The joining of precoated sheet steels to dissimilar contruction materials.

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The Joining of Precoated Sheet Steels to Dissimilar Construction Materials

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Doctorate of Engineering Thesis

EPSRC Engineering Doctorate Centre for Steel Technology
Swansea University, Materials Research Centre

DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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ABSTRACT

Within the UK steel industry it is believed that continued growth of steel usage in the construction sector would be facilitated by offering multi-material solutions which combine the benefits of several materials (i.e. precoated sheet steels, aluminium alloy, glass, timber and mortar). A review of both traditional and novel joining processes that are currently used to assemble sheet steels indicated that adhesive and sealant bonding has the most potential for joining both multi-metal and fundamentally dissimilar material combinations. Consequently, the aim of this Eng.Doc research project was to establish the robustness of bonded joints, test methodology procedures, and design guidelines for multi-material combinations.

The results obtained in this study have shown that a range of structural adhesive and sealant systems exist, capable of producing strong and durable multi-material joints. The highest levels of durability were obtained with organic coated steel – aluminium or glass joints which restricted the ingress of water to the exposed edges of the bond line. With precoated steel – timber or mortar joints, bond strength was adversely affected by rapid water penetration through the porous timber and mortar adherends promoting joint failure.

Furthermore, it was noted that the failure loads obtained with adhesive bonded steel – timber and glass joints were higher than anticipated. This was attributed to a change in the stress distribution, whereby a greater stress concentration was located at the overlap end of the higher modulus steel adherend. Guidelines were developed describing best practice joining techniques for adhesive bonding steel – brittle materials (i.e. glass and mortar), and the requirements for further work outlined to facilitate follow up projects.

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1.0 INTRODUCTION

In recent years there has been significant growth in the use of precoated steels in the construction sector. Primary growth has not been in traditional heavy gauge steels but in lightweight products that principally depend on profile configuration for their rigidity (e.g. cold formed steel sections and profiled cladding/decking panels). Within the UK steel industry it is believed that continued growth in steel usage would be facilitated by offering multi-material solutions, which combine the benefits of several construction materials. This is because synergy between dissimilar materials enables the achievement of function when design requirements demand for properties and performance levels unobtainable by a single material. The materials selected for this project include hot dip galvanised steels, organic coated steels, aluminium alloy, glass, timber and mortar. These materials were primarily chosen because they can all be used in structural load bearing applications and because they possess a diverse range of properties.

A key enabling technology for multi-material combinations is the development of robust joining processes that are tailored to the specific requirements of both the materials and the application considered. However, at present there are no standard procedures for evaluating sheet steel – dissimilar material combinations. Consequently the aim of this Eng.Doc research project was to establish test methodology procedures including appropriate test specimen geometry and design guidelines for the formation of sheet steel – dissimilar material joints where high strength and long-term durability are key requirements.

1.1 JOINING DISSIMILAR MATERIALS

The ability to join dissimilar materials has been one of the major drivers associated with developments in joining technologies for many years [1]. Joining processes used to assemble sheet steels (<3mm) can be broadly divided into traditional methods such as welding, brazing and soldering, mechanical joining, adhesive bonding, and, novel hybrid methods such as weld-bonding, weld-brazing, riv-bonding and clinch-bonding [**Figure 1**], [2]. These fabrication methods differ in the type of bond created i.e. mechanical, physical and chemical, loading limitations and life expectations and were reviewed to establish their potential and limitations in joining dissimilar material combinations.

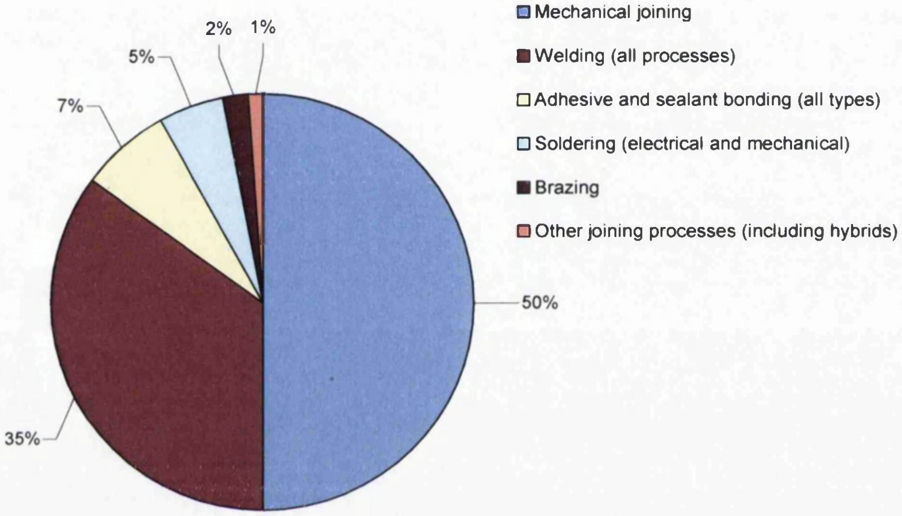


Figure 1 The estimated percentages of all joining accomplished by mechanical joining, welding, brazing, soldering, adhesive bonding and various hybrid methods [2].

In general, the selection of a joining process is determined by the inherent material properties, the end function and in-service working environment. However, when joining organic and metallic coated sheet steels, further consideration should also be given to minimizing coating damage as the aesthetic appearance and corrosion resistance of these materials are primary factors leading to their use in the construction sector. Coating damage to galvanised steel can eventually lead to problems such as corrosion of the steel substrate and loss of mechanical integrity, whereas, coating damage to organic coated steels can lead to ingress of water below the coating and coating delamination [3].

1.1.1 **Welding** [4]

Welding is a process in which materials of the same basic type or class are joined together through the formation of primary and secondary bonds under the combined action of heat and pressure. The combination of these variables can range from high temperature with no pressure (e.g. laser welding) to high pressure with no heat input (e.g. resistance spot welding and friction welding). Welding techniques used to join galvanised and organic coated steels include resistance spot welding, hot plate welding, induction welding, resistance implant welding, infrared welding and many more [5,6]. With regard to organic coated steels, welding can only be used to join thermoplastic coated products since thermosetting polymers cannot be re-melted [6].

By definition, a process that forms primary bonds to accomplish joining, means that welds cannot be produced between metallic and non-metallic materials (e.g. steel cannot be welded to glass, timber or mortar) but can be formed between dissimilar metals [7]. The main concerns with welding steel to aluminium alloys (and dissimilar metals in general) are the formation of brittle intermetallic compounds and the large differential in melting temperatures [7,8]. Mild steel melts at approximately 1538°C and aluminium alloy 6082 melts in the range of 570 – 660°C. However, regardless of these concerns arc welding, resistance spot welding, laser welding, clad bonding, friction stir welding and magnetic pulse welding techniques have all been used to join steel to aluminium [8,9]. With many techniques, it is necessary to use a transition insert (produced without fusion) that enables like metal joints to be made on either side of the transition [8]. Laser welding steel to aluminium alloy is possible by applying the laser to the steel and closely controlling the beam and heat penetration into the aluminium component [8].

1.1.2 **Brazing and soldering** [10]

Brazing and soldering involves the joining of materials through the use of heat and a filler transition metal that has a composition different from that of the joint components [10,11]. The filler material is melted between close fitting (0.025 –

0.25mm) joint surfaces and is distributed by surface wetting and capillary action. Brazing is distinguished from soldering on the basis that the melting temperature of the filler metals is above 450°C, whereas, the filler metals used for soldering melt below 450°C. The strength of the joint is controlled by the properties of the chosen filler material. Brazing produces more robust joints than soldering because of the stronger filler materials employed and is the preferred joining technique for load bearing applications. Bonding is almost always primary, and can be metallic, ionic, and covalent depending on the specific natures of the materials [10].

With regard to joining organic coated steels, the high heat input required to melt the filler metal would damage the polymeric coatings and prevent wetting of the surfaces. Hot-dip galvanised steels can be readily brazed and soldered to itself or aluminium alloys and other metals provided an appropriate filler metal can be found to wet both material surfaces (e.g. aluminium-silicon alloys) [8,12]. Furthermore, joining does not involve significant melting of the joint components and limits the formation of brittle intermetallic compounds [8,12]. Brazing and soldering are inappropriate processes for joining steel to glass, timber and mortar.

1.1.3 Mechanical joining [13]

Mechanical fastening and integral attachments constitute what is known as mechanical joining. The role of a fastener is to cause interference and interlocking between the adjoining parts (e.g. self piercing rivets, nuts and bolts, screws and pins). Integral attachment involves interlocking features built into the mating parts being joined (e.g. dovetail, tongue and groove and clinching). The unique advantage of mechanical joining is that it allows intentional relative motion between mating parts and intentional disassembly without damaging the components involved.

Penetration through the protective coating layers of precoated sheet steels is a key concern with many mechanical fastening systems. This exposes the steel base, which can lead to corrosion and coating delamination as a result of water ingress [3]. However, self-piercing rivets and the Tog-l-loc clinching system can both be used to join precoated steels without interrupting the continuous coating layers [6].

As mechanical joining is an extremely versatile process it can be used to join hot-dip galvanised steels and organic coated steels to aluminium, glass, timber and mortar. Although, one concern when joining hot-dip galvanised steel to aluminium is galvanic corrosion between the two substrates and between the substrates and fastener [8].

1.1.4 Adhesive and sealant bonding

Materials can be adhered to one another by creating secondary or occasionally primary chemical bonds across an interface using an intermediate substance called an adhesive or sealant [14]. For structural load bearing applications thermosetting adhesives and sealants are applied; these organic materials resist creep deformation under constant load and include epoxy, acrylic, polyurethane and silicone resins [15].

As the interactions of surface forces are responsible for bonding, adhesives and sealants have no adverse affects on the surface properties of the materials being joined. The initial consideration with regard to adhesive selection is the compatibility of the adhesive with the chosen materials. In general, flexible adhesive systems are preferred when bonding dissimilar material combinations to ensure that the adhesive can accommodate the differential rates of thermal expansion of the substrates used [16]. Hot-dip galvanised steels, organic coated steels, aluminium, glass, timber and mortar and any combination of these materials can be joined using adhesives and sealants.

1.1.5 Hybrid joining

Increasing demand on fabricators to improve joint integrity whilst at the same time reducing costs has led to continued improvement in existing joining technologies and an increasing interest in combining these processes in order to consolidate the benefits offered by each individual process. There are four main types of 'hybrid' joining, which combine two fundamental joining processes to create synergistic benefits [6,17,18]. These are riv-bonding, clinch-bonding, weld-bonding and weld-brazing.

1.1.5.1 Riv-bonding

Riv-bonding is a hybrid of adhesive bonding and mechanical joining using rivets as fasteners [6,17]. The rivets provide resistance to out-of-plane peel and cleavage forces and hold the joint components together while the adhesive cures. Likewise, the adhesive acts to reduce localized stress concentrations around the rivet and improve fatigue resistance. Riv-bonding is only suitable for joining hot-dip galvanised steel and organic coated steel to aluminium.

1.1.5.2 Clinch-bonding

Clinch-bonding is a hybrid of adhesive bonding and integral attachment using the Tog-l-loc clinching system to mechanically interlock the joint components [6,17]. The Eckold clinch is unsuitable for use with clinch-bonding as the punch tool shears through the joint components and would become contaminated with adhesive. The benefits provided by clinch-bonding are the same as those provided by riv-bonding. Clinch-bonding can only be used to join hot-dip galvanised steel and organic coated steel to aluminium.

1.1.5.3 Weld-bonding

Weld-bonding is generally a hybrid of resistance spot welding and adhesive bonding [17]. Typically a layer of adhesive is applied to the joint components prior to welding. Whereas the adhesive reduces localized stress concentrations around the weld and improve fatigue resistance, the spot weld provides high peel and cleavage strength and holds the joint components together while the adhesive cures. Weld-bonding has the same limitations as welding alone and is only suitable for joining hot-dip galvanised steel to aluminium.

1.1.5.4 Weld-brazing

Weld-brazing is a hybrid of resistance spot welding and brazing [17]. This technique involves spot welding joint components together prior to application of a molten braze filler metal between the overlapped joint elements. Alternatively, braze alloy preforms can be used in which there are pre-punched holes through which spot welds are made, and then the braze filler is melted to flow through the joint. Weld-brazing has the same limitations as welding and brazing alone and is only suitable for joining hot-dip galvanised steel to aluminium.

1.2 JOINING PROCESS SUMMARY

A review of the joining processes that are currently used to assemble sheet steel components has shown that adhesive and sealant bonding has the most potential for joining multi-material combinations **[Table 1]**. Unlike other processes, adhesive and sealant bonding is suitable for joining all multi-material combinations and has no adverse effects on the protective coating layers of precoated steels.

Table 1 A summary of multi-material combinations and appropriate joining processes

Substrate A	Substrate B	Recommended joining process‡
Galvanised steel	Galvanised steel	M, A, W, B, S, RB, WB_o, WB_r, CB
	Organic coated steel	M, A, RB, CB, W^*, WB_o^*
	Aluminium	M, A, B, S, W, RB, WB_o, WB_r, CB
	Glass	A, M
	Timber	A, M
	Mortar	A, M
Organic coated steel	Organic coated steel	M, A, RB, CB, W^*, WB_o^*
	Galvanised steel	A, M, RB, CB, W^*, WB_o^*
	Aluminium	A, M, RB, CB, W^*, WB_o^*
	Glass	A, M
	Timber	A, M
	Mortar	A, M

‡ A = adhesive bonding, B = brazing, S = soldering, W = welding, M = mechanical fastening or integral attachment, RB – riv-bonding, WB_o – weld-bonding, WB_r – weld-brazing, CB – clinch-bonding

* Localised removal of the organic coated is required with techniques such as resistance spot welding

1.3 PROJECT OBJECTIVES

The work undertaken in this Eng.Doc research project was aimed at developing an understanding of the adhesive and sealant bonding process, and its potential for joining both multi-metal and fundamentally dissimilar material combinations. One of the primary factors currently limiting the widespread usage of adhesives and sealants in structural applications in the construction industry is the lack of confidence in the long-term durability of bonded components when exposed to hostile environments. A solution to this is essential if adhesives and sealants are to facilitate the further usage of precoated steels in construction applications, which are not at present steel intensive. The key objectives of this work can be divided into:

1. Assess the compatibility of a range of adhesives, sealants and surface pretreatments with galvanised steel, organic coated steel, aluminium alloy, glass, timber and mortar joints. This objective will require an assessment of appropriate joint configurations and test methods for multi-material combinations. Tensile testing will be used to provide quantitative data on the ultimate failure load of a joint, whereas, the mode of failure will be used to establish the quality of a joint.

2. Using both short-term and long-term (for precoated steels only) artificial weathering regimes, develop an understanding of the mechanisms controlling the durability of adhesive and sealant bonds, and the changes that occur both within the adhesive/sealant itself and at the adhesive/sealant – adherend interface. The mechanism(s) of joint degradation will be evaluated and determined from the changes in the mode of failure and using sophisticated surface analysis techniques. Furthermore, identify any correlations that exist between short-term and long-term weathering studies. Such trends can be used to estimate the life expectancy of a bonded assembly and eliminate the need for long-term durability testing.

3. Evaluate the performance of multi-material joints with consideration to the properties of the dissimilar adherends. Identify the critical factors controlling the ultimate failure load and durability of bonded joints. Also compare equivalent results obtained with uni-material and multi-material joints and assess the following statement:

If material 'A' is bonded to material 'A', and material 'B' is bonded to material 'B', then when material 'A' is joined to material 'B' the maximum failure load obtained will be equivalent to the weaker of the uni-material joints since the weakest part of a joint will always fail first.

2.0 ADHESIVE AND SEALANT BONDING TECHNOLOGY

In an attempt to understand how adhesives function and why they fail, both fundamental and practical adhesion has been reviewed. Fundamental adhesion refers to the theories of adhesion, wetting and spreading as they can all be explained by the attractive forces and their energies that exist between atoms and molecules at an interface. Whereas practical adhesion refers to the quantitative results obtained from destructive testing techniques and looks at issues such as modes of fracture. An overview of the many structural adhesives and sealant systems available is also provided.

2.1 ADVANTAGES OF ADHESIVE AND SEALANT BONDING [16]

1. The ability to join fundamentally dissimilar materials
2. Appropriate for joining heat sensitive and precoated materials
3. Adhesive and sealant bonded joints are mechanically efficient and are capable of supporting high shear and tensile loads. By distributing loads evenly over wide areas they avoid the localised stresses which are the associated with spot welds and mechanical fasteners.
4. Adhesives and sealants provide gap filling, sealing and vibration damping
5. Adhesive and sealant bonding minimises the affects of ‘thermal bridging’ between metallic joint elements.
6. Separation of substrates prevents galvanic corrosion between metallic joint components.

2.2 DISADVANTAGES OF ADHESIVE AND SEALANT BONDING [16]

1. Adhesives and sealants are susceptible to environmental degradation and loss of adhesion when exposed to moisture.
2. At elevated temperatures visco-elastic softening of organic material occurs, approximately 150 – 180˚C for epoxy adhesives.
3. Poor performance under peel, cleavage and impact forces.
4. Optimum performance can only be achieved if careful surface preparation is ensured.

5. Cure times can be long so jigging may be required until handling strength is achieved.
6. Joint disassembly can occasionally be accomplished, but never without difficulty and causing damage to the joint components.

2.3 STRUCTURAL ADHESIVES AND SEALANTS [15]

The most important group of adhesives and sealants used in the construction sector are chemically cross linked (i.e. thermosetting) polymers based on, epoxy, polyurethane, acrylic, silicone and many more. Structural adhesives used to assemble load bearing joints are defined as rigid polymers that resist creep deformation under constant load. Whereas, a structural sealant can be considered as an elastomeric polymer that exhibits high degrees of flexibility under loading and fully recovers when the load is released.

Several thermosetting adhesives and sealants can be subdivided into both one and two component systems. One part systems usually require additional energy in the form of heat or radiation (e.g. UV light) to initiate cure. Alternatively, cure can also be activated by atmospheric moisture or oxygen diffusing into the polymer from the outside surface, towards the inside. Two component systems will cure at room temperature on mixing of resin and hardener. The cure mechanisms of structural adhesives depend on the resin chemistry and can be based on chain polymerization or step polymerization reactions [19]. In addition, the term 'tough' or 'toughened' can be used to describe structural adhesives that contain a dispersed physically separate, although chemically attached rubbery phase. This modification gives adhesives and sealants enhanced resistance to crack propagation and brittle fracture without necessarily making them soft and ductile.

2.3.1 Glass transition temperature

Just like all polymeric materials, adhesives and sealants have glassy and rubbery/leathery states. The transition point between these states is at the glass transition temperature (T_g) [20]. At this point the mechanical properties of polymers radically change. Below T_g, polymers are relatively hard, brittle, inflexible and glassy, tending to break rather than deform under stress. Above T_g, polymers are tough, flexible and leathery, tending to deform under stress. Glassy polymers are used for structural adhesives whereas rubbery polymers are used for structural sealants. During service, adhesives and sealants should never pass through their glass transition temperatures.

2.4 THEORIES OF ADHESION

The definition of adhesion is best described by the following statement [21]:

'Intermolecular forces which hold matter together, particularly closely contiguous surfaces of neighbouring media e.g. a liquid in contact with a solid'

Several theories are needed to explain the mechanism of adhesion; no single theory explains this concept in a general comprehensive way. The bonding of an adhesive or sealant to a surface is the sum of a number of mechanical, physical and chemical forces that overlap and influence one another. The principal theories of adhesion relevant to structural bonding are adsorption theory, chemical bonding theory and mechanical interlocking theory [22,23]. Details of these key theories are described below. Other theories of adhesion include diffusion, electrostatic and weak boundary layer [22,23].

2.4.1 Physical adsorption theory [22,23]

In the field of adhesion between organic and inorganic systems it is the physical adsorption theory that is most relevant. It states that provided intimate contact is obtained between a substrate and adhesive, adhesion will occur because of the intermolecular forces (also known as van der Waals or secondary forces) that exist between atoms, molecules and ions of the two phases. Van der Waals forces involve attractions between permanent diploes and induced dipoles and are of three types: London dispersion forces, Debye induction forces and Keesom orientation forces. The most universal of these is the London dispersion forces, which are involved to some extent in every adhesive bond. The classification of secondary forces is shown in **Table 2**. Although these are the weakest forces that contribute to adhesive bond strength, they are sufficient to make strong joints. For a successful bond, contact between an adhesive/sealant and adherend must be less than 5 Angstroms (5×10^{-10}m).

Table 2 Classification of secondary bonds.

			Dipolar interaction
van der Waals	van der Waals	London dispersion	Transient/transient
	Polar forces	Debye induction	Permanent/induced
		Keesom orientation	Permanent/permanent

2.4.2 Chemical bonding theory [22,23]

This theory predicts that in certain circumstances the formations of primary chemical bonds are formed across an interface. These bonds are much stronger than van der Waals forces and include ionic, covalent, hydrogen bonds and acid-base interactions. The relative magnitudes of both primary and secondary bonds are listed in **Table 3**.

Table 3 Primary and secondary bond types and energies.

Bond type	***Bond energy (kJ/mol)***
Ionic bonds	600-1100
Covalent bonds	60-700
Lewis acid-base	Up to 80
Hydrogen bonds (including F)	Up to 40
Hydrogen bonds (excluding F)	10-25
van der Waals (permanent dipole-dipole)	4-20
van der Waals (dipole-induced dipole)	Less than 2
van der Waals (transient-transient dipole)	0.08-40

2.4.3 Mechanical interlocking [22,23]

This involves the interlocking of a solidified adhesive or sealant with the topological features and irregularities on the adherends surface. This theory of adhesion is particularly relevant with anodised aluminium alloys [24].

2.5 SURFACE PROPERTIES CRITICAL TO ADHESION

As adhesion is a surface phenomenon, the condition of the joint components prior to bonding is of fundamental importance to the compatibility and durability performance of adhesive and sealant bonded joints. Important surface qualities with regard to adhesion are [25]:

1. **Wettability** [26] – If adhesive bonds are to form between an adhesive and substrate then the liquid adhesive must establish intimate contact at, or, 'wet' the surface of the substrate. The degree of wetting is controlled by the balance between surface energy and surface tension of the liquid-solid interface. For an adhesive to wet a surface it should have a lower surface energy than the adherend. A measure of wettability is the contact angle that forms between a liquid and a surface; good wetting occurs when the angle is less than 90°.
2. **Roughness** [27] – an increase in surface roughness provides a larger effective bond area for the forces of adhesion to act across and greater mechanical interlocking between the adhesive and adherend. Low viscosity adhesive and sealant systems are best used with rough textured materials as they are more likely to fill the surface asperities and voids than thicker pastes.
3. **Soundness** – freedom from weak and loosely attached surface layers
4. **Stability** – the stability of surface layers and oxides, towards water, organic compounds and elevated temperatures, as a function of time following surface preparation.
5. **Contamination-free** – the absence of foreign particles on a prepared surface, or from the migration of matter through the bulk material to the bonded interface with time.
6. **Uniformity** – visible or measurable consistency of the other characteristics, and of the regularity of a treated surface area.
7. **Compatibility** – the chemical compatibility between adhesives and sealants and, particular substrate materials.

2.6 SURFACE PREPARATION AND PRETREATMENTS

In general, all substrates must be treated in some manner prior to bonding [28]. The main function of surface preparations and pretreatments are to ensure that adhesion develops to the extent that the weakest link in the joint is in the adhesive or in the adherend. Different materials demand very different surface treatments in order to provide a required joint performance, and there often exists a multitude of treatment possibilities for individual substrates. Particularly when bonding metals, the desired gain is not primarily to increase the strength of a newly made joint, but to increase resistance to environmental degradation. The vast range of pretreatments available for adhesive and sealant bonding applications can be categorised into four main groups:

1. Passive chemical removal of surface contaminants such as oil, mould release agents, grease and other foreign substances using solvents e.g. acetone
2. Mechanical removal of heavy surface contaminants such as rust and scale using wire brushes, abrasive papers and grit blasting.
3. Chemical pretreatments and primers e.g. etchants, conversion coatings, silane coupling agents and adhesive derived primers.

Removal of surface contamination using solvents is the simplest form of surface preparation. Solvent degreasing enhances initial adhesive bond strength when compared to as-received bonded surfaces and provides a consistent and repeatable surface finish. However, solvent degreasing alone is generally insufficient to provide high levels of bond durability especially when exposed to high relative humidity.

Mechanical abrasion and chemical etch treatments have a two fold purpose: to remove heavy surface contaminants and also to provide a modified surface profile. Enhanced adhesion achieved by mechanical abrasion and chemical treatment is unlikely, in general to be a consequence of the rougher surface and greater mechanical interlocking. The enhanced surface energy, increased chemical activity of the surface and removal of weak boundary layers will often be more significant than topological changes.

Chemical conversion coatings and surface primers improve adhesion by changing the chemical composition and morphology of the substrates surface. Firstly, this can result in a higher surface energy of the adherends, which promotes wetting and increases the contact area between adhesive and adherend surface forces. Secondly, improved adhesion can be a result of the formation of primary chemical bonds across the adhesive-adherend. Examples of chemical pretreatments are chromates, phosphates, mixed oxides and silanes.

2.7 ADHESIVE AND SEALANT JOINTS

In practice it is the ultimate strength of a joint (regardless of the mode of failure) that is a true measure of success. Although ways do exist of assessing the quality of joints by non-destructive testing [29], the decisive test is to measure the force needed to break the joint. As adhesives and sealants have different properties and functions they must be assessed using different methods. A test suitable for a rigid adhesive is unlikely to be suitable for a flexible sealant. Good joint design combines maximum possible bond area with mechanical interlocking and uniformly distributes the operating stress over the entire bond area. There are many mechanical test methods for assessing adhesive and sealant bond strength [30]. Ideally, bonding of large scale components should be used for design verification while test procedures using small scale specimens can be used for research and quality assurance. Typical joint configurations used for research purposes include:

1. Single/double lap joints with various edge details i.e. square or bevelled edges
2. Boeing wedge test, especially with structural aluminium alloys
3. T-peel joint, used when both adherends are flexible

4. H-joint, used to assess structural sealants on rigid adherends
5. Butt joint

Under operating conditions, bonded joints can be subjected to four basic types of loading stress i.e. tensile, shear, cleavage and peel [**Figure 2**] and four different loading regimes (i.e. static or monotonic, dynamic, creep and fatigue). Joints loaded in shear and tension offer higher strength than joints loaded in peel and cleavage because the stress is distributed over a larger area of the bonded region. However, even when joints are stressed primarily in shear and tension, peel and cleavage forces can still be produced. The relative use of the various joint types depends primarily on the structural loads to be achieved [**Figure 3**]. The complex stress distributions generated in bonded joints varies with joint geometry and adherend thickness and ultimately determines the maximum joint failure load [31].

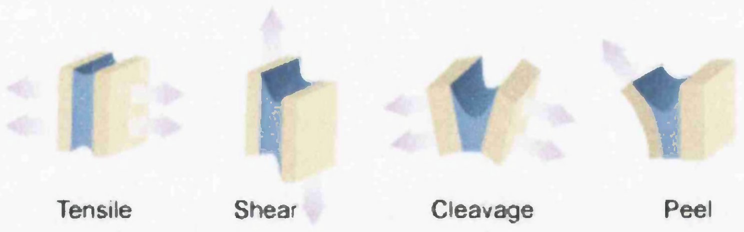


Figure 2 The four basic types of stress common to adhesive joints.

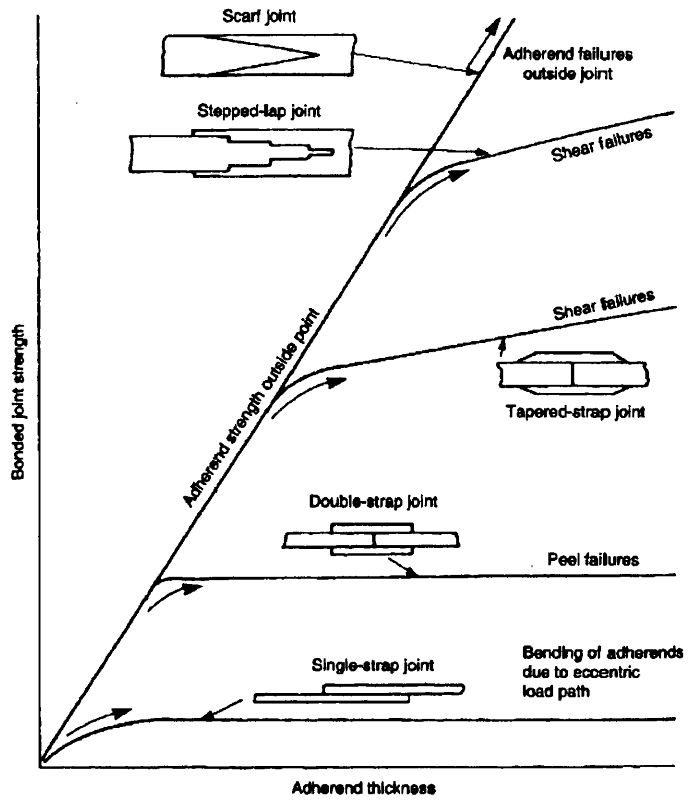


Figure 3 A schematic plot of joint design versus strength [32].

2.7.1 Shear stress distribution analysis

The single lap shear joint is the most commonly used joint configuration for assessing adhesives with metallic adherends. Although the design of this joint is simple, the stress distributions generated when loaded in shear are very complicated, especially with elastic, non-rigid adherends [33]. For rigid adherends the shear stress across a bonded lap joint is considered to be uniform [**Figure 4**]. The problem of elastic adherends was first analysed by Volkersen [33]. In his 'shear lag analysis' Volkersen assumed that the entire axial load was carried by the adherends and that all the shear deformation occurs within the adhesive layer and linear elasticity. Furthermore, he assumed that the tensile stress in each adherend falls to zero at the free end of the overlap, and hence the strain decays in a proportional manner. Assuming continuity of the adhesive/adherend interface, the uniformly sheared parallelograms of adhesive become distorted [**Figure 5**]. This phenomenon is called 'differential shear' and predicts that the maximum shear stress in an adhesive bonded lap joint occurs at the ends of the overlap [33].

However, Volkersen failed to account for the stress loads on a single lap shear joint are asymmetric, and that subsequent bending moments exist and the joint will rotate [**Figure 6**]. This further complication was addressed by Goland and Reissner [33]. Once again, the critical result was that an applied load leads to severe out-of-plane stresses at the end of each overlap, which initiates joint failure. More refined stress distribution models do exist for single lap shear joints where consideration is given to factors such as overlap end-effects (i.e. spew) and material non-linearity (i.e. plastic behaviour of the adhesive and adherend). However, these analyses are outside the scope of this project and will not be reviewed.

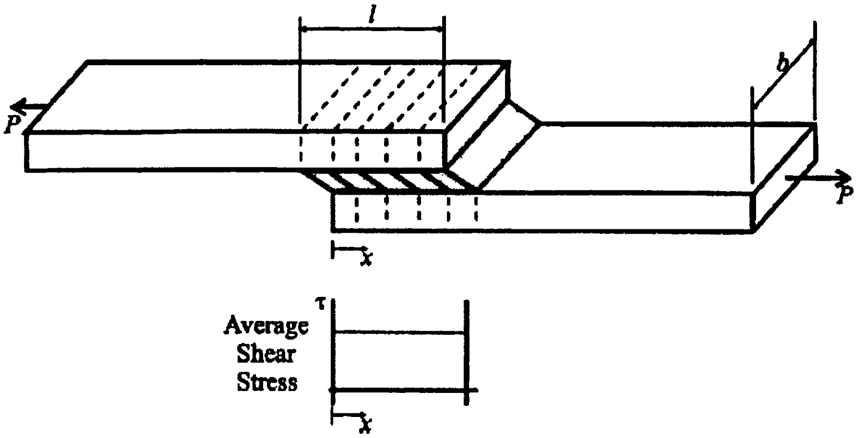


Figure 4 Simple rigid adherend model of a single lap joint [34].

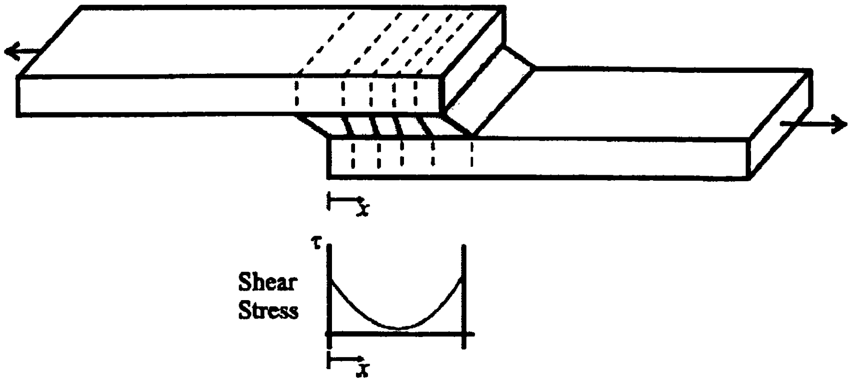


Figure 5 Volkersen's elastic adherend model of a single lap joint [34].

