6

Environmental durability

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6.1 Introduction

It is envisaged that many applications of fibre reinforced polymer (FRP) strengthening would be outdoors and hence the durability of the concrete/FRP system under aggressive environments must be considered. The environmental resistance of any bonded assembly depends on the durability of the individual component materials, as well as on the bond between them. In the use of FRP materials for external strengthening of concrete, the individual components are the concrete, the fibre reinforced polymer composite and the adhesive, which is usually an epoxy. In general, properly designed, compacted and cured concrete can be expected to show good long term durability and should remain maintenance free for many years under normal service conditions. The durability of concrete, either in a prestressed or reinforced form is possibly one of the most well studied subjects in civil engineering because of its importance to everyday life and, consequently, it will not be discussed in this book. It should nevertheless be stated that the cover concrete is likely to represent the weakest component in the strengthened zone, so that the integrity of the strengthening system is somewhat dependent upon the properties of the concrete in shear and in tension. In structural applications, the integrity of the adhesive bond and the external FRP strengthening medium under adverse environmental conditions are the issues of prime importance and these will be discussed in the following sections.

Progress in the field of plate bonding relies largely on demonstrating the long term durability of the strengthening system under varying environmental conditions. As a bridge strengthening technique, the minimum required life is 30 years. The environmental durability problems encountered when steel plates are utilised as the strengthening medium are more intractable than those which may arise when composite materials are used. This is because of the difficulties of ensuring an adequate bond between the adhesive and the steel, together with the possibility of electrochemical corrosion of the bonded surface.

One of the most important requirements of an adhesive joint is the ability to retain a significant proportion of its load-bearing capacity for long periods under the wide variety of environmental conditions which are likely to be encountered during its service life. The long term integrity of bonded joints implies both chemical and mechanical durability under varying temperature, moisture and other environmental factors which, for external purposes, may include spray from de-icing salts or from the sea. Adhesive bonded joints with equivalent bond strength values in short term static tests may differ markedly with respect to durability.

The measured residual joint strength after environmental exposure is a function of change in the cohesive properties of the resin, the properties of the adherends and in the adhesion between the adhesive and adherend. Therefore, joint durability demands a three-fold consideration of the structural integrity of the cured adhesive, the adherends and the environmental stability of the interface. Joint design and material data should allow selection of an adhesive type and FRP material which will themselves be sufficiently durable to withstand the service environment. The more complex problem and the far more difficult to design against, is that of the environment attacking the interfacial regions of a joint.

6.2 Environmental and service conditions

The durability of joints and particularly structural adhesive joints is generally more important than their initial strength. Bonded joints used in a civil engineering environment may be subjected to a variety of service conditions. The normal service conditions to be considered are:

- temperature
- moisture (humidity, liquid water, salt spray)
- chemical attack (oil, fuel, chemical spills).

An abnormal hazard condition which may also need to be considered is that of fire.

These service conditions should be considered in conjunction with the loading conditions which, for bridge strengthening, relate primarily to peak short term static loading. Sustained loading (leading to creep), fatigue and impact may also need to be considered.

It has been established that water, in liquid or vapour form, represents one of the most harmful environments for bonded joints (Kinloch, 1983). The problem is that water is found universally and the polar groups which confer adhesive properties make the adhesive inherently hydrophilic. High energy substrate surfaces (Section 3.4) are also generally hydrophilic.

Concrete itself is susceptible to the effects of moisture in a fairly predictable way (Section 6.6). Of greater significance at this stage is that the properties of the matrix resin in FRP materials, together with the properties of adhesives, are susceptible to the effects of heat and moisture. The result of moisture absorption, which is reversible, is to lower the glass transition temperature (T_g) of these materials, leading to a change in their mechanical properties. The effect of elevated temperature is to reduce the strength and modulus of polymers; the T_g of the adhesive is likely to be rather less than that of the matrix resin, so that the adhesive is the governing factor.

Adhesive bonded joints are generally affected by exposure to moisture and elevated temperature. In a well made joint where a sound bond has been achieved, the main effect will be on the adhesive layer. A small amount of moisture-induced plasticisation of the adhesive in highly stressed regions may actually be beneficial in reducing stress concentrations. However, a small reduction in joint strength should normally be anticipated, in relation to the effects of environmental conditions on the adhesive itself.

The resistance of connections to chemical attack depends upon the nature of the liquid and its effect on both the composite components and the adhesive, if present. Alkalis can cause severe matrix resin softening with a consequent effect on any form of connection. Isophthalic polyesters provide better resistance than orthophthalic polyesters in terms of alkalis and organic solvents and are to be preferred for the majority of glass fibre reinforced plastic (GFRP) components. FRP components made with vinyl ester resins are better still, but a little more expensive. Epoxy materials, both as the matrix resin and as adhesives, are regarded as very inert in acids and alkalis.

The resistance of joints to the effects of fire implies consideration of the entire FRP structure, and a useful commentary is contained in the EUROCOMP Design Code (Clarke, 1996). FRP materials and adhesives are very poor conductors of heat, which is an advantage over metals, but they can also possess a large coefficient of thermal expansion in directions that do not have a significant amount of continuous fibre reinforcement. The effect of dimensional changes of the components and joints directly affected by fire or heat should therefore be considered. Adhesives are weakened by the influence of elevated temperature and may char or burn if exposed directly to fire.

6.3 Factors affecting joint durability

It is inadvisable to discuss joint durability without first reviewing the general behaviour and characteristics of bonded joints. A bonded joint represents a layered system comprising different materials and interfaces, all of which respond in different ways to an externally applied load or change in environmental conditions. It follows that a complete understanding of the behaviour of a bonded joint under load is not a simple matter (Mays and Hutchinson, 1992).

A problem with bonded joints is that much of the load is transmitted through edge zones, and it is these which potentially come under environmental attack first. In fact, the load is progressively borne by the inner regions of the joint although, nevertheless, it is often the most highly stressed regions which are under the greatest amount of environmental attack. However, if the bonded area is sufficient to enable stress redistribution within the adhesive layer, any changes in adhesive or cohesive properties will not compromise the integrity of joints of a suitable geometrical configuration. The large areas involved in plate bonding imply that few problems may be anticipated, provided that a high degree of care has been exercised in the design, specification and fabrication of such joints.

The main factors which influence joint performance and durability are:

- adherend type and nature
- porosity/permeability of adherends
- pretreatment
- surface condition following pretreatment
- primer type (if applicable)
- moisture content of adherends at the time of bonding (concrete and FRP)
- adhesive type/cure cycle
- postcuring of joints (if applicable)
- joint configuration and exact geometrical details
- exposure conditions
- duration of exposure
- imposed stress.

It will be appreciated that changes in any of the above factors can give rise to variations in joint behaviour.

