of glulam include the roof of the Leisure Complex in Lerwick covering 7000m^2 and similar public buildings[8.7, 8.8]. Fig 35 shows a typical application. Glulam was selected for the main ribs of the shell roofs of the Thames Barrier, which cover the floodgate operating machinery[8.9]. The five main roofs are 19m in height, 11m wide and

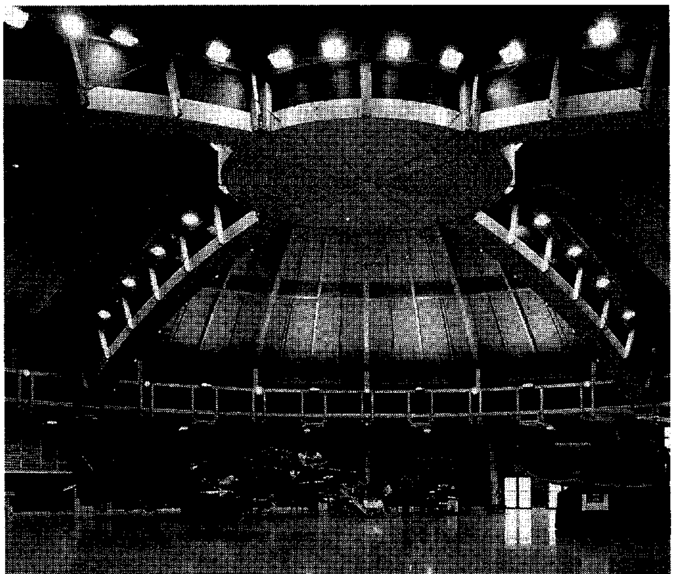


Fig 35. A glued laminated timber dome, Bournemouth International Centre

24m long. There are also two smaller structures of similar shape. Although the outer surfaces of the shells are clad with stainless steel, the glulam ribs are largely exposed to the environment. The shells were installed in about 1980.

Glulam has also been used in aggressive environments in which construction materials such as steel and concrete would not be sufficiently durable. Examples include chemical plants where glulam has been used for the storage of salt, which could cause corrosion of a steel container, and the roof of a battery manufacturing plant. The latter was designed to resist attack from sulphuric acid fumes; the 20-year design of the roof was based on a calculated deterioration rate for the timber in this very aggressive environment. A further application for glulam is in food processing plants; for example, lactic acid from milk products can seriously attack concrete[8.10].

Laminated veneer lumber is a bonded product similar to plywood except that most of the plies are parallel; it is manufactured in a range of standard widths and thicknesses. It has been used to fabricate a variety of structural elements, such as beams and columns, and to form shell structures[8.11]. Lengths up to 24m can be produced.

Prefabricated wood I-joists are composite members manufactured by a number of companies in North America. They are fabricated from either timber or plywood, or a combination, with the web being adhesively bonded to the flanges[8.12].

Adhesives are, in addition, used to bond in steel rods in connections between glulam members. This technique has been used since the 1980s[8.13].

8.2.3 Steel

It would appear that adhesive bonding has not been used to join steel sections carrying structural loads, though some preliminary trials have been carried out, see Chapter 10.

Some holding-down systems, for fixing steel stanchions to foundations, use resins to fix the bolts into the concrete[8.14]. The role of the resin will be to transfer any uplift forces on the column to the concrete, along with some of the shear, the remainder of the shear being transmitted by the packing under the baseplate, which will generally be a cementitious mortar or fine concrete.

8.2.4 Stainless steels

The main use of adhesively bonded stainless steels is in cladding panels, which will be a semi-structural application. Parts of the handrailing at the Waterloo International Terminal were adhesively bonded, which would require a full structural capability[8.15].

8.2.5 Fibre-reinforced polymer composites

Fibre-reinforced polymer composites have been used extensively in boats and other marine applications for a number of years, because of their corrosion resistance and light weight. Adhesives are used in the connections between major structural elements, such as bulkheads and the hull. Applications range from small dinghies to minesweepers. Fibre-reinforced polymer composites are also gaining in use in the aerospace and automotive industries.

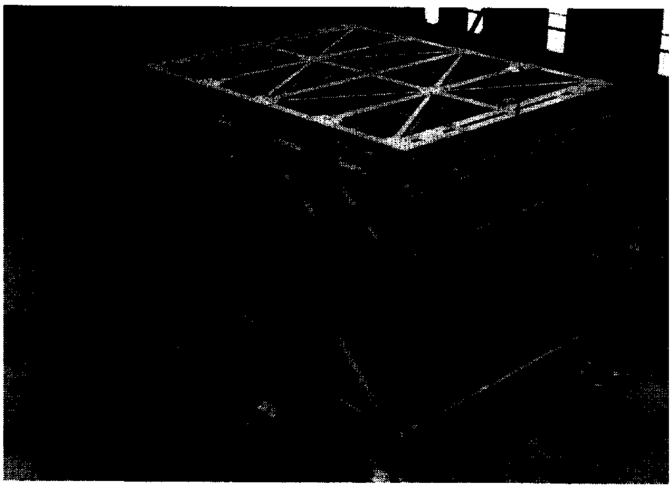


Fig 36. Fibre composite support structure with combined bolted-bonded connections

Pultrusion is a continuous manufacturing technique in which glass, carbon or other fibres are combined with a suitable resin, e.g. an epoxy or a polyester, to form a structural member. Such fibre-reinforced polymer composite structural sections are starting to be used in buildings and other structures, generally where there is a particular requirement such as low self-weight or low electrical interference[8.16]. In many cases adhesive bonding is used in connection with bolts passing through the joints as in the structure shown in Fig 36.

Glass fibre-reinforced polymer composite panels of the type used for the Advanced Composite Construction System (see Section 8.3.4) have been used to construct small one- and two-storey buildings.

8.2.6 Glazing and structural glass

Silicone adhesives are used to carry wind loads in some large panel glazing systems though, as indicated in Section 7.9.2, they are not suitable for carrying long-term loads. The panes of glass are bonded to aluminium frames in the factory and the frames are bolted to the supporting structure on site. Only sealing of the units is carried out on site, not any structural bonding.

Glass is starting to be use in structural applications, in which it must carry loads in excess of its self-weight. For example, glass panels have been strengthened by means of glass fins bonded to them and have been used to form staircases as well as awnings and similar structures[8.17]. This is an emerging technique which is discussed further in Section 10.2.

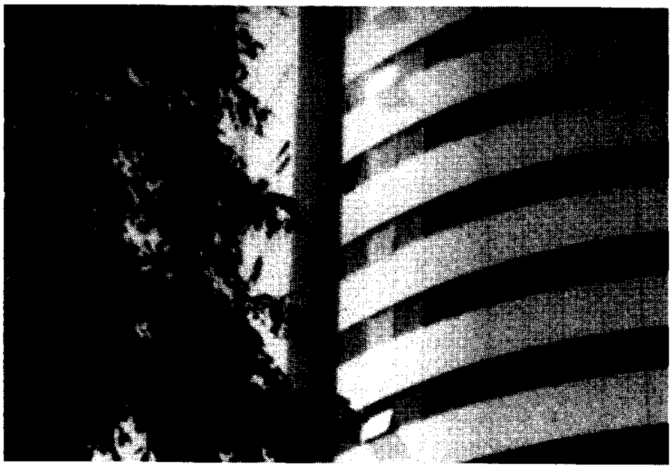


Fig 37. Building in Singapore with cladding panels fixed using adhesive tape

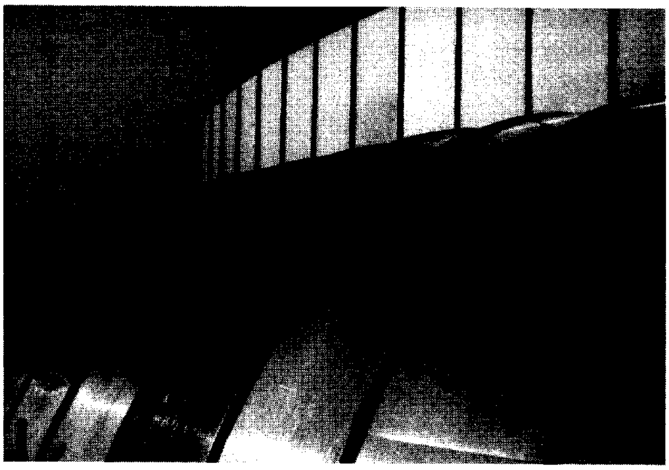


Fig 38. Roofing system using adhesive tapes

8.2.7 Cladding

Adhesive tapes are used to bond the light exterior panels of some cladding systems to the supporting framework, avoiding the use of mechanical fasteners or welding which would distort the surface. The tape accommodates the differential thermal movements between the exterior, which is subjected to solar gain, and the interior of the building which is at a more constant temperature. Figs 37 and 38 show typical applications.