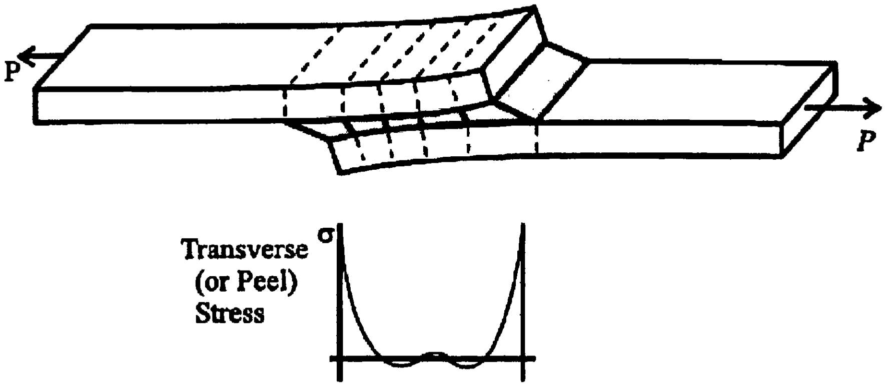


Figure 6 Goland and Reissner bending model of a single lap joint [34].

The effects of a non-uniform stress distribution across a lap shear joint have been summarised below:

1. Joint strength is independent of the bond area. The load carrying capacity of a lap joint is always proportional to its width but not overlap length [**Figure 7**].
2. As the overlap length is increased, the stress in the joint is redistributed, such that the maximum stress at the overlap ends decreases for an applied load, and a greater proportion of the load is transferred within the low stress region of the joint [35]. An overlap length can be attained where the stress at the centre of the joint approaches zero, beyond which increasing the overlap length is of little benefit.

3. The bending stresses in adhesive bonded lap joints are least when the over lap length is fifty to one-hundred times greater than the thickness of the joint components.
4. An increase in substrate thickness leads to an increase in lap shear strength because, the greater the substrate thickness, the greater the stiffness of the joint and the lower the stresses at the edges for a given load [36].
5. An increase in bond area improves durability performance. Again, the failure of the outer portions of the joint will increase the stresses on the central area of the joint, which may exhibit a high proportion of day one strength, despite the fact that a significant amount of the joint area has failed.

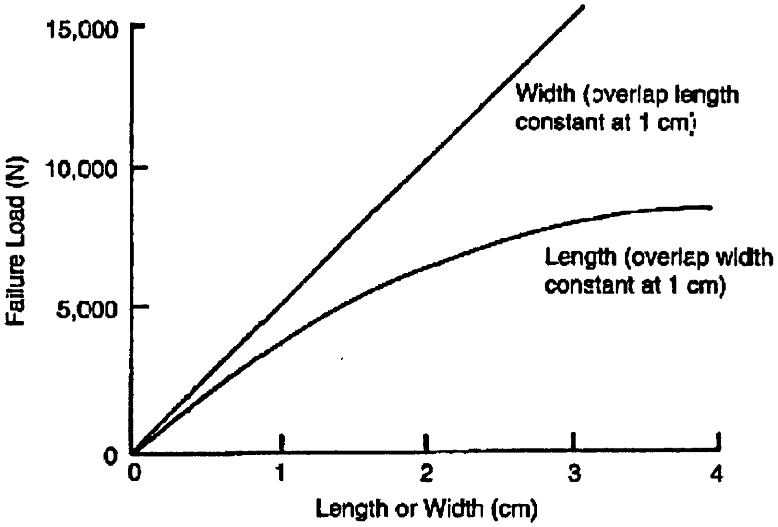


Figure 7 The effect of overlap length and width on the failure load of a bonded joint [37].

2.7.1.1 Adhesive bonding dissimilar materials

Adhesive bonded dissimilar materials produce a different stress distribution pattern across a lap joint when compared to a lap joint assembled from one material only [38,39]. For example, when bonding sheet steel to a lower modulus material the operating load and stress will be located at the overlap end of the higher modulus steel adherend [**Figure 8**]. Consequently the maximum stress transferred through the adhesive bond line is greater than the corresponding uni-material joint stresses. These high stress concentrations can be reduced by using compliant adhesives that are more effective at distributing stress across the bond area. Also by increasing the overlap length, the maximum stress peak at the end of the stiffer joining component decreases, whereas the lower stress peak becomes larger at the other end, with the result exhibiting an almost symmetrical stress distribution.

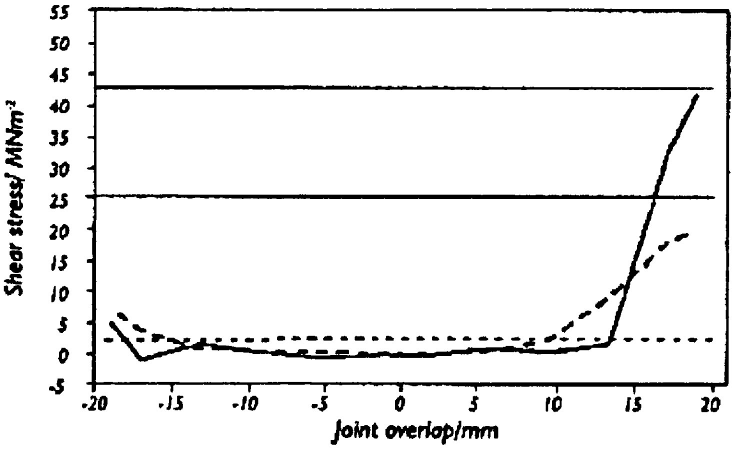


Figure 8 The stress distribution across a multi-material lap shear joint bonded with a rigid adhesive (solid line) and a more compliant adhesive (dotted line) [38]. The higher stress is located at the overlap end of the higher modulus material.

Furthermore, it has been demonstrated that by perforating the steel component of a steel – composite joint, higher failure loads can be supported [40]. The process of perforating the steel component increases the flexibility of the steel, reduces the elastic mismatch between the dissimilar materials and consequently produces a more symmetric stress distribution across the bond area.

2.7.2 Tension stress distribution analysis

The H-joint is the dominant joint configuration used to assess structural sealants with rigid adherends. Although this appears to be a simple test in which the sealant is loaded uniformly in tension, when the sealant layer is thick and pulled axially, it radially contracts and necking occurs [41], see **Figure 9**. This is because the same load is carried in both the adherends and sealant and the

Young's modulus ratio of the adherend: sealant may be greater than 20 [41]. Thus the axial strain in the sealant will also be 20 times greater than that in the adherend, with similar ratios for the lateral strain. But where the two materials join, the lateral strain in the sealant is restricted by the much stiffer adherends. This conflict is resolved by generating large radial shear stresses at the interface.

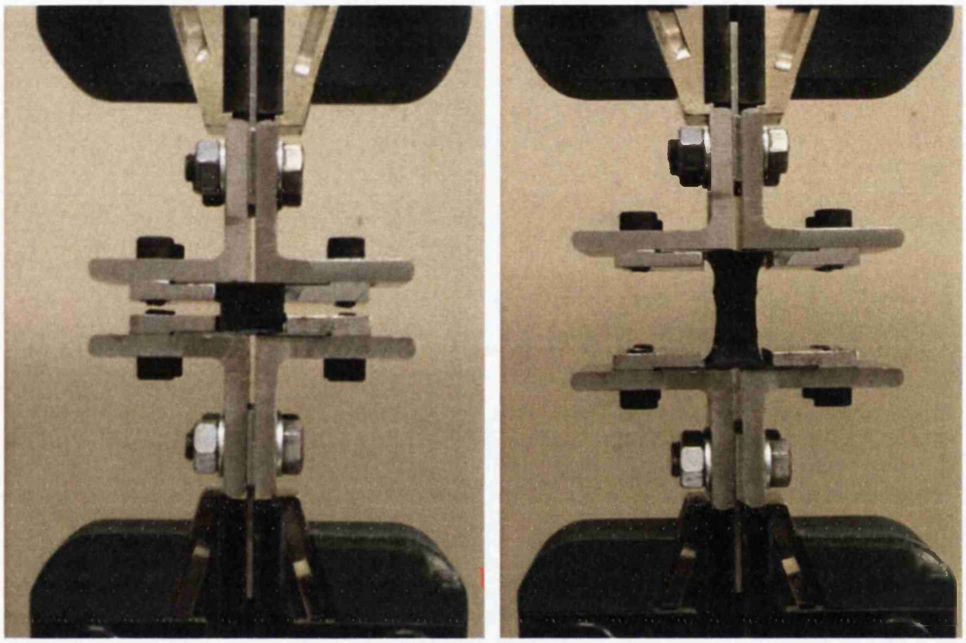


Figure 9 An unstressed sealant bonded H-joint (left). A sealant bonded H-joint loaded in tension and showing signs of necking (right).

2.7.3 Adhesive and sealant bond line thickness

The most important aspects of bond line thickness are magnitude and uniformity [42]. With adhesives, it is desirable to have as thin a layer as possible (ideally 0.1 – 0.3mm) without any chance of bond starvation (lack of coverage). With thicker sealant bond lines (approx. 10 – 12mm), there's a risk of incorporating high void concentrations into the joint. In addition, stresses at the corners of the joint tend to be larger due to the difficulty in keeping tensile loads axial. Parallel substrates require uniformity in adhesive thickness across the bonded area. If the substrates are not parallel, the loading will not remain aligned and cleavage stresses will develop.

2.7.4 Adhesive and sealant bond defects

Defects within adhesive and sealant bonded joints can be categorised according their location i.e. defects within the adhesive/sealant layer itself or defects in the proximity of the adhesive/sealant – adherend interface [43]. Defects within the adhesive/sealant layer cause a reduction in cohesive strength, whereas defects at the adhesive/sealant – adherend interface reduce bond strength. A description of the various defects is given below [43]:

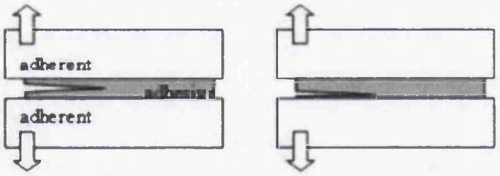
1. Disbonds occur as a result of poor surface preparation, which prevents bonding from taking place at the interface between the adhesive/sealant and adherend.
2. In the case of a zero volume disband, intimate contact is established between the adhesive/sealant – adherend but no bonding exists at the interface.
3. Partial cure resulting in reduced cohesive strength can arise from incorrect mixing of adhesive or sealant components, insufficient cure time, inadequate temperature, UV light or other forms of energy to active the cure mechanism.
4. Porosity and voids are due to volatile substances within the adhesive (such as water vapour), entrapped air or insufficient/incorrect application.
5. Cracking within the adhesive or sealant may happen as a result of incorrect cure or because of the inherently brittle nature of the polymer used. High strength adhesives and those without toughening agents tend to be more brittle and are therefore susceptible to cracking.

2.8 MODES OF FRACTURE

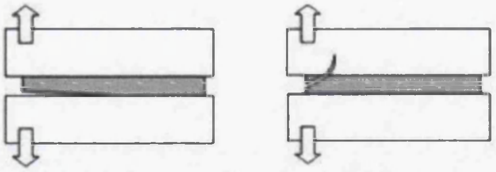
The fracture mode of a joint can be used to assess its quality. Failure of an adhesive or sealant bonded joint can occur in the following places [**Figure 10**].

1. Substrate failure.

2. Coating delamination (if relevant). If the coating – substrate interface is weaker than the adhesive – coating interface then this will dictate the maximum bond strength that can be achieved.
3. Cohesive and surface cohesive failure of the adhesive or sealant material. Surface cohesive failure can be observed in sealant joints with thick bond lines and is caused by large shear and or tension stresses in the sealant material close to the adherend, resulting in failure a thin layer of sealant remaining on the substrate [44].
4. Adhesion or interfacial failure between the adherend and the adhesive/sealant or between any other interfaces in the bonded system (e.g. adhesive/sealant and pretreatment/primer or pretreatment/primer and adherend).
5. Corrosion failure caused by metallic oxide hydration. Failure can occur within the oxidised layer of a metallic substrate, such that the oxide can be found on both the adhesive and substrate side of failure.



"Cohesive" and "cohesive near the interface" fracture



"Adhesive" or "interfacial" fracture

Fracture in the adherent

Figure 10 The modes of fracture/failure of adhesive and sealant bonded joints.

With optimum surface preparation of the bond area, joint failure should either occur within the adhesive bond line (i.e. cohesive failure), substrate or coating and, not at the adhesive-adherend interface. With cohesive, substrate or coating failure, the maximum strength of the adhesive and adherends has been reached and leaves no doubt as to insufficient surface preparation. Whereas interfacial failure generally occurs at lower failure loads and indicates a weak boundary layer, chemical incompatibility, or that an improved surface preparation is needed. Adherend corrosion is not usually a major mechanism of environmental failure. Corrosion of the surface of a metallic adherend is often a post failure phenomenon, occurring after water displacement of the adhesive. Joint failure during testing is usually a combination of failure modes.

2.9 WEATHERING AND ACCELERATED TESTS FOR BONDED JOINTS

The ideal method for weathering or ageing bonded joints would be to age the joints in their respective service environments in real time. However, this is impractical as it could take many years of natural weathering before any significant changes in the failure load and mode of failure are observed. Therefore a method of accelerating the degradation mechanisms is required so that typical failure patterns can be observed in a much shorter time period. This can be achieved using appropriate artificial weathering procedures [45],46]. These artificial weathering techniques are fully controllable and reproducible and are ideal for evaluating and comparing the relative durability performance of adhesive and sealant bonded joints. A combination of environmental factors such as ultra-violet (UV) light, moisture and heat can be used to simulate the required conditions. However, the use of inappropriate test conditions has the added complication of introducing mechanisms of degradation and failure modes that would not occur under normal service conditions.

2.10 MECHANISMS OF ENVIRONMENTAL DEGRADATION

The initial strength of a bonded joint is of little importance if a large reduction in this value is observed on exposure to a hostile weathering environment. Through an appreciation and understanding of the mechanisms of adhesive and sealant bond degradation the results obtained from this investigation can be carefully interpreted. Environmental factors that attack and deteriorate adhesives, sealants and adhesion are oxygen, UV light, temperature and infrared light, and water [47].

The main problem with oxygen and UV light is chemical degradation of the adhesive/sealant polymer, and the incorporation of stabilizers into the adhesive or sealant formula is the solution. Photodegradation initiated by UV light is not usually a problem if both substrates are opaque, although it should be considered when bonding glass or with thick sealant bond lines. At high and low temperatures, adhesive and sealant polymers can pass through their glass transition temperature, which can result in the strength loss of bonded joints [47]. At elevated temperatures (typically caused by infra red light) visco-elastic softening causes a loss of cohesive strength. At low temperatures, the materials become brittle and inflexible. Thermo-mechanical failure due to expansion and contraction cycles caused by changes in temperature can also lead to joint failure. However, of all environmental factors, it is water (either in a liquid or vapour state) that causes the greatest problems in terms of bond durability.

2.10.1 Environmental degradation in the presence of water and moisture

Water is a small, highly polar molecule that can enter a bonded joint by one or a combination of the following processes [47,48]:

1. Diffusion through the adhesive or sealant material. The rate of water diffusion and the maximum water content is determined by the polymer system. However, with time the adhesive/sealant – adherend interface will reach equilibrium with its surroundings irrespective of the intervening adhesive or sealant polymer.
2. Transportation along the adhesive/adherend interface, a process referred to as wicking.
3. Capillary action through cracks and crazes in the adhesive. This process is likely to occur more in joints that have been aged rather than those that are freshly prepared.
4. Diffusion through the adherends if they are porous or permeable.

The kinetics of environmental failure is largely governed by the rate of water diffusion into a bonded joint. Fortunately, water uptake by structural adhesives and sealants often behaves according to Fick's first law of diffusion, which states that the flux in the x-direction is proportional to the concentration gradient [48]. The concentration of water in a joint at any given time increases with temperature and water activity. Having entered a joint, water may cause degradation to the adhesive or sealant material and adhesion in the following ways [47,48]:

1. Altering the properties of the adhesive/sealant in a reversible manner. Plasticisation of the adhesive is such a process. This mechanism of degradation is typically responsible for strength loss during the initial stages of weathering but ceases to be a factor influencing durability once the water uptake reaches a maximum
2. Altering the properties of the adhesive/sealant in an irreversible manner, either causing it to hydrolyse, to crack or to craze. Typically this degradation mechanism requires a longer period of time than plasticisation.
3. Attacking at the adhesive-adherend interface (water disbondment). Water has a strong polar component of surface free energy, which leads to high concentrations of moisture accumulating at the adhesive-adherend interface. This can result in the rupture of secondary bonds.
4. Inducing swelling stresses in the adhesive.

The effect of water on the adherends can also be detrimental to adhesive and sealant bond durability [47,48]. For example, water penetration into a bonded joint with metallic components can lead to oxide hydration which forms a weak boundary layer and results in a loss of bond strength [49]. In addition with permeable adherends such as timber and mortar, water absorption can have adverse effects on the materials structural integrity.

2.11 WORK OF ADHESION

The interfacial free energy of a liquid drop on a solid surface is related by Young's equation [50], which resolves the interfacial tensions in a triangle of forces [**Figure 11**]:

$$\gamma_{sv} = \gamma_{sl} + \gamma_{lv}\cos\theta + \pi_e$$

γ_{lv} – the surface tension of the liquid in equilibrium with its vapour (mNm^{-1})
γ_{sv} – the surface free energy of the solid in equilibrium with the vapour (mJm^{-2})
π_e – the spreading pressure; this is usually small and is often neglected
γ_{sl} – the interfacial free energy between the solid and liquid

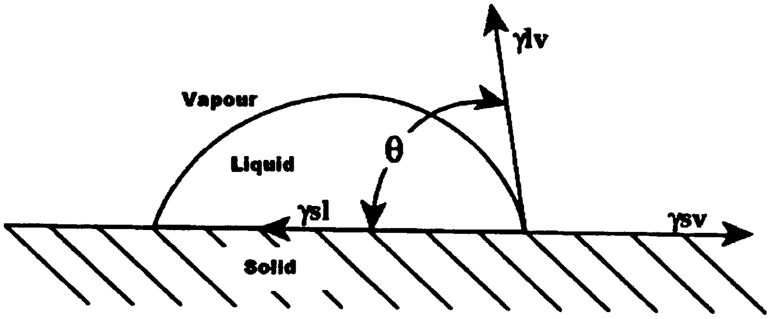


Figure 11 The forces acting at the circumference of a liquid drop on a solid surface.

Returning to the adsorption theory of adhesion, the surface properties of the solid (s) and liquid (l) can be described by their respective surface free energies in terms of the dispersion (γ^d) and polar (γ^p) contributions. An alternative expression to describe the interfacial free energy (γ_{sl}) is [50]:

$$\gamma_{sl} = \gamma_s + \gamma_l - 2(\gamma^d_s\,\gamma^d_l)^{1/2} - 2(\gamma^p_s\,\gamma^p_l)^{1/2}$$

The thermodynamic work of adhesion (W_A), that is the work required to separate a unit area ($1m^2$) of two phases in contact, is related to surface free energies by the Dupré equation [50]. If the phases are separated in dry air then:

$$W_A = \gamma_A + \gamma_S - \gamma_{AS}$$

But if separation is in the presence of water then:

$$W_{A,W} = \gamma_{AW} + \gamma_{SW} - \gamma_{AS}$$

Here the subscripts A, S and W denote adhesive, substrate and water respectively.

Although this parameter does not relate well to practical joint strength, it can be used to predict joint durability. More accurately it can be used to estimate the mode of failure between adhesive and substrate. In dry conditions, cohesive failure is energetically more favourable, which is indicated by a positive value of W_A. However, for wet conditions the locus of failure changes from cohesive to interfacial and is indicated by a negative W_A value. Using this knowledge it is possible to evaluate W_A in the presence of various liquid environments.

2.12 SUMMARY

In general, adhesives and sealants are not surface selective, in that they will bond to most uncontaminated surfaces, with the exception being surfaces which lack polar groups and hence, are of low surface energy. However, to identify the most compatible and durable material combinations, tensile testing of bonded joints is necessary. As water is the most detrimental substance to adhesive and sealant bond durability, the degradation of bonded joints exposed to high humidity at elevated temperatures will be the main focus of experimental work.

In the following section, consideration will be given to the issues associated with adhesive and sealant bonding hot dip galvanised steel and organic coated steel, aluminium, glass, timber and mortar. Typical material properties and construction applications will also be highlighted.

3.0 ADHESIVE AND SEALANT BONDING CONSTRUCTION MATERIALS

3.1 PRECOATED SHEET STEELS

Sheet steels for construction applications have a number of unique characteristics that favour their use; this includes a high strength to weight ratio; prefabrication adaptability and dimensional accuracy and stability. Light-gauge steel products can be grouped into three main categories; decking for concrete composite floors, walls and roofs; profiled cladding and sandwich panels for roofs and walls and; cold formed steel sections for structural and non-structural framing components. Steel composite decking panels and cold formed steel sections are usually formed from zinc coated or galvanised sheet steels that are typically 0.9 – 3.2mm thick, whereas, sheet steels used for cladding and sandwich panels are typically much thinner (0.7mm for roofs and 0.5mm for walls) and, are galvanised and organic coated. The application of metallic and organic coatings provides cathodic corrosion and barrier protection to the steel substrate. Typical yield strengths of the mild steels used for construction applications are between 140 – 220N/mm^2 and tensile strengths approx. 300N/mm^2.

3.1.1 Galvanised or zinc coated steels

Corus produce three types of zinc coated or galvanised steel. These are Galvatite (GI or HDG), Galvanneal (GA or IZ) and Galvalloy (or Galfan). These zinc coatings are applied to strip steels by immersion in a hot dip bath of molten zinc plus any additional alloying elements such as aluminium. The thickness of the deposit is controlled by the use of air knives. A common coating weight for hot dip galvanised steels is 275 grams/m^2; this produces a coating thickness of approximately 20µm. Zinc coated steels are either oiled or supplied with a passivation coating to prevent the onset of corrosion (i.e. white rust) during transportation.

Galvatite is a 98% pure zinc coating. Approximately 0.15wt% - 0.25wt% aluminium is added to the bath chemistry to control the formation of brittle iron-zinc intermetallics at the interface between the two materials. This also forms an aluminium rich oxidized surface layer between 50 – 80Å in thickness. Formation of zinc crystals during the solidification of the coating produces a durable 'spangle' effect on the surface of the steel. Typical construction applications include cold formed steel sections and decking.

Galvanneal is an iron-zinc alloy coating which is mainly used in the automotive sector because of its improved surface finish, enhanced adherence with paint and spot welding properties. Using the same bath chemistry as Galvatite, GA is produced by heating the strip steel to a temperature of 470°C – 500°C immediately after hot dipping. This changes the surface properties as 8 – 9% iron diffuses into the zinc to produce an iron-zinc alloy coating. Galvanneal has a uniform grey appearance without spangle.

Galvalloy is a zinc-aluminium alloy coating which is typically used as the base substrate with a variety organic coated premium products. A modified hot dip bath composition of zinc plus 4.5% aluminium at a temperature of 420°C – 440°C is used to produce this coating. The surface of Galvalloy is a smooth, flat, fine spangle pattern which provides better formability and corrosion resistance than standard Galvatite.

Zinc coatings can also be applied to strip steels by electrogalvanising. This produces a much rougher surface than the hot dip process. These materials are typically used in the manufacture of domestic appliances with a 2.5µm coating thickness but in the automotive sector where extra corrosion resistance is required the coating thickness is increased to 7.5µm.

3.1.1.1 Adhesive and sealant bonding galvanised steels

In general, high levels of adhesive bond strength can be obtained between most epoxy adhesives and a variety of zinc coated steel products. However, epoxy adhesives that contain rosin based tackifiers tend to form soaps with zinc, thus creating a weak boundary layer [51]. Polyurethane adhesives typically produced low – medium failure loads with galvanised steels [52]. In the case of acrylic adhesives, low shear strengths are obtained with both hot dip and electrolytically deposited zinc coatings [52]. This has been attributed to the passivation of reaction radicals by the free zinc, thereby inhibiting the curing process of the adhesive and formation of a weak interfacial layer of zinc acrylate. Higher failure loads have been demonstrated with acrylic adhesives with iron-zinc alloy coated steel [52]. This was attributed to the absence of free zinc in the coating, thereby allowing the adhesives to cure.

Previous research has shown that the initial strength of adhesive bonds with solvent degreased zinc coated steels is dependant on both the coating and adhesive type [52,53,54,55]. In general, higher bond strengths can be obtained with electrolytic zinc coatings than comparable hot dip zinc material. This trend can be partly accounted for by the differences in surface morphology of the various coatings [52]. For example, electrolytically deposited zinc has a fine crystal morphology orientated in the form of platelets, which provides good mechanical interlocking and a large surface area. In comparison, the microstructure of a hot dip zinc coating consists of large zinc crystals which are relatively flat and smooth.

The surface of an iron-zinc alloy coating also has a crystalline microstructure, which consists of columnar and granular phases. Typically the failure loads obtained with bonded iron-zinc alloy joints are lower than those obtained with standard hot dip zinc coated steels. This can be explained by their different modes of failure. Hot dip zinc coated steels tend to fail through the adhesive and at the adhesive – coating interface, whereas, iron-zinc alloy coated joints tend to fail at the coating – steel substrate interface at lower loads [53,55].

Many durability studies have indicated that surface degreasing alone is insufficient to retain high levels of bond strength with zinc coated steel joints when exposed to high humidity at elevated temperature [36, 52]. The durability of bonded galvanised steel joints strongly depends on both the surface morphology and chemistry of the galvanised steel and on the selection of an appropriate adhesive or sealant system [36,52,53,54,55]. In the particular case of hot dip zinc coatings, the segregation of elements such as Al and Pb at the grain boundaries has been shown to be responsible for inter-granular corrosion of zinc which facilitates the formation of a weak boundary layers and joint failure [56]. Removing these elements that are present as oxides improves adhesive bond durability.

Previous research has shown that the electrochemical activity of galvanised steels plays a vital role in both degradation and failure mechanisms [57]. An indication of electrochemical activity is surface corrosion. In general, zinc coated products with higher electrochemical activities demonstrate higher levels of corrosion (i.e. white rust) and lower levels of bond durability. The degradation of galvanised steel joints in the presence of water proceeds by anodic dissolution of the zinc coated substrate [55,57]. Local anodes and cathodes are set up on the surface and the following electrochemical reactions take place:

Anodic reaction $M \rightarrow M^{2+} + 2e^-$
Where M = Zn, Fe or Al...etc.

At the anode, dissolution of the metal takes place. The electrons produced by this anodic reaction are consumed in the cathodic reaction, which occurs adjacent to the anodic area, and involves the reduction of both oxygen and water:

Cathodic reaction $H_2O + 1/2O^2 + 2e^- \rightarrow 2OH^-$
$2H^+ + 2e^- \rightarrow H_2$

The cathodic reduction of water and oxygen leads to the production of hydroxyl ions, which in turn increases in the pH of the electrolyte (water) at the adhesive

– substrate interface. It is this alkalinity that is responsible for the rapid failure of bonded joints as it can lead to:

1. Interfacial separation, this is the classical form of alkaline induced failure and occurs as a result of the ingress of water molecules at the polymer – metal oxide interface.
2. Alkaline hydrolysis of the polymer close to the interface by hydroxyl ions (i.e. saponification), which leaves a very thin layer of polymer adhering to the substrate.
3. Oxide reduction, viz. the dissolution of the substrate oxide phase to which the polymer adheres, leaving a void at the interface and hence blistering.

The application of a variety of surface pretreatments on zinc coated steels has been shown to significantly improve the durability performance of bonded joints exposed to adverse weathering conditions [52,58]. Typical pretreatments used include chromates, phosphates and mixed oxides. The effectiveness of each pretreatment differs with the various zinc coatings and weathering environment. In general chromate pretreatments provide excellent durability in high humidity climates, whereas phosphates provide excellent durability in either salt or combined salt and high humidity environments. No individual generic type of pretreatment gives superior performance in all test environments.

3.1.2 Organic coated steels

Coil coating strip steel is an excellent method for diversifying the appearance and functional characteristics of the materials surface. An organic coated steel product is built up of five individual elements to achieve optimum performance i.e. steel substrate, zinc or zinc-aluminium coating, pretreatment, primer, organic topcoat and backing coat [**Figure 12**]. These layers provide a protective barrier against corrosion to the underlying steel, together with a decorative finish. The main tangible difference between pre-finished steel products is the organic topcoat, which provides properties such as resistance to weathering and water penetration. Organic coated galvanized steels used for construction applications (e.g. wall and roof cladding panels) can be divided into four main chemistries: polyvinylchloride (PVC)-plastisols, polyurethane, polyvinylidene fluoride (PVdF) and polyester.

Figure 12 The protective layers of organic coated steel products [59].

3.1.2.1 Adhesive and sealant bonding organic coated steels

Organic coated steels can be readily bonded with a range of structural and non-structural adhesives to give high shear strengths [6,36,57,60]. For the majority of organic coatings there is a threshold value above which coating failure is the predominant failure mode. The maximum bond strength developed is dependant on both the adhesive type and the particular coating being joined. A study by T. B. Jones [6] showed that epoxy and cyanoacrylate adhesives consistently exhibited high strength levels with PVdF, PVC-plastisol and polyester coated steels. With acrylic adhesives, lower levels of strength were noted with the PVC-plastisol coating than with the other coatings. T.B. Jones postulated that this effect could be due to the absence of metal ions in the PVC-plastisol coating. With certain acrylic adhesives the presence of metal elements on the surface is essential to catalyse the curing mechanism. Medium to high strengths were noted for most polyurethane adhesives with all coatings.

Typically, high levels of adhesive bond durability can be obtained with organic coated steels. Jones et al. suggest this is due to the application of a surface pretreatment and primer to the zinc coated steel base of an organic coated steel product [36,57]. Such pretreatments have been equally effective at enhancing the adhesive bond durability of galvanised steel and aluminium lap joints under conditions of high humidity [52]. In a series of weathering studies, T.B. Jones demonstrated that the high levels of strength retention achieved were independent of the paint system used [6,36,57,60]. However, adhesive selection was shown to have a critical influence on joint durability, with different adhesives exhibiting significant variations in the levels of strength retention and failure mode.

The application of a mechanical or chemical pretreatment on organic coated steels is generally considered inappropriate. This is because an abrasive medium would partially remove the organic coating layer and reduce its ability to protect the steel substrate. Also organic coated steels receive a chemical pretreatment prior to paint application. However, in an attempt to improve the adhesion performance of a glossy polyester coated steel, T.B. Jones mechanically abraded the surface prior to adhesive application [6]. Results indicated that abrasion had little effect on enhancing the bond strength of the polyurethane adhesive system.

3.2 ALUMINIUM AND ITS ALLOYS

The properties of aluminium can vary significantly depending on the alloying elements. For example pure aluminium has a low tensile strength (i.e. approx. 50 – 70N/mm^2), whereas, aluminium alloys can demonstrate high strength to weight ratios (e.g. approx 140 – 170N/mm^2 tensile strength for Al-Mg$_2$Si alloys). In addition, the mechanical properties of aluminium can be further enhanced by cold working or by heat treatment. Consequently, aluminium and its alloys can be used in structural and architectural applications within the construction sector. Typical aluminium alloys used for structural purposes include Al-Mg alloys (i.e. 5251 or 5454 containing up to 2.75% Mg), Al-Mg$_2$Si alloys (i.e. 6061 or 6082 containing up to 1.0% Si and 1.0% Mg) and Al-Zn alloys (i.e. 7020 containing 4.5% Zn and 1.2% Mg).

The surface of aluminium is very reactive and an oxide layer, typically 40 – 80Å thick, forms almost instantaneously when a freshly machined surface is exposed to the atmosphere. Aluminium oxide (alumina Al_2O_3) is very stable and non-permeable and, prevents further oxidation and corrosion of the underlying bulk aluminium. The oxide layer is also cohesively strong and adheres to the base metal with high strength. However, this layer is relatively complex and can be formed in many ways depending on the alloying elements and the conditions present during its formation.

3.2.1 Adhesive and sealant bonding aluminium and its alloys

The surface of aluminium (pure or alloyed) is ideal for bonding as it has a high surface energy when clean and free from contamination, which enables adhesives and sealants to readily wet the bond area. Aluminium and its alloys can be bonded with a wide range of adhesive and sealant systems to give high failure loads without the need for pretreating the surface [61,62]. The initial strength of bonded aluminium joints is primarily dependent on the specific alloy used. Typically joints made with structural aluminium alloys with superior tensile strength and rigidity support higher shear loads than non-structural aluminium grades [61,62].