One of the most important factors in joint durability is the environmental stability of the adhesive–adherend interface. This is dictated by the type of adhesive, the nature of the adherends and their surfaces. Changes in the adhesive and the adherend can be allowed for; changes in adhesion are less easy to estimate. Thus, optimisation of surface conditions and pretreatments often represents the key to maximising joint durability. The surfaces of both concrete and FRP materials are relatively stable and, if properly prepared (see Section 3.4), durable bonds with epoxy adhesives are formed relatively easily. This is in contrast to the situation with steel plate bonding, for which an adequate standard of surface preparation for mild steel surfaces is quite hard to achieve in practice. Further, the surface of steel is fairly unstable, especially in the presence of water, such that bonds to the oxide layer are susceptible to degradation. The substitution of

FRP materials for steel for strengthening applications is motivated in a large part by the assurance of superior bond integrity.

The adhesive system selected is clearly very important (Section 3.3). Generally a two-part cold curing paste–epoxy material is used without a primer. There are, however, occasions when a primer may be required for concrete surfaces to ensure satisfactory adhesion. Conceptually, adhesives represent natural candidates for joining FRP materials because they are often similar in composition and nature to the composite matrix resin. The fundamental concepts involved in adhesive selection are that it should:

- adhere well to the surfaces involved
- exhibit low permeability to water
- possess appropriate physical and mechanical properties.

The quality of the FRP material itself should be high for several reasons, as discussed in Section 3.2. These include the need for reproducible and predictable properties (for design and prediction purposes), flatness (to ensure uniform bonding and bondline thicknesses) and excellent consolidation (to reduce permeability and mechanical weakness). A poorly made composite will give rise to durability problems sooner or later.

Joint design, as discussed in Chapters 4, 5, and 8, has an important bearing on joint durability. Among the important concepts are to allow for a large bond area and to avoid unacceptably large stress concentrations in the joint. The synergistic effects of high temperature, excess moisture and applied stress normal to the bondline are undoubtedly detrimental. Joint design should therefore seek to minimise the buildup of stress concentrations which give rise to indirect peel and cleavage loads at adherend/adhesive interfaces.

Finally the bonding operation, including protection of the working environment, is important (Section 3.5). Trained operatives working under skilled supervision should ensure that surface preparation, adhesive application, temporary clamping arrangements and adhesive curing details are handled adequately. Poor control of the bonding operation generally manifests itself subsequently in joint performance and durability problems.

6.4 Environmental durability of adhesive bonded joints

6.4.1 General observations

Experience with structural adhesive bonding has shown that the mechanical properties of bonded joints often deteriorate under warm and wet conditions (Bodnar, 1977; Kinloch, 1983). This is particularly so if the joints comprise either high energy substrates such as metals, glasses and ceramics or else permeable substrates such as concrete and timber (Venables, 1984; Mays and Hutchinson, 1992). Further, failure at the adhesive/substrate interface, rather than failure within the adhesive layer itself, is commonly found only after environmental exposure.

With joints involving polymeric adherends, there are separate considerations relating to whether the adherends are thermoplastic or thermosetting in nature. Bonds to thermoset matrix composite surfaces, such as GFRP and carbon fibre reinforced plastic (CFRP), are stable in the presence of moisture; the effect of moisture is primarily to cause some plasticisation of the cured matrix resin. This may or may not affect the mechanical properties of the material and therefore of a bonded joint, depending on the fibre lay-up and mode of loading (e.g. Section 6.6.2).

6.4.2 Diffusion and absorption of water

Water possesses special properties which can be related to its molecular structure and which govern the way its molecules interact with each other and with other substances. The polarity and ability of a water molecule to form hydrogen bonds makes it a universal solvent, allowing it to dissolve, soften or swell organic substances whose molecules contain sufficient polar groups, such as epoxide. Thus, polar adhesives are naturally hydrophilic whereas non-polar plastics, such as polyvinyl chloride (PVC) and polythene, are not. The solubility of water in epoxies is of the order of a few mass percent, and the coefficient of diffusion of water at 20 °C is around $10^{-13}\,\mathrm{m}^2\,\mathrm{s}^{-1}$ (Mays and Hutchinson, 1992). The permeability of a material is given by the product of diffusion and solubility (Comyn, 1983).

For moisture to affect an adhesive joint it must first enter the joint either by ‘wicking’ along the interface between the adhesive and adherend, by diffusion into the adhesive and adherends, or through cracks and crazes in the materials involved. Wicking may be significant if appropriate surface treatments have not been carried out so that initial adhesion is minimal. However diffusion will be a dominant mode of entry in concrete and polymer composite adherends, together with the presence of cracks in the concrete.

Diffusion, whilst controlled primarily by concentration differences, is influenced significantly by temperature; the higher the temperature, the faster the rate of diffusion. Heat-cured polymers generally possess fairly rigid molecules which reduce their level of molecular motion and hinder water diffusion. The implication is that a pultruded composite matrix material, with a $T_g > 100\,°\mathrm{C}$, should be less permeable than a cold-cured epoxy material with a T_g in the range 50–60 °C.

6.4.3 Processes involved in joint degradation

In considering the behaviour of a bonded joint, it is useful to separate the effects of moisture, temperature and stress on the:

- adhesive material
- adherend material
- adhesion between the adhesive and adherend materials.

For the case of using FRP materials to strengthen existing concrete structures it is necessary to consider the effects of these agents separately on the adhesive, the concrete, the polymer composite, the adhesive/concrete interface and the adhesive/polymer composite interface. In general, the main processes involved in the hydrolytic deterioration of bonded joints are (Comyn 1983, 1985):

- absorption of water by the adhesive
- absorption of water by the adherends
- absorption of water at the bonded interface(s) through displacement of adhesive
- corrosion or deterioration of the substrate surfaces(s).

For the case of FRP materials bonded to concrete it is only necessary to consider in detail the first two points; absorption of water at the bonded interfaces, and corrosion or deterioration of the substrate surfaces can be disregarded. If FRP is bonded to other substrates such as timber, cast iron or steel then the considerations are rather more complex (e.g. Mays and Hutchinson, 1992).

The general effects of moisture on polymeric materials are outlined in Section 6.2. These may be summarised by stating that moisture will cause some plasticisation of both the adhesive and the polymer composite matrix material, and that such effects are reversible. The magnitude of such effects is dependent upon the particular formulations of polymer involved and the conditions under which they have been cured.

In GFRP it is known that moisture can attack the surface of glass fibres leading to corrosion, and that adhesion between the fibres and matrix resin may be reduced (see Section 6.6.2). Clearly this will lead to a reduction in the mechanical properties of the material and therefore also of the bonded joints that are made with it. However generalisations are dangerous because of the influence of the fibre sizing, the orientation of fibres with respect to applied loads and the quality and fabrication parameters associated with its production. In aramid fibre composites (AFRP), moisture may be absorbed by the fibres themselves, leading to a loss of fibre properties and therefore composite material properties; in turn this may lead to changes in the behaviour of bonded joints made with AFRP. No such difficulties have been reported for CFRP to date.

6.5 Procedures for assessing environmental effects on materials and on bonded joints

6.5.1 General remarks

A number of standard test procedures exist for assessing the effects of environmental conditions on materials such as concrete, polymer composite materials and on adhesives (in bulk form). Whilst a similar number of standard test procedures exist for assessing the behaviour of adhesive bonded joints, very few of these can provide useful information on environmental effects. Hardly any procedures actually provide quantitative data for the reasons outlined in Section 6.5.3.

