PART ONE

Adhesives and adhesion

CHAPTER ONE

Introduction

Adhesives can offer substantial economic advantages over more conventional methods of joining. Whilst the building and construction industries represent some of the largest users of adhesive materials, few applications currently involve adhesive joints which are required to sustain large externally-applied forces. However, recent advances in the science and technology of adhesion and adhesives suggest that structural adhesives have enormous potential in future construction applications, particularly where the combination of thick bondlines, ambient temperature curing and the need to unite dissimilar materials with a relatively high strength joint are important. Indeed adhesive bonding, either alone or in combination with other methods of fastening, represents one of the key enabling technologies for the exploitation of new materials and for the development of novel design concepts and structural configurations.

1.1 Definitions and bonding

An adhesive may be defined as a material which, when applied to surfaces, can join them together and resist their separation. Thus adhesive is the general term used for substances capable of holding materials together by surface attachment and includes cement, glue, paste, etc. There is no universally accepted definition of a structural adhesive, but in the following chapters the term will be used to describe monomer compositions which polymerise to give fairly stiff and strong adhesives uniting relatively rigid adherends to form a load-bearing joint.

The term adhesion refers to the attraction between substances whereby when they are brought into contact work must be done in order to separate them. Adhesion is an important phenomenon in science as well as in engineering, but it is used in a different sense. The engineer uses experimentally determined values, which describe joint behaviour under specified conditions, in order to classify the bond or adhesion between two phases. To the physical chemist adhesion is associated with intermolecular forces acting across an interface, and involves a consideration of surface energies and interfacial tensions. The modern science of adhesion is concerned at a fundamental level with increasing our knowledge of the nature of the forces of attraction between substances, determining the magnitude of such forces and their relation to measured joint strengths. For many adhesive/substrate interfaces of practical importance, however, there are still unresolved debates concerning the detailed mechanisms of adhesion and the mechanics of joint rupture.

The materials being joined are often referred to as the adherends or substrates. The properties of the composite made when two adherends are united by adhesive are a function of the bonding, the materials involved and their interaction by stress patterns. It can be appreciated that adhesive bonding technology presents some very unfamiliar concepts to all engineers and, in particular, to civil engineers.

The science of adhesion is truly multi-disciplinary, demanding a consideration of concepts from such topics as surface chemistry, polymer chemistry, rheology, stress analysis and fracture mechanics. It is, nevertheless, important for the technologist to possess a qualitatively correct overall picture of the various factors influencing adhesion and controlling joint performance in order to make rational judgements concerning the selection and use of adhesives.

As with any new technology there are both advantages and disadvantages so that when considering the use of adhesives the merits of the main alternative means of joining (e.g. by welding, bolting, riveting and brazing) should be assessed. The main advantages and limitations of adhesive bonding are given in Table 1.1. The opportunities for increased design flexibility and innovation in design concepts is very real, provided that due consideration is given to balancing the needs of the various materials in a bonded assembly. However, the difficulties of ensuring a good standard of surface pretreatment, particularly to enhance long-term joint durability, are very real, as are the difficulties inherent in verifying the integrity of bonded joints.

Table 1.1. *Advantages and limitations of adhesive bonding*

Advantages	Limitations
Ability to join dissimilar materials	Surface pretreatments normally required, particularly with a view to maximum joint strength and durability
Ability to join thin sheet material efficiently	Fairly long curing times frequently involved
More uniform stress distribution in joints, which imparts enhanced fatigue resistance	Poor resistance to elevated temperature and fire
Weight savings over mechanical fastening	Structural joints require proper design
Smooth external surfaces are obtained	Brittleness of some products, especially at low temperatures
Corrosion between dissimilar metals may be prevented or reduced	Poor creep resistance of flexible products
Glueline acts as a sealing membrane	Poor creep resistance of all products at elevated temperatures
No need for naked flames or high energy input during joint fabrication	Toxicity and flammability problems with some adhesives
Capital and/or labour costs are often reduced	Equipment and jigging costs may be high
	Long-term durability, especially under severe service conditions, is often uncertain

1.2 Structure of the book

Part 1 – Adhesives and adhesion

The first part of this book addresses the important factors involved in the formation of a successful adhesive joint, namely the:

(1) selection of a suitable adhesive
(2) adequate preparation of the adherend surface
(3) appropriate design of the joint
(4) controlled fabrication of the joint itself

(5) protection of the joint from unacceptably hostile conditions in service, including the provision of fire protection for primary structural bonding.