8.2.8 Sandwich panels

The outer skins of sandwich panels are adhesively bonded to the core material, such as a foam. A range of materials are used for the outer skins, including steel, fibre-reinforced plastics and timber.

8.2.9 Stone

Natural stone cladding panels are bonded to metal brackets or other assemblies so that they can be fixed to the main frames of buildings[8.18]. This results in significantly thinner, and lighter, panels than would be required if the fixings were directly into the stone. Other fixing systems consist of a combination of mechanical and adhesive connections, some with slots cut into the stone panels[8.19].

Relatively small limestone sections have been post-tensioned together, using adhesive in the joints, to form long panels[8.20]. The technique is similar to glued segmental construction for bridges, see Section 8.3.1.

Resin bonded anchors are suitable for attaching fixings to stone, because they exert less lateral pressure on the material than mechanical anchors. These are the only type of adhesive connection considered by the Institution of Structural Engineers guide *Aspects of cladding*[8.21].

Natural stone panels for use in raised floor systems from one supplier are strengthened by bonding fibre-reinforced polymer composite material to the tension face. Alternatively, cladding panels are formed by bonding stone to honeycomb material. Hence thinner sections may be used.

8.2.10 Masonry

In The Netherlands and elsewhere adhesives are being used to bond brickwork. The main advantage would appear to be that the adhesive is moisture resistant, which also results in improved frost resistance. In addition, Aramid fibre reinforcement has been embedded in the adhesive layer in some cases in order to build hidden lintels, with clear spans of up to 4.5m. The technique has been used for buildings in Utrecht and Leiden in The Netherlands and in Brussels in Belgium[8.22]. However, the formulation of the adhesive is not clear from the literature; it is described as a 'fine-grained cement'.

8.3 Bridges

8.3.1 Concrete

A major use of adhesives in concrete bridges is in glued segmental construction, in which successive units are 'match-cast'. In this system, each unit is cast against a previously cast one, with only a bond breaker between them. Thus when they are assembled to form the final structure only a thin layer of adhesive is required between them. However, despite the impression given by the name, this type of construction does not rely entirely on structural adhesives. The epoxy mortar, or similar, placed between the match-cast concrete units is primarily to seal the joint and to provide a uniform bearing area. Shear keys are provided to transfer the loads between the units before the adhesive has fully cured. Prestressing cables cross the joint and the precompression helps to develop the necessary shear capacity. Failure of the mortar is likely to lead to serviceability problems, such as increased rotation of the joint, but not structural failure as the shear keys should still carry the self-weight loads. Thus it should be considered, probably, as 'semi-structural' only. In addition, the adhesive helps to waterproof the joints.

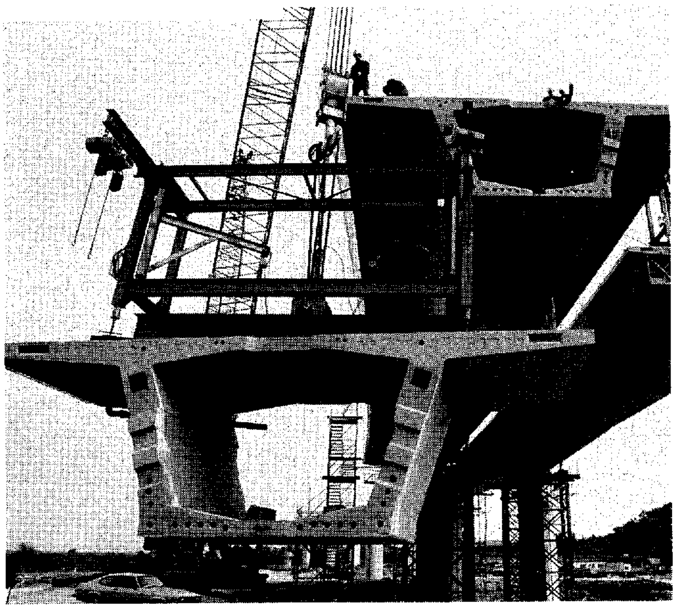


Fig 39. Glued segmental bridge under construction

The first use of the technique in the UK was the Rawcliffe Bridge near Doncaster, in about 1968[8.23]. Later examples include the Torridge Bridge, built in 1987, which consists of 250 precast units used to form the 640m long structure[8.24] and the 4.2km-long approach viaducts for the Second Severn Crossing[8.25]. A similar technique was used to connect the precast segments of the piers. Fig 39 shows a typical structure under construction.

8.3.2 Steel

Adhesive bonding would appear not to have been used in the construction of steel bridges, though laboratory trials on the use of bonded web stiffeners have shown that the technique may be appropriate, see Chapter 10.

8.3.3 Timber

Timber is extensively used for bridges, generally for pedestrian bridges but occasionally for those designed to carry higher loads[8.26]. It would appear that timber bridges are more widespread in continental Europe than in the UK. Design is covered by EC5: Part 2[8.27].

Laminated timber has been used for the construction of a large number of footbridges and highway bridges. Examples in the UK include the footbridge over the Thames at Temple, near Marlow, which was opened in May 1989 and has a total span of about 90m and a recently completed 28m span bridge in Buckinghamshire[8.28].

There are a number of significant bridges in Switzerland built with glulam, including the 3-span Langlaufbrücke Pradella at Scuol (total length 65m) built in 1990. The Wennerbrücke at St. Georgen in Austria is a two-lane arched highway bridge with a clear span of 45m and a total length of 85m built in 1993. The main arches are 1.2m deep by 360mm thick. The main beams supporting the deck are 1.0m deep and 360mm thick. The deck itself consists of precast prestressed concrete elements, connected to the main beams by means of adhesively bonded steel rods[8.26].

The Hiroshima Airport Bridge in Japan is believed to be the longest clear span timber vehicular bridge in the world[8.29]. The structure, which is cable-stayed, has a total length of 145m with a width of 5m. The main structural elements are parallel chord timber trusses, built up from glulam.

Bridge decks have been formed by bonding together parallel glulam elements, particularly in Canada and the USA. The first significant application in Europe was a two-lane road

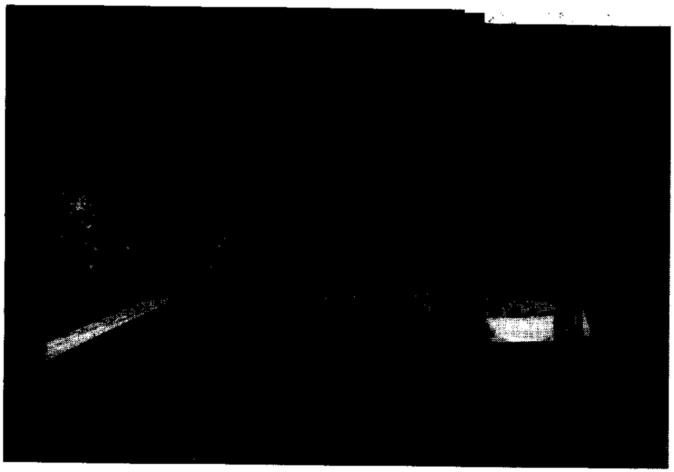


Fig 40. Adhesively bonded rod connections are used in this glued laminated timber pedestrain and cycle bridge near Zurich, Switzerland

bridge, the Dörfli-Brücke at Eggiwil, Switzerland in 1984[8.26]. The deck was fabricated in three pieces, each one third of the width of the bridge and the full length, which were bonded together on site. Glulam was also used for the 30m span main arches. Connections between the various members on site was by a combination of mechanical and adhesive joints.