The selection of laboratory exposure conditions presents a significant dilemma. Accelerated testing is commonly achieved by increasing the temperature, proximity to moisture and the imposition of load. However, only moderate increases in temperature above likely operating maxima should be used in order to prevent degradation mechanisms taking place which would not occur in practice. For example, the mechanical properties of the adhesive material will be reduced above its T_g, water uptake will increase markedly above T_g and hydrolysis of some adhesive materials may occur. Freeze–thaw cycling is favoured for construction applications in particular, where thermal shock or freezing of clustered water molecules may give rise to joint failures either directly or indirectly. BS EN 29142 (1993) describes several single and multivariable atmospheric ageing regimes.

When considering the use of accelerated testing involving elevated temperatures, it is advisable to postcure joints constructed with cold cure adhesives. This is to prevent the exposure environment itself from postcuring the adhesive and altering its mechanical properties. Clearly it is necessary to maintain a known base line of joint performance and this can only be achieved by being able to eliminate the effects of temperature itself on behaviour. The joints described in Section 6.7.3 were postcured at 50 °C prior to exposure.

It is most useful to collect information on joints exposed to natural weathering conditions because some workers have found that natural exposure is worse than laboratory ageing. This may be related to the effects of cyclic environmental effects. Exposure in hot/wet climates gives rise to faster joint degradation than exposure in more temperate climates. Sea coast exposure is also generally more demanding than exposure to industrial environments.

6.5.2 Experimental considerations – adhesive and composite material behaviour

Bulk material characterisation represents a useful adjunct to durability trials on joints, enabling environmental effects on the adhesive and composite materials themselves to be separated from those on adhesion and on overall joint behaviour. It has already been stated that the influence of water (and heat) on the adhesive and on a composite matrix resin is generally reversible; water uptake is accommodated largely by swelling and its effect is to reduce T_g. The modulus and strength of adhesives and matrix resins are lowered by plasticisation although fracture toughness and ductility generally increase (Figs. 3.6 and 3.7).

Tests may be carried out using adhesive materials in bulk form which have been cast to shape. Typical geometrical configurations include tensile dumb-bells, blocks for compression, rods or strips for torsion pendulum tests and films for water sorption experiments. Quantitative information on shear stress–strain behaviour can also be obtained from elaborate joints which ensure 'pure' shear deformation in the bondline. Fracture mechanics specimens employing cantilever beam arrangements can be used to obtain values of tensile opening (mode 1) fracture energy, G_1, in order to map toughness as a function of environment (see Section 3.3.6).

Short term tests on fibre reinforced polymer composite materials are well documented in various Standards, and many of these can be extended into environmental exposure trials. For example, flat rectangular test pieces can be subjected to tensile and bending stresses in order to determine strength and modulus following periods of accelerated ageing. Small pieces can also be used for water sorption experiments.

6.5.3 Experimental considerations – bonded joints

In the majority of test joint configurations, the adhesive bondline stresses are far from uniform. Failure loads are therefore related to stress concentrations of the ends of a joint, so that if the bonded area is sufficient to enable stress redistribution within the adhesive layer due to changes in the adhesive material properties, apparent increases in joint 'strength' and 'toughness' may occur initially.

A number of competing mechanisms are taking place and the effects of these are more noticeable in smallish joints unless initial adhesion is very poor. Test joints using small bonded areas are preferred for durability testing in order to minimise experimental timescales. Thus the small joints which are generally used do provide fairly rapid information, but the quite dramatic changes in joint behaviour which sometimes occur should not necessarily cause undue alarm. Small joints can provide useful comparative information on, say, the behaviour of different bonding systems or the effectiveness of different surface treatments. However the size effects inherent in testing mean that no direct correlation with the behaviour of large real-scale joints can be made.

Appropriate comparative tests of adhesion and bond durability should subject the interface to tensile, peel or cleavage forces. Thus pull-off tests, peel tests, fracture energy tests and, ironically, lap-shear tests are routinely employed. The choice depends largely upon the nature of the adhesives and substrate materials involved.

Special consideration needs to be given to the modes of loading imposed on joints involving both concrete and polymer composite materials. Concrete represents a brittle substrate material of low tensile strength, such that direct loading of joints made with it tends to result in premature failure of the concrete. Thus joint configurations which put the concrete into compression are often recommended to avoid substrate failure. Such configurations include slant shear (Fig. 6.1) and compressive shear tests (Fig. 6.2), resulting in a measure of the resistance of a bondline to a combination of shear and compression. Three- and four-point bending tests are also employed (Fig. 6.2), resulting in a measure of average shear or shear and tension resistance. Notwithstanding the above, the partially cored pull-off test (Fig. 6.3a) is used routinely for testing the bond integrity of concrete repair materials. It has also been used in modified form to assess bonds between epoxy adhesives and concrete surfaces (Fig. 6.3b). Results using this procedure are outlined in Section 6.7.2.

Polymer composites are also relatively brittle materials. The distribution and orientation of the fibre reinforcement has an enormous influence on the

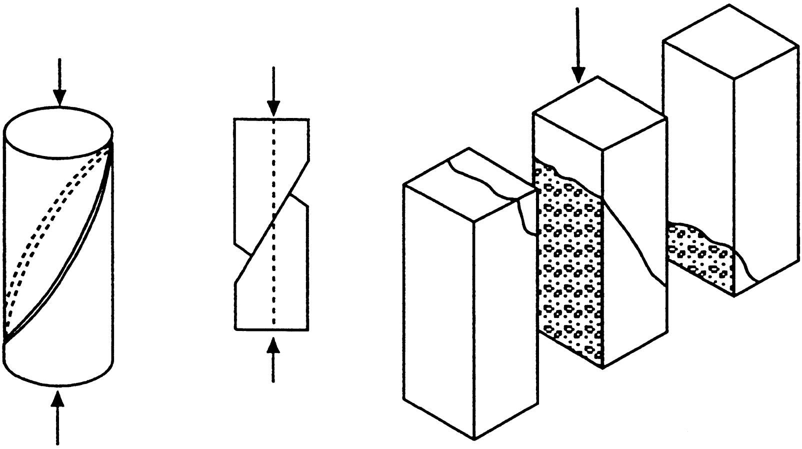

Figure 6.1 Different types of slant shear test configurations for joints involving concrete substrates.