The durability of bonded aluminium joints is dependent on the corrosion resistance properties of an alloy to a weathering environment. For example, a study by J. D. Minford showed that in a humid environment, more durable bonds were made with pure aluminium (clad over aluminium alloy 2024-T3), than the more highly alloyed surface of 6061-T6 alloy [63]. Furthermore it has been demonstrated that the initial strength and durability of aluminium alloy joints decreased with increasing magnesium concentration, which is present on the surface as an oxide layer [61,62]. This magnesium oxide is readily hydrated on exposure to moisture, which results in relatively poor bonding. However, subsequent work has demonstrated that a low level of magnesium is not the sole criterion for attaining good durability, but that good durability may be unattainable if magnesium levels are high.

In general, solvent degreasing alone is insufficient to provide high levels of strength retention in the presence of high humidity. To obtain strong and durable bonds with aluminium, the surface oxide layer has to be removed and replaced by a pretreatment layer that is continuous and corrosion resistant in wet climates. However, when aluminium is anodised the surface oxide layer is actually retained but is rendered more receptive to bonding [24]. Many studies have shown that an anodised aluminium alloy can constitute a very durable surface for adhesive bonding with excellent resistance to various climates [61,62]. In an extensive review of the mechanical and chemical surface pretreatments used to enhance the durability of aluminium joints, G. W. Critchlow concluded the following [64]:

1. Grit blasting can produce relatively durable joints particularly when exposed to a sea coast environment. In general, grit blasting is outperformed by chromic acid etch treatments (CAE) when joints are exposed to high humidity at elevated temperatures.
2. Of the chemical treatments CAE gives the overall worst results. However, there are instances where CAE has outperformed either chromic acid anodizing (CAA) or chrome conversion coating.
3. Phosphoric acid anodising (PAA) yields either equivalent or as in most cases better durability results than CAA treatment in crack propagation tests (i.e. the Boeing wedge test). However, in lap shear tests both treatments are shown to demonstrate an equivalent performance.
4. Chromate based conversion coatings when optimised can produce durable alp shear joints when compared to PAA or CAA treatment.

Many of these surface pretreatments (e.g. anodising) involve multiple cleaning stages, require precise control and are generally considered too expensive for construction applications.

The main concern with joining aluminium alloy to precoated sheet steel is the differential rates of thermal expansion. The linear expansion coefficient for aluminium is approximately double that of mild steel (i.e. 23×10^{-6}/K and 11×10^{-6}/K respectively). At elevated temperatures it is anticipated that this mismatch in physical property will generate a stress gradient across the thickness of the bond line, which could lead to premature joint failures. Further concerns arise with galvanic corrosion. This is the additional corrosion that occurs when dissimilar metals are in contact in the presence of an electrolyte (e.g. water).

3.3 GLASS

The use of glass as a building material has experienced dramatic changes over recent years. Traditionally glass is used in facade openings for its light transmitting qualities. However, new processes continue to increase the material's strength while advances in the field of lamination enable glass to be used as a structural element. Also, integration of glass facades with climate control is possible with the use of low-emissivity, photovoltaic and variable transmission 'smart' glass products [65]. As a result of these developments in manufacturing technology, glass has been identified as the biggest threat to steel to be the leading construction material [66]. Three types of glass that are commonly used in the construction industry are float, toughened and laminated glass. All products have the same chemical composition (i.e. soda-lime-silica) but toughened and laminated glasses undergo further processing than annealed glass to enhance their strength **[Table 4]**. For construction purposes, glass typically ranges from 3 – 12mm thick.

Table 4 A typical composition of float glass.

Silica (SiO_2)	Soda ash (Na_2CO_3)	Limestone ($CaCO_3$)	Dolomite ($MgCa(CO_3)_2$)	Alumina (Al_2O_3)	Iron oxides (Fe_2O_3)	Other
72.6	13.0	8.4	4.0	1.1	0.11	0.79

In the glass manufacturing process, a ribbon of molten glass at approximately 1100°C flows continuously over a refractory spout from a furnace onto a large shallow bath of molten tin [67]. Due to the difference in surface tension between the two materials, the glass floats on the tin, spreading out and forming level parallel surface on both sides. As the two surfaces of the molten glass (air-side and tin-side) are in contact with different mediums during manufacture, they develop different physical and chemical properties. These differences are due to the absorption of 2 – 3% tin (Sn^{2+} and Sn^{4+}) onto the lower surface [68]. Such differences are illustrated by the fact that the tin-side of glass is more hydrophobic (absorptive), surface reactive (both due to a higher OH density) and resistant to hydrolytic degradation than its air-side [69].

3.3.1 Adhesive and sealant bonding glass

The high energy surface of glass can be readily bonded with a wide variety of adhesive and sealant systems without the need for chemical pretreatments. However, prior to bonding, it is important to thoroughly clean glass components to remove the polymethylmethacrylate powder coating (Lucite) that is often applied to the surface in order to prevent corrosion during transportation and storage [70]. With regard to adhesive and sealant selection, when bonding glass structures consideration should be given to the resistance of the bonding medium to ultra-violet light (UV) degradation (i.e. photodegradation). The most common bonding systems used are one-component, moisture curing silicone sealants, which have excellent resistance to UV light degradation [71]. In contrast, polyurethane sealants (and adhesives) suffer from photodegradation so when used to bond glass a primer or protective barrier is required to inhibit UV light. In addition to the more common adhesives, UV curing adhesives (e.g. acrylic) can also be used for bonding glass structures and should be considered for high volume production when a rapid curing process is required [72]. With regard to aesthetic appearance, transparent bonding systems (e.g. acrylics and polyurethanes) can be used to create invisible joints.

The key issue with adhesive and sealant bonding glass is that the silicon-oxygen bond on the materials surface is susceptible to hydrolysis in warm, wet environments. The corrosion reaction/mechanism between water and the surface of float glass occurs in two stages; ion leaching and layer deposition [73]. The first stage consists of a diffusion controlled process, where a proton or hydronium anion from the water penetrates into the glass network replacing an alkali ion, which diffuses into the water solution. The dealkalization of glass results in an increase in surface pH. At a pH value greater than 9, the breakdown/decomposition of the glass silica network near the surface begins and proceeds at a fast rate. It is believed that this mechanism (breakdown of siloxane bonds at high pH values) is responsible for the extremely poor durability of bonded glass joints in the presence of moisture. In general, a chemical pretreatment is required to enhance the durability of bonded glass joints. The most common types available are silane coupling agents that contain both organic and inorganic reactivity in the same molecule. These pretreatments react with the materials surface to form covalent bonds across the interfaces that are both strong and durable.

An investigation into the effect of float glass composition on sealant adhesion concluded that combinations of certain chemical elements did appear to influence bond durability [70]. Low levels of sodium (Na) and potassium (K) resulted in higher levels of strength retention, although higher surface concentrations of these ions were tolerated when the glass surface was also rich in aluminium (Al) ions. Poor adhesion resulted when high levels of alkaline Na or K oxides were combined with a low level of Al. In addition, no correlation was observed between the hydrolytic stability (surface orientation) of float glass (air-side or tin-side) and adhesion/ sealant durability.

The biggest concern with joining glass to organic coated steels is the vast difference in mechanical properties. Glass differs from other building materials in respect of it being very brittle. The application of a force produces elastic behaviour only; the absence of any plastic deformation leads to the susceptibility of localised stresses and a vulnerability to flaws. Consequently, it is anticipated that adhesive bonded glass joints will fail at relatively low loads compared to a precoated steel joints.

3.4 TIMBER

Timber has been used for centuries as a construction material because of its high strength to weight ratio in tension and compression, availability and workability. In general, wood is either used in solid timber sections, or it is processed into board materials (e.g. ply and orientated strand board). Prior to use in construction applications, solid timber sections are stress graded to ensure the material meets the necessary standards. Typically, timber sections are used in light – medium load bearing applications such as roof trusses, partitions, screens, floors and wall panels. Solid timber sections can also be used for heavy constructional purposes where availability and cost are favourable. However, the general need for larger and stronger structural members has been met largely by the development of modern structural composites such as laminated veneer lumber and glulam members [74].

The structure of timber is built up of cells that are composed of cellulose and hemicellulose which are bonded into fibres by lignin [75]. As a natural product, material properties vary widely between different species, between trees of the same species, in different parts of a tree and in different directions [**Figure 13**]. Furthermore, the properties of timber vary with its moisture content i.e. as the moisture content rises, the timber strength decreases. Therefore the lumber from a freshly cut tree which contains approximately 50 – 100 % water must be carefully dried (seasoned) before it can be used. Typical moisture contents for timbers used in construction are 16% for prefabricated buildings and external joinery and, 15% for bonded construction or internal joinery.

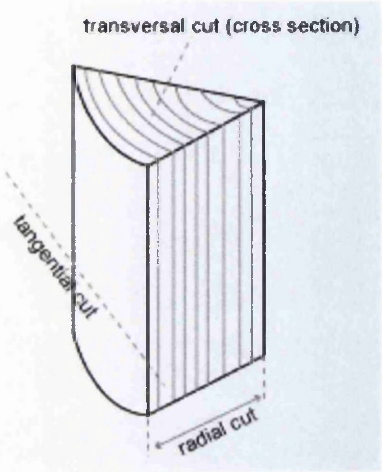


Figure 13 Transversal, radial and tangential cross cut sections of wood.

3.4.1 Adhesive and sealant bonding timber

The surface of timber can be readily bonded with a wide variety of adhesive and sealant systems without the need for surface pretreatments [76]. The most common types of adhesives used to assemble wooden structures include resorcinol – formaldehyde, phenol – formaldehyde and urea – formaldehyde [77]. As in most cases, secondary bonds (i.e. van der Waals forces) and mechanical interlocking largely contribute to the strength of bonded timber joints. If the adhesive or sealant material has a low viscosity then it is more capable of penetrating into and between the cellulose fibres where intimate contact will be established and mechanical interlocking takes place once cured [76]. The heterogeneous, anisotropic, porous and hygroscopic characteristics of timber can affect the performance of bonded joints in the following ways [76]:

1. The porous structure of timber allows liquid adhesives to penetrate into the surface and form a 'key' when cured. However, with highly porous woods (e.g. pine) adhesives may be completely absorbed into the surface, which will result in bond starvation and low bond strength. In order to prevent this, a thicker bond line is required. Alternatively, with low porosity woods (e.g. rosewood), it may be necessary to abrade the bond area in order to

allow some penetration of the adhesive or sealant material into the cellular structure of wood.

2. All timber fibers are aligned in one direction and will therefore have different properties and appearance according to the way in which the wood is cut. As radial and tangentially cut timber sections are mechanically stronger, less absorptive and more stable than transversally cut timbers they produce stronger, more durable joints. In general, adhesive bonding of transversal cross cut sections (i.e. end grain) should be avoided.
3. Wood can absorb or lose moisture according to the temperature and humidity of ambient air and will stabilize at an equilibrium value. The cells enlarge and shrink during these variations so that the shape and dimensions of the timber will also vary. Therefore, when bonding wood it is necessary to dry it to a humidity content that is appropriate for the end use.
4. The surface of wood is subject to self contamination and surface inactivation, which results in a loss of bond strength. Several changes to the surface condition of wood are known to occur over time: oxidation of the surface during exposure to high temperature, migration of extractives to the surface (e.g. oils, resins and tannin), modification of cellulose/lignin ratio and acidification of the surface. Such changes not only interfere with wetting and adhesion but can also interfere with the development of cohesive strength within an adhesive or sealant.

Both mechanical and chemical pretreatments can be used on timber surfaces to improve bond strength and durability. Migration of resin to the materials surface forms a weak boundary layer and must be mechanically removed either by sanding or planing prior to bonding. Mechanical abrasion also removes other contaminants that cause bonding problems (e.g. weathering, fungi, fire and insect treatments) and exposes a fresh surface. High viscosity primers (e.g. an epoxy) can be used to enhance adhesion by sealing the surface of timber and preventing moisture from within the substrate attacking the adhesive/sealant –

timber interface. The application of adhesives or sealants to timber should always be made immediately after surface preparation before changes occur at the surface.

The greatest concerns with joining timber to precoated sheet steels are the differential mechanical and physical properties of the two adherends. It is anticipated that timber substrate failure will be the critical factor limiting the ultimate failure load of a timber – steel joint. Furthermore, the porosity and hygroscopic nature of timber and its ability to swell are expected to restrict the durability of multi-material joints in a humid environment.

3.5 CEMENT, MORTAR AND CONCRETE

The term 'cement' is often applied to certain inorganic adhesives. However, this section is concerned with the cements used as a binding agent to make mortar and concrete. The most widely used cement is Ordinary Portland Cement (OPC). This type of cement is hydraulic and depends upon water for its strength development (i.e. the water: cement ratio). The addition of sand to cement and water produces a substance known as mortar, whereas the addition of a coarse aggregate such as stone produces concrete. Besides the W/C ratio, the strength of these materials is also dependent on the quantity and type of aggregate, blend consistency, compaction and, curing time and conditions. Mortars and concretes have excellent compressive strength but have limited resistance to tensile forces. Mortar is generally a less durable material than concrete because it has a higher porosity and, lower hardness and abrasion resistance.

Cement, mortar and concrete are the most frequently used materials in the construction industry. Infrastructures such as roads, bridges, buildings, airports, sewers, canals and dams are all built using these materials. Typical forms of concrete are blocks, beams and slabs. Mortar is used as a bonding medium to distribute structural loads between concrete and other masonry structures.

3.5.1 Adhesive and sealant bonding mortar and concrete

Mortar and concrete substrates are deceptively difficult to join with adhesives and sealants because they have several surface characteristics that are hazardous to bonding and sealing [78]. The main factors that contribute to the problems associated with bonding cement based products are:

1. The surfaces of mortar and concrete are extremely alkaline and will destroy any hydrolysis sensitive materials that are present at the interface.
2. It has a friable surface, which must be penetrated or removed prior to bonding. This should be achieved without causing cracking and sub-surface damage. The condition of the new surface should not be excessively irregular or undulating as this will require filling.
3. Mortar and concrete are hygroscopic and can absorb and retain moisture/water. Pure water has no direct chemical effect on mortar and concrete but can cause leaching of soluble constituents. However, rain water can dissolve calcium carbonate which is the binding agent of lime. Prior to bonding, the surface should be dried so that its water content is preferably below 4%.

With regard to adhesive and sealant selection, materials used for bonding mortars and concretes should be able to cure in the presence of moisture. However, some moisture curing sealants release acetic acid as a by product of the curing process [71]. This can cause surface corrosion problems with the formation of water-soluble salts at the interface and loss of adhesion during rain. To avoid this, moisture curing sealants that release less or non-corrosive by-products should be used.

The generation of a sound surface undamaged by the method of treatment is necessary for reliable bonding. As stated above, mortar and concrete has a weak surface layer that must be penetrated and removed before being bonded. The substrates surface should also be free from contaminants such as laitance (a cement rich skin), oils, waxes, greases, and curing compounds. A multiplicity of surface pretreatments exist for mortar and concrete, this includes mechanical abrasion (e.g. wire brushing and grit blasting), acid etching (e.g. 10-15% dilute solution of hydrochloric acid) and high viscosity primers (e.g. an epoxy) that consolidate and moisture proof the surface [79].

The main concerns with adhesive bonding mortar to galvanised steel are the significantly different mechanical properties. Due to the friable nature of mortar, it is anticipated that failure of bonded joints will occur within the mortar adherend at relatively low loads in comparison to adhesive bonded steel joints.

4.0 EXPERIMENTAL PROGRAMME

4.1 MATERIAL DETAILS AND CHARACTERISATION

Adherends

Due to demand on coil coating manufacturers to provide longer functional performance guarantees against corrosion and photodegradation, coating formulations are continually being modified. The inclusion of additives in a coating formulation can have profound effects on the surface properties exhibited by a precoated steel product, which can significantly alter the ability to bond these materials. Consequently this experimental programme has incorporated a wide variety of the latest precoated steel products including three different types of hot dip galvanised steel (i.e. non-passivated and, chrome and vanadium passivated), and eight organic coated steels (i.e. four polyurethane, two polyester, polyvinylidene fluoride and polyvinyl chloride-plastisol organic topcoats). Details of all pre-coated steel products are shown in **Tables 5 and 6**. Dissimilar materials selected were aluminium alloy, glass, timber and mortar. Details of these materials are shown in **Table 7**.

Table 5 Galvanised steel details.

Galvanised steel substrate	Substrate thickness (mm)	Zinc coating weight (g/m^2)	Passivation coating weight (mg/m^2)		
			Cr	Va	Ti
Non passivated (HDG)	1.0	293	/	/	/
Chromium passivated (HDG$_{Cr}$)	1.5	291	24.2	/	/
Vanadium passivated (HDG$_{V}$)	1.0	293	/	55.6	7.8

Typical mechanical properties: Yield – 288N/mm^2, UTS – 386N/mm^2.

Table 6 Organic coated steel details.

Organic coating			Substrate thickness (mm)
Chemistry and colour	**Thickness (µm)**	**Primer**	
PVdF – dark grey	21	polyester	0.7
PVC-plastisol – light grey	200	acrylic	0.7
Polyester top coat – white	20	polyester	0.5
Polyester backing coat – grey	10	polyester	0.7
Polyurethane – black	25	polyurethane	0.5
Polyurethane – green	25	polyurethane	0.7
Polyurethane – white	25	polyurethane	0.5
Polyurethane – metallic effect	25	polyurethane	0.5

Typical mechanical properties: Yield – 288N/mm^2, UTS – 386N/mm^2.

Table 7 Dissimilar material details.

Dissimilar material	Substrate thickness (mm)	Description
Aluminium 6082T6	3	Aluminium-magnesium-silicon alloy (Al-Mg_2Si) in the fully heat treated condition (i.e. artificially aged and precipitation hardened). Alloy composition - 1% Si, 0.9% Mg and 0.7% Mn. Tensile strength 310 MPa.
Float glass	6	Soda-lime-silica composition. The edges of glass were ground to remove any cutting defects and imperfections that would generate localised stress concentrations.
Timber	9	Tangentially cut pine. Surface planed and smoothed with fine grit abrasive paper.
Mortar	12	Mortar components: ordinary Portland cement (C), sand (S) and water (W). Ratio by mass 1C: 3S and W/C 0.5. Surface prepared in accordance to method M1, BS ISO 13640:1999 [80].

Structural adhesives and sealants

The structural adhesives selected for this investigation include a range of two-part, room temperature cure epoxy, polyurethane and acrylic systems. In addition to construction and glazing sealants, two automotive sealants were selected for assessment as they are often used for joining galvanised steel, organic coated steels and glass in automotive applications. All structural sealants used were one-component, moisture curing systems and include silicone, polyurethane, MS polymers and hybrid types. These materials were chosen because of their different chemistries, moduli and cure rates. Details of these products are shown in **Tables 8 and 9**. With the exception of acrylic adhesive A1, all two-part adhesives were dispensed via a mixing nozzle using a hand held applicator. The two components of acrylic adhesive A1 were applied separately onto the two joint components before being brought into contact.

Table 8 Structural adhesive details.

Adhesive type	Identity code	Resin/ base and hardener/ activator	Handling strength	Full strength
Epoxy	E1	Epoxy/Amine	8-12 hours	7 days
Toughened Epoxy	E2	Epoxy/Polyamide	6-8 hours	3 days
Polyurethane	P1		8 hours	3 days
Polyurethane	P2	Polyol/Isocyanate	1 hour	1 day
Transparent Polyurethane	P3	Polyol/Isocyanate	2 hours	7 days
Acrylic	A1	/	2-5 minutes	1 day
Acrylic	A2	Methyl methacrylate	3-5 minutes	1 day
Acrylic	A3	Methyl methacrylate	15-20 minutes	36 hours

Table 9 Structural sealant details.

Sealant type	Resin/base	Identity code	Cure rate and conditions
Glazing sealants	Silicone	S1	25˚C, 50% RH for 72hrs → 3.5mm cure depth
	Silicone	S2	23˚C, 50% RH for 72hrs → 4.5mm cure depth
Constructional sealant	MS hybrid polymer	H1	20˚C, 65% RH for 24hrs → 2.5mm cure depth
	Hybrid silicone	H2	23˚C, 50% RH for 3wks → 3.0mm cure depth
	Hybrid polymer	H3	20˚C, 65% RH for 24hrs → 2.5mm cure depth
Automotive sealant	Polyurethane	PS	23˚C, 50% RH for 24hrs → 3.5mm cure depth
	Silane modified polyether	SMP	20˚C, 50% RH for 24hrs → 3.0mm cure depth

Primers and pretreatments

A variety of surface primers and pretreatments were selected for assessment on non-passivated galvanised steel, aluminium, glass, timber and mortar substrates. These materials were evaluated with respect to their ability to enhance both the initial failure load and durability of bonded joints. An acid etch solution suitable for cleaning galvanised steel and aluminium was also obtained. Details of these materials are shown in **Table 10**.

Table 10 Primer and pretreatment details.

Product description	Composition	Details and recommended uses
Acid etch cleaner	Tetrafluoroboric acid (10 - 25%). pH - 2	Acid pickling agent for aluminium and galvanised steel surfaces
Silane primer	Methyl alcohol (99 - 99.9%) Amino silane (0.1 – 1.0%)	For use with galvanised steel, aluminium and glass substrates. Desired coating thickness ~1μm.
Chromate pretreatment	Silicon dioxide (10 - 25%) Dischromium tri-chromate (10 - 25%) Chromium dioxide (2.5 – 7.0%)	No-rinse, dry-in-place Cr/Si complex oxide pretreatment. Use with galvanised steel and aluminium. Recommended coating weight 0.05-0.3g/m^2.
Polymer pretreatment	Hexafluorozirconic acid (1.0 - 2.5%) Hydrofluoric acid (1.0 - 2.5%)	No-rinse, dry in place, chromium free, zirconia polymer. Conversion coating for galvanised steel and aluminium.
Silane pretreatment	No details available	For use with galvanised steel, aluminium and glass substrates.
High viscosity primmer	Epoxy resin base	For use with porous substrates

4.1.1 Surface energy measurements

The surface energy values provided in **Table 11** were calculated from the equilibrium contact angles formed by three liquids on each substrate **[see appendix 1]**. For this study distilled water (polar), glycerol (polar) and di-iodomethane (apolar) were used. Droplets were formed from 10μl of liquid, placed directly onto the flat substrate, and allowed 30 seconds to equilibrate. Images of the droplets were recorded using a digital camera. The contact angle (θ) was measured directly from these images **[Figure 14]**. Twelve angles were recorded from six droplets for each liquid-substrate combination, with the highest and lowest values discarded. All surface energy measurements were provided by the RD&T department at Swinden technology centre, Corus.

Table 11 Surface energy measurements.

Material description	Surface energy γ_S (mNm^{-1})	Standard deviation
Float glass	46.3	0.2
Vanadium passivated HDG steel	46.0	2.0
Polyester backing coat	41.8	0.7
Polyester top coat	39.2	0.4
Chromium passivated HDG steel	38.2	1.3
Polyurethane top coat – white solid colour with smooth texture	37.1	0.1
PVC-plastisol top coat	36.7	1.8
Polyurethane top coat – green solid colour with rough texture	36.2	1.9
PVdF top coat	35.6	3.1
Non passivated HDG steel	34.7	2.7
Polyurethane top coat – silver colour with metallic effect	34.7	0.7
Polyurethane top coat – black solid colour with smooth texture	31.7	1.1
Aluminium	30.2	1.8
Mortar	13.8	0.9
Softwood	-	-

Values for timber are not included as the liquids were absorbed into the substrate too quickly for accurate contact angle determination.

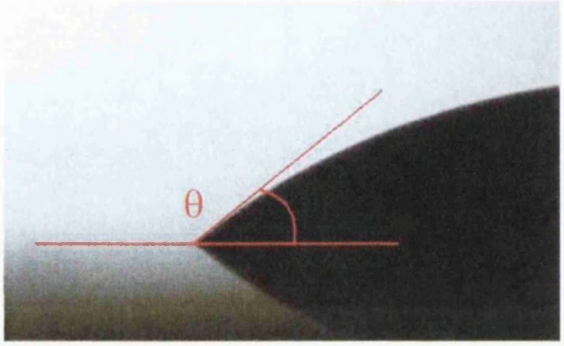


Figure 14 The contact angle formed between a liquid droplet on a solid surface.

4.1.2 Surface roughness measurements

The surface roughness (R_a) values displayed in **Table 12** are the arithmetic mean values of the absolute departures of the roughness profile from the mean line [**Figure 15**]. These measurements were taken over an 8 × 10mm area using a contact profilometer (Taylor Hobson Form Talysurf). This equipment consisted of a 2μm spherical diamond stylus, which was drawn across the material's surface, and followed its contours and irregularities. All surface roughness measurements were supplied by Testing Solutions, ECM^2 materials research centre, Corus. A selection of precoated steel textures is provided in **appendix 2.**

Table 12 Surface roughness measurements.

Material description	Surface roughness, Ra (μm)
Mortar	29.8
PVC-plastisol top coat	7.6
Polyurethane top coat – green solid colour with rough texture	7.5
Softwood	4.0
Polyurethane top coat – silver colour with metallic effect	2.4
Polyurethane top coat – black solid colour with smooth texture	2.2
Polyurethane top coat – white solid colour with smooth texture	1.7
Polyester backing coat	1.4
Non-passivated HDG steel	1.7
Vanadium passivated HDG steel	1.2
Polyester top coat	0.9
Chromium passivated HDG steel	0.8
PVdF top coat	0.8
Aluminium	0.3
Float glass	0.1

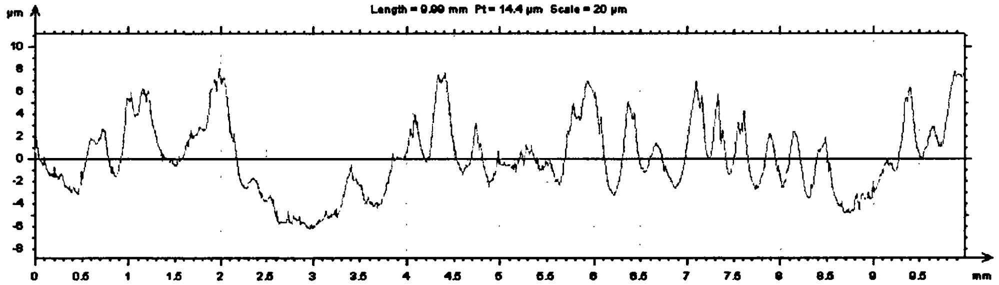


Figure 15 A typical surface roughness profile of an organic coated steel.

4.1.3 Measuring the moisture content of timber

After four weeks of conditioning at room temperature and humidity, ten timber samples with dimensions 50 × 40 × 9mm were accurately weighed and then oven dried (to remove any moisture) at 105°C until they reached a constant weight. The moisture content (r) was calculated using the following equation:

$$r = ((M_r - M_0)/M_0) \times 100\%$$

Where M_r is the moist weight of samples and M_0 is the fully dried sample weight. The average moisture content of the timber was calculated to be 10%.

4.2 TESTING TECHNIQUES

In terms of identifying appropriate adhesive and sealant systems for joining precoated sheet steels to dissimilar materials there are two criteria that need to be established. The compatibility of the adhesive or sealant system, which is a measure of lap shear and tensile strength prior to joint failure and the level of strength retention after weathering. For the latter, the mode of failure also provides an indication of the stability of the bonded system.

4.2.1 Adhesive joint design and weathering conditions

The single lap shear joint was selected as the primary method for assessing the compatibility and durability of structural adhesives on all substrates. Adhesive joints were assembled and tested using BS EN 1465:1995 specifications for guidance [81]. Test specimen geometry and dimensions are illustrated in **Figure 16**. Prior to adhesive application, bond areas were rinsed with acetone for approximately two seconds. The bond-line thickness was controlled by adding 300µm ballotini (glass spheres) to the bond area. Any excess adhesive (spew) was removed prior to curing. During adhesive cure, the adherends were held together with clips until handling strength was achieved. After a one-week cure at room temperature, all adhesive lap joints were post cured at 70°C for one hour. This was to reduce any post cure effects (e.g. further cross linking of the adhesive) occurring during weathering, where the samples were exposed to elevated temperatures, and allows a fair comparison of initial and weathered results. For each adhesive-adherend combination, five identical lap joints were made for both initial and short-term weathering studies. Thirty-six test specimens were required for long-term weathering.

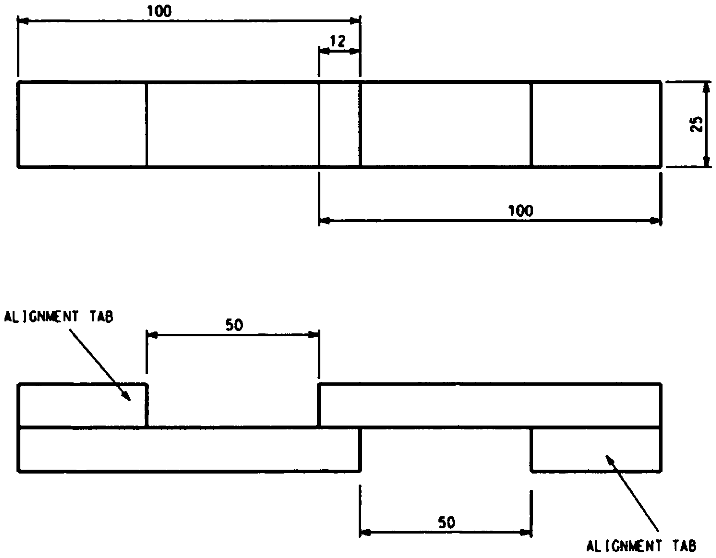


Figure 16 Single lap shear joint dimensions. With thicker adherends, alignment tabs must be bonded to the free ends of the joint components to allow correct alignment of the joint when positioned in the tensile machine.

Short-term weathering procedure

Short-term or accelerated ageing was used to assess and compare the relative durability performance of all adhesive – adherend combinations. This test procedure required adhesive joints to be wrapped in cotton wool and exposed to 100% relative humidity (R.H.) at 70°C for fourteen days. This was achieved by placing the joints into a sealed container with a layer of water in the bottom. The container was then placed in an oven maintained at 70°C. After this heating period, the test specimens were then placed in a freezer at -30°C for two hours. At the end of this time the samples were removed, and allowed to warm up to room temperature before being tensile tested.

Long-term weathering procedure

The most durable pre-coated steel – adhesive combinations identified during short-term weathering were further assessed in a twelve month humidity exposure study to provide more information on the mechanisms of degradation. This test procedure involved exposing adhesive bonded lap joints to 100% R.H. with a temperature cycle of 42-48-42°C every sixty minutes [82]. This study was carried out in a humidity cabinet (C&W Specialist Equipment), where thirty-six lap joints of each adherend – adhesive combination were placed into horizontal racks [**Figure 17**]. The lap joint strength retention was monitored progressively over twelve months by tensile testing three lap joints each month.

Figure 17 Humidity cabinet used for long-term weathering studies. The sets of lap joints were positioned horizontally in slotted racks.

Tensile testing lap shear joints

Tensile testing of lap joints was carried out at the University of Wales, Swansea using a bench top universal testing machine (Hounsfield) with a 50kN load cell capacity [**Figure 18**]. The joints were positioned symmetrically so that the grips were 50mm from the end of the nearest overlap. The crosshead speed of the equipment was set at 2mm/min. The mean average failure loads (kN), standard deviations (σ), and modes of failure are provided in figures and tables.

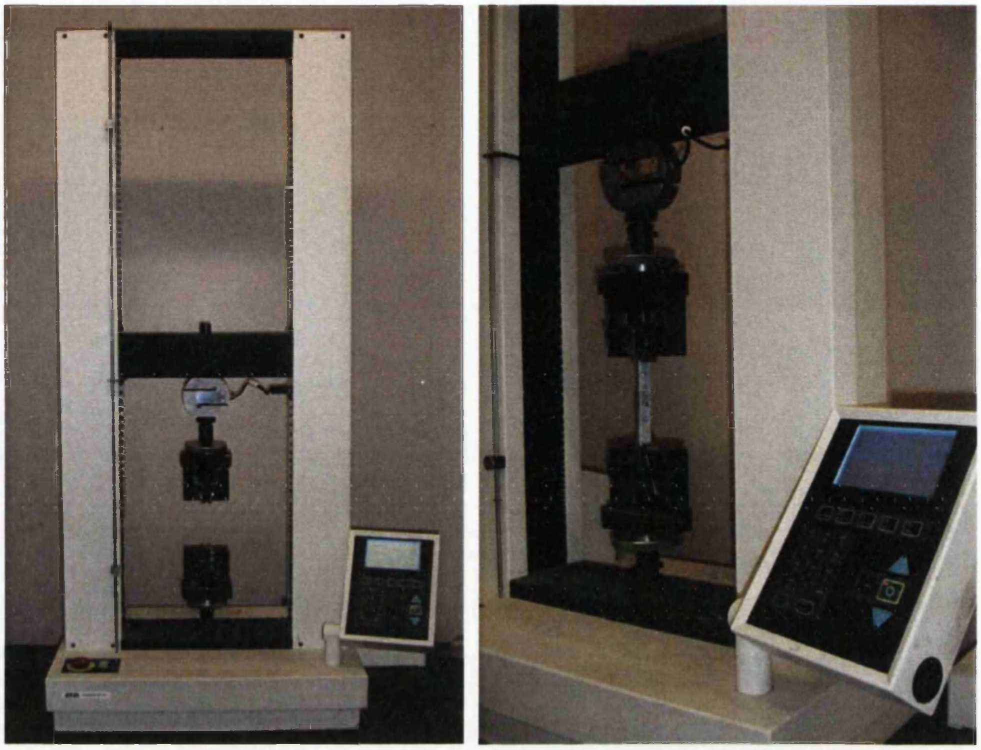


Figure 18 Bench top universal testing machine with a 50kN load cell.