Glulam reinforced with fibre composite material has been used for the main girders of a highway bridge in the USA. The structure consisted of two 25m spans[8.30].

Fig 40 shows an example of a glulam bridge.

8.3.4 Fibre-reinforced polymer composites

Pultruded sections

Pultruded sections, generally of glass fibre-reinforced polymer composite, have been used to construct a number of footbridges. The connections have generally been a combination of adhesive bonding and bolting or bonding with mechanical interlocking.

Advanced Composite Construction System

This system consists of glass reinforced polyester hollow core planks, made by pultrusion, which are joined together by means of an interlocking connection. It was originally designed as a bridge enclosure system[8.31] and was used on the A19 Tees Viaduct in 1989[8.32]. More recently the system was used on the bridge at Bromley South station and on the approach spans and the overbridges for the Second Severn Crossing.

The connection system was later developed for structural applications, with adhesive in the longitudinal joints to carry the shear forces between the units so that the planks could be formed into box sections. They were used to build the 63m span Aberfeldy Bridge in Scotland (see Fig 41), the world's first long-span composite structure to rely totally on adhesive connections for shear transfer between the units of the deck[8.33]. This was followed by the Bonds Mill lift bridge in Gloucestershire, which carries full highway loading. In addition, a number of smaller footbridges have been built.

8.3.5 Composite steel and concrete

Precast concrete deck panels have been bonded directly to the top flanges of the main steel girders to form a composite structure (see also Chapter 10).

8.3.6 Aluminium

An adhesively bonded aluminium beam formed the main supporting member of a proposed footbridge across the River Granta at Abington in Cambridgeshire[8.34].

8.3.7 Prestressing tendon anchorages

Resins have been used to bond prestressing tendons made of fibre-reinforced polymer composites into the end anchorages.

Fig 41. Aberfeldy Bridge

Examples include glass fibre-reinforced composite tendons first used in the Ulenbergstrasse road bridge in Dusseldorf, Germany, in 1986[8.35]. More recently, carbon fibre and aramid fibre-reinforced polymer composite tendons have been used in Japan, Canada and the USA.

8.4 Tunnels

There is currently little use of adhesive bonding in tunnel linings because of concerns over the effects of fire on the structural behaviour. Bonded rock bolts are used but generally for temporary support prior to further excavation or the construction of the permanent lining.

However, adhesives have been used in repairs to tunnel linings, as outlined in Section 9.4, and for direct rail fixing, see Section 8.8.

8.5 Foundations

Epoxy connections have been used to extend piles, during driving, to achieve the required final length. The requirement would be chiefly to distribute the bearing stress between adjacent units and hence this may be considered as a semi-structural application.

8.6 Geotechnical applications

Adhesives are used extensively in conjunction with rock bolts for the retention of rock faces in cuttings and also with soil nails for the stabilisation of slopes and embankments.

8.7 Offshore platforms

Steel beams and pipework on offshore oil platforms have been strengthened by bonding on carbon fibre composite materials[8.36].

8.8 Railways

A recent development has been the use of adhesives for fixing rails in both light rail (tram) and main line systems. The rail may be fixed directly, for example to a concrete track bed, or else conventional chairs may be used, which are bonded to the supporting structure (see Fig 42).

The adhesive acts as cushion, reducing structure-borne sound transmission[8.37] as well as carrying all the loads. In addition, the resulting system is lighter than conventional sleeper and ballast approaches and is more compact, which increases the available headroom under bridges and in tunnels.

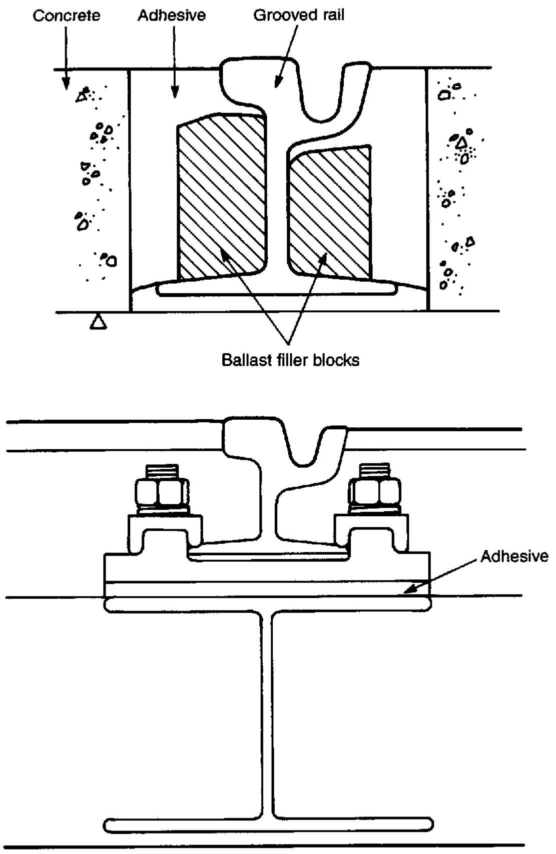


Fig 42. Direct fixing of railway tracks

The approach is also being used for fixing crane rails, for example, in container handling facilities where the adhesive is subjected to high compressive loads as well as high shear loads due to braking.

8.9 Miscellaneous applications

Fibre-reinforced polymer composite materials have been used for coastal and offshore structures. As in buildings, the adhesive connections have often included bolts[8.16].

Road signs are commonly bonded to the supporting framework by means of double-sided tape, with the framework being connected in turn to the main support structure by mechanical means. The same approach is used for large advertising signs.

Transmission masts, with either a solid or a hollow cross-section, have been made from glued laminated timber material[8.38]. Transmission masts have also been constructed from fibre-reinforced polymer composites in the form of a three-dimensional lattice, successive units being bonded together to form a mast of the required height.

In Denmark in 1984 the fibre-glass blades of an existing windmill were replaced with timber blades, consisting of glulam leading edges and the various stringers and plywood covering are assumed to have been bonded. In addition, adhesives were used to fix the blades to the hub[8.39].

8.10 References

8.1 Rendel, Palmer & Tritton. *Adhesive bonding in a civil engineering environment.* Report to Scottish Development Agency, December 1983

8.2 O'Brien, T., Nutt, J.: 'Adhesives for structural jointing'. *The Arup Journal,* **8** (3), October 1973, p48-49

8.3 Mettem, C. J., Gordon, J. A,. Bedding, B.: *Structural timber composites: Design guide.* High Wycombe: TRADA Technology Ltd, 1996

8.4 TRADA: *Glued laminated timber – an introduction.* Wood information, Section 1, Sheet 6, High Wycombe: Timber Research and Development Association, 1995

8.5 Mays, G. C., Hutchinson, A. R.: *Adhesives in civil engineering.* Cambridge: Cambridge University Press, 1992

8.6 BS EN 386: *Glued laminated timber – performance requirements and minimum product requirements.* London: BSI, 1995

8.7 Anon: 'Laminated timber'. *The Structural Engineer,* **74** (18), 17 September 1996, pA9

8.8 Anon: 'St Paul's, Brentford'. *The Structural Engineer,* **74** (12), 18 June 1996, pA12

8.9 Mettem, C. J.: 'Timber shell roof structures, lecture E21'. In: Blass, H. J. *et al.,* eds.: *Timber engineering, STEP 2,* Almere, The Netherlands: 1995

8.10 Hartl, H.: 'Timber structures in aggressive environments, lecture E26'. In: Blass, H. J. *et al.,* eds.: *Timber engineering, STEP 2.* Almere, The Netherlands: 1995

8.11 Ranta-Maunus, A.: 'Laminated veneer lumber and other structural sections, lecture A9'. In: Blass, H. J. *et al.,* eds.: *Timber engineering, STEP 1,* Almere, The Netherlands; 1995, Lecture A9

8.12 Smith, I., Chui, Y. H.: 'Applications of modern wood based composites in construction'. In: Garas, F. K., Armer, G. S. T., Clarke, J. L.: *Building the future – Innovation in design, materials and construction.* London: Spon, 1994, p85-92

8.13 Buchanan, A. H., Deng, X. J.: 'Strength of epoxied steel rods in glulam timber'. *Proceedings of 4th International Wood Engineering Conference,* New Orleans, 1996