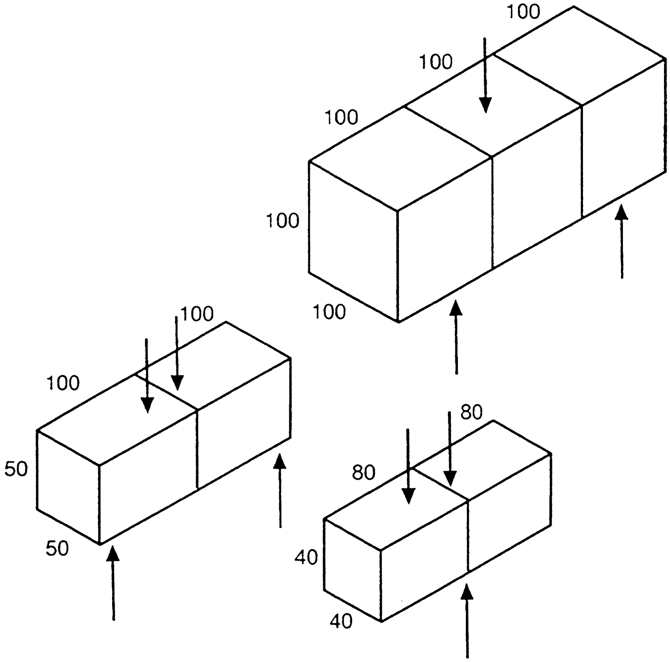

Figure 6.2 Different types of bending and compressive shear tests for joints involving concrete substrates.

load-carrying capacity of joints. In general, the through-thickness strength of composite materials is low because of the layered composition and, sometimes, resin-rich layers. Bonded joints are therefore prone to interlaminar failure. Laboratory experience has shown that single lap shear joints and wedge cleavage joints are satisfactory for use where a high proportion of fibres are parallel to the principal direction of loading. Single lap shear data is given in Section 6.7.3.

6.6 Effect of environment on the component materials used in the ROBUST system

To verify that the ROBUST material systems could maintain stability, separately and in combination under hot/wet environments, the consortium experimentally studied exposed samples of Sikadur 31PBA adhesive and the carbon fibre/vinylester polymer composite strengthening plates. Reinforced concrete (RC) beams 0.8 m long strengthened with these materials were also manufactured and their specifications and results are discussed in Section 6.7.4.

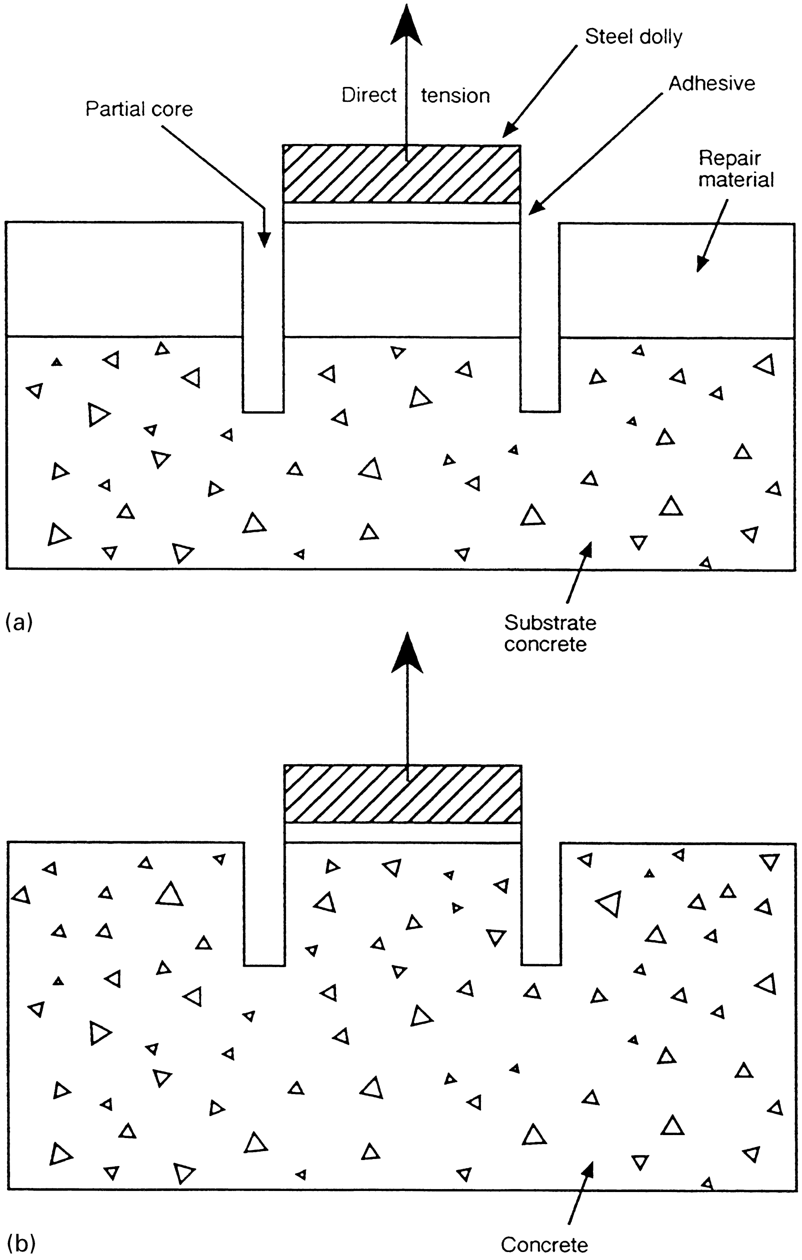

Figure 6.3 Partially cored pull-off tests.

The test and exposure conditions adopted for the Sikadur 31 PBA adhesive, composite materials and plated beams were as follows:

- Thermal cycling of Sikadur 31PBA adhesive, GFRP and CFRP composite plate coupons and unloaded CFRP plated RC beams, between temperatures of −20 °C and +50 °C, represented warming and cooling effects. One cycle took 24 h with the rising temperature taking 5 h and cooling temperature taking 17 h; at the extreme temperatures there was a dwell time of one hour. During exposure, the natural moisture in the air condensed on to the material coupons of adhesive, CFRP and GFRP. After each of the exposure periods of 0, 50 and 180 thermal cycles the specimens were loaded to failure to assess the influence of the freeze–thaw environment.
- Sikadur 31PBA adhesive, GFRP and CFRP composite plate coupons were exposed to a warm, moist atmosphere of 30 °C and 100% relative humidity. They were tested after 0, 50 and 180 days; in each case the material was tested 24 h after its removal from the humid atmosphere.

The results from these tests are described in Sections 6.6.1 and 6.6.2, and summarised in Tables 6.1 and 6.2.

6.6.1 Sikadur 31PBA adhesive

The general properties and characteristics of this two-part cold curing filled epoxy adhesive are discussed in Section 3.3, together with the effects of moisture on its properties. In general, the type of structural adhesive used can affect both the rate and degree of environmental attack on bonded joints (Minford, 1983). A bonded joint may be appreciably weakened if the adhesive is chemically attacked to any significant extent by the service environment. The detailed chemistry of the adhesive also appears to influence the stability of the interfacial regions due to the formation of more stable intrinsic interfacial forces. Furthermore, the physical impact which the service environment has on the adhesive is dependent on the composition of the adhesive.

The more highly filled the adhesive, the lower should be its long term water absorption (Tu and Kruger, 1996). The absorption of moisture tends to accelerate time-dependent processes by lowering the T_g, thereby reducing the performance of the adhesive at high temperatures. As such, moisture combined with heat has a particularly unfavourable influence on the adhesive. However, whether plasticisation of the adhesive layer by the ingress of the water actually affects the strength of the bonded joint is hard to predict since, for many joint configurations, a decrease in the adhesive modulus may decrease the stress concentrations in the joint and lead to an increase in joint strength. Similarly, the toughness of joints subjected to fracture often increases somewhat because of greater plastic deformation and enhanced crack-tip blunting properties within a plasticised matrix (Ripling *et al.*, 1971; Kinloch and Shaw, 1981; Kinloch, 1982). Cohesive strength may, however, eventually be reduced sufficiently to offset the increased toughness (Hutchinson, 1986).