The development of methods for post-bonding quality assurance might also be added to these factors, since a barrier to the general introduction of structural adhesives into construction is the lack of a reliable method of assessing the quality of bonded joints.

The broad overview of materials and applications, both current and potential, which follows in this chapter leads into a classification and characterisation of adhesive materials in Chapter 2. The various types of (particularly engineering) adhesives are discussed briefly, and it is shown how physical and mechanical characteristics are linkable to chemical compositions. It is apparent that adhesives are in general complex and sophisticated blends of many components, and this background serves to familiarise the reader with an introduction to the chemistry and formulation of adhesives.

In Chapter 3, theoretical aspects of adhesion are reviewed with the object of discussing why adhesives stick, before addressing practical aspects of the surface pretreatment of a number of common construction materials. It is shown that merely establishing interfacial contact between adhesive and adherend is often not sufficient in itself to ensure satisfactory performance. Particular, and sometimes elaborate, pretreatment procedures are found to be necessary for maximising joint durability, and this subject is further elaborated in the following chapter.

Chapter 4 discusses the design and mechanical performance of adhesive joints with particular reference to load-bearing assemblies. The problem of joint design is approached from a consideration of the strains and stresses induced in joints as predicted from stress analysis techniques. Design and testing are natural partners, and in this chapter an extensive review of test procedures is made from which a valuable insight into the adhesive layer behaviour in larger-scale joints may be deduced. Finally the factors influencing joint behaviour and service-life are given.

Chapter 5 looks at the process of joint fabrication, discussing the procedures necessary to ensure a reliable outcome and the methods for testing and quality control of the bonding operation. Emphasis is again given to optimising conditions for maximising potential performance, and some consideration is given to methods of protecting the joint from unacceptably hostile conditions in service.

Part 2 – Applications

The second part of this book is devoted to current and potential applications of adhesive materials in construction. Chapter 6 deals with both the repair and the strengthening of concrete structures, covering applications ranging from non-structural patch repairs and resin overlays to externally bonded steel plate reinforcement. The theme of repair and strengthening is extended to applications involving steel, timber and masonry structures. A number of 'case histories' are reviewed and discussed with reference to the successes and failures, and the results of allied research work are presented. In Chapter 7 a number of applications of adhesives in new construction are described, and specific examples are given. The final chapter, Chapter 8, examines the potential for future developments in adhesive usage.

The link between the first and the second parts of the book is emphasised throughout in an attempt to connect theory with practice, highlighting some of the problems and identifying methods for overcoming them.

1.3 Historical development

Sticking things together is a common enough task, and materials exhibiting adhesive properties have been employed in a sophisticated manner since earliest times. Natural adhesives such as starch, animal glues and plant resins have been used for centuries, and are still used widely today for packaging and for joining wood. Rubber-based adhesives were introduced in the shoe and tyre industries towards the end of the nineteenth century, but the birth of modern structural adhesives is generally dated from the early twentieth century with the introduction of phenol-formaldehyde resins. Mainly as a result of the Second World War, many natural products were not available in the early 1940s and this spurred the further development of synthetic resins. The construction of wooden wartime aircraft was, nevertheless, facilitated by the availability of phenol-, resorcinol- and urea-formaldehyde adhesives, and since then reactive formaldehyde-based adhesives have continued to be used in the manufacture of timber-based building elements such as plywood, chipboard, and laminated timber beams.

Over the past four or five decades the natural adhesives have been improved, and there has been an intense development of synthetic adhesives to meet more technically demanding applications. These synthetic polymers and ancillary products, which include thermoplastic and thermosetting types, have been developed to possess a balance of properties that enables them to adhere readily to other materials, to have an adequate cohesive strength and appropriate mechanical characteristics when cured, to possess good durability, and to meet various application and manufacturing requirements.