8.14 Blake, A. C. L. *et al*: *Holding down systems for steel stanchions.* Concrete Society/British Constructional Steelwork Association/Construction Steel Research and Development Organisation, 1980

8.15 Baddoo, N., Burgan, R., Ogden, R.: *Architects' guide to stainless steel.* Ascot: Steel Construction Institute, 1997

8.16 *Design Manual: Extren fiberglass structural shapes.* Bristol, Virginia: Strongwell, 1989

8.17 Guard, M.: 'Structural glass'. *The Structural Engineer.* **76** (1), 7 January 1998, p11-12

8.18 Carbary, L. D., Schoenherr, W. J.: 'Structural silicone sealants used to adhere stone panels on exterior building facades'. In: Donaldson, B.: *New stone technology, design and construction for exterior wall systems,* ASTM STP 996. Philadelphia: American Society for Testing and Materials, 1988, p160-165

8.19 Smith, D. S., Peterson, C. O.: 'The marriage of glass and stone'. In: Donaldson, B.: *New stone technology, design and construction for exterior wall systems,* ASTM STP 996. Philadelphia: American Society for Testing and Materials, 1988, p166-182

8.20 Kluesner, H. F.: 'Post-tensioned panels of Indiana Limestone'. In: Donaldson, B: *New stone technology, design and construction for exterior wall systems,* ASTM STP 996. Philadelphia: American Society for Testing and Materials, 1988, p119-127

8.21 Institution of Structural Engineers. *Aspects of cladding.* London: SETO, 1995

8.22 Anon: *Verlijmen van baksteen,* Koninklijk Verbond van Nederlandse Baksteenfabrikanten (Royal Association of Dutch Clay Brick Manufacturers), February, 1997

8.23 Sims, F. A. and Woodhead, S.: 'Rawcliffe bridge in Yorkshire'. *Civil Engineering and Public Works Review,* April 1968, pp385-391

8.24 Pothecary, C. H., Brindle, L.: 'Torridge Bridge; erection of superstructure'. *Proceedings of the Institution of Civil Engineers, Part 1*, **88**, April 1990, p233-260

8.25 Fletcher, M. S., Maury, Y., Khadivi, H.: 'Second Severn Crossing approach viaducts; an example of total external prestressing'. In: *Post-tensioned concrete structures (FIP Symposium 1996)*, London: The Concrete Society, 1996, p856-864

8.26 Fischer, J.: 'Timber bridges, lecture E17'. In: Blass, H. J. *et al.*: *Timber engineering, STEP 2*. Almere, The Netherlands: 1995

8.27 ENV 1995-2: 1997. *Design of timber structures*, Part 2, *Timber bridges*. London: BSI, 1997

8.28 Anon: 'Historic Bucks. bridge recreated'. *The Structural Engineer*, **74** (18), 17 September 1996, pA9

8.29 Gilham, P. C., Iimura, Y.: 'Design, testing and erection of the Hiroshima Airport Bridge'. *Proceedings of 4th International Wood Engineering Conference*, New Orleans, 1996

8.30 Boles, M.: FiRP glulams for bridge girders, *FRP International*, **IV** (4), Autumn, 1996, p3

8.31 Irvine, R. A., Thorpe, J. E.: 'Bridge enclosure: facilitating construction, inspection, maintenance, upgrading and operation'. In: Harding, J. E., Parke, G. A. R., Ryall, M. J. eds.: *Bridge management 3*. London: Spon, 1996, p429-436

8.32 Head, P. R.: 'Design methods and bridge forms for the cost effective use of advanced composites in bridges'. In: Neale, K. W., Labossiere, P. eds.: *Advanced composite materials in bridges and structures*. Montreal: Canadian Society for Civil Engineering, 1992, p15-30

8.33 Head, P. R.: 'Advanced composites in civil engineering – a critical overview at this high interest, low usage stage of development'. In: El-Badry, M. ed.: *Advanced composite materials in bridges and structures*. Montreal: Canadian Society for Civil Engineering, 1996, p1-15

8.34 McGrath, G.: 'Aluminium footbridge demonstrates adhesive durability'. *Research Focus*, no.15, October 1993, p7

8.35 Wolff, R., Meisseler, H-J.: 'Glass-fibre prestressing system'. In: Clarke, J. L. ed: *Alternative materials for the reinforcement and prestressing of concrete*. Glasgow: Blackie Academic and Professional, 1993, pp127-152

8.36 Barnes, F.: 'CFRP's for strengthening and repair'. *Construction Repair*, **11** (3), May/June 1997, p39-42

8.37 Fitzgerald, B. M., Shaw, M.: 'The mitigation of structure borne noise on a steel railway bridge using a polyurethane resiliant track fixing system'. *Bridge Management 3*, London: Spon, 1996, pp810-817

8.38 Solli, K. H.: 'Structures for transmission systems, lecture 24.' In: Blass, H. J. *et al:*. *Timber engineering, STEP 2*. Almere, The Netherlands: 1995

8.39 Clorius, C. O., Pederson, M. U., Damkilde, L., Hoffmeyer, P.: 'The strength of glued-in bolts after 9 years *in situ* loading'. *Proceedings of 4th International Wood Engineering Conference*, New Orleans, 1996

9 Examples of repairs, refurbishment and upgrading

9.1 Introduction

Adhesives are used extensively in repairs, refurbishment and upgrading to bond additional material to existing structures. The purpose is to make good a deficiency in strength or stiffness which may be due to a number of causes, including:

- corrosion of structural steel
- corrosion of steel reinforcement or prestressing tendons in concrete
- damage to timber due to fungal or insect attack
- cracks in concrete
- under-design
- change of use
- change of design criteria, such as increased seismic requirements
- impact damage to steel and concrete structures

The new material may be either the same as the original, such as timber bonded onto timber, or may be different, such as steel plate or carbon fibre-reinforced polymer composite plate bonded to concrete. In the following Sections the applications are divided up according to the parent material and not the strengthening material.

The design requirements for an adhesive repair will be somewhat different from a new-build application. The first difference is that the design life will be less, probably of the order of 30 years; there would be little point in having a design life for the repair that was significantly greater than the remaining life of the structure. Secondly, many repairs are inspected and can be replaced if necessary. Finally, the consequences of failure of a repair will generally be relatively small, not leading to the collapse of the structure.

Fibre-reinforced polymer composite material used for strengthening is in one of two forms. Either it is fully cured, generally in the form of a plate or strip, or it may be partially cured, in which case it is generally in the form of a sheet. The latter material is generally referred to as a 'prepreg'. Final curing of the resin in the composite, which also acts as an adhesive to bond the composite to the structure, takes place *in situ.*

Finally, resin injected into cracks in concrete, timber or masonry to restore its loadcarrying capacity might be considered to be a structural adhesive.

This Chapter gives an overview of some of the applications of adhesives, grouped according to the type of structure

9.2 Buildings

9.2.1 Concrete

Steel plate bonding was developed during the 1960s. An early application was in a building in the early 1970s; the columns of the stairway and the lift shafts were continuously reinforced by external plates over the full height of the structure to provide the necessary vertical ties[9.1].

Steel plates are now regularly used to strengthen concrete beams and slabs, generally being bonded to the soffits to improve the loadcarrying capacity. The first application in the UK was in London in 1978[9.2]. In 1985 steel plate was bonded to the top surface of floors in an office building in Leeds to improve the punching shear resistance around columns[9.1]. More recently steel plates were bonded to the top surface of the concrete slab of a computer hall in a building in Reading to increase its loadcarrying capacity[9.3]. The alternative to steel plates would have been the addition of a structural screed, up to 75mm thick; it was considered that this would add too much weight to the existing structure.

While steel plates continue to be used, advanced fibre-reinforced polymer composites are now being developed as alternative materials for strengthening buildings and other structures. Carbon fibre-reinforced polymer composite strips have been used to strengthen balcony slabs in Germany[9.4] to overcome problems due to deflections caused by insufficient steel reinforcement. In Switzerland extensive strengthening of the floor slabs of a shopping centre was required so that openings could be cut in the slabs to allow for the installation of new lifts and escalators. Carbon fibre-reinforced polymer composite strips were bonded to the soffit in both directions on either side of each opening[9.4]. The same technique was used in the City Hall at Gossau St. Gall, Switzerland[9.5].