The mode of failure of bonded joints when initially prepared is usually by cohesive fracture in the adhesive layer, or possibly in the substrate materials if these are particularly weak. However, a classic symptom of environmental attack is that after such exposure, the joints exhibit some degree of interfacial failure between the adhesive and the adherend (Brewis *et al.*, 1982). The extent of such failure increases with time of exposure to the hostile environment. Whether the failure path is truly at the interface, or whether it is within a boundary layer of the adherend or adhesive remains a matter of debate. Several authors (e.g. Brockmann, 1983; Kinloch, 1987) have emphasised that the structure of the cured adhesive adjacent to the adherend surface differs from that of the bulk, because of the influence of surface morphology and chemistry on the initial wetting and absorption of adhesive. The inference is that this weak boundary layer of adhesive may be less densely cross-linked and/or have a lower concentration of filler particles than that of the bulk material, and may therefore be more susceptible to hydrolytic destruction. The rate of interfacial transport of water could also be somewhat higher than that through the bulk material.

To enable some material characterisations of the adhesive used in the ROBUST system to be obtained, bulk coupons were exposed to the hot and wet environmental conditions described earlier.

Table 6.1 shows the adhesive characteristics after the three periods of the two types of exposure; the modulus is given as the initial tangent modulus

Table 6.1 Adhesive material characteristics after environmental exposure (Garden and Hollaway, 1997)

Exposure type and duration	Modulus of elasticity (GPa)	Tensile strength (MPa)	Ultimate strain (microstrain)
Thermal cycling			
Unexposed (control)	9.0 (± 21.1%)	26.3 (± 27.0%)	4300 (± 46.5%)
50 thermal cycles	11.3 (± 0.5%)	29.6 (± 10.8%)	3467 (± 18.3%)
100 thermal cycles	11.5 (± 1.1%)	31.4 (± 9.7%)	4302 (± 17.6%)
180 thermal cycles	11.8 (± 19.7%)	38.2 (±13.3%)	4333 (± 19.2%)
Humidity exposure			
Unexposed (control)	9.0 (± 21.1%)	26.3 (± 27.0%)	4300 (± 46.5%)
50 days	7.8 (± 1.2%)	13.4 (± 5.3%)	3663 (± 22.5%)
100 days	6.4 (± 10.2%)	16.2 (± 7.2%)	5284 (± 21.5%)
180 days	5.7 (± 19.7%)	15.7 (± 2.5%)	7980 (± 20.8%)

value at zero stress. In the thermal cycling environment the stiffness of the material increased in value, indicating a continuing polymerisation process. However, the negative influence of the humidity atmosphere on the adhesive indicates an increase in ductility associated with the plasticisation of the material. The ultimate strain increase indicates moisture uptake with plasticisation occurring and the experiment does reflect the serious effect of a high humidity environment. However it should be noted that plate bonding systems, whether for strengthening of bridge or building structures, will not generally be exposed to such extreme environments.

6.6.2 FRP adherends

Joints involving FRP adherends are far less susceptible to environmental attack by water than are joints made with adherends with higher energy surfaces such as metals (see also Section 3.4). However, in most environments, polymer composites show a degree of change with time. In Section 6.4.3 it was stated that the most important factors in inducing such change are moisture and natural weathering, and to these might be added elevated temperatures. In addition, the effects of sunlight, particularly the UV component, can have some influence on degradation. Separately, and in combination, these factors may all contribute to a deterioration in properties.

The effects of the service environment on the mechanical, physical and chemical properties of polymer composites depend to a large extent on the efficiency with which the composite is prepared, in particular the quality of exposed surface. However, the contribution of the polymer resin system used is the most important factor in relation to durability. The stability of the polymer depends on the chemistry and conformation of the molecules, and is strongly dependent on the cross-linked structure in thermosetting polymers. Since the resins used to manufacture composite materials and adhesives subsequently used to bond them are both polymeric, consideration of the effects of the environment are equally applicable to both cases.

In civil engineering structures it should be mentioned that the composite will not normally be heated to a temperature near to the limit of its mechanical performance. This temperature is dependent upon the manufacturing technique, but would typically be in excess of 140° for polyesters, vinylesters and epoxies. However, temperature exposure has three effects on polymer composites. In conditions of constantly fluctuating temperatures, differences in the thermal expansion coefficients of the resin and reinforcing fibres could contribute to progressive debonding and weakening of the materials. However, for well prepared composites (this invariably implies mechanical production) this is not generally a problem.

Unreinforced polymers have very high coefficients of thermal expansion, but the values are considerably reduced by the addition of fibres and fillers. The effect of temperature on the matrix properties is usually reversible unless the T_g is approached. The resistance of materials to strain under load is highly dependent on temperature because of the viscoelastic properties of the matrix. It must be stated that the above conditions are the worst scenario for composites and, although plate bonding which is undertaken inside buildings is not generally exposed to continually fluctuating or large variations of temperature, these effects might be relevant to bridge strengthening where externally bonded plates are exposed to diurnal and seasonal fluctuations.

As discussed for adhesives in Sections 6.2 and 6.6.1, moisture is usually a more significant factor than heat in causing deterioration of composites, since it is likely to have both chemical and physical effects on all of the components individually and on their interaction. The effects of moisture depend upon the specific polymer and fibre materials utilised in the manufacture and design of the composite, as well as the duration and global environment to which it is exposed. Moisture will be absorbed by the composite if the resin is sufficiently hydrophilic (Loos *et al.*, 1981). In addition, the ingress of water through capillary channels, voids and at exposed cut surfaces will affect the rate and extent of degradation since moisture molecules destroy some of the chemical bonds in the resin. However, this problem is mainly relevant to GFRP composites. The ROBUST system uses CFRP in which the matrix is vinylester; this system has excellent resistance to corrosive environments and to moisture uptake (see Section 3.2).

Moisture reduces the T_g of polymeric resins and has a plasticising effect which, in turn, affects the properties of FRP composites. However, changes in matrix moduli have little effect on longitudinal tensile strength and modulus of the composite since the matrix plays only a minor role in these properties. In addition, the decrease in elastic modulus of the resin due to any uptake of water is reversible in that the modulus returns to its original value when the moisture diffuses out. As the coefficient of thermal expansion of unidirectional carbon fibre/polymer composite of about 60–65% by weight of fibre is almost zero (carbon fibre has a negative coefficient of thermal expansion), the ultimate tensile strength of this type of composite is relatively insensitive to temperature in the range $-73\,^{\circ}\mathrm{C}$ to $+107\,^{\circ}\mathrm{C}$, regardless of the moisture content of the material. The temperature range over which plate bonding would be utilised is well within these limits. Temperatures in the range $-73\,^{\circ}\mathrm{C}$ to $+177\,^{\circ}\mathrm{C}$ were observed by Shen and Springer (1981) to have a negligible effect on the modulus of elasticity, regardless of the moisture content of the material (their moisture content varied from dry to fully saturated). It might also be supposed that moisture will have little effect on the tensile properties if the fibres themselves are unaffected, as should be the case with carbon.