Performance criteria

As the maximum strength of adhesive bonded lap joints is dependent on factors such as the mechanical and surface properties of the adherend and, the modulus of the adhesive, a minimum performance criterion was not set. However, the mode of failure was used as an indicator of bond quality. For example, cohesive, substrate and coating failures were interpreted as good adhesive – adherend compatibility and high bond strength, whereas, interfacial failure was considered as being indicative of poor adhesive – adherend compatibility and low bond strength (unless it occurred at similar or higher failure loads than cohesive, substrate or coating failures). After discussions with relevant experts in the field of adhesive bonding, an acceptable level of strength retention was set at 70% for short-term weathering studies. For long-term weathering, a minimum performance criterion was not defined as these studies were only intended to provide more detail on the mechanisms of degradation.

4.2.1.1 Sustainability – adhesive bonding pre-weathered OCS

The ability to reuse construction materials in new applications avoids unwanted waste when a building or product has reached the end of its life cycle. This limited investigation assessed the potential for recycling and reusing pre-weathered PVC-plastisol and polyurethane (white with smooth texture) coated steels in adhesive bonding applications. These materials were chosen because of their long functional performance guarantees.

Pre-weathering procedure

A vertical QUV accelerated weather tester (Q-panel Company) was used to artificially age the organic coated steels prior to joint assembly [**Figure 19**]. This provided exposure to alternating cycles of condensation and ultra-violet light at 40°C. Fluorescent UV-A lamps were used to simulate ultra-violet light radiated by the sun. The weathering cycle was set at eight hours UV-A exposure followed by four hours of condensation; this allowed two complete cycles in one day. Organic coated steel samples were removed and adhesive bonded after 1500, 3000, 4500 and 6000 hours of exposure.

Figure 19 A vertical QUV weathering station.

4.2.2 Sealant joint design and weathering conditions

The H-joint configuration was chosen as the primary method for assessing the compatibility and durability of structural sealants on all substrates. Sealant joints were assembled and tested using EOTA ETAG 002 part-one specifications for guidance [83]. Prior to joint formation, bond areas were rinsed with acetone for approximately two seconds and the 12mm thick wooden spacers used to control the bond line were coated with wax. For each joint, two adherends and two spacers were assembled and held together using fold back clips. The rectangular void formed between the substrates and spacers was then filled with sealant. Test specimen geometry and dimensions are illustrated in **Figure 20**. Samples were cured for thirty days at room temperature before either tensile testing or weathering. In total for each sealant – substrate combination fifteen H-joints were required; five for initial assessment and ten for weathering.

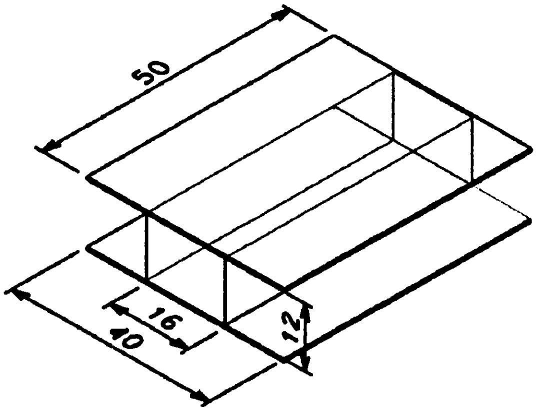


Figure 20 H-joint configuration and dimensions.

Weathering sealant joints – water immersion and UV light exposure

For H-joints with metallic substrates, weathering involved immersing the H-joints in water maintained at 45°C for periods of twenty-one and forty-two days. The depth of water was kept level with the upper substrate surface. After twenty-one days of immersion, five test specimens were removed from the weathering environment and conditioned at room temperature for twenty-four hours before tensile testing. After a further twenty-one days the five remaining samples were removed and again tensile tested after conditioning.

However, for H-joints with glass substrates, samples were simultaneously exposed to warm water at 45°C and ultra-violet light. This was carried out in a horizontal QUV accelerated weather tester (Q-panel Company) as shown in

Figure 21. Fluorescent UV-A tubes (wavelength 300-340nm) were used to simulate sunlight in the UV region. UV-A lamps were repositioned within the QUV machine every 400 hours and replaced every 1600 hours. This ensured that all samples were exposed to the same intensity levels of UV-A light.

Figure 21 A horizontal QUV weathering station.

Tensile testing structural sealant H-joints

Tensile testing of H-joints was also carried out at the University of Wales, Swansea using a bench top universal testing machine (Hounsfield) with a 50kN capacity load cell. A custom made jig was used to hold the H-joints in the tensile testing equipment; this test set up is shown in **Figure 22**. The crosshead speed of the equipment was set at 8mm/min. The mean average failure loads (kN), average extension at maximum failure loads (mm), standard deviations (σ), and modes of failure are provided in the figures and tables.

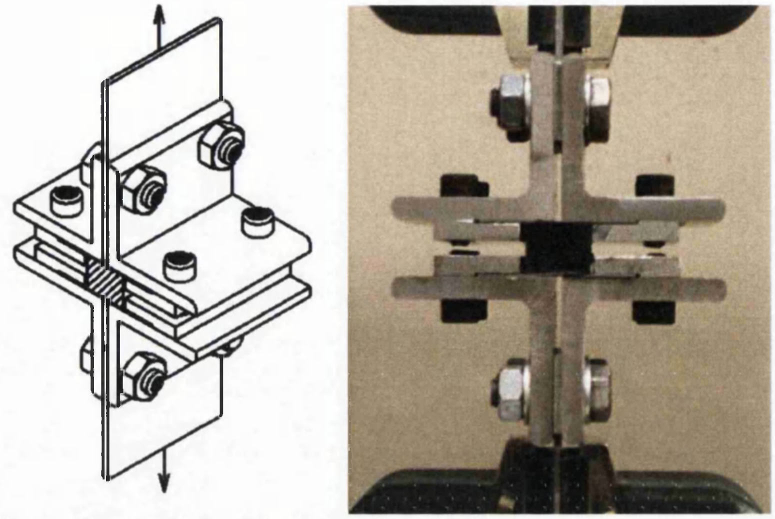


Figure 22 H-joint tensile jig.

Performance criteria

As structural sealants are designed to be flexible to accommodate differential rates of thermal expansion between adjoining materials they fail at much lower loads than structural adhesives. A minimum performance criterion was set at 0.4N/mm^2 or 0.32kN for an 800mm^2 bond area. This is the value specified in BS EN 11600:2003 for the modulus of a structural sealant at 23°C [84]. The durability performance of a sealant bonded H-joint was deemed successful if it failed at a tensile load greater than 0.32kN after 42 days of water immersion and UV exposure (for H-joints with glass substrates only).

4.3 SURFACE PREPARATION, PRIMERS AND PRETREATMENTS

4.3.1 The water break test

The water break test was used to indicate the effectiveness of acetone degreasing as a method to provide consistently clean surfaces with non-porous substrates. This test makes use of the fact that carbonaceous films (e.g. grease) on solids are hydrophobic. When a sample is immersed in a beaker of deionised (or distilled) water and removed, a clean surface will be indicated by a uniform film of water across the surface. If residual contamination is present then the water film will break up into a discontinuous layer.

4.3.2 Acid etch cleaning solution

Prior to the application of surface primers and pretreatments to non-passivated galvanised steel and aluminium, test coupons were dipped into an acid etch cleaning solution that was heated to 40°C in a water bath. The water break test was used to determine the optimum concentration of acid and immersion time for both substrates. For HDG steel, a three minute dipping time in a 5% volume solution (i.e. 50ml of etchant mixed with 950ml of distilled water) was required to produce a uniform film of water across the surface. For aluminium, a five minute immersion time in a 2% volume solution was required

4.3.3 Silane primer

This ready mixed primer was used on non-passivated galvanised steel, aluminium and glass substrates. However, unlike both metallic substrates that were acid etched, the glass test specimens were only acetone degreased prior to primer application. A thin coating of the silane primer was brushed onto the cleaned substrates. Once applied, the samples were then heated in an oven for thirty minutes at 90°C. A pale pink colour indicated an appropriate coating thickness of a few microns.

4.3.4 Chrome pretreatment

This chrome pretreatment was used on non-passivated galvanised steel and aluminium substrates. A 10% volume solution was heated in a water bath to 40°C and brushed onto joint components. Once coated, the samples were heated in an oven to 100°C peak metal temperature (PMT). A pale yellow hue was noted on the substrate surfaces and was indicative of an appropriate coating weight (i.e. 0.05-0.3g/m^2).

4.3.5 Polymer pretreatment

This zirconia polymer pretreatment was used on non-passivated galvanised steel and aluminium substrates. Samples were immersed into a 3% volume solution that was heated in a water bath to 40°C. After approximately ten seconds, effervescence was observed and the samples were removed from the pretreatment and lightly brushed. This was followed by ten minutes of heating at 100°C in an oven.

4.3.6 Silane pretreatment

This ready mixed silane pretreatment was used on non-passivated HDG steel, aluminium and glass substrates. Prior to application, both metallic materials were acid etched, whereas the glass components were degreased with acetone. The pretreatment was heated in a water bath to 45°C; all samples were dipped for approximately two minutes. Once removed, the samples were lightly brushed and then heated in an oven to 80°C for 10 minutes.

4.3.7 High viscosity primer

This high viscosity primer was used on both porous substrates i.e. timber and mortar. Prior to application, dust and loosely bound particles were removed from the materials surfaces. The primer was then brushed onto the substrates and cured for one hour at room temperature before joint assembly.

4.4 SURFACE ANALYSIS TECHNIQUES

In order to fully characterize the failure modes of adhesive and sealant bonded joints, a method more accurate than just visual inspection was required. The use of sophisticated surface analysis techniques such as scanning electron microscopy (SEM), x-ray photoelectron spectroscopy (XPS), Fourier transform infrared spectroscopy (FT-IR) and many more can be used to define the exact locus of failure in a bonded assembly. All SEM and FTIR surface analysis was completed by Testing Solutions in the materials research centre, ECM^2, Corus. All XPS analysis was carried out by the RD&T department at Swinden technology centre, Corus.

4.4.1 Scanning electron microscopy and energy dispersive spectroscopy

A scanning electron microscope (SEM) equipped for energy dispersive x-ray spectroscopy (EDS) was used for two functions; to create high resolution images and to provide elemental analysis. SEM analysis was carried out on a

JEOL JSM840A instrument operating at an accelerating voltage of 20kV and a working distance of 15mm. An Oxford LINK ISIS 300 microanalysis tool was used to detect characteristic x-rays and provide information on the chemical composition of the materials surface.

4.4.2 X-ray photoelectron spectroscopy (XPS)

X-rays were generated using non-monochromatic AlKα radiation from a Thermo Scientific XR3 duel anode X-ray source operating at 15kV power and 10mA current. The XPS experiments were conducted at pressures of $<5 \times 10^{-8}$ mbar at ambient temperatures. A survey scan was recorded over the binding energy range 0 – 1100 eV, with a 0.5eV step size and dwell time of 20ms. A Thermo Scientific Alpha 110 concentric hemispherical analyser was used in constant analyser mode to collect the count intensity. Sensitivity factors were applied to the raw data to produce a quantified surface composition (atomic %).

4.4.3 Fourier transform infrared spectroscopy (FT-IR)

Surface analysis was carried out on a Perkin Elmer system 2000 Fourier transform infrared spectrophotometer with auto image microscope and attenuated total reflectance crystal. Multiple scans for each sample were recorded over the range 4000 – 760 cm^{-1} at a resolution of $8cm^{-1}$.

5.0 RESULTS

In an attempt to simplify the results section, each adhesive and sealant system has been designated an identity code. For example, epoxy – E, polyurethane – P or PS, acrylic – A, silicone – S, hybrid polymer – H and silane modified polyether – SMP. For more details see **Tables 8 and 9**. Also, due to the large matrix of adhesive, sealant and substrate combinations assessed, only the key results and trends will be highlighted. Comments will be made with regard to the initial failure load and mode of failure, strength retention and changes in the predominant mode of failure, surface condition effects and, the influence of adhesive and sealant selection. Details on the modes of fracture are provided in **appendix 3**.

5.1 ADHESIVE BONDED UNI-MATERIAL JOINTS

5.1.1 Galvanised steel

Only epoxy adhesives were assessed with hot-dip galvanised steels because of the known incompatibility of acrylic adhesives and the low – medium bond strength of polyurethane adhesives with zinc. Chromium (HDG_{Cr}) and Vanadium (HDG_{V}) passivated galvanised steels were assessed in the acetone degreased condition while bare galvanised steel (HDG) was also assessed with a selection of surface primers and pretreatments.

Compatibility and short-term weathered – Figure23

Initial failure loads ranged from 3.0 – 5.9kN with galvanised steel joints. Both epoxy adhesives demonstrated high bond strengths with all galvanised steel substrates; in most cases, E2 bonded joints failed at greater loads than E1 bonded joints. Higher loads were supported by both passivated galvanised steel substrates than the bare galvanised steel. At the highest failure load obtained with HDG_{V} steel joints a predominantly cohesive fracture mode was noted. A high incidence of interfacial failure was obtained with HDG and HDG_{Cr} steel joints, which suggests that an improved surface preparation method could be used with these substrates. The application of surface primers and pretreatments to bare galvanised steel had different effects on adhesive bond strength. For example, the silane primed substrate generated higher failure loads with both epoxy adhesives when compared to acetone degreased galvanised steel. Whereas, chrome pretreated, polymer pretreated and silane pretreated galvanised steel substrates only produced higher loads with adhesive E2.

Following short-term weathering, shear failure loads and strength retention values ranged from 0 – 2.4kN and 0 – 68% respectively. In all instances, the durability of adhesive E1 was superior to that of adhesive E2 with all galvanised steel substrates, which highlights the importance of adhesive selection. Significantly higher levels of strength retention were noted with both passivated galvanised steels than the bare galvanised steel. The durability of both epoxy adhesives on HDG steel joints was enhanced by all primers and pretreatments used. Interfacial failure was the predominant mode of fracture with all joints after weathering. In addition, with all galvanised steel products zinc corrosion (i.e. white rust) was noted on the surface of the bond area. This occurred at the joint edges and was only visible on the substrate side of failure. The absence of corrosion from the primed and pretreated joints indicated that the interface between the adhesive-substrate was more stable, inhibiting the hydration of zinc and the formation of a weak zinc oxide/hydroxide boundary.

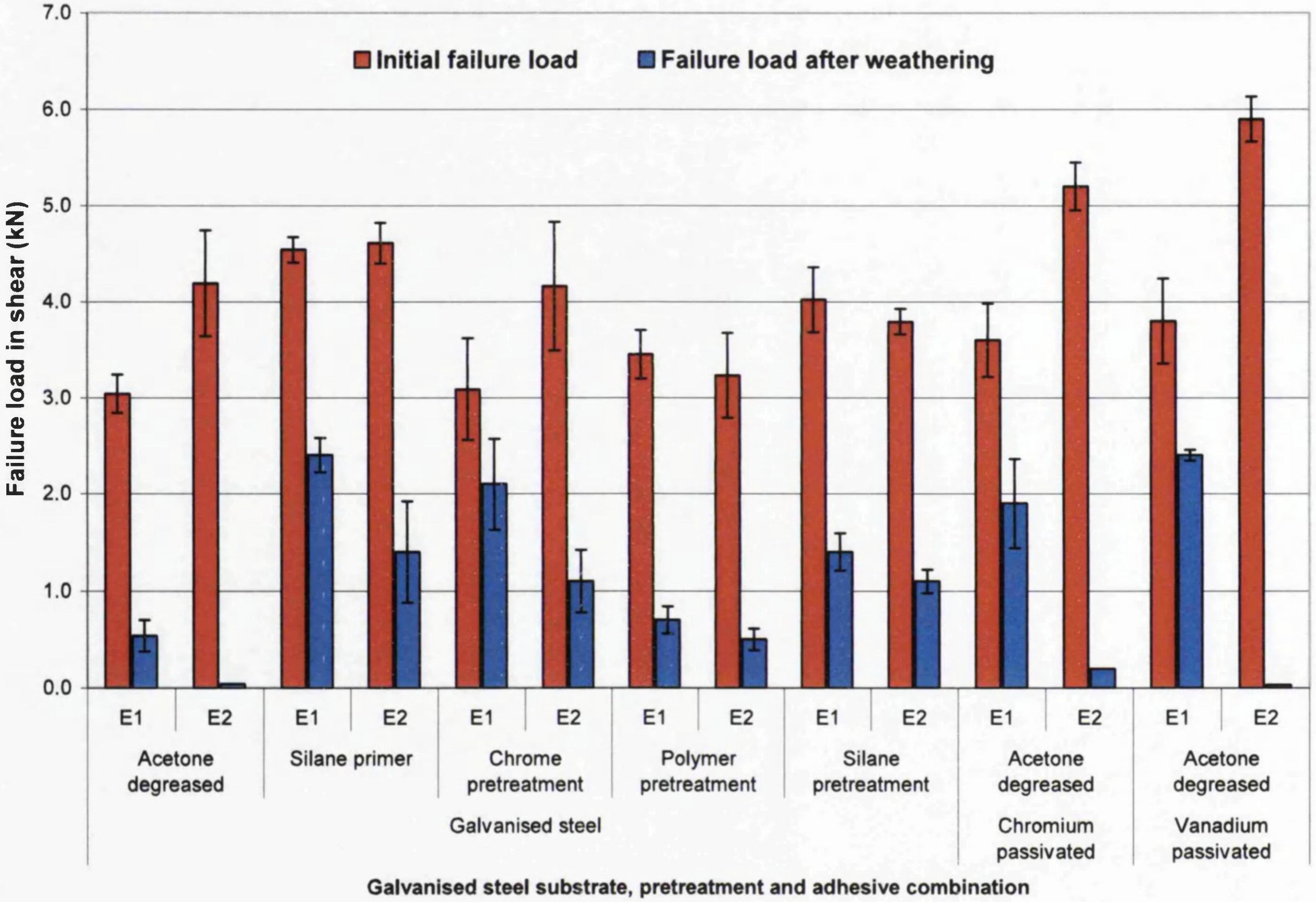


Figure 23 The short-term durability performance of adhesive bonded galvanised steel lap joints.

Long-term weathered

For this study, the durability of epoxy (E1) bonded chromium and vanadium passivated galvanised steel joints was assessed over a period of twelve months. With HDG_{Cr} steel joints, a gradual increase in zinc corrosion (approx. 25%) was noted with a progressive decrease in the shear failure load over 10 months of humidity exposure [**Figure 24**]. This period was followed by a sudden increase in surface corrosion and a total loss of adhesion (i.e. joints failed prior to tensile testing). With HDG_V steel joints, a significant decrease in bond strength was noted with a large increase in interfacial failure during the initial stages of weathering [**Figure 25**]. Afterwards, a gradual development of zinc corrosion (approx. 20%) was noted with relatively constant failure load. In both cases, corrosion of the galvanised steel was first observed at the edges of the bond area and progressively moved inwards [**Figure 26**].

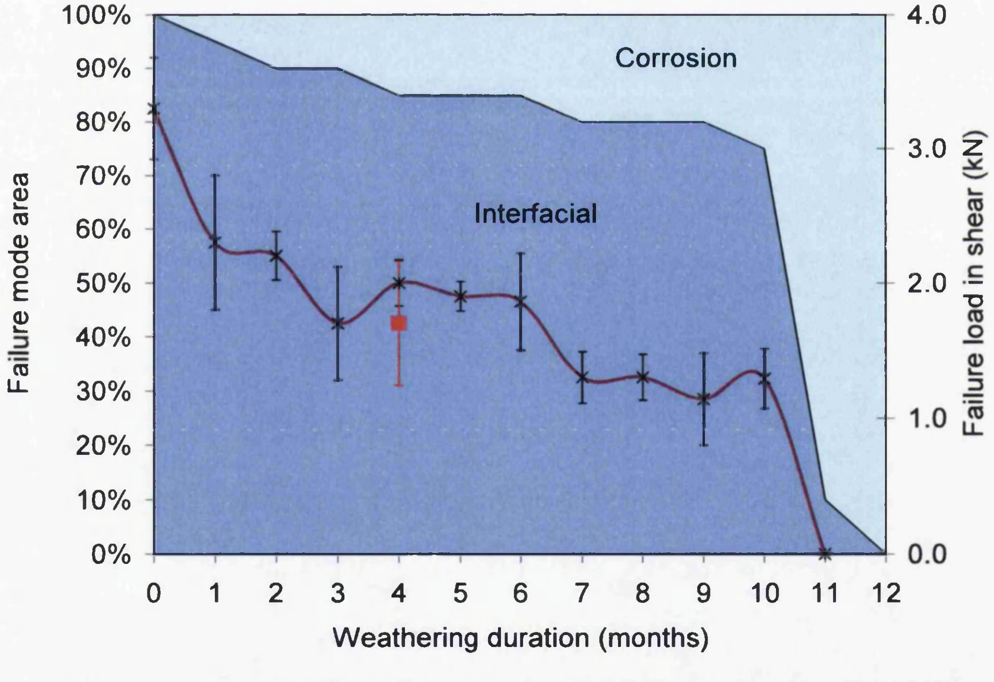


Figure 24 The long-term durability performance of epoxy bonded chromium passivated galvanised steel lap joints. The red datum point shows the equivalent short-term durability performance.

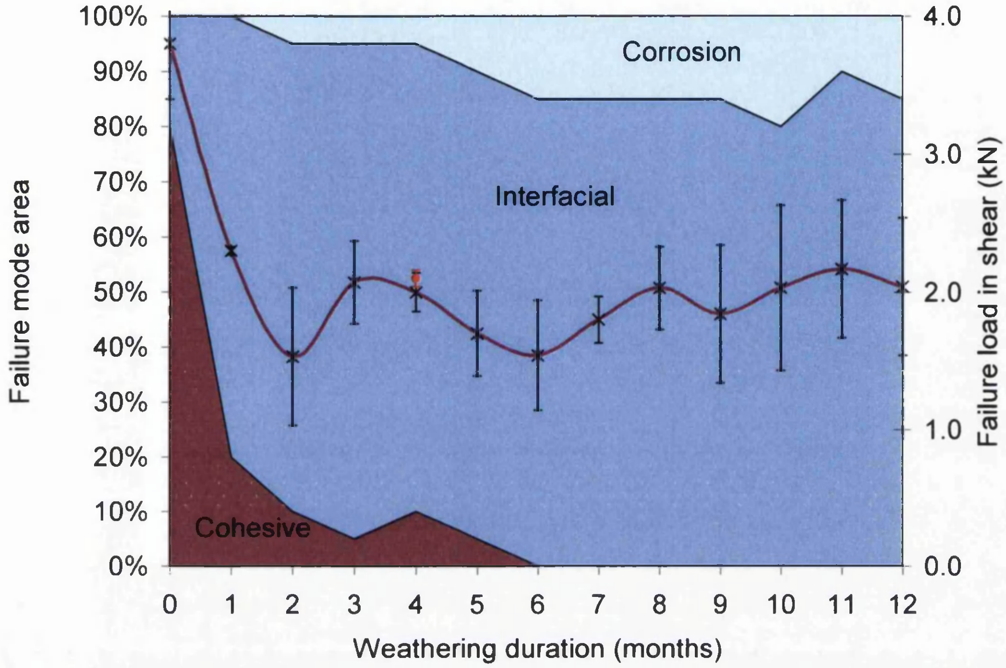


Figure 25 The long-term durability performance of epoxy bonded vanadium passivated galvanised steel lap joints. The red datum point shows the equivalent short-term durability performance.

Figure 26 Zinc corrosion products formed on the bond area of a galvanised steel joint. Corrosion was visible on both substrate (left) and adhesive (right) sides of failure.

5.1.2 Organic coated steels

For initial compatibility and short-term durability assessment, all epoxy, polyurethane and acrylic adhesives were evaluated with all organic coated steel products. Based on these results, the four strongest and most durable adhesive systems were selected for long-term durability studies. All organic coated steel products were assessed in an acetone degreased condition.

5.1.2.1 PVdF coated steel

Compatibility and short-term weathered – Figure 27

High shear strengths were provided by all adhesive types; failure loads ranged from 1.7 – 6.1kN with PVdF coated steel lap joints. At the higher loads obtained with epoxy and acrylic bonded joints, coating delamination [**Figure 28**], cohesive failure and yielding of the steel substrate were noted. At the lower failure loads obtained with polyurethane adhesives, interfacial failure was predominant.

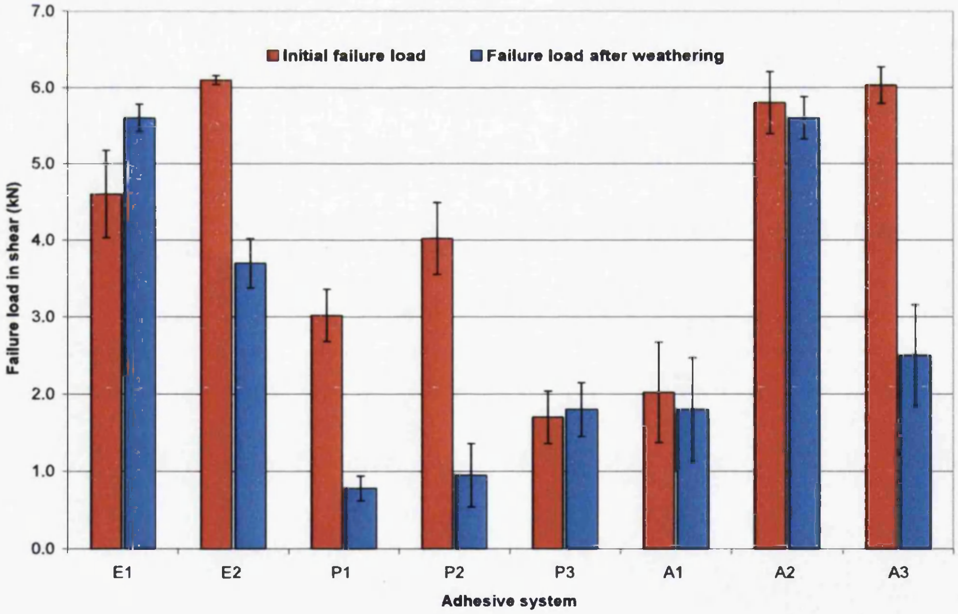


Figure 27 The short-term durability performance of adhesive bonded PVdF coated steel lap joints.

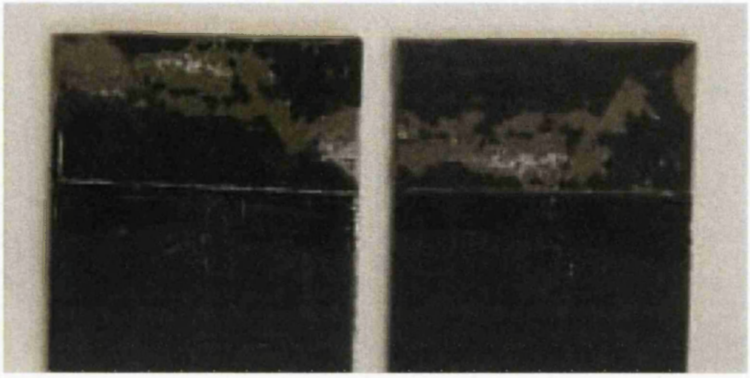


Figure 28 PVdF coating failure.

Following short-term humidity exposure, shear failure loads and strength retention values ranged from 0.8 – 5.6kN and 24 – 122% respectively. Each type of adhesive provided high levels of adhesive bond durability with PVdF coated steel (i.e. greater than 70% strength retention). The different epoxy and acrylic adhesive bonded joints responded in different ways to weathering, whereas strength loss occurred with all polyurethane bonded joints. Both adhesives E1 and A1 increased in strength as a consequence of weathering (i.e. strength retention values were greater than 100%). The mode of fracture of polyurethane bonded joints remained unchanged (i.e. 100% interfacial failure) regardless of the strength retention value, whereas, the poor durability of A3 bonded joints was accompanied by a large increase in interfacial failure.

Long-term weathered – Figure 29

After twelve months of humidity exposure, shear failure loads ranged from 1.5 – 4.5kN. The performance of E1 and P1 joints remained relatively constant during the test duration. Both E2 and A3 bonded joints demonstrated similar reactions to humidity exposure; an initial decrease in bond strength was followed by a relatively steady state. With regard to the mode of fracture, P1 and A3 bonded joints demonstrated predominantly interfacial failure throughout weathering, whereas a change in the primary failure mode was again observed with both epoxy bonded joints i.e. a change from interfacial to cohesive failure occurred.

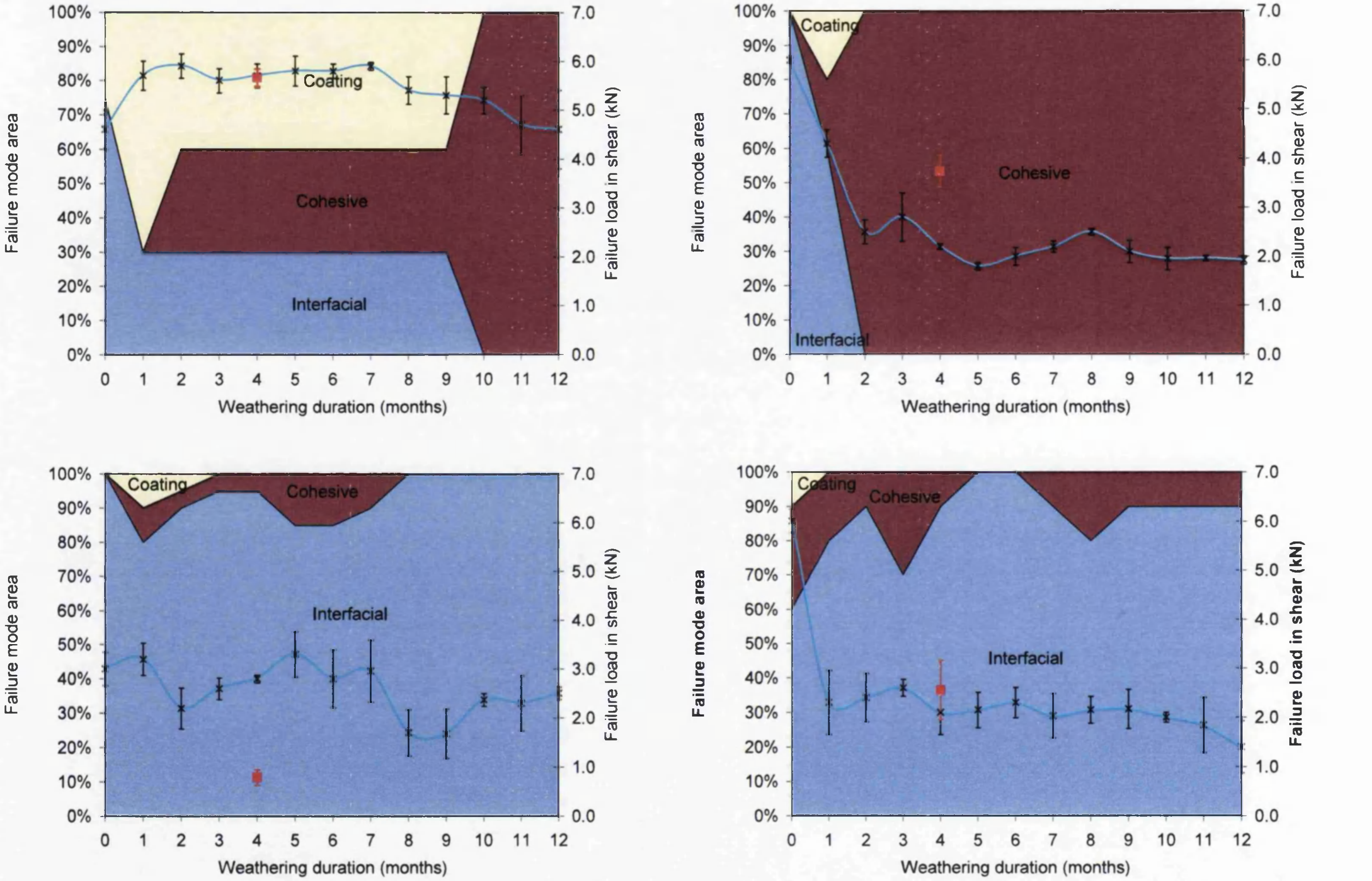


Figure 29 The long-term durability performance of adhesive bonded PVdF coated steel lap joints. Adhesives used – E1 (top left), E2 (top right), P1 (bottom left) and A3 (bottom right). The red data points show the equivalent short-term durability performance.