In the UK, carbon fibre-reinforced polymer composite strips were bonded to the soffit of the concrete flat roof of Normanby College, part of King's College Hospital in London, to strengthen it sufficiently to carry an additional floor[9.6]. It was suggested that the more traditional strengthening approach using steel plates would not have been possible because of design and application constraints.

Elsewhere in the UK, the material has been used to strengthen precast stair treads which had been installed the wrong way up and to provide additional reinforcement round a newly created opening in a floor slab.

In Italy carbon fibre strips have been bonded in two directions to both faces of a prestressed double curvature concrete shell roof structure[9.7]. The structure had been damaged, resulting in the loss of some of the prestress; conventional repair techniques were deemed not to be appropriate. Carbon fibre strips were also used to strengthen the main roof beams of an exhibition building, increasing both the flexural and shear capacity. The ground floor beams of a residential building, which had been damaged by an earthquake were repaired by the use of carbon fibre sheets wrapped round and bonded to the concrete.

Canada has seen the use of glass fibre-reinforced polymer composite shells have been bonded to the surface of damaged columns to improve their loadcarrying capacity[9.8].

In Japan columns have been strengthened following earthquake damage by wrapping them with carbon fibre-reinforced polymer material, either in the form of a thin strip or in sheet form[9.9]. Similarly, columns have been strengthened by wrapping them with aramid fibre tape, bonded to the surface[9.10].

In Florida the beam-column connections in a parking garage have been strengthened by bonding carbon fibre sheet material to the sides of the beams[9.11]. This approach was chosen in preference to the conventional solution of increasing the size of the connection by dowelling in additional steel reinforcement and encasing the joint with additional concrete. It was estimated that the adhesively bonded repair was 35% cheaper than the conventional method.

Carbon fibre composite strips have been used in various applications in a number of other countries, including Austria, Belgium, The Czech Republic, Hungary and New Zealand.

Fig 43 shows a typical application.

9.2.2 Masonry

Unreinforced masonry has been strengthened to provide seismic resistance in two six-storey apartment blocks in Switzerland using carbon fibre-reinforced polymer composite strips[9.4] (see Fig 44).

A natural stone column in Zurich has been strengthened by the application of a spiral strip of carbon fibre-reinforced polymer composite[9.4].

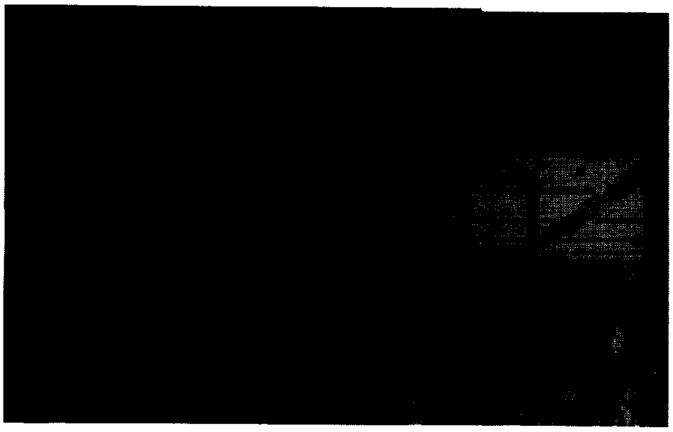


Fig 43. Strengthening the roof slab of an underground carpark

Fig 44. Carbon fibre strengthening of a masonry wall

Adhesives are used widely to fix replacement wall ties for cavity walls. Similarly adhesives are used to fix inserts set into masonry to supplement bed-joint reinforcement.

In California unreinforced masonry walls have been repaired and strengthened using fibre-reinforced polymer composite sheet material following seismic damage[9.12]. The same approach is being used to improve the lateral strength of masonry walls.

In Houston, marble cladding panels, which had come loose from the facade of a 31-storey building, have been refixed using a polyurethane adhesive. The work was carried out without the need to remove the panels from the building, reducing the cost of the repair from $6M to $0.5M[9.13].

9.2.3 Timber

In many traditional repairs to timber, adhesives are used to bond the new timber to the old, with nails or clamps being used chiefly to hold the units together while the adhesive cures. More recently connections have been developed which include bonded in rods or plates passing across the interface[9.14, 9.15]. Generally steel is used but techniques using fibre composites are being developed. It has been suggested that the lower elastic modulus of fibre composites make them more compatible for use with timber. In addition, their lower coefficient of thermal conductivity may make their performance in fire superior. When rods or plates are used in applications such as the addition of new material to the ends of beams, they carry the majority of the load, the adhesive being relatively lightly stressed. The techniques have been developed over the past 20 years or so and are being validated by laboratory testing and site monitoring[9.16].

Fig 45. Timber beams strengthened with carbon fibre plates

An extension of the technique is the strengthening of beams by means of steel reinforcing bars. A vertical slot is cut along the beam, to a suitable depth and width, and is then filled with an appropriate number of bars surrounded with epoxy adhesive.

A further use of adhesive is for filling cracks and other damage in timber members, though care must be taken to ensure that the adhesive does not form a stiff wedge that can lead to further damage to the timber member. In some applications a heavily filled epoxy grout has been used to replace completely the timber at the ends of beams, shear connection between the epoxy block and the parent timber being by means of steel dowels.

One objection to the use of adhesives in embedded repairs is that they are irreversible, which is a concern to owners of some historic buildings.

The main beams of a historic building in Tunbridge Wells[9.17] were strengthened with steel plates bonded to the soffits; because the beams were twisted and deflected, the plates were formed to the correct shape before installation.

Carbon fibre composite strips were used to strengthen a 200-year old oak beam in a museum in Lucerne, Switzerland, (see Fig 45).

9.3 Bridges

9.3.1 Concrete

Steel plate bonding has been used extensively for the strengthening of concrete bridges, with the plates generally being applied to the soffits of the beams. The first major use of steel plate bonding in the UK on a bridge was on the Quinton interchange on the M5 in 1975. Cores were taken through the plates in 1995; the subsequent tests showed that the adhesive layer was performing satisfactorily, despite some slight corrosion of the steel surface[9.18]. Other applications include two bridges at Swanley, Kent, in 1977, and one at Rotherham in 1982. In 1990 the Austen Fen Bridge in Lincolnshire was strengthened with steel plates bonded over the supports and also onto the sides of the beams[9.19]. The transverse stiffness of the Bolney Flyover on the London-Brighton road was increased in 1992 by bonding steel plates to the top of the deck[9.19].

In 1986 the joints in the Kattenbusch Bridge in Germany were strengthened by bonding a large number of glass fibre-reinforced polymer composite plates across them[9.5]. The plates were each 3.2m long, 150mm wide and 30mm thick.

Woven carbon-fibre mats have been bonded directly to the

Fig 46. Carbon plate bonding to the soffit of a small bridge

soffit of a bridge over the A2 autoroute in France to strengthen it[9.20]. This would appear to be the first application in which carbon mats have been used. Elsewhere various techniques using carbon fibre-reinforced plates or strips are being developed.

The first use of carbon fibre-reinforced polymer composite strips for the repair of a bridge was in Switzerland. The Ibach Bridge, near Lucerne was repaired with strips up to 5m long following damage to a prestressing tendon[9.5]. The strips were bonded to the soffits of the beams. Subsequently, a number of concrete bridges in Switzerland have been strengthened using carbon-fibre composite strips, either on the soffit to increase the sagging bending capacity or on the top surface to increase the hogging capacity.

Similar repair work to the soffits of beams has been carried out in Italy[9.7] to repair the damage caused by vehicle impact, the carbon strips being used to provide some additional shear capacity as well as increasing the flexural capacity. Also in Italy, carbon fibre sheet material has been used to strengthen short columns supporting the end region of a bridge.

In the UK, the ROBUST project developed the ROBUST SYSTEM of strengthening existing structures in flexure using both unstressed and prestressed carbon fibre-reinforced polymer composite strips[9.21, 9.22]. A full account of structural strengthening using FRP, including a description of the ROBUST SYSTEM, is given by Hollaway and Leeming[9.23]. In 1997, a small concrete underpass beneath a major road in Buckinghamshire was repaired with carbon-fibre composite strips of the type previously developed in Switzerland[9.24]. Similar repairs have been carried out in various parts of the country since. Fig 46 shows a typical application.