As stated in Section 6.2, composites composed of glass fibres in polyester matrix can be vulnerable to environmental attack but their resistance does increase when going from orthophthalics to isophthalics to vinylester polymers (Norwood, 1994). Furthermore, a reduction in strength of the fibres under atmospheric conditions has been observed within short periods of time after they have been subjected to load. This static fatigue or stress corrosion results from a chemical reaction between water vapour and the surface of the glass that permits a pre-existing flaw to grow to critical dimensions and bring about spontaneous crack propagation. The rate of this reaction is dependent on the magnitude and local stress conditions, as well as the temperature, pressure and composition of the surrounding atmosphere. ROBUST confirmed that CFRP composites were far superior to GFRP under these atmospheric conditions and consequently this system concentrated upon CFRP composite.

Table 6.2 shows the results of the CFRP and GFRP tensile tests following exposure of the specimens to the thermal cycling and humidity regimes

Table 6.2 Composite material characteristics after environmental exposure (Garden and Hollaway, 1997)

Material type and exposure time	Modulus of elasticity (GPa)	Tensile strength (MPa)	Ultimate strain (microstrain)
CFRP thermal cycling			
Unexposed (control)	110.88 (± 4.2%)	1414 (± 7.6%)	12340 (± 6.0%)
50 thermal cycles	113.40 (± 5.1%)	1386 (± 6.2%)	11827 (± 5.2%)
100 thermal cycles	116.28 (± 3.4%)	1627 (± 7.9%)	14060 (± 7.1%)
180 thermal cycles	121.44 (± 2.2%)	1734 (± 8.1%)	14348 (± 6.0%)
GFRP thermal cycling			
Unexposed (control)	36.09 (± 2.9%)	955 (± 6.5%)	26185 (± 7.3%)
50 thermal cycles	36.65 (± 3.5%)	1056 (± 5.2%)	28512 (± 5.8%)
100 thermal cycles	37.62 (± 2.5%)	973 (± 5.8%)	28104 (± 8.8%)
180 thermal cycles	37.17 (± 4.8%)	1004 (± 4.8%)	19350 (± 7.3%)
CFRP humidity exposure			
Unexposed (control)	110.8 (± 4.2%)	1414 (± 7.6%)	12340 (± 6.0%)
50 days	109.95 (± 3.8%)	1587 (± 8.5%)	13967 (± 5.2%)
100 days	111.77 (± 4.5%)	1476 (± 3.7%)	13471 (± 3.7%)
180 days	114.57 (± 3.5%)	1609 (± 8.8%)	14326 (± 2.3%)
GFRP humidity exposure			
Unexposed (control)	36.09 (± 2.9%)	955 (± 6.5%)	26185 (± 7.3%)
50 days	35.82 (± 3.4%)	862 (± 4.8%)	23813 (± 6.0%)
100 days	36.31 (± 2.6%)	857 (± 5.9%)	26116 (± 6.5%)
180 days	35.71 (± 1.8%)	835 (± 5.4%)	27664 (± 7.8%)

described earlier. Mean data points are quoted, the values in parentheses representing the maximum deviation as a percentage. The moduli of the CFRP specimens subjected to thermal cycling exhibited a consistent increasing trend with increasing exposure time, whereas those values for the GFRP specimens showed a decreasing trend. The lack of consistent trends for all other values suggests that the exposure conditions had no conclusive influence on those material properties.

All tests were conducted at a time of 24 h after removal from the temperature cabinet to enable them to reach the surface dry state; the specimens were stored under ambient laboratory conditions during this time.

6.6.3 Key observations

The observations that the ROBUST consortium made from these environmental tests were that:

- The adhesive mechanical properties were increased by the temperature cycling, the modulus of elasticity increasing rapidly initially. The postcuring effect of temperatures greater than the cure temperature was believed to be responsible for the improvement in properties.
- The CFRP composite experienced an increase in modulus and strength due to the thermal cycling between −20 °C and +50 °C. This was possibly caused by postcuring of the epoxy matrix, indicating the superior performance of CFRP compared with GFRP which experienced no significant improvement.
- Under elevated temperature and humidity there is softening of the adhesive, whilst the CFRP composite became stiffer and stronger but to a lesser extent than under thermal cycling exposure. These effects were not considered to be significant.

6.7 Influence of surface treatment and effects of environment on joints and interfaces

6.7.1 Introduction

It was stated in Section 6.3 that optimisation of substrate surface conditions and pretreatments often represents the key to maximising joint durability. Whilst the surfaces of both concrete and polymer composite materials are relatively stable, they do require adequate preparation for structural bonding (Section 3.4). Central to optimisation of surface conditions to provide joints of high strength and durability is the adoption of appropriate mechanical test techniques and methods.

There is a clear emphasis at the beginning of this section on the use of test procedures which seek to test the integrity of bonded interfaces. Later subsections deal with an assessment of the overall performance of small scale beams.

6.7.2 Joints involving adhesive–concrete interfaces

The tensile pull-off test is probably the most frequently used on-site test method for assessing the quality of concrete and also for examining the adhesion of repair materials and coatings. Tests may be conducted to determine both initial and long term ‘strength’ following environmental exposure.

The partially cored pull-off test (PrEN 1542, 1996) was employed in the ROBUST project. This was used to assess the effects of concrete surface preparation and concrete surface moisture content on the bond performance of Sikadur 31PBA, a two-part cold cure paste epoxy resin. Essentially, steel dollies were bonded to the concrete pull-off locations as defined by 50 mm diameter partial cores to a depth of 15 mm (Fig. 6.3b). The bondline thickness was of the order of 2 mm and a minimum time period of 7 days elapsed before any pull-off tests were carried out. The characteristic concrete cube strength was 42 MPa and the typical age of the concrete at the time of testing was around 20 weeks.

The test parameters used were:

- Three concrete surface moisture contents, generated by:
  - 14 weeks laboratory ageing (20 °C/50% rh)
  - 8 weeks laboratory ageing, 3 weeks water immersion at 20 °C, followed by 3 weeks laboratory ageing
  - 11 weeks laboratory ageing, followed by 3 weeks water immersion at 20 °C.
- Two types of surface treatment:
  - low pressure alumina grit blasting (just exposing small aggregate particles)
  - high pressure chilled iron grit blasting (exposing medium sized aggregate particles).
- Two types of ageing following exposure:
  - 50 24 h freeze–thaw cycles (−18 °C to +18 °C)
  - laboratory ageing (20 °C/50% rh)

The results of the concrete pull-off tests are given in Table 6.3. The average pull-off strengths ranged from 1.65–2.91 MPa with the lower figures corresponding to concrete subjected only to laboratory conditions prior to adhesive bonding. Curiously, the highest figures corresponded to joints made with the dampest concrete and then subjected to freeze–thaw cycling. In all cases the locus of failure was cohesive within the concrete. No distinction could be drawn between the relative merits of ‘low’ and ‘high’ pressure

Table 6.3 Results of partially cored pull-off tests (Rahimi, 1996)