Thermoplastic adhesives may be softened by heating and rehardened on cooling, and included in this group are polyvinyl acetates (PVACs). Since the 1950s they have been used extensively as general-purpose adhesives for bonding slightly porous materials, from floor screeds to timber; they are, however, sensitive to wet alkaline service conditions, effectively restricting them to indoor use. Similar adhesives suitable for external situations are based on other polymer dispersions such as styrene butadiene rubbers (SBRs), acrylic polymers, and copolymers of vinyl acetate with other monomers. Cyanocrylates, or 'superglues', also belong to this class of thermoplastic adhesives and are very useful for bonding small parts involving plastics, rubber, metal, glass, and even human tissue.

Thermosetting materials are so called because, when cured, the molecular chains are locked permanently together in a large three-dimensional structure; they may, therefore, be regarded as structural resins. Unlike thermoplastics they do not melt or flow when heated, but become more rubbery and lose strength with increasing temperature. Phenolic resins, and their modifications, belong to this group of adhesives and are numbered among the early structural adhesives used extensively within the aerospace industry for bonding metal parts. Epoxides and polyesters also belong to this group of thermosetting adhesives, and they find widespread use in civil engineering applications. Unsaturated polyesters are often used as binders in glass-reinforced plastics, or as mortars in conjunction with stone and cementitious materials. However, high shrinkage on curing, poor resistance to creep and low tolerance of damp conditions significantly restricts their application. Epoxides, on the other hand, are generally tolerant of many surface and environmental conditions, possess relatively high strength, and shrink very little on curing. There are available a range of epoxy materials which cure at ambient or elevated temperatures, whose mechanical and physical characteristics vary widely. Indeed the general term epoxy may include materials which vary from flexible semi-elastic coatings and sealants to epoxy resin based concretes. Epoxy adhesives are available as single- or two-component materials in liquid, paste or filmic form, which may additionally be 'toughened'.

The increasing use of adhesives in a diversity of demanding situations has given confidence in the successful application of synthetic polymers, and has provided the spur for further fundamental research and the development of improved products. In the future it is possible that acrylates and polyurethanes, and their toughened variants, may challenge the epoxides – particularly as they are perceived to be safer to use and less environmentally harmful. Structural silicone adhesives may also be introduced for certain applications where gap-filling and flexibility are required, but where high strength is relatively unimportant; they also possess the added advantage of very high thermal and environmental stability.

1.4 Engineering applications of adhesives

It is clearly impossible to identify and to document all of the applications of adhesives in engineering assembly and fabrication. Many uses are, anyway, either of a relatively trivial nature or else do not place great demands on the adhesive material. The following sections review some of the major applications of adhesives in several different engineering sectors, in order to put a number of the general design and process considerations discussed later in the book into perspective.

Aerospace

It has often been observed that the application of adhesives to metal fabrication, in common with many other technological innovations, was pioneered by the aircraft industry. It is ironic that this industry, in which safety and reliability command paramount attention, should lead the departure from traditional methods of joining. Today adhesives are used to bond critical parts in commercial and military aircraft and helicopters, spacecraft, rockets, missiles and the US Space Shuttle. The American Primary Adhesively Bonded Structure Technology (PABST) Programme, which ran from 1976–81, was an imaginative attempt to advance significantly the use of bonded structures in aircraft. The project involved the construction and testing of an entire adhesively-bonded fuselage section of a military aircraft.

The earliest structural adhesive application was made during the First World War for bonding the wooden frames of Mosquito aircraft; strength was adequate but, by today's standards, moisture resistance was poor. Structural adhesive bonding of metal parts began in the early 1940s with the introduction of Ciba Geigy's Redux 775, phenol formaldehyde-polyvinyl formvar (the trade name is a composite of *Re*search and *Dux*ford airfield), to bond metal honeycomb to metal skins. The de Haviland Comet jet airliner was one of the first civil aircraft to make significant use of structural bonding with Redux 775, followed by the Trident, Nimrod and VC10, and this adhesive is still in use today on the British Aerospace European Airbus; indeed, no other adhesive has such a good and well-proven track record. However, a cure temperature of 150 °C and pressures between 0.2 and 0.7 MNm^{-2} (25 and 100 psi) are required, and this spurred the development and use of alternative products. For example, epoxy-based filmic adhesives are commonly used which require lower curing temperatures and pressures, making the use of autoclaves and the cure cycle less expensive than with the phenolics.