In Canada, carbon fibre-reinforced polymer composite sheet material was applied to the soffits and the sides of a bridge in Edmonton, to improve the shear resistance[9.25]. The paper makes some comparisons with a conventional external stirrup system, showing a 30% saving in costs. Similar repairs were carried out in Québec where 9 columns of a bridge over a main highway were repaired, 5 with glass fibre and 4 with carbon fibre[9.26].

Similar carbon fibre-reinforced polymer composite sheet material has been applied to bridge piers in Japan to improve their seismic resistance[9.9].

The use of fibre-reinforced polymer composite wraps around columns to improve their seismic resistance has now been approved by the California Department of Transportation[9.27, 9.28] and a number of different systems are undergoing prototype trials.

9.3.2 Masonry

Steel plates have been bonded to the undersides of masonry arch bridges. A technique has been developed for strengthening masonry arch bridges by bonding in a grid of stainless steel rods. Chases are cut into the soffit of the arch, both longitudinally and transversely, the rods are installed and fixed in place with a high performance adhesive mortar. Trials were carried out on a model bridge at the Transport Research Laboratory, which showed a significant increase in strength due to the repair technique[9.29]. The first actual application of the technique was on a canal bridge in Rochdale, which raised the load limit from 7.5t to the full 40t[9.30].

It has been suggested that fibre-reinforced polymer composite material could be bonded to masonry parapet walls to improve their impact resistance.

9.3.3 Steel

The bottom flanges of a steel bridge beam in Delaware, USA, which were locally damaged by vehicle impact, were strengthened by bonding on carbon fibre composite strips[9.31]. The material was bonded to the upper surface of the damaged flanges to decrease the stress in the steel to the point at which fatigue cracks would not propagate.

9.3.4 Cast iron

Steel plates have been bonded to cast iron bridge beams to strengthen them. Conventional repair techniques which involve bolting would not have been appropriate as they would have weakened the structure. In 1991 the 90-year old Bures Bridge over the River Stour in Suffolk was strengthened by bonding steel plates to each of the five main cast iron arches, which were severely damaged[9.32]. Large-scale trials were carried out to prove the technique prior to work starting on the actual bridge.

Similarly, steel plates were used to strengthen the Mythe Bridge at Tewkesbury. Originally built in 1826, the structure was seriously weakened and had a very restricted load capacity. Steel plates were used to strengthen the lateral cross-beams and also the struts spanning between the supporting arch and the deck[9.33].

Three historic cast iron footbridges in Birmingham were restored and upgraded using steel plates bonded to the soffits of the main beams to increase the loadcarrying capacity[9.34]. Plates were also bonded to the sides of the beams at various locations to improve the lateral stability and to the top surface of the deck plate on one of the bridges.

A cast iron beam over the London Underground line at Sloane Square, which had cracked due to thermal fatigue loading, was repaired with carbon fibre composite strips[9.35].

9.3.5 Timber

An historic wooden bridge near Sins, Switzerland was strengthened by means of carbon fibre-reinforced polymer composite strips which were bonded to the cross-beams[9.5].

9.4 Other structures

In Japan, deteriorated concrete chimneys have been strengthened by means of carbon or aramid fibre tapes bonded to the surface, generally to increase the seismic resistance but also to increase the resistance to wind and thermal loading[9.10, 9.36].

Carbon fibre sheets have been used in a number of cases to repair cracks in concrete tunnel linings and also to increase the strength. Fukuyama *et al*[9.36] reported that there were approximately 25 such applications in Japan in 1996.

A concrete retaining wall at the portal of a tunnel was badly cracked during construction. It was subsequently repaired and strengthened using steel plates bonded to the exposed surface.

9.5 References

9.1 Mays, G., Calder, A.: 'External plates extend reinforcement's reach'. *Concrete*, **22** (11), November 1988, p25–28

9.2 Mays, G. C., Hutchinson, A. R.: *Adhesives in civil engineering*. Cambridge: Cambridge University Press, 1992

9.3 Godfrey, J., Sharkey, P.: 'Plate bonding to strengthen hall floor'. *Construction Repair*, **10** (4), July/August 1996, p39–40.

9.4 Steiner, W.: 'Strengthening of structures with CFRP strips'. In: El-Badry, M.: *Advanced composite materials in bridges and structures*. Montreal: Canadian Society for Civil Engineering, 1996, p407–417

9.5 Meier, U., Deuring, M., Meier, H., Schwegler, G: 'Strengthening of structures with advanced composites'. In: Clarke, J. L.: *Alternative materials for the reinforcement and prestressing of concrete*. Glasgow: Blackie Academic and Professional, 1993, p151–171

9.6 Parker, D.: 'Sticking to the task'. *New Civil Engineer*, 11 July 1996, p22.

9.7 Nanni, A.: 'CFRP strengthening'. *Concrete International*, **19** (6), June 1997, p19–23

9.8 Labossière, P.: 'Column repairs'. *FRP International*, **IV**, (2), Spring 1996, p3

9.9 Anon: 'Rehabilitation following earthquake disaster'. *FRP International*, **III**, (4), Autumn 1995, p4–5

9.10 Okamoto, T.: 'Aramid tape for seismic strengthening'. *FRP International*, **IV**, (3), Summer 1996, p3

9.11 Kliger, H.: 'Repair of parking structures'. *FRP International*, **IV**, (4), Autumn 1996, p3–4

9.12 Ehsani, M. R.: 'Strengthening of earthquake–damaged masonry structures with composite materials'. In. Taerwe, L.: *Non-metallic (FRP) reinforcement for concrete structures*. London: Spon, 1995, p680–687

9.13 Kraker, J. M.: 'Fix salvages unglued panels, saving tower owner $5.5 million'. *Engineering News Record*, 10 March 1997, p9

9.14 TRADA: 'Resin-bonded repair systems for structural timber'. *Wood information*, Section 4, Sheet 22. High Wycombe: Timber Research and Development Association, 1995

9.15 Mettem, C. J., Davis, G.: 'Resin bonded repair systems for structural timber'. *Construction Repair*, **10** (2), March/April 1996, p23-28 (Part 1); and **10** (3), May/June 1996, p43-47 (Part 2)

9.16 Mettem, C. J., Page, A. V., Robinson, G. C.: *Repair of structural timbers*. Part 1: *Tests on experimental beam repairs*. Part 2: *Fire resistant repairs*, Research Report PIF 63/1, 1993

9.17 Midwinter, K. R.: 'Plate bonding carbon fibre and steel plates'. *Construction Repair*, **11** (1), January/February 1997, p5-8

9.18 Hutchinson, A. R.: 'Strengthening of the Quinton bridges with externally bonded steel plate reinforcement'. In: Harding, J. E., Parke, G. A. R., Ryall, M. J.: *Bridge management 3*. London: Spon, 1996, p743–750

9.19 Ramsey, W.: 'Steel plate bonding for concrete bridge strengthening'. *Construction Repair*, **7** (1), January/February 1993, p14-16

9.20 Anon: 'Reinforcement of structures with carbon fibres'. *Freyssinet Magazine*, December 1996/ January 1997

9.21 Leeming, M. B.: 'A ROBUST solution to strengthening RC and PC beams', *Construction Repair*, **10** (1), January/February 1996, p15–17

9.22 Peshkam, V., Leeming M. B.: 'The use of advanced composite materials in strengthening and maintaining bridges'. In: Harding, J. E., Parke, G. A. R., Ryall, M. J.: *Bridge management 3*. London: Spon, 1996, p732–742

9.23 Hollaway, L., Leeming, M. B. (Eds.): *Structural strengthening with bonded fibre-reinforced polymer composites*. Woodhead Publishing, 1998

9.24 Anon: 'Passing the plate'. *New Civil Engineer*, 13 February 1997, p9

9.25 Alexander, A. G. S., Cheng, R. J. J.: 'Field application and studies of using CFRP sheets to strengthen concrete bridge girders'. In: El-Badry, M.: *Advanced composite materials in bridges and structures*. Montreal: Canadian Society for Civil Engineering, 1996, p465–472