5.1.2.2 PVC-plastisol coated steel

Compatibility and short-term weathered – Figure 30

High levels of adhesive compatibility were provided by all adhesive types, initial failure loads ranged from 0.1 – 2.4kN with PVC-plastisol coated steel lap joints. At the higher loads obtained with adhesives P1 and A2, coating failure within the thick porous topcoat was predominant [**Figure 31**]. At lower loads, interfacial failure was the primary mode of fracture. The extremely low failure loads of E1, A1 and A3 bonded joints indicated poor adhesive compatibility with the PVC-plastisol coating. Alternatively, the poor performance of adhesive A3 could be due to the absence of metal ions on the PVC-plastisol coating surface. With certain acrylic adhesives the presence of metal elements on the adherends surface is essential to catalyse the curing mechanism [6].

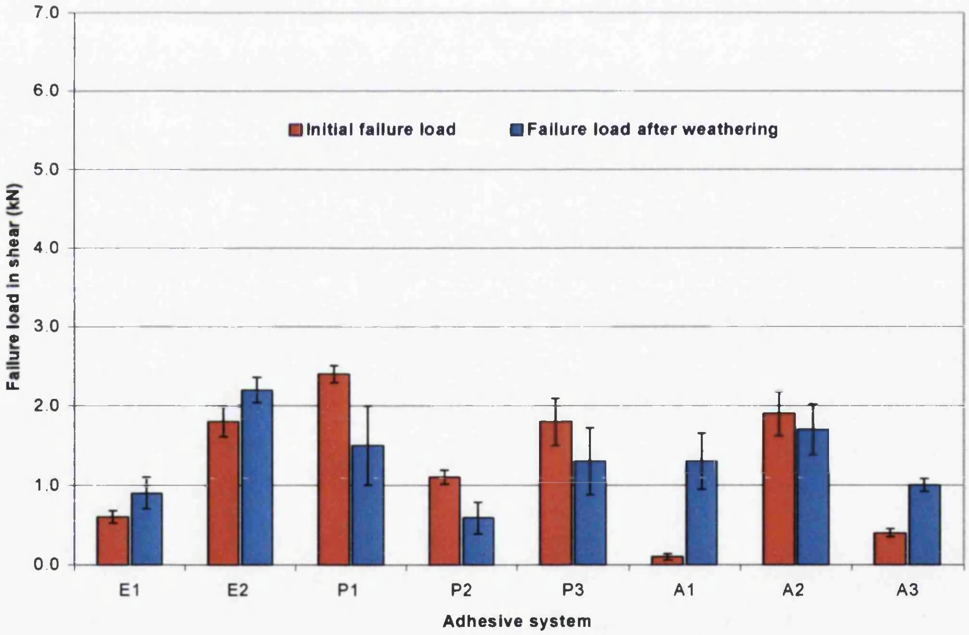


Figure 30 The short-term durability performance of adhesive bonded PVC-plastisol coated steel lap joints.

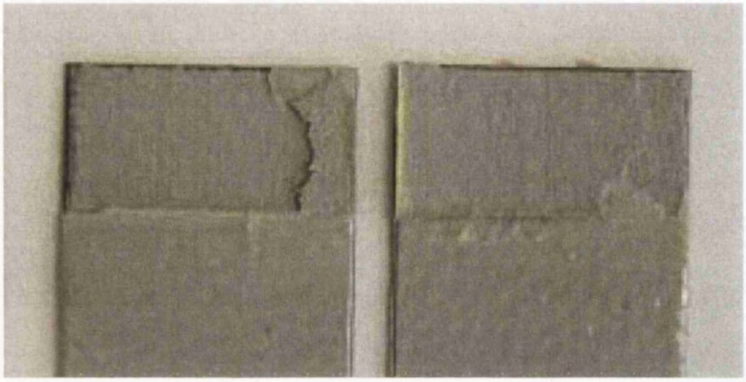


Figure 31 PVC-plastisol coating failure.

Following short-term weathering, shear loads and strength retention values ranged 0.6 – 2.2kN and 56 – 120% respectively. Durable adhesive bonded joints (i.e. greater than 70% strength retention) were provided by all adhesive types on the PVC-plastisol coated steel substrate. The different epoxy and acrylic adhesive systems displayed different responses to weathering, whereas, the occurrence of strength loss and interfacial failure was apparent with all polyurethane bonded joints. This was also accompanied by a change in the primary mode of fracture with P1 and P3 bonded samples.

Pre-weathered PVC-plastisol coated steel lap joints – Figure 32

For this study, adhesive selection was based on interfacial failure being the initial failure mode with PVC-plastisol. This allowed any favourable changes in the failure load and mode of failure to be easily monitored (i.e. a change from interfacial to cohesive or coating failure). Epoxy adhesive E1 satisfied this condition.

Lap joints assembled from pre-weathered PVC-plastisol coated steel showed a significant increase in failure load from 0.5 – 1.5kN after 1500 hours of ageing. This was also noted with the development of approximately 15% failure within thick PVC-plastisol coating. Further analysis providing possible explanations for this observation will be undertaken and discussed in section 12. Further ageing of the PVC-plastisol coated steel prior to bonding showed no further effects on adhesive bond strength, as similar failure loads were obtained with substrates aged for 3000, 4500 and 6000 hours.

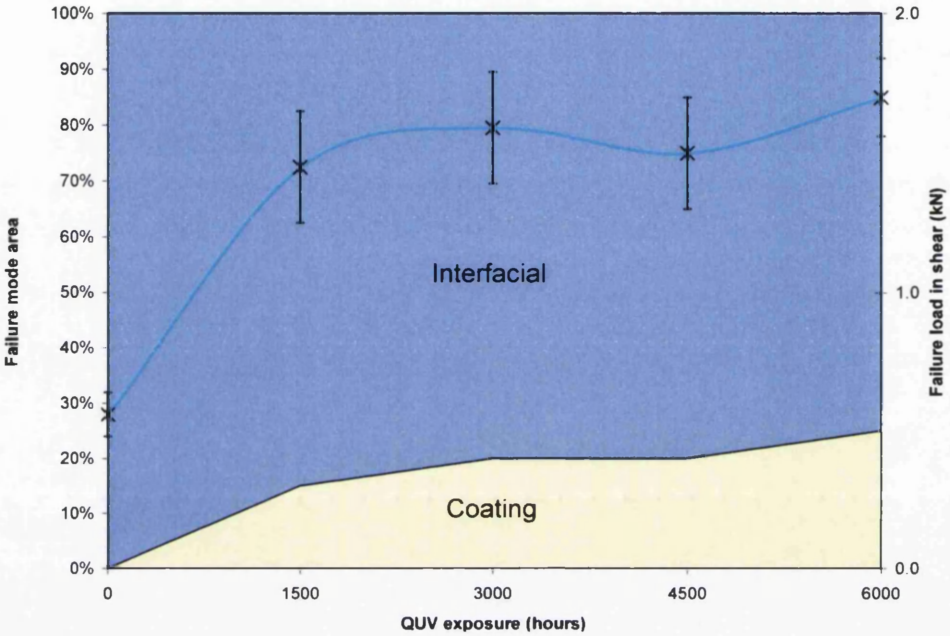


Figure 32 The compatibility of E1 bonded pre-weathered PVC-plastisol coated steel lap joints. Weathering cycle – eight hours UV-A exposure followed by four hours of condensation at 40°C.

Long-term weathered – Figure 33

After twelve months of humidity exposure, all adhesive bonded joints failed within the range of 0.5 – 1.0kN. The performance of E1 and A3 bonded joints remained relatively constant during weathering, whereas, E2 and P1 bonded joints demonstrated approximately 50 – 60% strength losses. With P1 bonded joints, the predominant failure mode changed to interfacial failure during the initial stages of weathering, whereas a gradual increase in interfacial failure and decrease in cohesive failure was noted with A3 bonded joints.

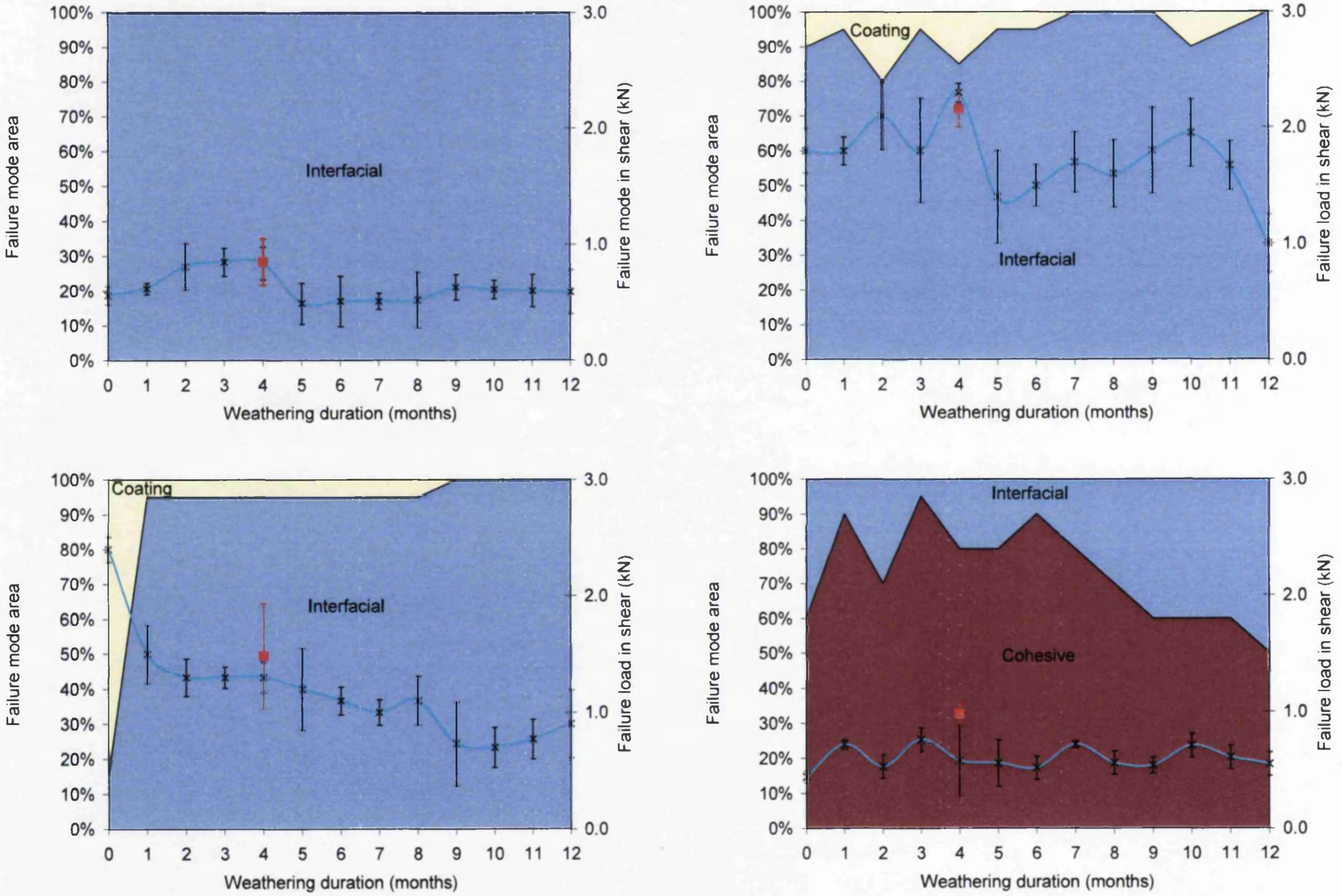


Figure 33 The long-term durability performance of PVC-plastisol coated steel lap joints. Adhesives used – E1 (top left), E2 (top right), P1 (bottom left) and A3 (bottom right). The red data points indicate the equivalent short-term durability performance.

5.1.2.3 Polyurethane coated steel – black solid colour

Compatibility and short-term weathered – Figure34

High levels of adhesive bond strength were obtained by all adhesive systems, shear failure loads ranged from 3.1 – 4.5kN with polyurethane coated steel lap joints. Due to the relatively uniform failure loads obtained, no trends were noted between the failure load and mode of failure. Failure modes varied from 100% interfacial, to 100% coating [**Figure 35**] and 100% cohesive. Yielding of the steel substrate occurred at failure loads above 4kN.

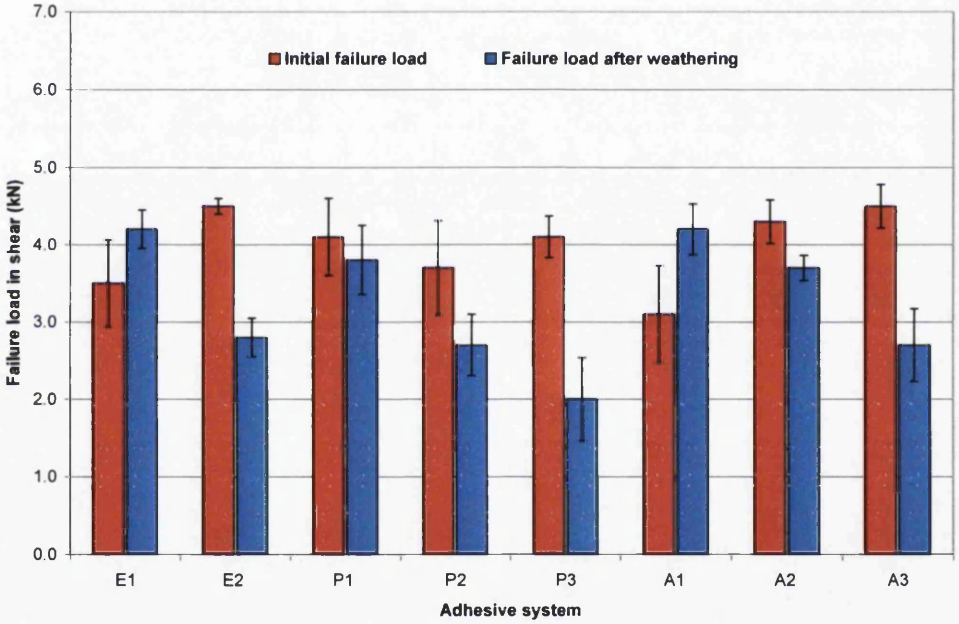


Figure 34 The short-term durability performance of adhesive bonded polyurethane coated steel lap joints.

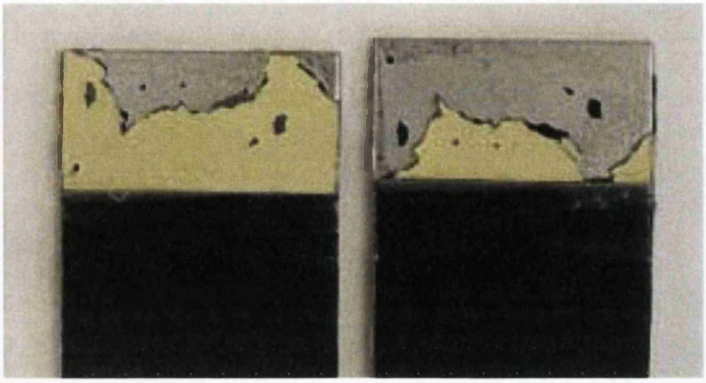


Figure 35 Polyurethane coating failure.

Following short-term weathering, shear loads and strength retention values ranged from 2.0 – 4.2kN and 49 – 120% respectively. High levels of durability (i.e. greater than 70% strength retention) were demonstrated by all adhesive types on the polyurethane coating. The different epoxy and acrylic adhesive systems reacted in different ways to weathering, whereas, all polyurethane bonded joints displayed strength loss. Both E1 and A1 bonded joints increased in strength as a consequence of weathering. The largest increase in interfacial failure was also observed with the lowest strength retention value.

Long-term weathered – Figure 36

After twelve months of humidity exposure, shear failure loads ranged from 1.6 – 3.2kN. A gradual decrease in bond strength was observed with E1 bonded joints; no changes were noted with the mode of fracture i.e. interfacial failure remained dominant. The relatively uniform failure loads obtained with P1 bonded joints was also noted with a stable mode of fracture i.e. cohesive failure remained dominant. Both E2 and A3 bonded joints showed similar reactions to humidity exposure; an initial decrease in failure load was followed by a steady state. In both cases, this decrease in bond strength was accompanied by a significant increase in cohesive failure.

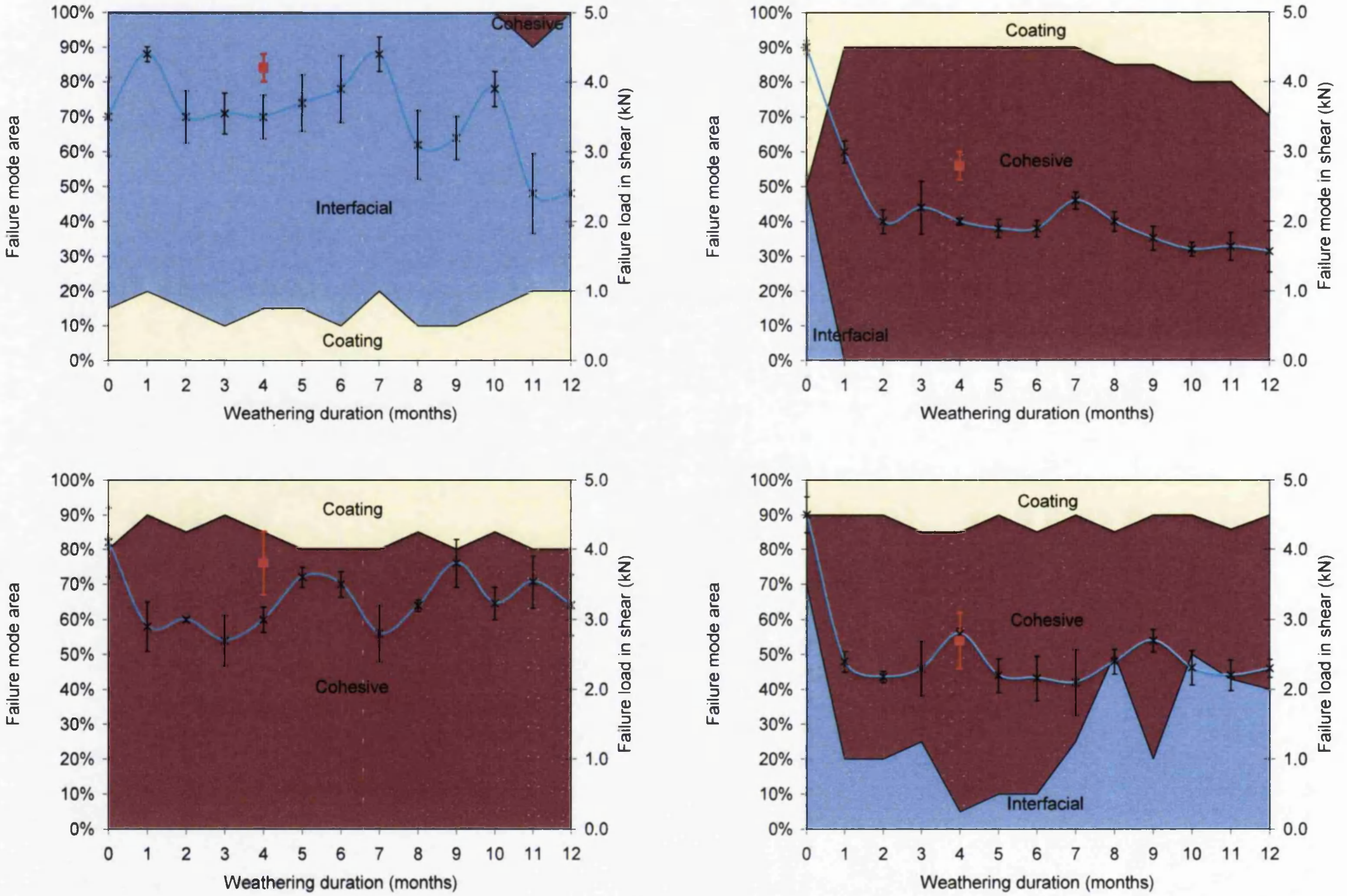


Figure 36 The long-term durability performance of polyurethane coated steel lap joints. Adhesives used – E1 (top left), E2 (top right), P1 (bottom left) and A3 (bottom right). The red data points indicate the equivalent short-term durability performance.

5.1.2.4 Polyurethane coated steel – white solid colour

Compatibility and short-term weathered – Figure 37

High levels of adhesive compatibility were demonstrated by all adhesive types; shear failure loads ranged from 1.9 – 4.7kN with polyurethane coated steel lap joints. No trends were noted between failure load and mode of fracture as three completely different failure modes were generated at 4.1kN i.e. E2 joints demonstrated 100% interfacial failure, P1 joints displayed 90% cohesive failure, and P3 joints showed 100% coating failure [**Figure 38**]. This suggests that the mode of fracture was dependent on the properties of the adhesive.

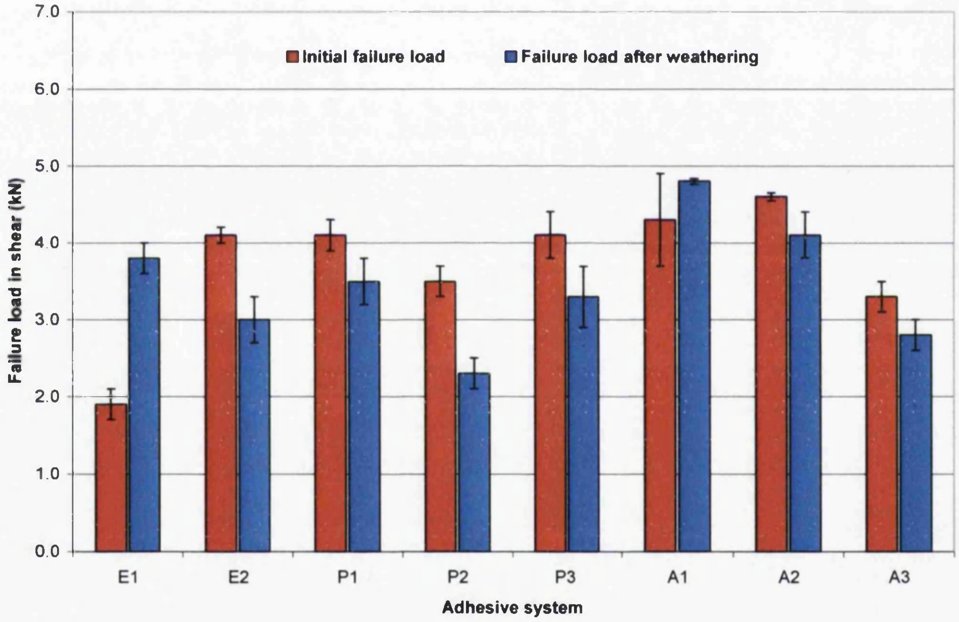


Figure 37 The short-term durability performance of adhesive bonded polyurethane coated steel lap joints.

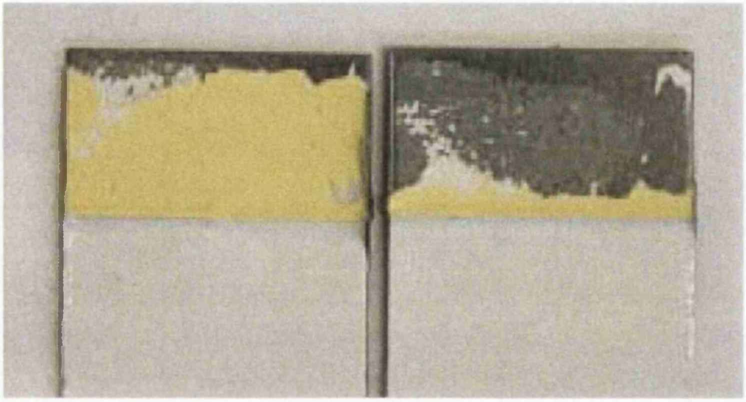


Figure 38 Polyurethane coating failure.

Following short-term humidity exposure, shear failure loads and strength retention values ranged from 2.4 – 4.8kN and 67 – 197% respectively. With the exception of adhesive P2, durable adhesive bonds (i.e. greater than 70% strength retention) were demonstrated by all other adhesive systems used. The various epoxy and acrylic adhesives showed different responses to weathering, whereas, strength loss occurred with all polyurethane bonded joints. Again, adhesives E1 and A1 bonded joints increased in strength as a consequence of weathering; in both cases this was also noted with an increase in coating failure. With all other bonded joints, strength loss was always accompanied by an increase in cohesive failure.

Pre-weathered polyurethane coated steel – Figure 39

Pre-weathering polyurethane coated steel prior to bonding had no effect on adhesive bond strength as similar failure loads were obtained with substrates aged for 0, 1500, 3000, 4500 and 6000 hours. However, after pre-weathering for 1500 hours, a change in the predominant failure mode from interfacial to coating failure was noted and was indicative of coating degradation.

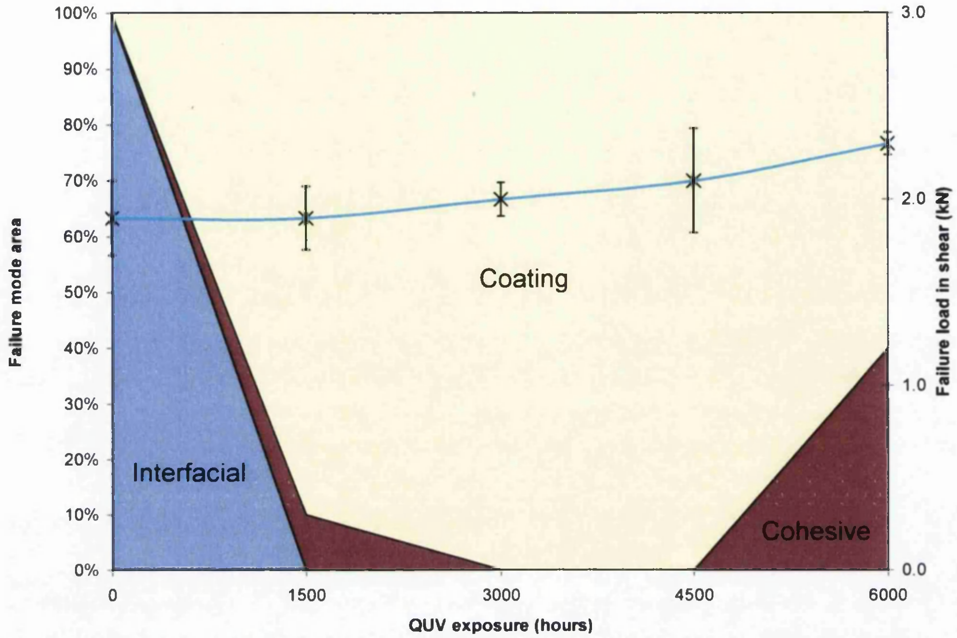


Figure 39 The compatibility of E1 bonded pre-weathered polyurethane coated steel lap joints. Weathering cycle – eight hours UV-A exposure followed by four hours of condensation at 40˚C.

5.1.2.5 Polyurethane coated steel – green solid colour with rough texture

Compatibility and short-term weathered – Figure 40

High levels of adhesive bond strength were initially obtained by each type of structural adhesive; shear failure loads ranged from 1.3 – 3.7kN with polyurethane coated steel lap joints. No correlation was noted between the failure load and mode of failure as similar failure modes were obtained at high and low loads. For example, interfacial failure was the predominant mode of fracture at 1.3kN and 2.9kN; cohesive failure was the primary failure mode at 1.1kN and 2.7kN and; coating failure [**Figure 41**] was the principal mode of fracture 1.7kN and 3.7kN.

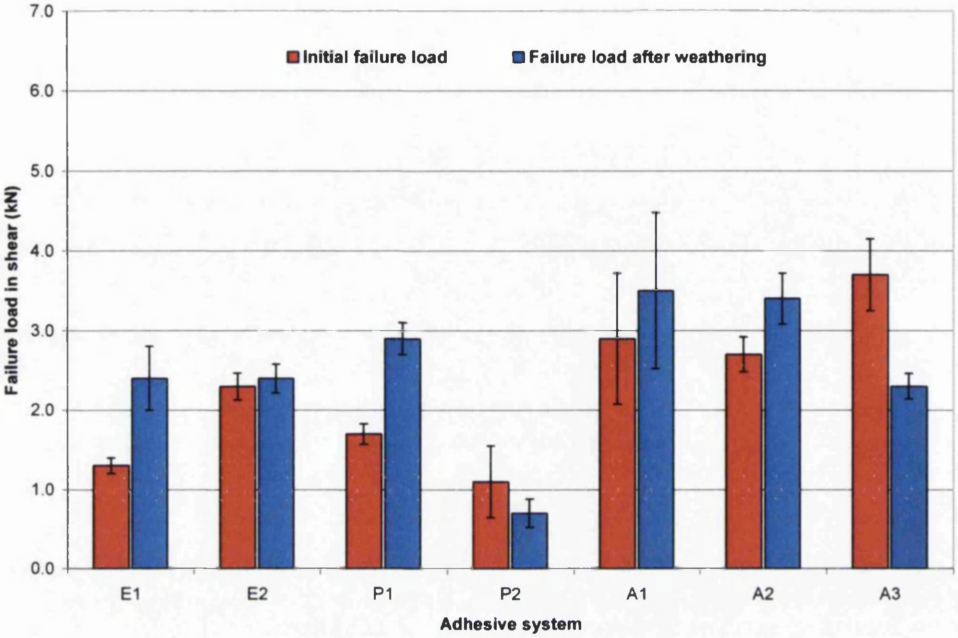


Figure 40 The short-term durability performance of adhesive bonded polyurethane coated steel lap joints.

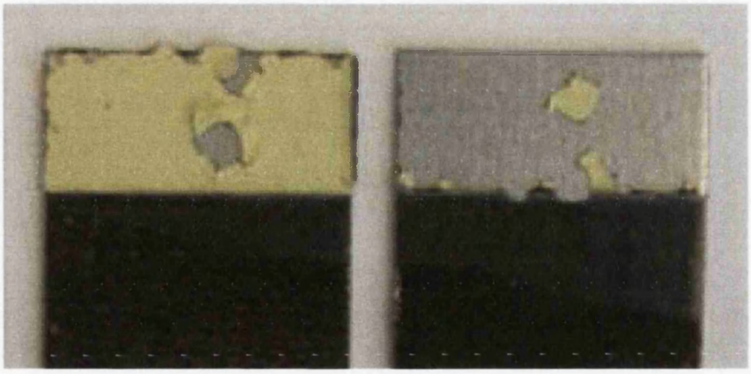


Figure 41 Polyurethane coating failure.

Shear failure loads and strength retention values ranged from 0.7 – 3.5kN and 62 – 185% respectively after fourteen days of humidity exposure. High levels of adhesive bond durability (i.e. greater than 70% strength retention) were provided by all adhesive types on polyurethane coated steel. The different epoxy, polyurethane and acrylic adhesive systems displayed different responses to weathering. E1, E2, P1 and A1 bonded joints increased in strength as a consequence of weathering; this was also noted with an increase in either cohesive or coating failures. The development of interfacial failure was not observed as a result of weathering which indicates the presence of stable bonds between the adhesives and substrate.

5.1.2.6 Polyurethane coated steel – silver colour with metallic effect

Compatibility and short term weathered – Figure 42

High levels of adhesive bond strength were initially obtained by all adhesive types, shear failure loads ranged from 1.3 – 4.7kN with polyurethane coated steel lap joints. With the exception of E1 bonded joints which failed at the adhesive – coating interface at 1.3kN, all other adhesive bonded joints either failed primarily within the adhesive or within a layer of the polyurethane coating [**Figure 43**].

After short-term weathering, shear failure loads and strength retention values ranged from 2.1 – 4.2kN and 68 – 246% respectively. Excellent levels of adhesive bond durability (i.e. greater than 70% strength retention) were provided by all adhesive types on polyurethane coated steel. The different epoxy, polyurethane and acrylic adhesive bonded joints demonstrated different responses to weathering. E1, P1 and A1 bonded joints increased in strength as a result of weathering. Coating and cohesive modes of fracture were predominant with all bonded joints.