The motivation in the aerospace industry to replace mechanical fasteners with adhesives stems from the desire to prolong aircraft life and to reduce costly maintenance. Rivet holes, for example, are points of weakness where fatigue cracks can form, and metal fasteners can corrode or loosen. Equally important is that aircraft are now designed to include a large amount of composite materials, and the fabrication of honeycomb sandwich panels frequently involves connecting dissimilar materials for the skin and core. The Fokker Friendship F27 airliner employed large amounts of adhesive in both load-bearing and secondary structures, the wing assemblies being tested up to 14.5 million cycles of reverse loading (Fig. 1.1).

The use of material combinations has continued in aircraft such as the Boeing 747, McDonnell Douglas DC10, Lockheed Tristar and Concorde, as designers recognised the high stiffness to weight ratio that can be achieved with these components. The sheet metal skin materials are predominantly aluminium alloys, although titanium and stainless steels are also used for special purposes. The honeycomb material is often aluminium foil but paper, laminated nylon paper and phenolic impregnated glass fibre are alternatives. As much as

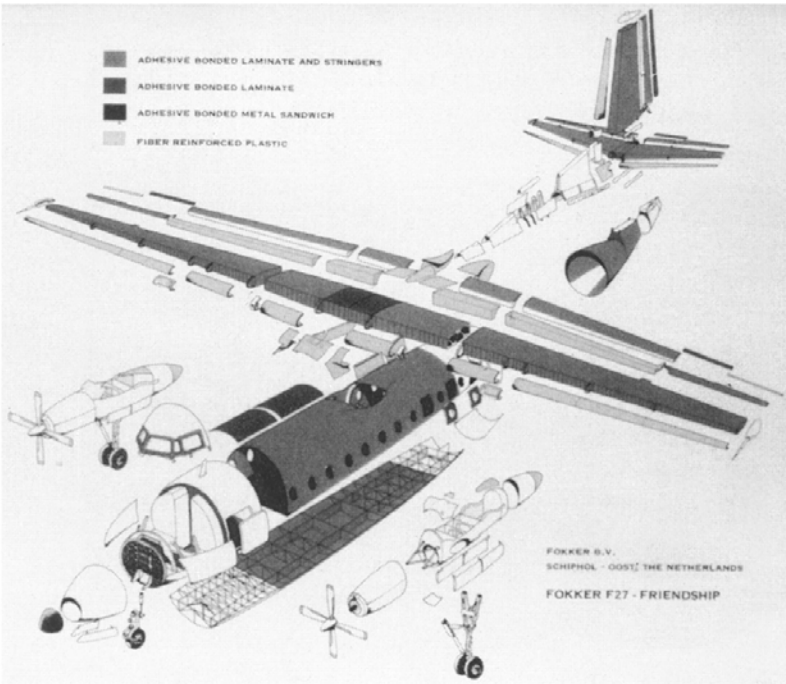

Fig. 1.1. Adhesively bonded components in the Fokker Friendship F27 airliner.

50% of the airframe of modern military aircraft may be carbon fibre reinforced plastic (cfrp) composite, with adhesives being used for primary structural bonding. It is worth noting also that helicopter rotor blades are complex structures which are highly stressed and of limited fatigue life, and are wholly dependent upon adhesive to join the extruded aluminium spar, nomex core, grp skin and aluminium trailing edge.

Honeycomb structures are susceptible to physical damage because of their location and their weakness to loads, applied normal to the skin forces. Airlines and Air Forces are, therefore, developing repair techniques which they can carry out themselves in preference to purchasing expensive replacement components. For *in situ* repairs alternative techniques in terms of surface preparation, adhesive type and curing regime have to be used to those employed during initial manufacture. Surface preparation is vitally important bearing in mind that a typical airliner operating temperature range is from −80 °C to +80 °C, and for many aircraft salt spray conditions may