9.26 Neale, K.: 'Rehabilitation of columns of a highway overpass using fiber composite materials'. *FRP International*, **IV**, Issue 4, Autumn 1996, p4

9.27 Anon: 'Caltrans now permits composite wraps'. *Engineering News Record*, 25 December 1995

9.28 Tarricone, P.: 'Composite sketch'. *Civil Engineering* (ASCE), 65 (5), May 1995, p52–55

9.29 Parker, D.: 'Rod repair'. *New Civil Engineer*, 14 March 1996, p28-29

9.30 Minnock, K.: 'Masonry arch repair and strengthening'. *Construction Repair*, **11** (4), July/August 1997, p45–46

9.31 Anon: 'Composite rehab comes of age'. *Emerging Technology*, **4** (2), March/April 1997, p2 & 8–9

9.32 Robbins, J.; 'Premium bond'. *New Civil Engineer*, 17 October 1991, p18-19

9.33 Bolton, A.: 'Strength on a plate'. *New Civil Engineer*, 19 November 1992, p16–17

9.34 Haynes, M.: 'Repair and restoration of three cast iron footbridges in Birmingham'. *Construction Repair*, **9** (1), January/February 1995, p16–17

9.35 McLellan, A.: 'Loading crisis on iron tunnel'. *New Civil Engineer*, 28 November 1996, p8

9.36 Fukuyama, H. *et al*: 'JCI state-of-the-art on retrofitting by CFRM, Part 1, Materials, construction and application'. *Proceedings of the Third Symposium on Non-metallic (FRP) Reinforcement for Concrete*, Japan Concrete Institute, October 1997, **1**, p605–612

10 Future developments

10.1 Introduction

This Chapter reviews developments that are at the laboratory or prototype stage at present but have shown themselves to be sufficiently promising that they may be used in practice in the not too distant future.

10.2 New construction

10.2.1 Steel structures

Some trials have been carried out on a combined bolted-bonded beam-column connection[10.1]. Similarly work has been carried out on lapped plate connections in direct tension and on beam-beam end connections in bending, all using a combination of bonding and bolting[10.2]. In both series of tests the aim was the development of a more rigid connection. They concluded that initially the load was transferred adequately by bond but, as discussed in Chapter 5, once the adhesive failed all the load was carried by the bolts.

Development trials are being carried out on sandwich panels, consisting of two steel plates separated by a corrugated plate. Adhesive bonding has the advantage that the exterior surfaces of the steel plates are not damaged by the connectors, as would be the case when using spot welding, for example[10.3].

10.2.2 Steel-concrete composite structures

Limited trials have been carried out on composite beams, formed from a precast concrete slab adhesively bonded to the top flange of a steel beam[10.4]. The beams were loaded in sagging bending, under fatigue loading, and also in hogging. The results were compared with those from beams with standard shear connectors. The authors concluded that adhesive bonding was a suitable technique for forming steel-concrete composite beams, but they suggested that durability aspects needed to be considered further. Though not stated, the behaviour of the composite structure in fire would obviously be an important consideration.

10.2.3 Timber structures

Work in Switzerland is looking at an approach for increasing the capacity of bolted connections in timber trusses by bonding layers of fibre-reinforced polymer composite to the surface, which prevent premature failure caused by local splitting[10.5]. Fibre-reinforced polymer composites are also being used to increase the strength and stiffness of glulam beams[10.6].

10.2.4 Aluminium structures

Aluminium box sections have been fabricated from channel sections and plate using adhesive bonding. Extruded aluminium sections have been strengthened by bonding on steel or carbon fibre composite plates to improve the strength and stiffness in critical locations. While both these developments were primarily for the transport industry, the approach obviously has potential applications in lightweight structures.

10.2.5 Glass structures

Development work is being carried out on methods of forming structural shapes, such as T- and box beams, out of glass sheet. This arises from architectural requirements for structures which are totally transparent[10.7]. Trials have been carried out on T-beams made from toughened glass, bonded with a modified epoxy adhesive which appeared to achieve the required level of composite action between the members. The authors identify a number of practical problems with this form of construction, including the lack of knowledge of the appropriate properties of the glass, such as its shear strength. In addition they noted that the adhesive and any primer used must not affect the surface of the glass and hence reduce its strength.

10.3 Repair techniques and applications

10.3.1 Concrete structures

A number of workers are developing methods of pretensioning carbon fibre-reinforced polymer sheets or strips before they are bonded to concrete members, leading to greater improvements in the performance than the present use of unstressed material[10.8].

10.3.2 Timber structures

In the USA preliminary trials have been carried out to strengthen wooden railway ties (sleepers) using a system of glass fibre-reinforced polymer bands wrapped round the member[10.9]. This has shown that the bending strength can be increased. Similarly, trials have been carried out in Canada on the possibility of strengthening concrete railway ties using bonded polyester fabric[10.10].

10.3.3 Steel structures

Some trials have been carried out on the bonding of additional stiffeners to the webs of steel beams[10.11].

10.4 Testing

There is a need for the development of simple, non-destructive test apparatus which can be used to check the condition of adhesive joints. The equipment would be used not only as a quality control measure for the construction process but also as a means of monitoring the in-service behaviour.

10.5 Education and training needs

As has been indicated a number of times in this Guide, workmanship has a major influence on the behaviour of adhesive joints. This will be particularly important for structural joints carrying significant load. Currently, many applications of structural adhesives are carried out by specialist staff. However, as they become more widely used by the Construction Industry, there will be a need for the education and training of staff at all levels, both in the design office and on site.

Such a scheme is being developed by the European Federation for Welding, Joining and Cutting, which identifies three grades of staff, with the appropriate qualifications and/or experience, as outlined below:

- *European Adhesives Engineer*: Graduate in engineering from an accredited university
- *European Adhesives Specialist:* Appropriate training courses, e.g. City and Guilds or Construction Industry Training Board
- *European Adhesive Bonder:* Based on experience of using a particular adhesive

Courses will be recognised by Approved National Bodies and will cover all European Community countries, together with some associated states. The courses will not be aimed at any specific industry but are intended to give participants a thorough grounding in adhesives technology. The scheme was launched in 1998 and, initially, there will be training centres in the UK (at TWI), Germany and France.

In a parallel initiative, FORMACOL, is a series of distance learning packages on adhesive technology being developed under the European COMETT programme. The material has been designed specifically to address the needs of senior staff working in small companies who have limited time available to attend conventional training courses but could be much more widely used. It will be available in 6 European languages[10.12].

10.6 References

10.1 Eaton, K. J.: 'The use of adhesive bonding in steel framed buildings and structures'. Precis of work carried out by British Steel Swinden on behalf of Eurofer Steel Promotion Committee, 1993 (Unpublished)

10.2 Albrecht, P., Sahli, A. H.: 'Static strength of bolted and adhesively bonded joints for steel structures'. In: Johnson, W.S. ed. *Adhesively bonded joints: testing, analysis and design*, ASTM STP 981. Philadelphia: American Society for Testing and Materials, 1988, p229–251

10.3 Davies, C. M., Stevens, A. J.: 'Steel skin sandwich construction'. 3rd International Conference on Sandwich Construction, Southampton, 1995

10.4 Prakash Rao, D. S., Sharma, S. P.: 'Steel-concrete composite girder with epoxy bonding'. *Proceedings of the Institution of Civil Engineers*, Part 2, **89**, June 1990, p251–260

10.5 Chen, C-J.: 'An optimization of timber joint by fiberglass reinforcements'. In: El-Badry, M.: *Advanced composite materials in bridges and structures.* Montreal: Canadian Society for Civil Engineering, 1996, p811–818

10.6 Dorey, A. B., Cheng, J. J. R.: 'The behaviour of GFRP glued laminated timber beams'. In: El-Badry, M.: *Advanced composite materials in bridges and structures.* Montreal: Canadian Society for Civil Engineering, 1996, p787–794

10.7 Pye, A. J., Ledbetter, S. R.: 'The engineering of composite glass beams'. In: *Proceedings of International Conference on Building Envelope Systems & Technology.* Bath, April, 1997