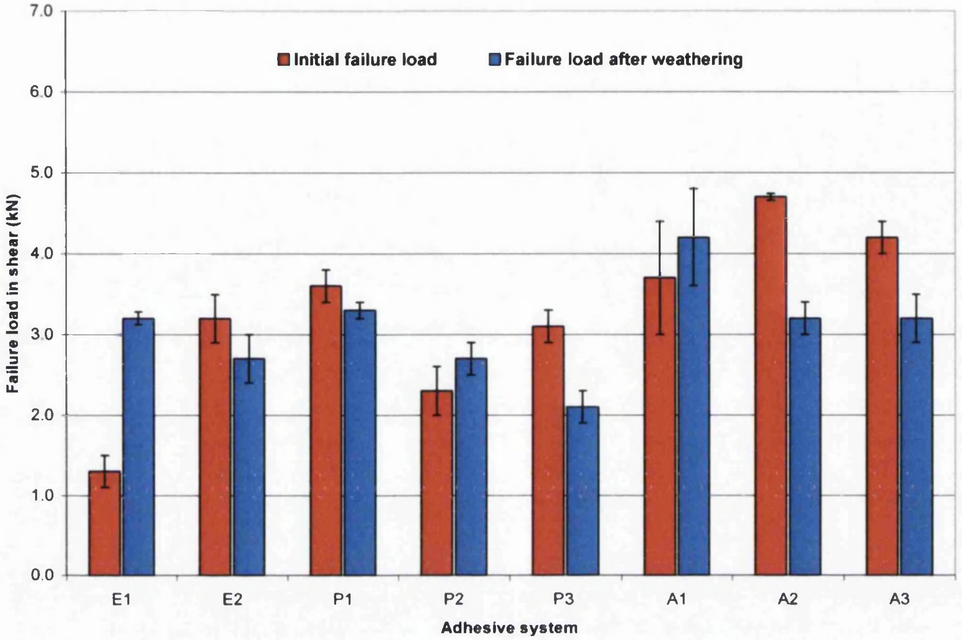


Figure 42 The short-term durability performance of adhesive bonded polyurethane coated steel lap joints.

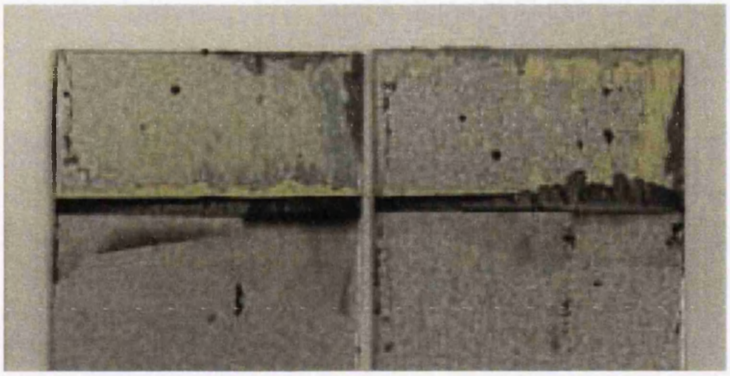


Figure 43 Polyurethane coating failure.

5.1.2.7 Polyester coated steel – top coat

Compatibility and short-term weathered – Figure 44

All epoxy, polyurethane and acrylic adhesive bonded joints exhibited high shear loads with yielding of the steel substrate occurring prior to failure of the bond area. Initial failure loads ranged from 3.9 – 4.4kN with polyester coated steel lap joints. Due to the relatively uniform failure loads obtained, no correlations were made between failure load and mode of failure. A diverse selection of failure modes were evident, ranging from primarily coating failure [**Figure 45**] to 100% cohesive and 100% interfacial. Yielding of the steel substrate was responsible for the uniform failure loads obtained with all adhesive bond joints since the mechanical properties of the steel substrate was the critical parameter controlling the maximum shear load and the properties of the various adhesive systems.

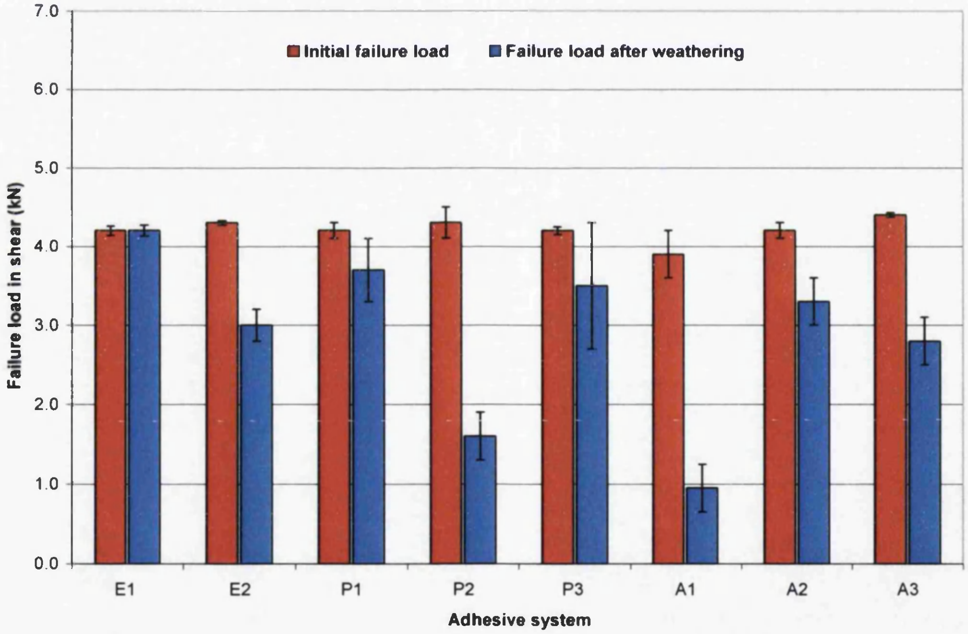


Figure 44 The short-term durability performance of adhesive bonded polyester coated steel lap joints.

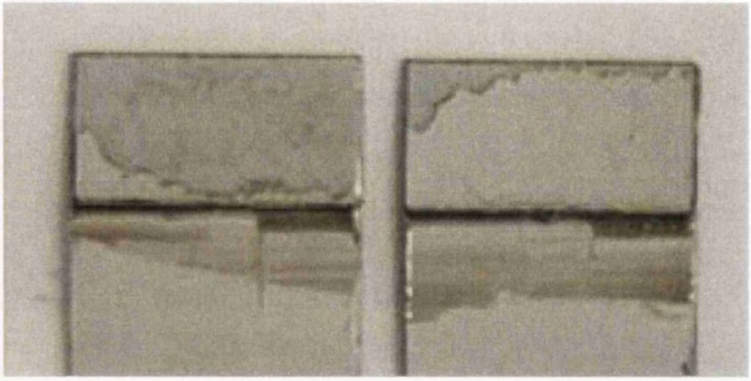


Figure 45 Polyester coating failure.

Following short-term weathering, shear loads and strength retention values ranged from 0.9 – 4.2kN and 23 – 100% respectively. High levels of adhesive bond durability (i.e. greater than 70% strength retention) were provided by all adhesive types on polyester coated steel. The predominant modes of fracture changed to coating failure with E1, P1 and P2 bonded joints as a result of humidity exposure. An increase in coating failure was noted with all lap joints after weathering and was the critical factor in limiting the durability performance.

Long-term weathered – Figure 46

After twelve months of humidity exposure, shear failure loads ranged from 1.9 – 3.7kN. The failure loads obtained with E1 bonded joints remained relatively constant throughout testing, whereas a gradual loss of strength was noted with E2, P1 and A3 bonded joints. The predominant modes of fracture changed with all adhesive bonded joints as a consequence of weathering. Again, the development of polyester coating failure was observed and became predominant with E1, P1 and A3 bonded joints. Whereas, the primary failure mode changed from interfacial to cohesive failure with E2 bonded joints.

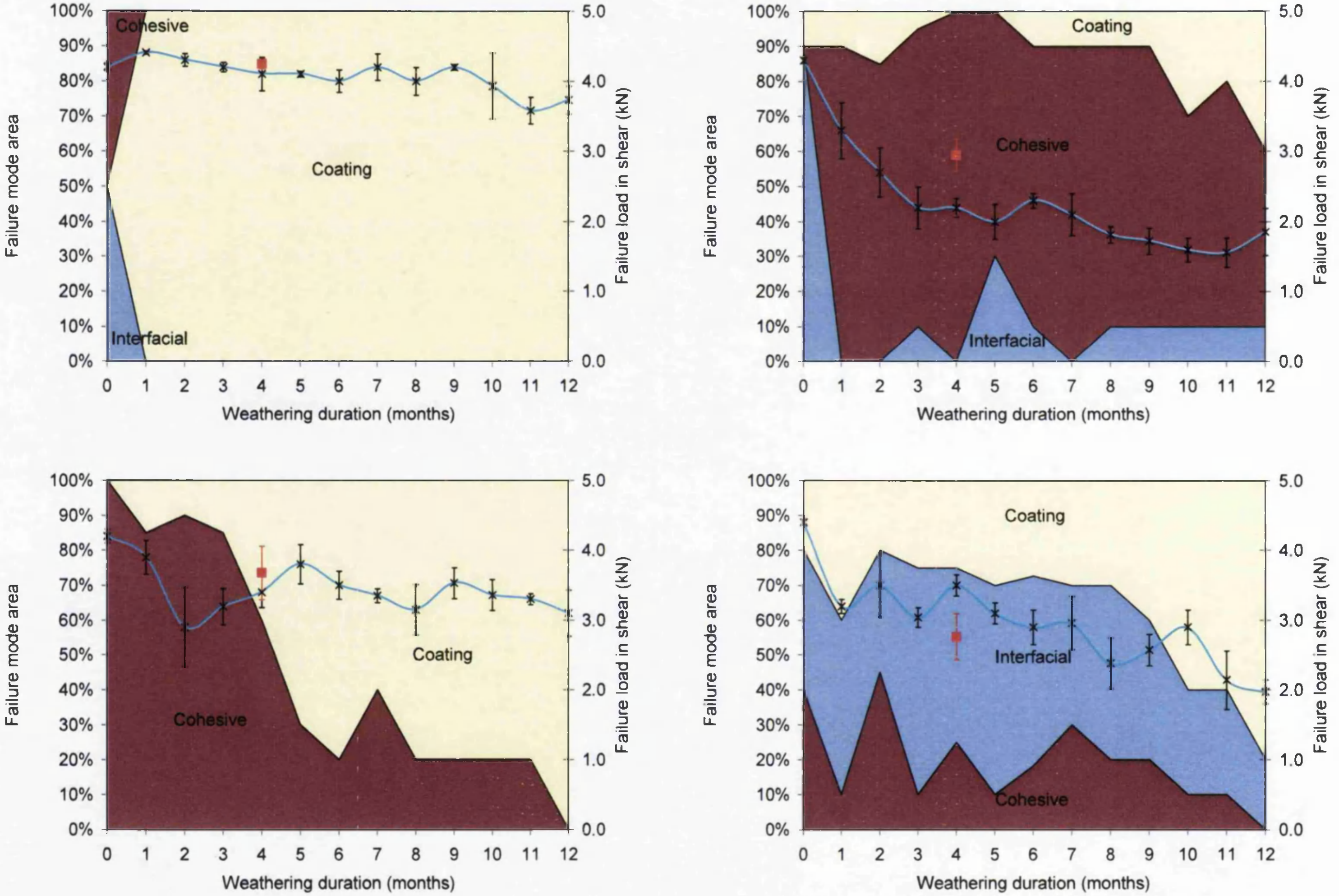


Figure 46 The long-term durability performance of polyester coated steel lap joints. Adhesives used – E1 (top left), E2 (top right), P1 (bottom left) and A3 (bottom right). The red data points indicate the equivalent short-term durability performance.

5.1.2.8 Polyester coated steel – backing coat

Compatibility and short-term weathered – Figure 47

For this study, adhesives E1, E2, P1 and A3 were assessed with the polyester backing coat of PVC-plastisol coated steel. High degrees of adhesive bond strength were demonstrated by all adhesive types, failure loads ranged from 2.2 – 4.7kN. At the lowest failure load, interfacial failure was the primary mode of fracture; however, at higher loads cohesive and coating failures [**Figure 48**] were predominant.

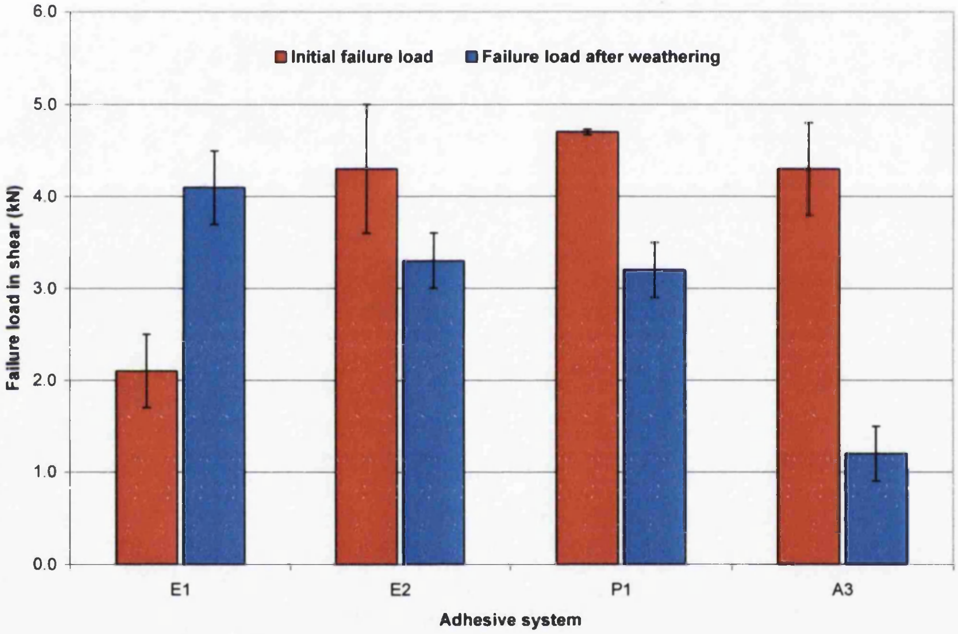


Figure 47 The short-term durability performance of adhesive bonded polyester coated steel lap joints.

Following short-term weathering, shear failure loads and strength retention values ranged from 1.2 – 4.1kN and 28 – 186% respectively. Only adhesives E1 and E2 demonstrated high levels of adhesive bond durability (i.e. greater than 70% strength retention). The development of coating failure was observed with P1 bonded joints as a consequence of weathering. Whereas, an increase in interfacial failure was noted with both E2 and A3 bonded joints.

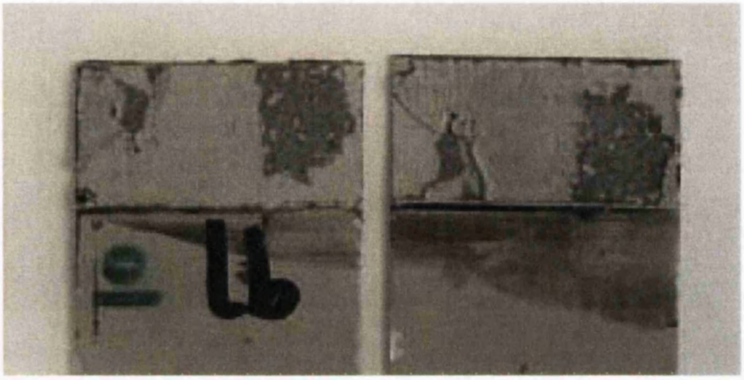


Figure 48 Polyester coating failure.

5.1.3 Aluminium alloy 6082T6

Compatibility and short-term weathered – Figure 49

For this investigation, the compatibility and durability of adhesives E1, E2, P1, A2 and A3 were assessed with acetone degreased, mechanically abraded and chemically pretreated aluminium alloy 6082T6. High levels of adhesive bond strength were initially obtained by all adhesive types on all aluminium alloy surfaces. Shear failure loads ranged from 0 – 6.1kN. A change from interfacial failure to cohesive failure was noted with an increase in the failure load. In general, higher loads were obtained with the mechanical and chemical pretreated aluminium alloy surfaces than the acetone degreased aluminium alloy substrate. The maximum load obtained by each adhesive was dependent on the chemical pretreatment used. .

Following short-term weathering, shear loads and strength retention values ranged from 0 – 5.3kN and 0 – 92%. As anticipated, all chemically pretreated aluminium joints provided the highest levels of durability with all adhesives. The durability performance of each adhesive was dependent on the chemical pretreatment used. The lesser durability of acetone degreased and mechanically abraded aluminium alloy joints was noted with an increase in interfacial failure and corrosion of the aluminium surface [**Figure 50**]. With chemical pretreated aluminium joints, strength loss was either observed with an increase in interfacial or cohesive failure; no corrosion was visible.

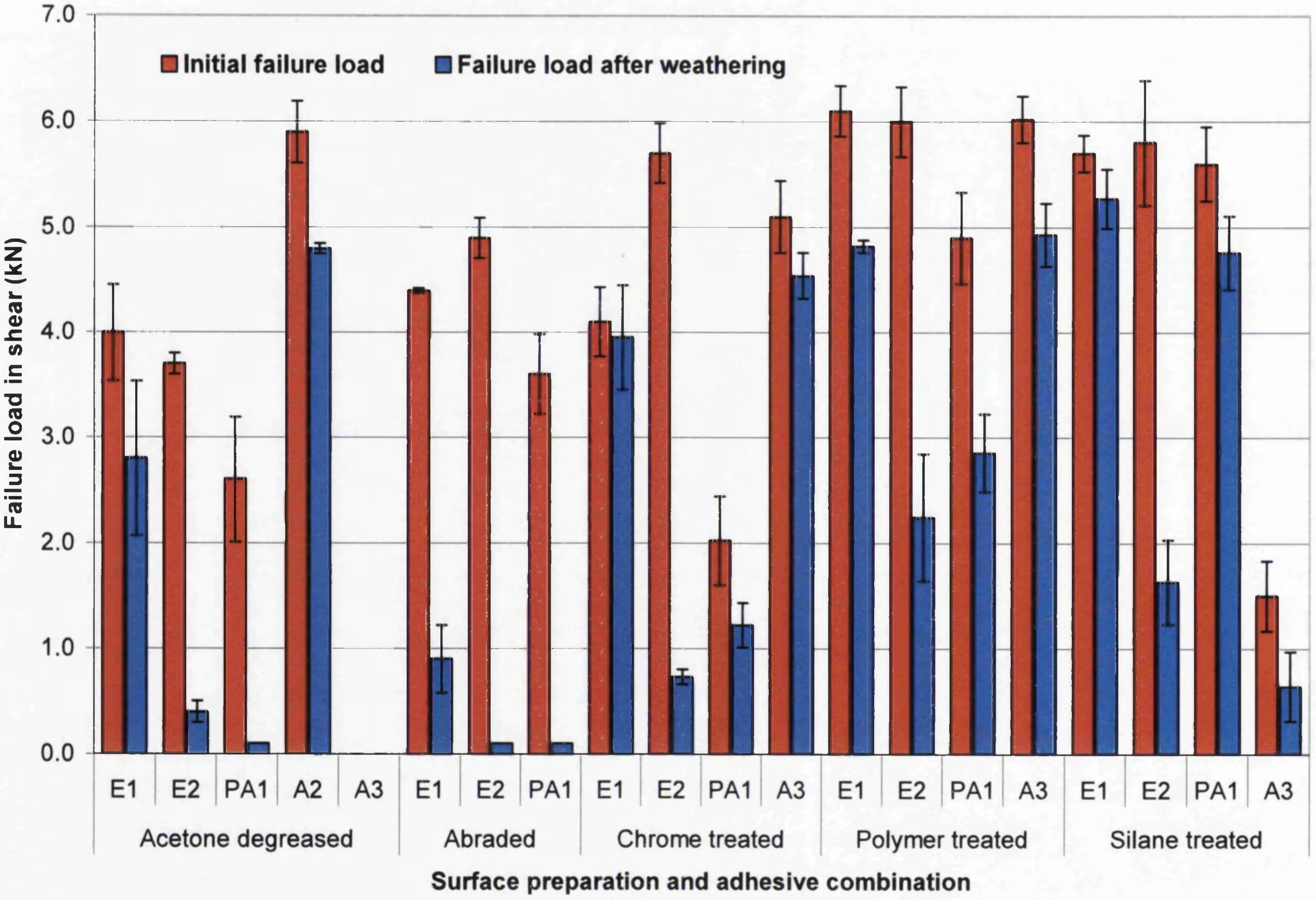


Figure 49 The short-term durability performance of adhesive bonded aluminium alloy 6082T6 lap joints.

Figure 50 Aluminium interfacial and corrosion failure.

5.1.4 Glass

Test methodology development

The single lap shear joint was found to be an inappropriate joint configuration for assessing the compatibility of structural adhesives on glass. Using the standard lap joint configuration and dimensions, it was seen that glass lap joints were failing within the glass substrate at relatively low loads i.e. approximately 0.9kN with epoxy adhesive E1. This was probably due to the inherently brittle nature of glass and the out of plane bending moments generated by a stressed lap joint. Furthermore, cut edge defects (e.g. feathering) acting as stress concentrators may have contributed to the premature substrate failure. Hence, the ultimate failure load of bonded glass lap joints was limited by the joint design and the materials mechanical properties. This prompted the need to identify or develop an alternative joint configuration in order to optimize the performance of adhesive bonded glass joints. Any new joint design must satisfy the following criteria:

1. Adhesive joints need to be tested in shear so the results can be compared to the failure loads obtained with standard lap joints.
2. The joint design should be simple and, sensitive to changes in adhesive selection and surface condition/pretreatment.
3. The joint should either fail within the adhesive bond line or within the glass substrate in the overlap region.

4. The adherend properties must not be modified or reinforced by adhesive bonding steel stiffeners along the components of the joint.
5. The edges of the glass components should be ground to remove or minimise any cutting defects.
6. The joint design should also be easily adaptable for assessing glass – precoated steel material combinations.

Using four new joint designs [**Figure 51**], the initial failure load of adhesive E1 was assessed with glass. These joint designs were based on the standard single lap shear joint but had smaller component dimensions. It was considered that reducing the length of the joint components would make them more rigid, reduce substrate failure at low loads and change the stress distribution across the adhesive bond area. Joints with the same length components (i.e. 50mm or 75mm) are described as modified lap shear joints. These modified lap joints were tensile tested in the same way as the standard lap joint. Joints with different length components (i.e. 25mm and 50mm or 25mm and 75mm) are described as constrained lap joints. This joint configuration required a jig to hold the joints in the tensile machine and eliminated the need for alignment tabs as well as reducing the number of protective metal covers required.

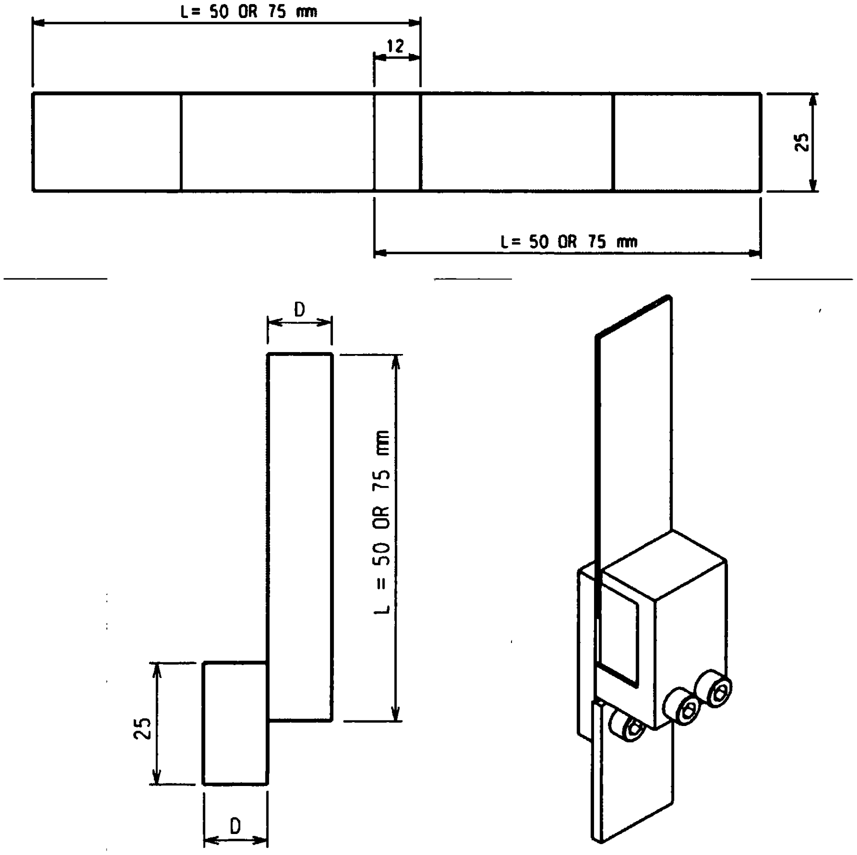


Figure 51 Glass joint designs and dimensions: modified lap joint (top) and constrained lap joint with required jig (bottom).

Initial results showed that all joints failed at higher loads than the original lap joint design [**Table 13**]. The highest failure load was obtained by the constrained lap joint with the 50mm long upper substrate. Glass substrate failure outside of the overlap/bond area was still the predominant mode of fracture with all joint designs. This indicated that further improvements were needed to optimize the performance of adhesive bonded glass joints

Table 13 Test methodology development part 1 – adhesive joint design.

Joint design	Component Dimensions (mm)	Average failure load (kN)	σ (%)	Mode of failure
Standard lap joint	100 × 25	0.9	20	Substrate
Modified lap joint	75 × 25	2.0	23	Substrate
	50 × 25	1.8	25	Substrate
Constrained lap joint	75 × 25 25 × 25	1.5	16	Upper substrate
	50 × 25 25 × 25	2.2	19	Upper substrate

A second study looked into the affect of reducing the overlap length on failure load. This was carried out using only the modified lap joint with 75 × 25mm components and the constrained lap joint with the 50 × 25mm longer substrate. As expected, with both joint designs a reduction in the failure load was observed with a smaller overlap length [**Table 14**]. However, the failure stress was shown to increase with a reduced overlap. Similar performance levels were provided by joints with the same size overlap. Substrate failure was again the predominant failure mode but now occurred within the bonded overlap region. Higher standard deviation values were noted with joints with a shorter overlap length, which was probably due to the increased difficulty and inaccuracy in assembling these joints.

Table 14 Test methodology development part 2 – adhesive joint design.

Joint design	Overlap length (mm)	Failure load (kN)	Failure stress (N/mm^2)	σ (%)	Mode of failure
Modified lap joint	12	2.0	6.5	23	Substrate
	8	1.5	7.3	22	Substrate
	5	1.2	9.5	26	Substrate
Constrained lap joint	12	2.1	6.6	19	Substrate
	8	1.5	7.5	18	Substrate
	5	1.3	10.1	25	Substrate and interfacial

Ultimately, the constrained lap joint with an 8mm overlap was selected as the joint design most suitable for assessing structural adhesives on glass. When compared to both the standard and modified lap joint, the constrained lap joint was easier and quicker to assemble and, produced the highest failure stress with good repeatable results (i.e. the lowest standard deviation).

Compatibility and short-term weathered – Figure 52

For this study, adhesives E1, E2, P1, A2 and A3 were assessed with acetone degreased, silane primed and silane pretreated glass. Initial failure loads ranged from 0 – 1.9kN. High failure loads were only provided by adhesives E1, E2 and A2 on acetone degreased glass; whereas all adhesives demonstrated high failure loads on silane primed or pretreated glass. Adhesive A3 prematurely failed at the adhesive – glass interface prior to tensile testing, which indicated chemical incompatibility and/or incorrect mixing and cure of the adhesive constituents. With regard to initial bond strength, the effect of priming or pretreating the glass substrates was only noticeable with P1 bonded joints as significantly higher loads were generated. A change in the primary mode of fracture from interfacial to substrate failure (of the longer glass component) was noted with an increase in failure load.

Note – A 1.9kN failure load obtained with an 8mm overlap has a failure stress of 9.5N/mm^2. This is equivalent to a 3kN failure load with a 12mm overlap.

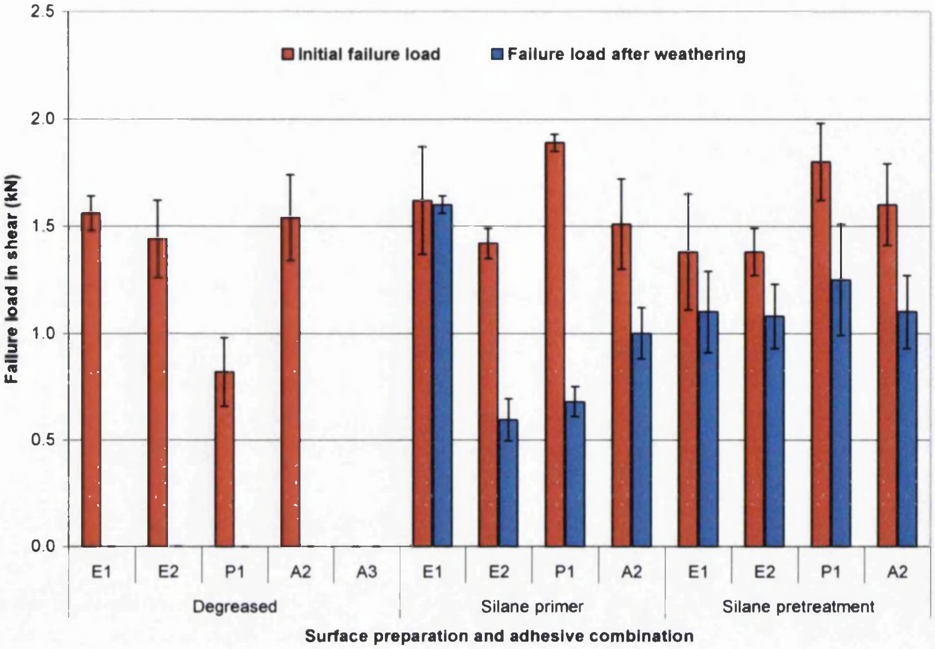


Figure 52 The short-term durability performance of adhesive bonded glass lap joints.

Catastrophic failure of all adhesives bonded to acetone degreased glass was observed at the adhesive – glass interface within a few days of exposure to high relative humidity. Shear failure loads and strength retention values ranged from 0.6 – 1.6kN and 37 – 99% with silane primed or pretreated glass joint. All adhesive types provided high levels of durability with pretreated glass joints (i.e. greater than 70% strength retention). Overall, superior durability was demonstrated by the silane pretreated joints. The development of interfacial failure was noted with lower levels of strength retention.

5.1.5 Timber

Compatibility and short-term weathered – Figure 53

For this investigation, adhesives E1, E2, P1, A2 and A3 were assessed with tangentially cut pine. In addition to the modes of fracture listed in section 2.8, the term interphase failure will be used in this section to describe a mixture of both substrate and interfacial failure which occurred close to the adhesive – substrate interface and could not be individually quantified [**Figure 54**].

High shear loads were initially obtained with all adhesive types; failure loads ranged from 0 – 2.6kN. At high loads a combination of cohesive, substrate and interphase failures were the predominant failure modes. Again, adhesive A3 prematurely failed at the adhesive – timber interface prior to tensile testing, which indicated chemical incompatibility and/or incorrect mixing and cure of the adhesive components.

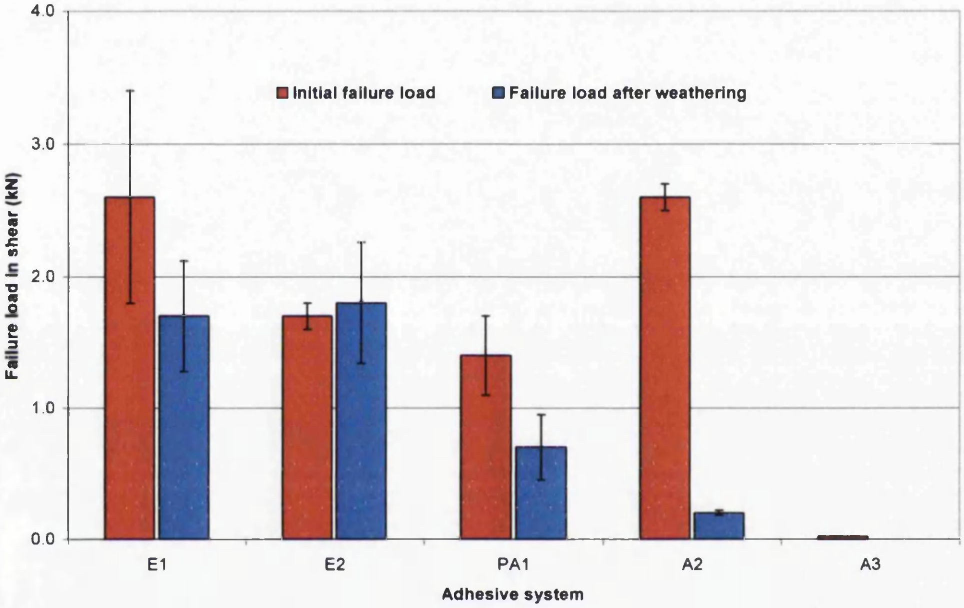


Figure 53 The short-term durability performance of adhesive bonded timber lap joints.