Concrete conditioning before bonding	Concrete surface treatment		Conditioning after bonding		Test results		Failure mode
	low pressure alumina grit blasting	high pressure chilled iron grit blasting	50 24 h freeze–thaw cycles (−18 °C to 18 °C)	ambient laboratory conditions (20 °C, 50% rh)	average failure load (kN) with SD in brackets	average pull-off strength (MPa)	
14 weeks under ambient laboratory conditions (20 °C, 50% rh)	X		X		5.08 (1.13)	2.59	within concrete
	X			X	3.24 (1.2)	1.65	″
		X	X		5.20 (0.75)	2.65	″
		X		X	3.80 (0.34)	1.94	″
8 weeks under ambient laboratory conditions plus 3 weeks water immersion at 20 °C followed by 3 weeks under ambient laboratory conditions	X		X		5.26 (0.7)	2.68	″
	X			X	4.38 (1.41)	2.23	″
		X	X		5.62 (1.36)	2.86	″
		X		X	4.54 (0.45)	2.31	″
11 weeks under ambient laboratory conditions followed by 3 weeks water immersion at 20 °C	X		X		5.36 (0.88)	2.73	″
	X			X	5.72 (0.69)	2.91	″
		X	X		5.14 (0.93)	2.62	″
		X		X	4.78 (1.46)	2.43	″

Failure loads represent the average of four to five test results.

grit blasting. Furthermore the dampness of the substrate did not affect the bond between this particular adhesive and the concrete, at least as determined by this test procedure.

6.7.3 Joints involving adhesive–FRP interfaces

The lap shear joint is that used almost universally in testing adhesives or surface preparation techniques. It owes its popularity to its convenience of manufacture and test, as well as to the fact that the adhesive is subjected to cleavage as well as to shear. It thus simulates the actual use of an adhesive in a variety of applications, including that in plate bonding.

The single lap shear joint is suited to assessing qualitatively the adhesion and bond integrity between materials, since joints made with relatively stiff adhesives and thin adherends fail by a cleavage mechanism. Data so generated are qualitative only, but the locus of joint failure can provide information on the durability of the bond. Joints may be subjected to environmental exposure both unstressed and stressed in suitable fixtures.

Single lap shear joints fabricated generally in accordance with ASTM D3163 (1973) were used in the ROBUST project. In fact the adherend coupons measured only 60 mm × 20 mm, the joint overlap was set at 10 mm, and the bondline thickness of Sikadur 31PBA adhesive was 0.5 mm. The joints were postcured at 50 °C for 6 h prior to environmental exposure. The test parameters used were:

- peel-ply surface treatments for the adherends
- two types of polymer composite adherends (fabricated from prepreg materials): GFRP (1.8 mm thick) and CFRP (1.2 mm thick)
- unstressed exposure for up to 1.5 years at 40 °C/95% rh
- three levels of exposure at 40 °C/95% rh under stress at 10% to 30% of the initial control joint strength.

A comparison of the results of unstressed exposure is shown in Fig. 6.4 (Rahimi, 1996). The somewhat erratic response in the first few weeks simply indicates some plasticisation of the bondline perimeter, resulting in a relief of bondline stress concentration and changes in joint behaviour. Thereafter the dominant effect of plasticisation of both the bondline and the adherends takes over, resulting in an overall reduction of perhaps 15% in the joint strength. The reduction in strength stops somewhere between 20 and 50 weeks. In all cases the locus of failure remained cohesive within the adhesive layer, except for the initial joints tested. This is very encouraging and indicates a stable adherend/adhesive system.

The results of the stressed joints are shown in Fig. 6.5 (Rahimi, 1996). It is clear that as the applied stress increased, the time to failure decreased, as expected. Again the locus of failure for all joints remained

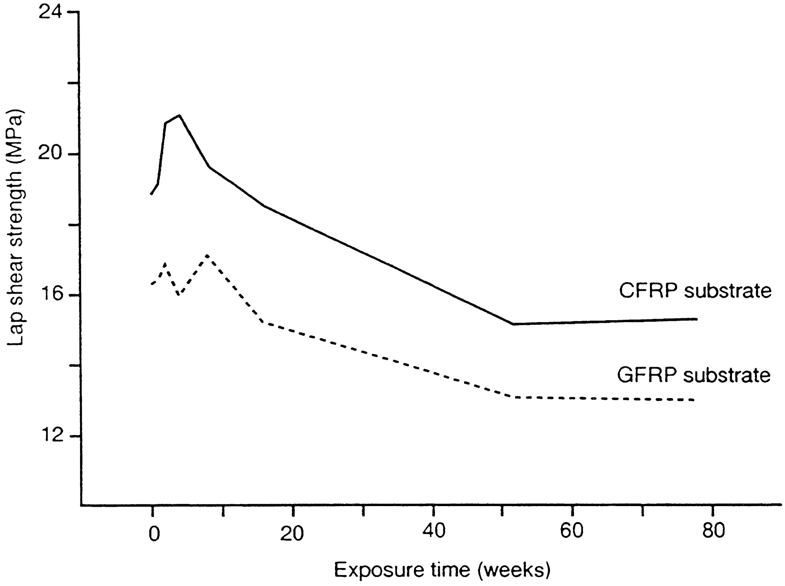

Figure 6.4 Effect of exposure at 40°C/95% rh on the performance of unstressed single lap shear joints made with CFRP and GFRP adherends.

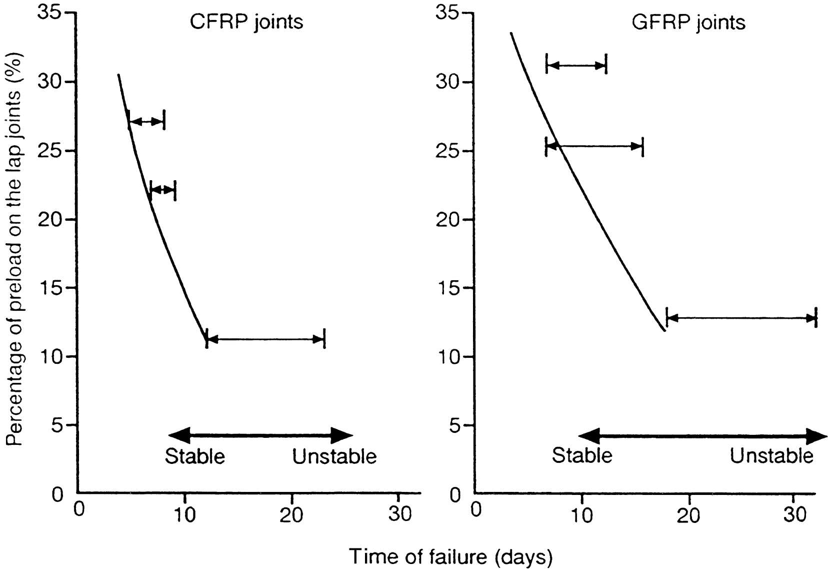

Figure 6.5 Effect of exposure at 40°C/95% rh on the performance of single lap shear joints made with CFRP and GFRP adherends, stressed at different levels.

within the adhesive layer. The data suggest that joints made with such small bonded areas are unable to carry sustained loads for long periods, but this should not cause alarm for the joint size-effect reasons stated in Section 6.5.3.