10.8 Wight, R. G., Green, M. F., Erki, M-A.: 'Post-strengthening prestressed concrete beams with prestressed FRP sheets'. In: El-Badry, M.: *Advanced composite materials in bridges and structures.* Montreal: Canadian Society for Civil Engineering, 1996, p449–456

10.9 GangaRao, H. V. S., Sonti, S. S.: 'Service life improvement of wood crossties using composite fabrics'. In: El-Badry, M.: *Advanced composite materials in bridges and structures.* Montreal: Canadian Society for Civil Engineering, 1996, p827–834

10.10 El-Hacha, R., El-Badry, M., Aballa, H.: 'Strengthening of prestressed concrete railway ties using composite straps'. In: El-Badry, M.: *Advanced composite materials in bridges and structures.* Montreal: Canadian Society for Civil Engineering, 1996, p489–496

10.11 Martin, D. M.: 'Tests on transverse intermediate stiffeners'. *The Structural Engineer*, **70** (15), 4 August 1992, p261–267

10.12 FORMACOL – Adhesive technology distance learning packages (CD ROM and printed material). Abington: TWI, 1998

Appendix A Organisations providing specialist advice on adhesive technology

The following organisations are able to provide specialist advice on the use of adhesives for structural applications, though a charge may be made for their services.

General adhesives advice
Centre for Adhesive Technology
TWI
Abington Hall
Abington
Cambridge CB1 6AL
Tel: 01223 891 162
Fax: 01223 892 588

Joining Technology Research Centre
Oxford Brookes University
Gypsy Lane Campus
Headington
Oxford OX3 0BP
Tel: 01865 483 504
Fax: 01865 484 179

Timber products
TRADA Technology Ltd
Stocking Lane
Hughenden Valley
High Wycombe
Buckinghamshire HP14 4ND
Tel: 01494 563 091
Fax: 01494 565 487

Appendix B British and international standards

This Appendix lists some of the British and International Standards that deal with adhesives and adhesive joints. It should be noted that British Standards are in the process of being superseded by European Standards; the reader should always ensure that the most recent relevant Standard is being used.

British Standards

BA 30/94: *Strengthening of concrete highway bridges using externally bonded plates.* The Highways Agency, London, 1994

BS EN 301: 1992: *Adhesives for loadbearing timber structures – Polycondensation adhesives of the phenolic and aminoplastic types – Classification and performance requirements.* London: BSI, 1992

BS EN 302: 1992: Parts 1–4: *Adhesives for load-bearing timber structures – Polycondensation adhesives of the phenolic and aminoplastic types – Test methods.* London: BSI, 1992

BS EN 385; Finger jointed structural timber – performance requirements and minimum product requirements, London, BSI, 1995

BS 1204: Part 1: *1979: Synthetic resin adhesives (phenolic and aminoplastic) for wood; specification for gap filling adhesives.* London, BSI, 1979

BS prEN 1840: 'Structural adhesives – guidelines for the surface preparation of plastics'. London, BSI, 1995

BS 1881: Part 207: 1992: *Recommendations for the assessment of concrete strength by near-to-surface tests.* London: BSI, 1992

BS 5268: *Structural use of timber.* Part 2: *Code of practice for permissible stress design, materials and workmanship,* London, BSI, 1996

BS 5350: *Adhesives: Adhesively bonded joints: Mechanical tests; Group C* Part C5, *Determination of bond strength in longitudinal shear; Group C* Part C15, *Determination of bond strength in compressive shear.* London, BSI, 1991

BS 7079: *Preparation of steel substrates before application of paint and related products.* London, BSI

BS EN ISO 10365: *Adhesives – designation of main failure patterns.* London, BSI, 1995

BS prEN 12768: 'Structural adhesives – guidelines for surface preparation of metals'. London, BSI, 1997

European Standards

EN 301: *Adhesives for loadbearing timber structures – polycondensation adhesives of the phenolic and aminoplastic types – classification and performance requirements.* London, BSI, 1992.

prEN 387: *Glued laminated timber – production requirements for large finger joints; performance requirements and minimum production requirements.* London: BSI, 1991.

EN 923: *Adhesives – terms and definitions.* London: BSI, 1997 (Draft).

prEN 1504: *Products and systems for the protection and repair of concrete structure;* Part 4, *Structural bonding.* London: BSI.

DD ENV 1995–1–1: Eurocode 5 *Design of timber structures. General rules and rules for buildings.* London: BSI, 1994.

prENV 1995–1–1: *Design of timber structures.* Annex A: *Glued in steel rods.* London: BSI, 1994 & 1998.

American Standards

ACI 503R–93: *Use of epoxy compounds with concrete.* ACI Manual of Concrete Practice, Detroit, American Concrete Institute.

ACI 503.1–92: *Standard specification for bonding hardened concrete, steel, wood, brick and other materials to hardened concrete with a multi-component epoxy adhesive.* ACI Manual of Concrete Practice, Detroit, American Concrete Institute.

ACI 503.5R–92: *Guide for the selection of polymer adhesives with concrete.* Detroit, American Concrete Institute.

ASTM C882–91: *Test method for bond strength of epoxy-resin systems used with concrete.* West Conshohocken, American Society for Testing and Materials.

ASTM D907–969: *Standard terminology of adhesives.* West Conshohocken, American Society for Testing and Materials.

ASTM D2093–93: *Standard practice for preparation of surfaces of plastics prior to adhesive bonding,* West Conshohocken, American Society for Testing and Materials.

ASTM D2651–90 (1995): *Standard guide for preparation of metal surfaces for adhesive bonding.* West Conshohocken, American Society for Testing and Materials.

Appendix C
Health and Safety regulations

Some of the Health and Safety regulations which need to be taken into consideration when using adhesives in construction are listed below. The reader should check that the most appropriate current regulations are used.

General regulations

The Health and Safety at Work Regulations 1992
The Construction (Design and Management) Regulations 1994 (CDM)
The Construction (Health Safety and Welfare) Regulations 1996

Other regulations

Work in Confined Spaces Regulation 1997
Workplace (Health, Safety and Welfare) Regulations 1992
Personal Protection Equipment (PPE) at Work 1992
Provision and Use of Work Equipment Regulations (PUWER) 1992
Manual Handling Operations Regulations 1992
Reporting of Injuries, Diseases and Dangerous Occurrences Regulations (RIDDOR) 1995
Noise at Work Regulations 1989
Electricity at Work Regulations 1989
Control of Substances Hazardous to Health Regulations (COSHH) 1994
Construction (Head Protection) Regulations 1989
Health and Safety (First Aid) Regulations 1981

Appendix D
Acknowledgment of illustrations

The Institution gratefully acknowledges the assistance of the following organisations for granting permission for the use of the illustrations in this Guide.

Ove Arup & Partners
Figs 1 and 34.

3M
Figs 2, 24, 26, 37, and 38.

Queen's University, Belfast
Fig 7.

Thomas Telford Ltd
Fig 8 (taken from Mays, G. C.: 'The use of bonded external reinforcement in bridge strengthening: structural requirements of the adhesive'. In: Harding, J. E., Parke, G. A. R., Ryall, M. J. (eds): *Bridge management 2: Inspection, maintenance, assessment and repair.* Thomas Telford, London, 1993.

Business Books Ltd
Fig 16 (taken from Semerdjiev, S: *Metal to metal adhesive bonding*, 1970 1st ed. Fig 5.15, p71).

Kluwer Academic Publishers
Fig 17 (taken from Adams, R. D., Comyn, J., Wake, K. C.: *Structural adhesive joints in engineering*, 2nd edn. Fig 1.4, p8, London: 1997 (*after* Argyris, J. H. in *Research*, 1962, **15**, p183)).

G. C. Mays & J. D. Turnball
Figs 19 and 20.

Maunsell Structural Plastics Ltd
Figs 21 and 41.

Sika Ltd
Figs 23, 25, 27, 28, 42, 43, 44, 45, and 46.

Oxford Brookes University
Figs 29, 30, 31, 32 and 33.

Technical Timber Services Ltd
Fig 35.

CETEC Consultancy Ltd
Fig 36.

Reinforced Concrete Council
Fig 39.

TRADA Techonolgy
Fig 40 (courtesy of Chris Mettem)