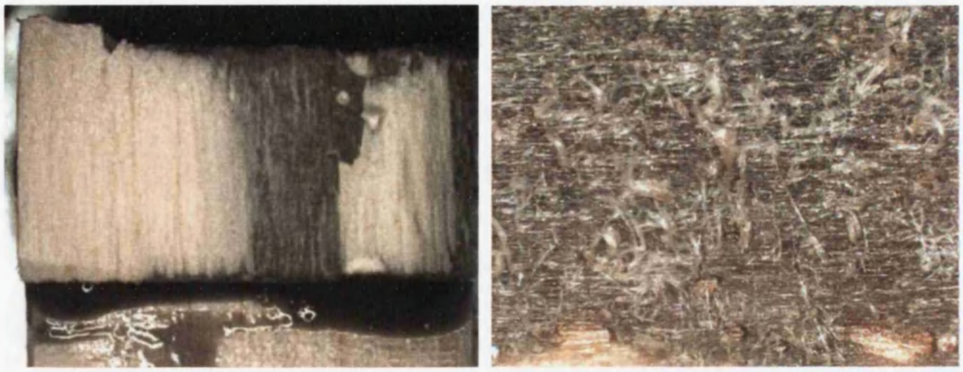


Figure 54 Timber interphase failure. The image on the right shows the interphase region (magnification × 40) which is a combination of interfacial failure and splintering of the timber fibres.

Following short-term weathering, shear failure loads and strength retention values ranged from 0.2 – 1.8kN and 8 – 106% respectively. Only E2 bonded joints demonstrated high levels of durability with timber (i.e. greater than 70% strength retention). The poor durability of E1, P1 and A2 bonded joints was noted with an increase in interphase failure. This indicated that the weathering procedure was detrimental to the integrity of the surface fibres of timber.

5.1.6 Mortar

Test methodology development

The test methodology used to develop an appropriate glass joint design [section 5.1.4] was also carried out with mortar. As with glass joints, the constrained lap joint produced higher failure loads with mortar adherends than the standard and modified lap shear joint. However, unlike glass joints, a reduction in the overlap length did not produce a favourable change in the mode of fracture. Mortar substrate failure in the longer/upper joint component, outside of the overlap region was the predominant failure mode with all joint designs and overlap lengths. Unfortunately, 1mm HDG steel reinforcement strips had to be bonded to the mortar components to prevent this failure from occurring. However, as mortars and concretes are often reinforced with steel bars and are used in much thicker sections in construction (i.e. thicker than the 12mm thick substrates used), this deviation from the joint design criteria was deemed as acceptable. Again, a jig was required to hold the constrained lap joints in the tensile machine. Also a 1mm thick bond line was required with mortar substrates because of its rough surface texture. This was controlled by placing two pieces of 1mm diameter wire into the bond line.

Compatibility and short-term weathered – Figure 55

For this study, epoxy adhesives E1 and E2 were assessed with mortar. Initial failure loads were 0.6kN with E1 bonded joints and 0.7kN with E2 bonded joints. Although failure occurred at significantly lower loads than those obtained with metallic adherends (which suggests poor adhesive compatibility), joint failure occurred through a layer of mortar adjacent to the adhesive – substrate interface and indicated that the maximum strength of the adherend had been reached. Therefore the maximum failure load of mortar joints was limited by the friability of the mortar surface.

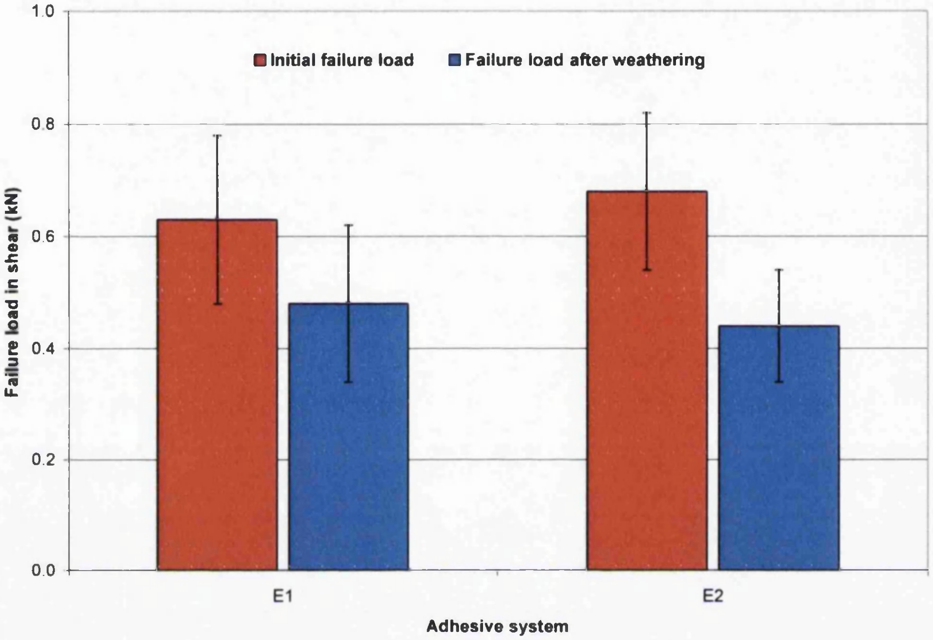


Figure 55 The short-term durability performance of adhesive bonded mortar lap joints.

Following short-term weathering, shear loads and strength retention values were 0.5kN and 76% with adhesive E1 and, 0.4kN and 65% with adhesive E2. Again mortar failure along a plane adjacent to the adhesive – adherend interface was the predominant mode of fracture. This indicated that the weathering cycle was detrimental to the surface integrity of the mortar.

5.2 SEALANT BONDED UNI-MATERIAL JOINTS

5.2.1 Galvanised steel – Figure 56

For this study, the compatibility and durability of all hybrid polymer sealants and the silane modified polyether were evaluated with acetone degreased chromium and vanadium passivated galvanised steels (referred to as HDG_{Cr} and HDG_V respectively). Initially, all sealant bonded galvanised steel H-joints failed at higher tensile loads than the desired 0.32kN, which is the British standard for the modulus of a structural sealant [84]. Failure loads ranged from 0.7 – 1.6kN with HDG_{Cr} steel joints and 0.7 – 1.4kN with HDG_{V} steel joints. Similar performance levels were demonstrated by each sealant on both galvanised steel substrates. Sealant SMP supported considerably higher tensile loads than all hybrid polymer sealants. Cohesive and surface cohesive failures were the predominant modes of fracture with all sealants on both substrates.

Following forty-two days of water immersion all sealant bonded joints still demonstrated failure loads greater than the minimum performance criterion. Tensile loads and strength retention values ranged from 0.3 – 0.5kN and 31 – 70% with HDG_{Cr} steel joints and, 0.4 – 0.6kN and 45 – 61% with HDG_{V} steel joints. Again, sealant SMP achieved the highest tensile loads with both galvanised steel substrates; however, these joints also showed the lowest levels of strength retention. All joints demonstrated the biggest strength loss after twenty-one days of weathering. In most instances, joint degradation occurred with the development of interfacial failure at the edges of the bond area.

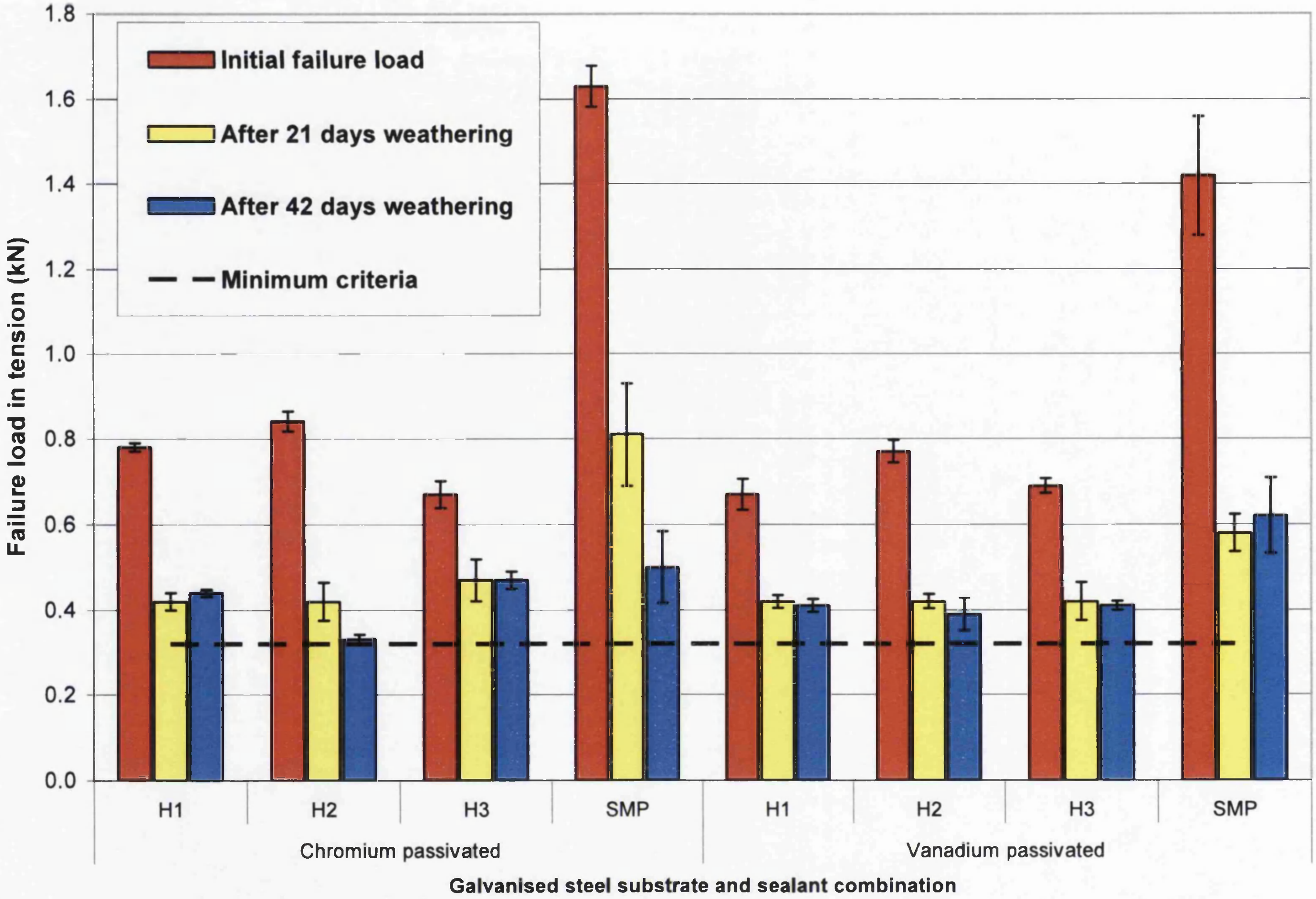


Figure 56 The durability performance of sealant bonded galvanised steel H-joints.

5.2.2 Organic coated steel

For this investigation, the compatibility and durability of all structural sealants were evaluated with PVdF coated steel, PVC-plastisol coated steel, polyurethane coated steel (black solid colour) and polyester coated steel. All organic coated steel substrates were acetone degreased prior to sealant bonding.

5.2.2.1 PVdF coated steel – Figure 57

Initially, all sealant bonded PVdF coated steel H-joints achieved tensile loads greater than the minimum performance criterion of 0.32kN, where failure loads ranged from 0.5 – 1.2kN. Both automotive sealants (PS and SMP) failed at significantly higher loads than the other types of structural sealant used. This was also noted with deformation of the organic coated steel substrates. Relatively uniform performance levels were noted between silicone glazing sealants and the hybrid polymer sealants. Silicone sealants S1 and S2 demonstrated the highest degrees of flexibility i.e. the longest extension at the maximum failure load. Cohesive and surface cohesive failures were the primary failure modes with all joints.

After weathering, all joints except those bonded with sealant H2 failed at loads greater than the minimum performance threshold. Tensile loads and strength retention values ranged from 0.2 – 0.7kN and 26 – 86%. With glazing and constructional sealants, the rate of strength loss was quickest during the initial stages of water immersion. However, with both automotive sealants strength loss was more rapid during the latter stages of weathering. Again, cohesive and surface cohesive failure modes were predominant. In most cases, the development of interfacial failure had occurred around the edges of the bond area.

5.2.2.2 PVC-plastisol coated steel – Figure 57

Tensile loads initially ranged from 0.6 – 0.9kN with sealant bonded PVC-plastisol coated steel H-joints. Relatively uniform levels of bond strength were provided by all structural sealants. Again, both silicone sealants displayed superior flexibility than constructional and automotive sealants. Cohesive and surface cohesive failures were the predominant failure modes with all bonded joints. Furthermore, at the higher failure loads, deformation of the steel substrate was noted.

Following forty-two days of water immersion, only S2 and PS bonded joints attained tensile loads greater than the 0.32kN minimum performance criterion. All sealant types showed poor levels of durability with PVC-plastisol coated steel; failure loads and strength retention values ranged from 0.1 – 0.7kN and 16 – 105%. Excluding S2 and PS bonded joints, strength loss occurred more rapidly during the initial stages of weathering. The development of interfacial failure was observed with all bonded joints, where the lowest strength retention values were noted with the largest areas of interfacial failure. Finally, a higher occurrence of surface cohesive failure was noted after weathering.

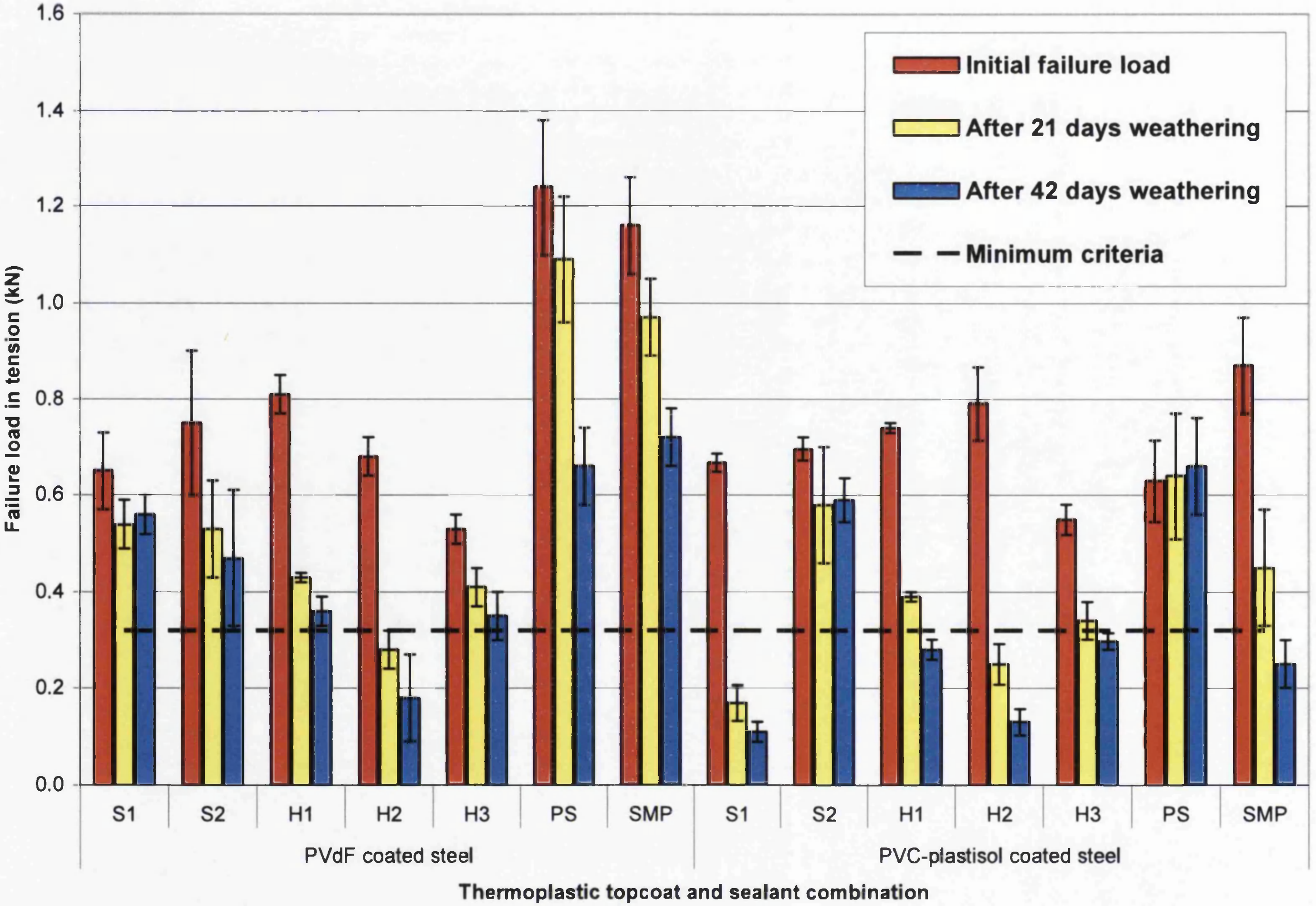


Figure 57 The durability performance of sealant bonded PVdF coated steel and PVC-plastisol coated steel H-joints.

5.2.2.3 Polyurethane coated steel – Figure 58

Initial tensile loads ranged from 0.6 – 1.2kN with sealant bonded polyurethane coated steel H-joints. The two highest loads were obtained by automotive sealants PS and SMP. Similar failure loads were generated by silicone sealants and hybrid polymer sealants. Cohesive and surface cohesive failures were the primary failure modes of all joints. At the higher failure loads obtained with sealants PS and SMP, deformation of the steel substrate occurred.

With the exception of H2 and PMS bonded joints, all other sealants provided failure loads greater than the minimum criterion for a structural sealant. Tensile loads and strength retention values ranged from 0.2 – 0.6kN and 18 – 73%. The highest levels of strength retention were provided by both structural glazing sealants. In most cases, the rate of strength loss was more rapid during the first stages of weathering. The predominant mode of fracture changed from cohesive to interfacial with H2, PS and SMP bonded joints, which also demonstrated the lowest strength retention values.

5.2.2.4 Polyester coated steel – Figure 58

Tensile loads initially ranged from 0.5 – 1.3kN with sealant bonded polyester coated steel H-joints. The highest tensile loads were provided by both automotive sealants; substrate deformation also occurred with these bonded joints. Both silicone sealants demonstrated the highest degrees of flexibility i.e. the longest extension at the maximum failure load. Relatively uniform failure loads were shown by silicone and hybrid polymer sealants. Cohesive and surface cohesive failures were predominant with all joints.

As a consequence of weathering, the bond strength of most joints deteriorated and did not attain the minimum criterion for a structural sealant. Tensile loads and strength retention values ranged from 0.1 – 0.4 and 6 – 39%. With the exception of SMP bonded joints, the rate of strength loss was more rapid during the initial stages of weathering. With most sealant bonded joints, the predominant mode of failure changed from cohesive to interfacial failure.

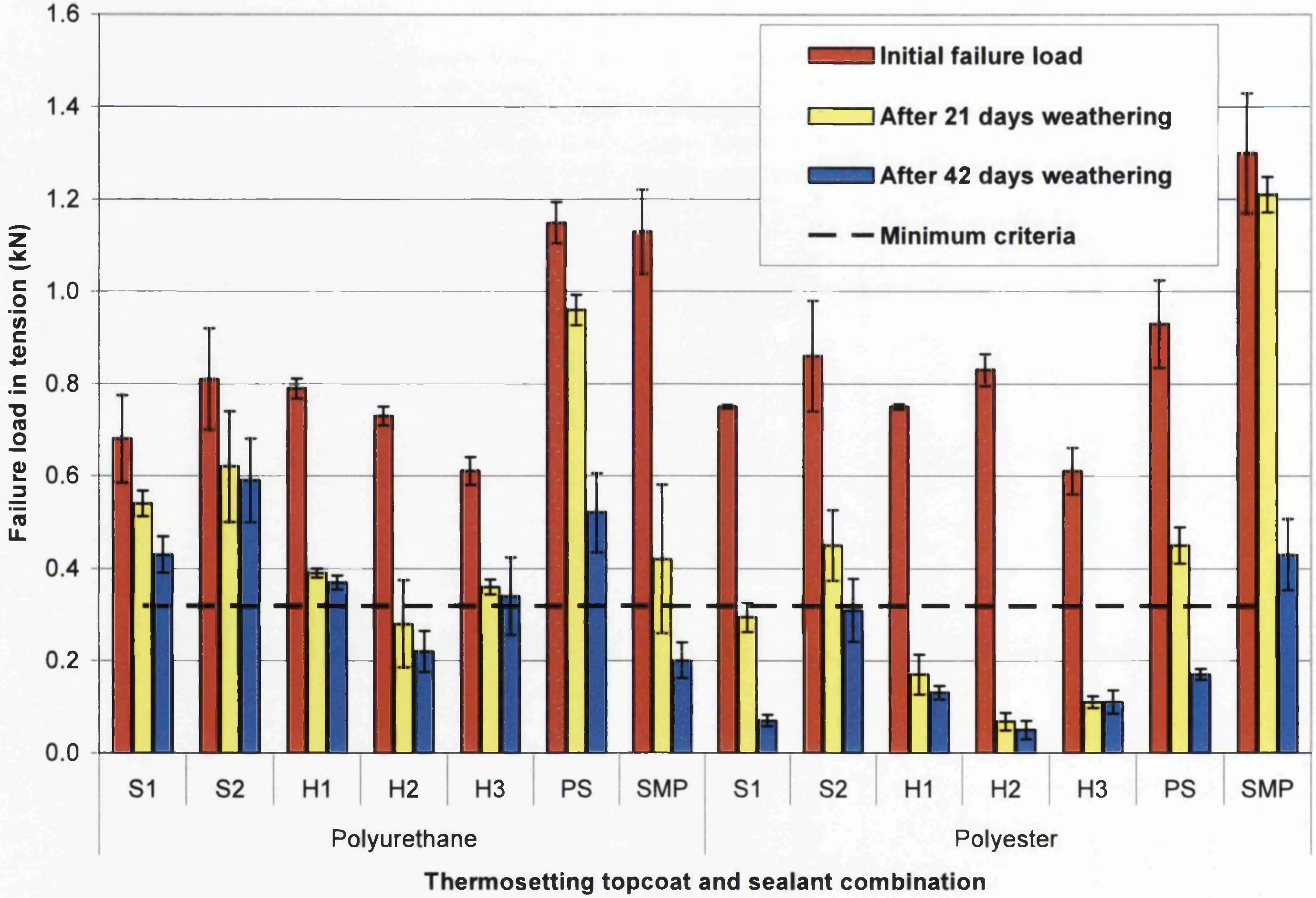


Figure 58 The durability performance of sealant bonded polyurethane coated steel and polyester coated steel H-joints.

5.2.3 Aluminium alloy 6082T6– Figure 59

For this investigation, the compatibility and durability of all hybrid polymer sealants (i.e. H1, H2 and H3) and the silane modified polyether (SMP) were evaluated with acetone degreased aluminium alloy 6082T6. Initial tensile loads ranged from 0.7 – 1.4kN with sealant bonded aluminium alloy H-joints. The highest tensile load was provided by SMP bonded joints; all hybrid polymer sealants showed similar bond strength levels. Cohesive and surface cohesive failures were the primary modes of failure with all bonded joints.

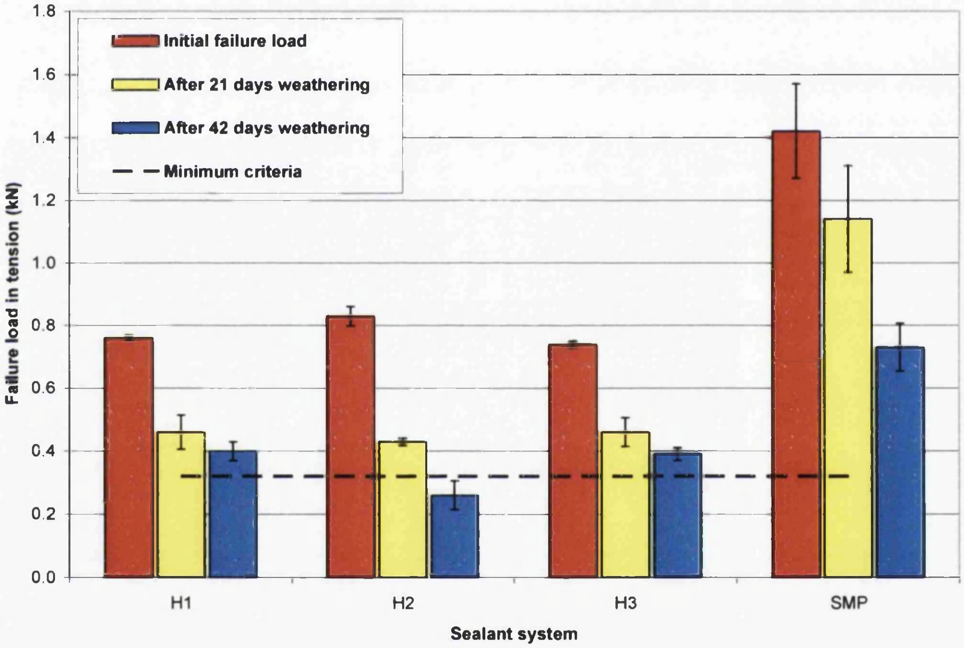


Figure 59 The durability performance of sealant bonded aluminium alloy 6082T6 H-joints.

Only H2 bonded joints failed to achieve the minimum standard after forty-two days of water immersion. Tensile loads and strength retention values ranged from 0.3 – 0.7kN and 33 – 56%. The rate of strength loss was quickest during the initial stages of weathering with all hybrid sealant joints. Furthermore, the development of interfacial failure around the periphery of the bond area was noted with all hybrid type sealants. The poor durability of H2 bonded joints was noted with a change in its primary mode of failure i.e. surface cohesive to interfacial failure.

5.2.4 Glass – Figure 60

For this study, the compatibility and durability of silicone glazing sealants S1 and S2, hybrid polymer sealant H1, and automotive sealants PS and SMP were evaluated with acetone degreased float glass. Initial failure loads ranged from 0.6 – 1.6kN with sealant bonded glass H-joints. Automotive sealants PS and SMP achieved the highest bond strengths. Similar tensile loads were demonstrated by both silicone sealants S1 and S2 and, hybrid polymer sealant H1. Both silicone glazing sealants displayed superior flexibility than constructional and automotive sealants. Cohesive failure and surface cohesive failure were the primary failure modes with all joints.

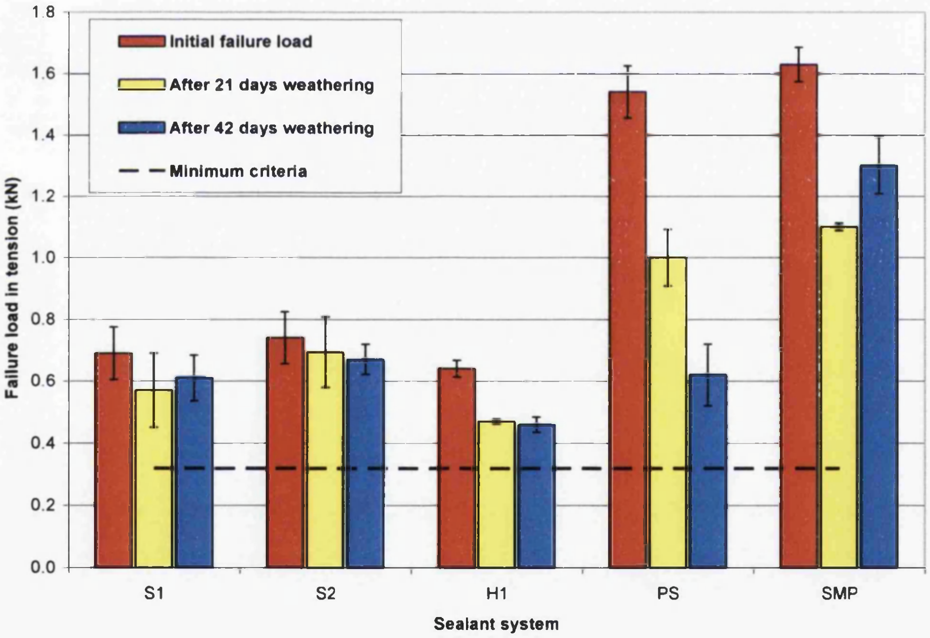


Figure 60 The durability performance of sealant bonded glass H-joints.

All sealant bonded joints exceeded the minimum performance criterion after forty-two days of simultaneous water immersion and UV light exposure. Tensile loads and strength retention values ranged from 0.5 – 1.3kN and 39 – 91%.

Both silicone sealants retained the highest percentages of initial strength. No change in the mode of fracture was noted with S1, S2, H1 and SMP bonded joints as a consequence of weathering. However, a higher incidence of surface cohesive failure and the development of interfacial failure at the UV light exposed surface were noted with the poor durability of PS bonded joints. Overall, the performance of both silicone bonded joints was largely unaffected by weathering.

5.2.5 Timber – Figure 61

For this study, the compatibility and durability of all hybrid polymer sealants and the silane modified polyether were evaluated with tangentially cut pine in unprimed and primed conditions. All sealants bonded to both unprimed and primed timbers failed at tensile loads greater than the minimum criterion. Initial failure loads ranged from 0.6 – 1.4kN. An increase in the maximum tensile load was noted with all hybrid sealants bonded to the primed timber substrate. Cohesive and surface cohesive failures were the predominant modes of failure with all joints. The highest loads were recorded with sealant SMP on both timber substrates; this was also accompanied with some timber substrate failure.

The failure loads of all sealant bonded joints with both unprimed and primed timber adherends fell below the minimum standard after twenty-one days of weathering. Final tensile loads and strength retention values ranged from 0.1 – 0.2kN and 7 – 29%. The rate of strength loss was quickest during the initial stages of weathering with all sealant bonded joints. The failure mode of all hybrid polymer joints was dependent on the condition of the timber adherends. For example, on unprimed timber joints the mode of failure was unchanged after weathering, whereas, on primed timber the development of interfacial failure was noted. The development of surface cohesive failure and interfacial failure was noted with SMP bonded joints.

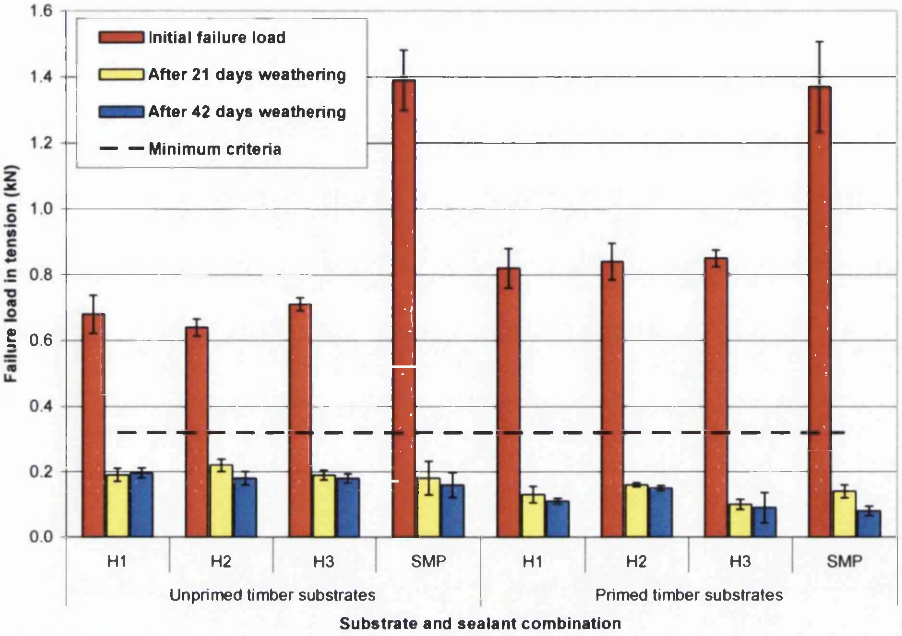


Figure 61 The durability performance of sealant bonded timber H-joints.

5.2.6 Mortar – Figure 62

For this investigation, the compatibility and durability of all hybrid polymer sealants and the silane modified polyether were evaluated with unprimed and primed mortar. The term interphase failure will be used in this section to describe a mixture of failure modes i.e. substrate, cohesive and interfacial failures that occurred close to the sealant – substrate interface and could not be individually quantified.

All sealants bonded to both unprimed and primed mortar substrates failed at tensile loads greater than the minimum criterion of 0.32kN. Initial failure loads ranged from 0.4 – 0.9kN. Relatively uniform loads were obtained by all hybrid sealants on each substrate; higher failure loads were noted with all hybrid sealants bonded to the primed mortar substrate. Typically surface cohesive failure was the predominant mode of failure with all sealant bonded joints. The highest failure loads were obtained by the silane modified polyether on both mortar substrates; this was also noted with largest area of substrate failure [**Figure 63**].