For the case of the particular adherend/adhesive systems studied here, the results indicate that there was some water-induced plasticisation of the small scale laboratory joints. This was caused predominantly by some softening of the adhesive layer, an outcome which small joints are far more sensitive to than large ones, but which nevertheless can be designed for. The most important point, which gives great confidence, is that the bond between the adhesive and FRP materials was stable under hot/wet conditions.

6.7.4 Effects of environment on strengthened small scale beams

To investigate the environmental effects on the ROBUST plated beam system, RC beams 0.8 m long and 100 mm × 100 mm cross-section were used. The reinforcement of the concrete consisted of three, 6 mm diameter steel rebars in the tensile region and two, 6 mm diameter rebars in the compression region; the beams were over-reinforced in shear. The CFRP composite plates had a cross-section of 65 mm × 0.7 mm. The concrete was 54 MPa grade with an elastic modulus of 35 GPa. The beams were exposed to the same environmental history as described for the individual components in Section 6.6.2; the thermally cycled specimens were unloaded during the exposure but the humidity-exposed specimens were loaded in four point bending as specified below.

The testing regime for the post-environmental exposure (thermal cycling) utilised a four point loading system in which the constant moment length was 100 mm and the span was 740 mm. This arrangement was also used during the humidity exposure and the total load applied to the beam during this time was 17 kN. This represented the value of load that would cause yield of the steel reinforcement and this was well above the serviceability load of that beam.

Table 6.4 shows the results for the plated RC beams after a period of 180 thermal cycles between $-20\,^\circ\mathrm{C}$ and $+50\,^\circ\mathrm{C}$. The values obtained for the beams in terms of comparative strengthening and stiffening effects are shown relative to identical beams tested directly to failure.

The beams exposed to the hot humid conditions showed no appreciable creep (measured by removable deformation dial gauge) or fall-off of load (measured by load cells permanently in position). There was no detectable degradation of either of the beams.

Table 6.4 Strengthening comparison of 0.8 m long durability beams subjected to thermal cycling (Garden and Hollaway, 1997)

Beam	Yield load (kN)	Ultimate load (kN)	Postyield stiffness (kN mm^{-1})
Unexposed (control)	24.0	48.9	7.3
Beam 1	26.0	46.9	5.4
Beam 2	25.0	44.0	6.3

6.8 Other factors affecting service performance

6.8.1 Freeze–thaw action

Consideration has been given to repairing bridges in cold countries, particularly where structural strength needs to be restored following damage by corrosion to reinforcing steel. Green and Soudki (1997) devised some experiments on small columns and beams to investigate the effects of freeze–thaw action. One 24 h freeze–thaw cycle consisted of 16 h at −18 °C, followed by 8 h in water at +18 °C. Cylinders 150 × 300 mm wrapped with CFRP sheets were subjected to 200 cycles; beams 1200 × 150 × 100 mm were plated with both CFRP and GFRP, and then subjected to 50 cycles. They concluded that the FRP sheets were very effective at restoring the strength of the columns damaged by freeze–thaw action and that the strengthened beams behaved in a similar way to their counterparts maintained at laboratory ambient temperatures. The FRP materials and the bond between the concrete and the FRP sheets were unaffected by the freeze–thaw cycling.

6.8.2 Fire

The vinylester polymer (Palatal A430-01), which was the polymer used in forming the pultruded composite plate in the ROBUST project, is a non-fire-retardant resin. During the project no attempt was made to increase the fire resistance of the pultruded composite as the aim of the research work was specifically to investigate strengthening of the reinforced concrete beams by composite plate bonding.

However, polymer materials composed of carbon, hydrogen and nitrogen atoms (i.e. they are organic materials), are all inflammable to varying degrees and could suffer some deterioration if exposed to fire unless some form of protection against it is provided (Hollaway, 1993). It is possible to incorporate additives into the resin formulations or to alter their structure, thereby modifying the burning behaviour and producing a composite with enhanced fire resistance. Furthermore, it is possible to provide a fire protective coating after the plate is bonded into position onto the external surface of the structural unit.

The fire hazards of polyester resins (vinylester is an enhanced polyester) may be reduced by incorporating halogens; halogens are one of the fluorine, chlorine, bromine and iodine family of chemicals. Fire hazards can also be reduced by combining synergists such as antimony oxide into the resin formulations; these are commonly known as hot acid resins. The commonest way, and indeed the cheapest, of obtaining these is by the addition of chlorinated paraffin and antimony oxide or by the utilisation of halogenated phosphates such as trichloroethylphosphate. Such systems when combined with fibres would conform to the British Standard Test for Fire Retardance, Class 2, of BS 476 Part 7.

To enable polyester composites to be used in building applications, resins have been developed which can attain a Class 1 rating, thus complying with the Building Regulations. Thus numerous other means of introducing halogens, either by additives such as pentabromotoluene and tris(dibromopropyl)phosphate or by reactants such as tetrabromophthalic anhydride or dibromoneopentyl glycol have been developed. The effects of alternative synergists and inert fillers have resulted in the availability of clear and opaque resins which can be fabricated into composites to give a Class 1 fire rating.

An alternative method of fire protection is by employing intumescent coatings. These can be based on polymer resins with three additives:

- a source of phosphoric acid
- a polyhydroxy compound which reacts with phosphoric acid to form a char
- a blowing agent.

In a fire situation these coatings yield a carbonaceous expanded char which protects the underlying composite. Structures treated by this method can develop fire ratings of Class 1 and Class 0.

Deuring (1994), undertook fire tests on RC beams, plated with carbon fibre/epoxy matrix polymer composites, bonded with Sikadur 30 S-02 and Sikadur 31 SBA S-08 epoxy adhesive. Some of the plates were protected with 60 mm thick PROMATECT-L.

When decisions are required regarding fire protection, it is advisable for the engineer to discuss the most appropriate system to be used with the resin manufacturers. If fire protection is required for plate bonding it is unlikely that the additives, which would be incorporated into the resin, would affect the strength of the composite significantly, but the in-service properties of colouring and UV might be affected. However, as the polymer composite plate is located on the soffit of a concrete beam, and therefore protected from the direct rays of the sun, any degradation from this source will be minimal. Additionally, any change in the colouring of the composite will be masked by the black carbon fibre; consequently, from the weathering point of view, degradation will be insignificant. It is worth mentioning, however, that if UV degradation is a problem, UV stabilisers can be added to the liquid resin in addition to any additives for fire resistance.

6.9 Summary

The main considerations relating to the environmental durability of externally bonded reinforcement are the quality of the materials used and the integrity of the adhesive bonds. The ROBUST system of strengthening represents an environmentally stable system with good durability as demonstrated in laboratory experiments. This behaviour results from the use of good quality unidirectional CFRP/vinylester matrix material manufactured by the pultrusion process, an epoxy adhesive which exhibits good all round physical and mechanical characteristics (together with low permeability to water), excellent adhesion to concrete and excellent adhesion to CFRP conferred by use of the peel-ply surface preparation technique coupled with the wetting characteristics of the adhesive. It has been shown that the materials, and bonds to them, are very stable within the normal range of operating conditions anticipated.

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