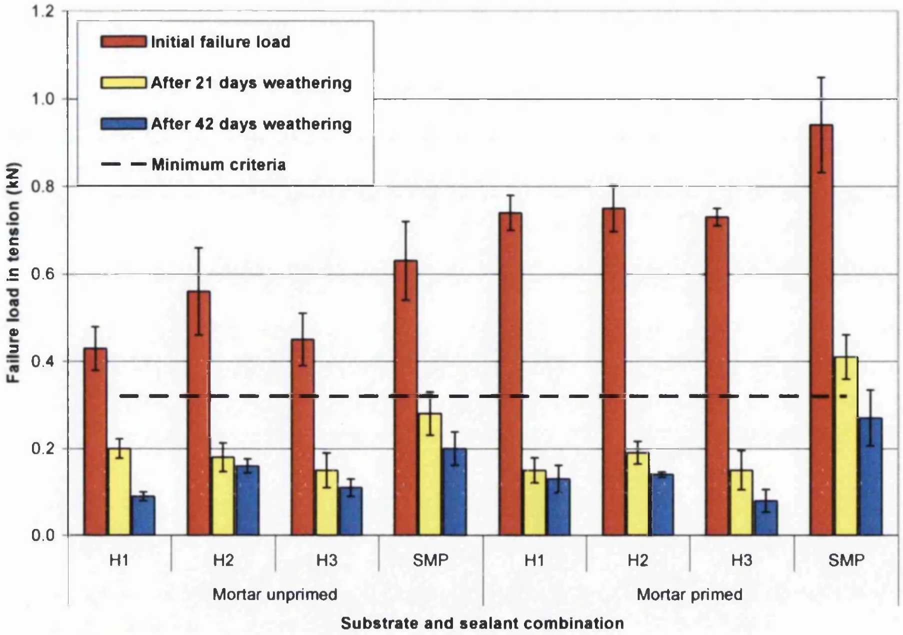


Figure 62 The durability performance of sealant bonded mortar H-joints.

Figure 63 The fracture mode of a sealant bonded H-joint with mortar adherends. Failure has occurred within the thick sealant bond line and within the mortar blocks

After forty-two days of water immersion, all sealant bonded joints demonstrated failure loads below the minimum standard. Tensile loads and strength retention values ranged from 0.1 – 0.3kN and 11 – 33% respectively. The rate of strength loss was greatest during the early stages of weathering with all bonded assemblies. The development of interphase failure was observed with all unprimed mortar joints and indicated that the surface of the mortar adherends had weakened. An increase in interfacial failure occurred with primed mortar joints as a consequence of weathering.

5.3 ADHESIVE BONDED MULTI-MATERIAL JOINTS

The dissimilar material and adhesive combinations investigated in this section were chosen because of their compatibility, superior strength and durability. By carefully comparing the results obtained with adhesive bonded uni-material joints, the optimum performance of each multi-material combination was postulated; see **appendix 3**. Any deviations between predicted and actual results will be an indication that something unexpected has occurred.

5.3.1 Galvanised steel – dissimilar materials

Test methodology for galvanised steel – mortar joints

As explained earlier, the single lap shear joint was not a suitable design for assessing structural adhesives with mortar substrates so the constrained lap joint was developed. Using this design it was possible to assess galvanised steel – mortar joints by replacing the 50mm mortar component with a 100mm steel component. Again, the bond line thickness was 1mm and a jig was used to hold the joints in the tensile machine.

Compatibility and short-term weathered – Figure 64

Initial failure loads ranged from 0.7 – 4.9kN with HDG_V – dissimilar material joints. The highest failure load was obtained with HDG_V – PVdF coated steel joints. Similar levels of adhesive bond strength were noted with polyurethane coated steel, aluminium and timber variants. By far the lowest failure load was obtained with HDG_V – mortar joints, where failure of the friable mortar surface adjacent to the adhesive – adherend interface was noted. With all multi-material joints, the predominant mode of fracture was either cohesive failure or interfacial failure at the surface of the 'dissimilar' material. This indicates that epoxy adhesive E1 was most compatible with the high energy surface of vanadium passivated galvanised steel.

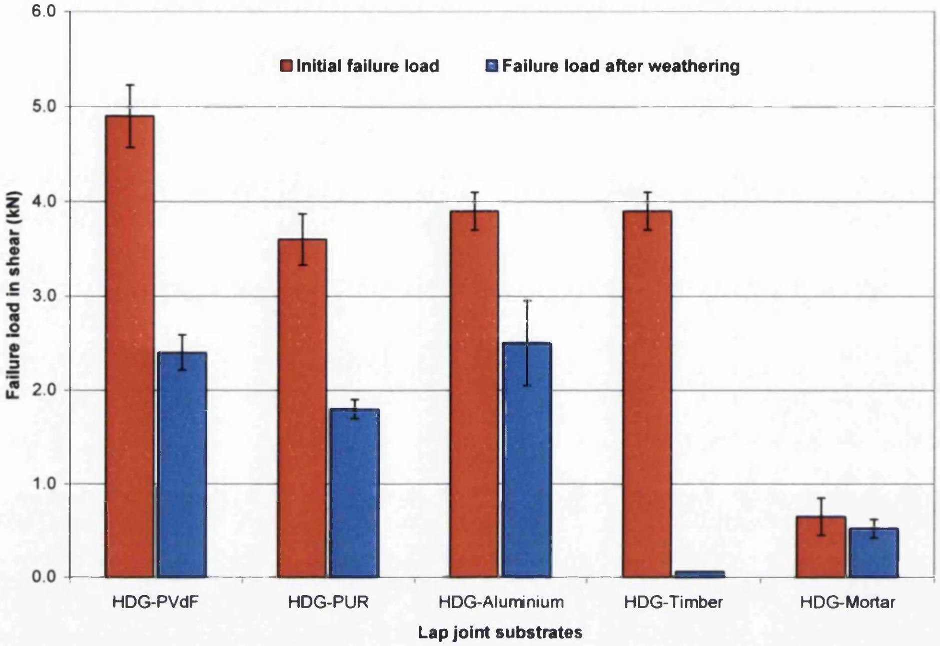


Figure 64 The short-term durability performance of adhesive bonded vanadium passivated galvanised steel multi-material joints.

Following short-term weathering, shear failure loads and strength retention values ranged from 0.1 – 2.5kN and 3 – 80% respectively with HDG_V steel – dissimilar material joints. Only galvanised steel – mortar joints demonstrated a strength retention value greater than 70%. A change in the primary mode of fracture was noted with all bonded joints. Interfacial failure at the zinc surface was the predominant mode with all multi-material joints except HDG_V – timber, where corrosion failure dominated. Corrosion of the galvanised steel substrate was noted with all multi-material joints and was particularly more evident with HDG_V steel – porous material combinations.

5.3.2 Dissimilar organic coated steels, Figure 65

Shear loads initially ranged from 3.9 – 6.0kN with dissimilar organic coated steel joints. All adhesive types provided high bond strengths. Higher loads were provided by the PVdF – polyester coated steel joints. Cohesive failure was predominant with adhesive P1 on both multi-material combinations whereas different failure modes were obtained with joints bonded with adhesives E1 and A3.

Following short-term weathering, failure loads and strength retention values ranged from 1.3 – 4.9kN and 30 – 100% respectively. Only epoxy adhesive E1 provided high strength retention with both multi-material combinations. Both adhesives E1 and A3 failed at higher loads with PVdF – polyester coated steel joints; also with this multi-material combination joint degradation was noted with the development of polyester coating failure. Polyurethane – polyester coated steel joints bonded with adhesive E1 increased in strength as a consequence of weathering; degradation of P1 and A3 bonded joints was noted with an increase in interfacial failure.

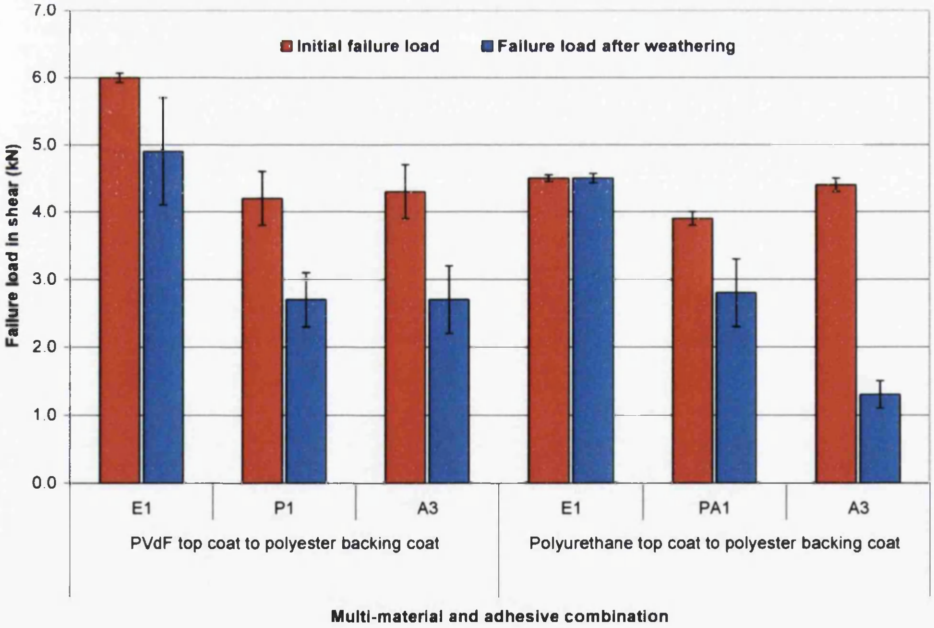


Figure 65 The short-term durability performance of adhesive bonded dissimilar organic coated steel lap joints.

5.3.3 Organic coated steel – Aluminium alloy 6082T6, Figure 66

Initial failure loads ranged from 2.4 – 6.1kN with organic coated steel – aluminium joints. Higher loads were obtained with PVdF – polyester coated steel joints. All epoxy, polyurethane and acrylic adhesives demonstrated high shear loads. Interfacial failure was predominant with many adhesives when bonded to acetone degreased aluminium. Typically, higher failure loads were obtained when the aluminium alloy was silane pretreated. This was also noted with either interfacial failure at the organic coating or cohesive failure.

After short-term weathering, shear failure loads and strength retention values ranged from 0 – 4.6kN and 0 – 138% respectively. High levels of strength retention (i.e. greater than 70%) were obtained with all organic coated steel – aluminium alloy combinations. Typically an increase in adhesive bond durability was obtained when the aluminium alloy substrate was silane pretreated. A variety of failure modes were evident after weathering. In particular, the development of aluminium corrosion was observed on the surface of acetone degreased aluminium and a change in the predominant mode of failure was noted with all organic coated steel – silane pretreated aluminium joints.

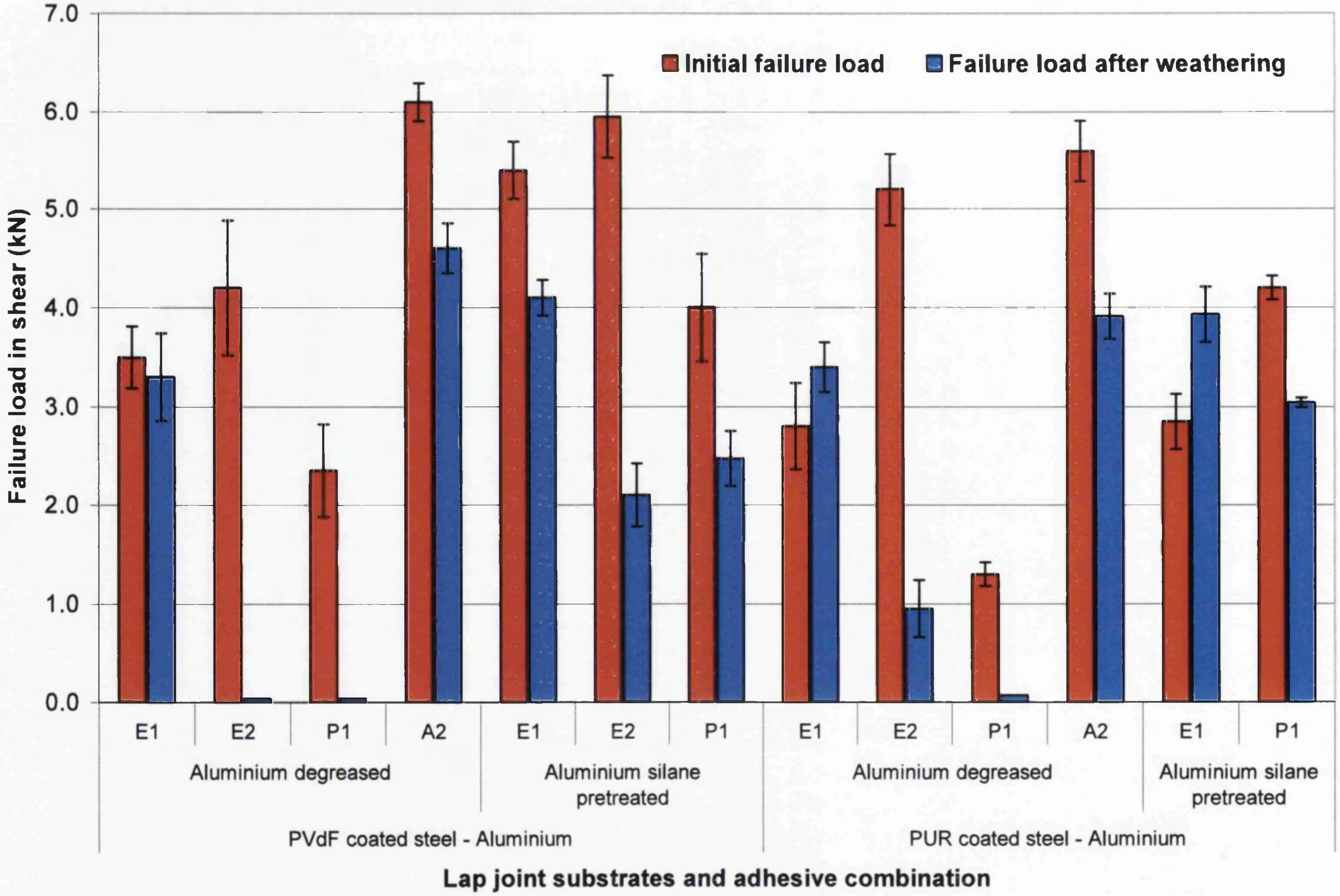


Figure 66 The short-term durability performance of adhesive bonded organic coated steel – aluminium alloy 6082T6 lap joints.

5.3.4 Organic coated steel – Glass, Figure 67

Test methodology development for organic coated steel – glass joints

As described earlier, the single lap shear joint was not a suitable design for assessing structural adhesives with glass, so the constrained lap joint was developed. Using this design it was also possible to evaluate OCS – glass joints by replacing the 50mm upper glass component with a 100mm OCS component. Again, an 8mm overlap length was used and a jig was required to hold the joints in the tensile machine.

Initial failure loads ranged from 0.8 – 3.4kN with organic coated steel – glass joints. With the exception of P1 bonded joints, adhesive bond strength did not significantly increase when the glass was silane pretreated. High levels of adhesive bond strength were demonstrated by all adhesive types. At higher loads, mixed failure modes were evident, whereas, at lower failure loads interfacial failures either at the glass or organic coating were predominant.

All organic coated steel – acetone degreased glass joints failed at the glass surface within a few days of humidity exposure. However, shear failure loads and strength retention values ranged from 0.9 – 2.9kN and 31 – 94% respectively when the glass component was silane pretreated. High levels of strength retention were provided by epoxy and acrylic adhesives on both organic coated steel – silane pretreated glass combinations. A variety of failure modes were observed after weathering. In particular, the poor durability of adhesive P1 was noted with interfacial failure at the PVdF coating. Minor strength losses were noted with a small increase in interfacial failure at the glass substrate.

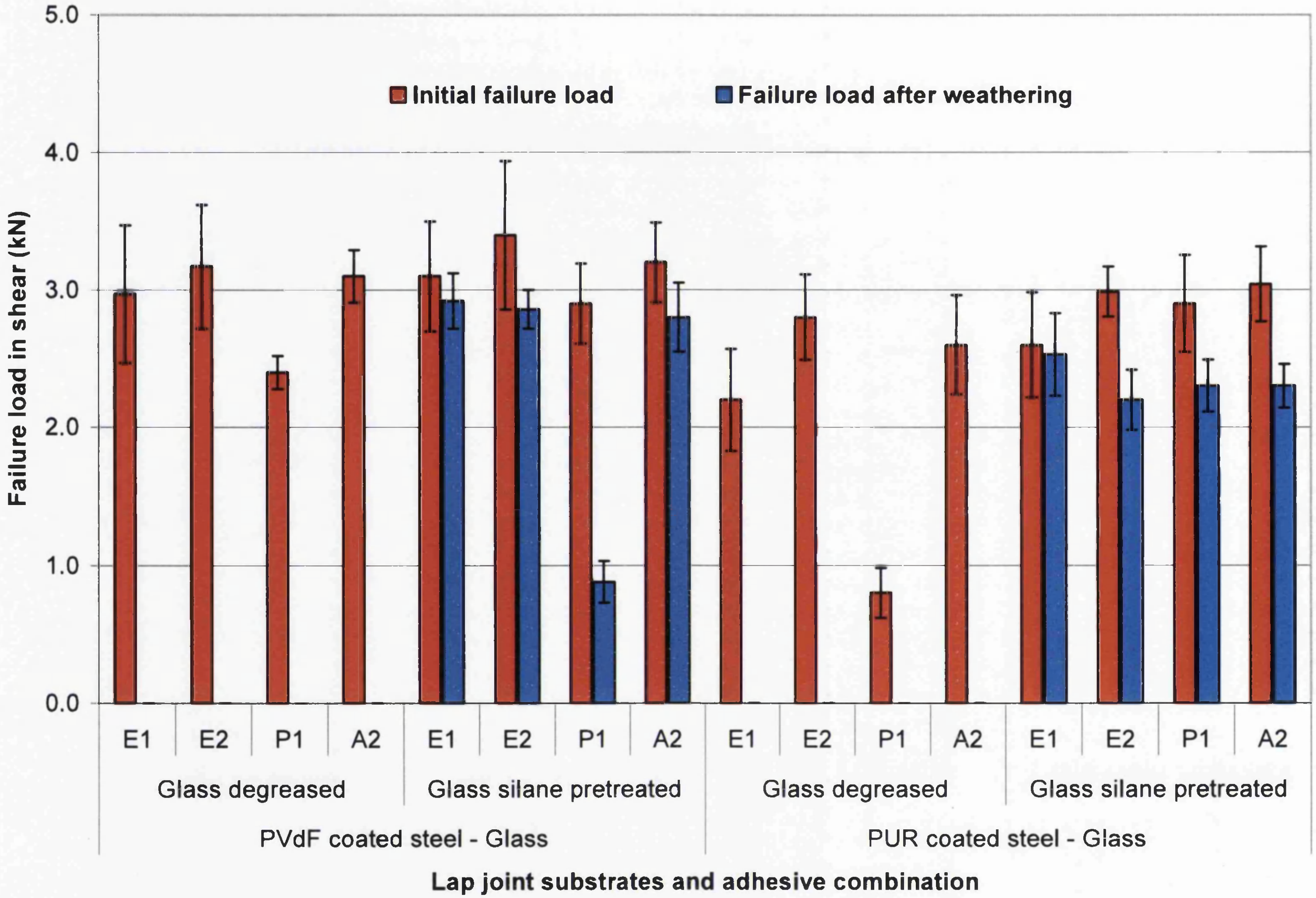


Figure 67 The short-term durability performance of adhesive bonded organic coated steel – glass lap joints.

5.3.5 Organic coated steel – Timber, Figure 68

Initial failure loads ranged from 1.2 – 4.4kN with organic coated steel – timber joints. Higher failure loads were provided by PVdF coated steel – timber joints. All adhesives demonstrated high failure loads with both multi-material combinations. A mixture of timber substrate and timber interphase failure was noted at higher failure loads. At the lowest loads, interfacial failure at the organic coatings was predominant.

After weathering, shear failure loads and strength retention values ranged from 0 – 1.4kN and 0 – 32% respectively with PVdF coated steel – timber joints. No correlations were noted between strength loss and mode of failure development. Failure modes varied from PVdF interfacial to timber interfacial after weathering. All polyurethane coated steel – timber joints failed prior to tensile testing.

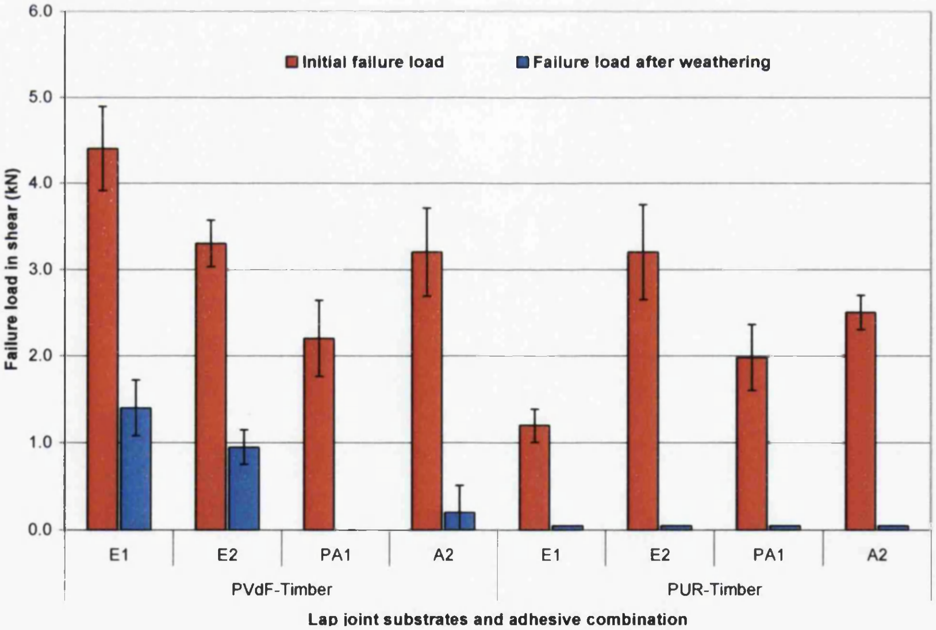


Figure 68 The short-term durability performance of adhesive bonded organic coated steel – timber lap joints.

5.4 SEALANT BONDED MULTI-MATERIAL JOINTS

The dissimilar material and sealant combinations investigated in this section were chosen because of their compatibility, superior strength and durability. Again, the optimum performance of each multi-material combination has been postulated [**appendix 3**]. Any deviations between predicted and actual results will be an indication that something unexpected has occurred.

5.4.1 Galvanised steel – Organic coated steel, Figure 69

Initially all sealants surpassed the 0.32kN minimum criterion; tensile loads ranged from 0.82 – 1.44kN. The highest failure load was provided by sealant SMP. All hybrid polymer sealants failed at similar tensile loads. Cohesive failure was the predominant mode of failure with all structural sealants used.

After forty-two days of water immersion the failure loads and strength retention values ranged from 0.3 – 0.68kN and 35 – 47% respectively. The most durable joints were bonded with sealant SMP. Similar levels of durability were demonstrated by all hybrid polymer sealants. Both sealants failed to meet the minimum performance criteria with galvanised steel – polyurethane coated steel joints. The greatest strength losses occurred during the initial stage of weathering. Surface cohesive failure close to the HDG_{Cr} steel surface was the predominant mode of failure with all sealant – substrate combinations. A small development of interfacial failure at was also noted at the edges of the bond area on both substrate surfaces.

5.4.2 Galvanised steel – Aluminium alloy 6082T6, Figure 69

Initially failure loads were 0.65kN and 1.39kN with sealants H1 and SMP respectively. Cohesive and surface cohesive failures (close to the galvanised steel surface) were the primary mode of failure with both bonded joints.

After weathering the tensile loads and strength retention values were 0.31kN and 48% with H1 bonded joints and 0.66kN and 47% with SMP bonded joints. The greatest loss in bond strength occurred during the first twenty-one days of weathering with both structural sealants. Cohesive failure and surface cohesive failures (close to the galvanised steel surface) were still the primary mode of failure after weathering.

5.4.3 Galvanised steel – Timber, Figure 69

Initially failure loads were 0.85kN with H1 bonded joints and 1.46kN with SMP bonded joints. Cohesive and surface cohesive failures (close the galvanised steel surface) were the predominant modes of failure.

Tensile loads and strength retention values after weathering were 0.14kN and 16% with H1 bonded joints and, 0.15kN and 10% with SMP bonded joints. Almost all strength loss occurred during the initial stages of weathering. Surface cohesive failure was the predominant failure mode with both sealant bonded joints. A small development of interfacial failure at the timber surface was noted with sealant H1, whereas, interfacial failure at the HDG_{Cr} steel surface was observed with SMP bonded joints.

5.4.4 Galvanised steel – Mortar, Figure 69

Initial tensile failure loads were 0.72kN and 1.35kN with sealants H2 and SMP respectively. Cohesive failure was the primary mode of failure with both bonded assemblies; however, at higher tensile loads mortar failure was also observed.

As a result of weathering, both sealant bonded joints failed to meet the minimum performance levels defined for a structural sealant. The tensile loads and strength retention values were 0.13kN and 18% with H2 bonded joints and, 0.21kN and 16% with SMP bonded joints. The majority of strength loss was observed during the first twenty-one days of water immersion. The predominant failure mode was surface cohesive failure (at the mortar surface) with both sealant bonded joints.

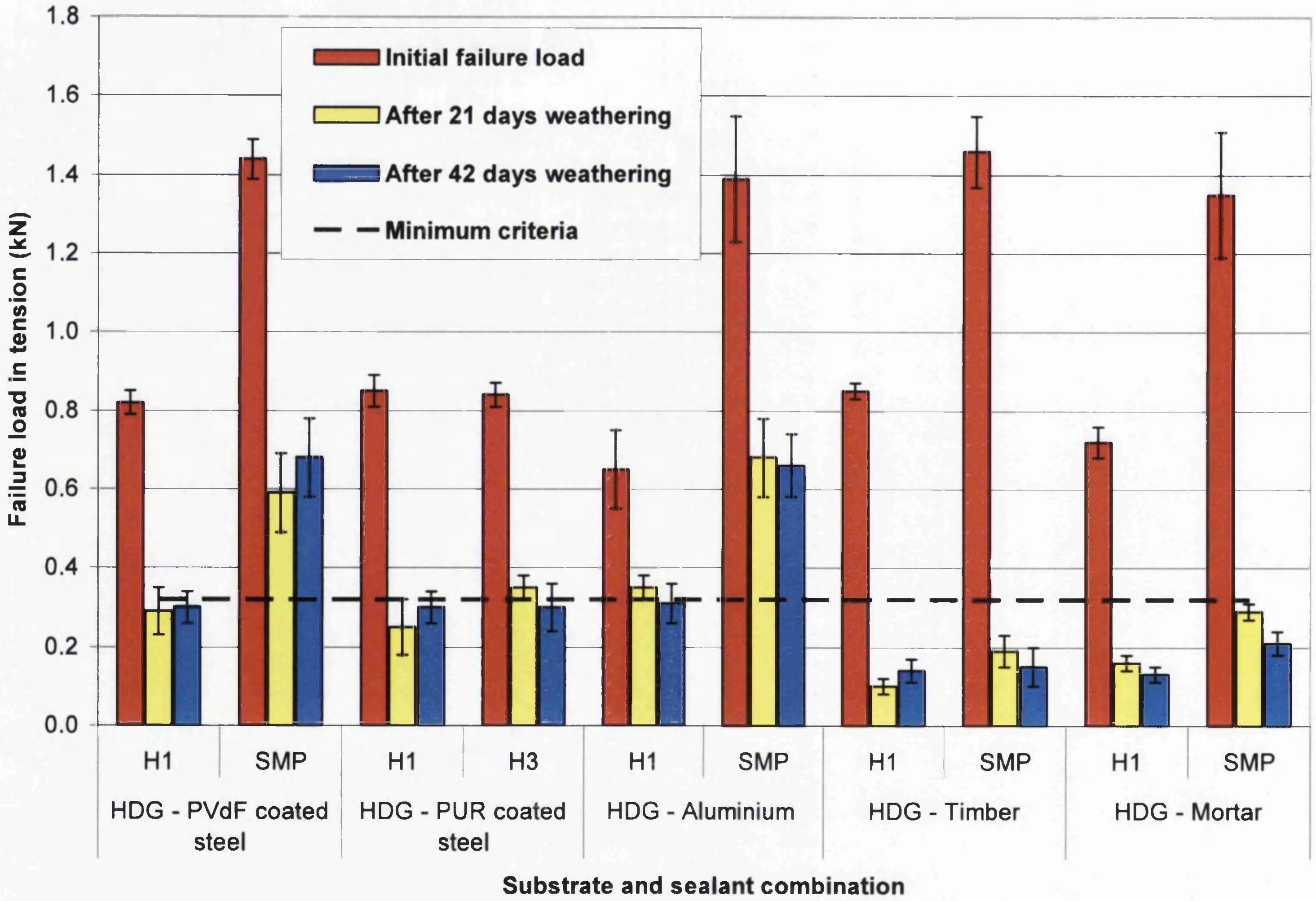


Figure 69 The durability performance of sealant bonded chromium passivated galvanised steel – organic coated steel, aluminium alloy 6082T6, timber and mortar H-joints.

5.4.5 Organic coated steel – Aluminium alloy 6082T6, Figure 70

Initial tensile loads ranged from 0.73 – 1.18kN with organic coated steel – aluminium alloy joints. The highest failure load was obtained with PVdF coated steel – aluminium alloy joints bonded with sealant SMP. All hybrid polymer sealants failed at similar tensile loads. Cohesive and surface cohesive failures (near the aluminium adherend) were the primary failure modes with both material combinations.

After forty-two days of water immersion, tensile loads and strength retention values ranged from 0.28 – 0.5kN and 38 – 46% respectively. PVdF coated steel – aluminium joints bonded with sealant SMP failed at the highest load. Similar levels of durability were demonstrated by all hybrid polymer sealants. Both sealants failed to meet the minimum performance criteria with polyurethane coated steel – aluminium alloy joints. Typically, strength loss was most rapid during the early stages of weathering. Surface cohesive failure at both organic coated steels was the predominant failure mode after weathering. In addition, the development of interfacial failure at the polymer coatings was observed.

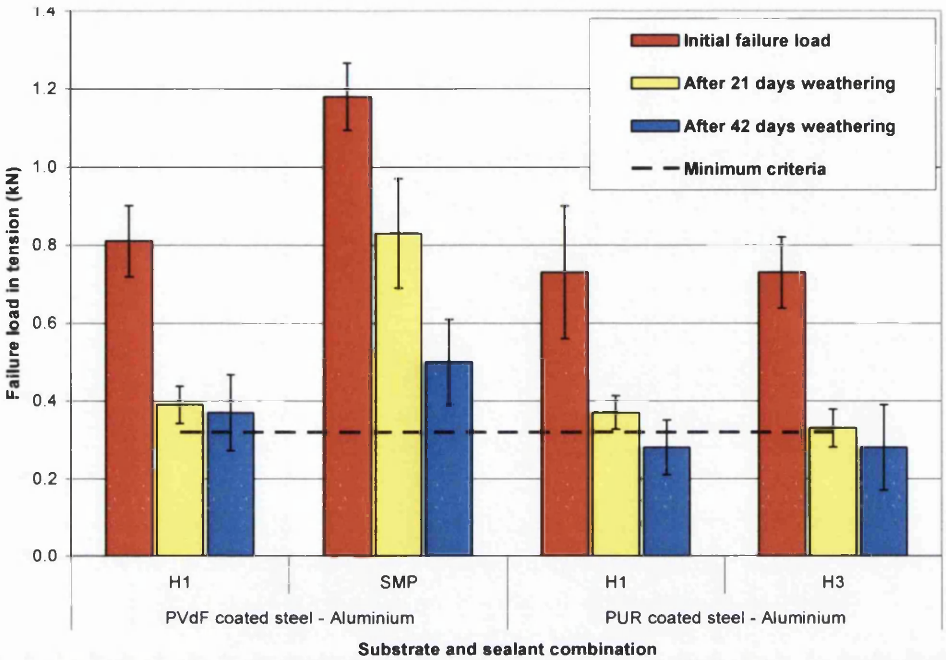


Figure 70 The durability performance of sealant organic coated steel – aluminium alloy 6082T6 H-joints.

5.4.6 Organic coated steel – Glass, Figure 71

Initial tensile loads ranged from 0.75 – 1.41kN with organic coated steel – glass joints. Each sealant demonstrated equal levels of compatibility with both multi-material combinations. The highest tensile strengths were provided by sealants PS and SMP; silicone and hybrid polymer sealants failed at similar loads. Cohesive and surface cohesive failures were the primary failure modes with all sealant bonded joints. At the highest tensile loads, deformation of the steel substrates was also observed.

After weathering, tensile loads and strength retention values ranged from 0.16 – 1.25kN and 14 – 101% respectively. The rate of strength loss varied between different sealants and at different stages of weathering. Again, both cohesive and surface cohesive failures were predominant after weathering. With H1 and PS bonded joints, surface cohesive failure occurred at the UV-A light exposed glass surface; these joints also showed the lowest levels of strength retention.

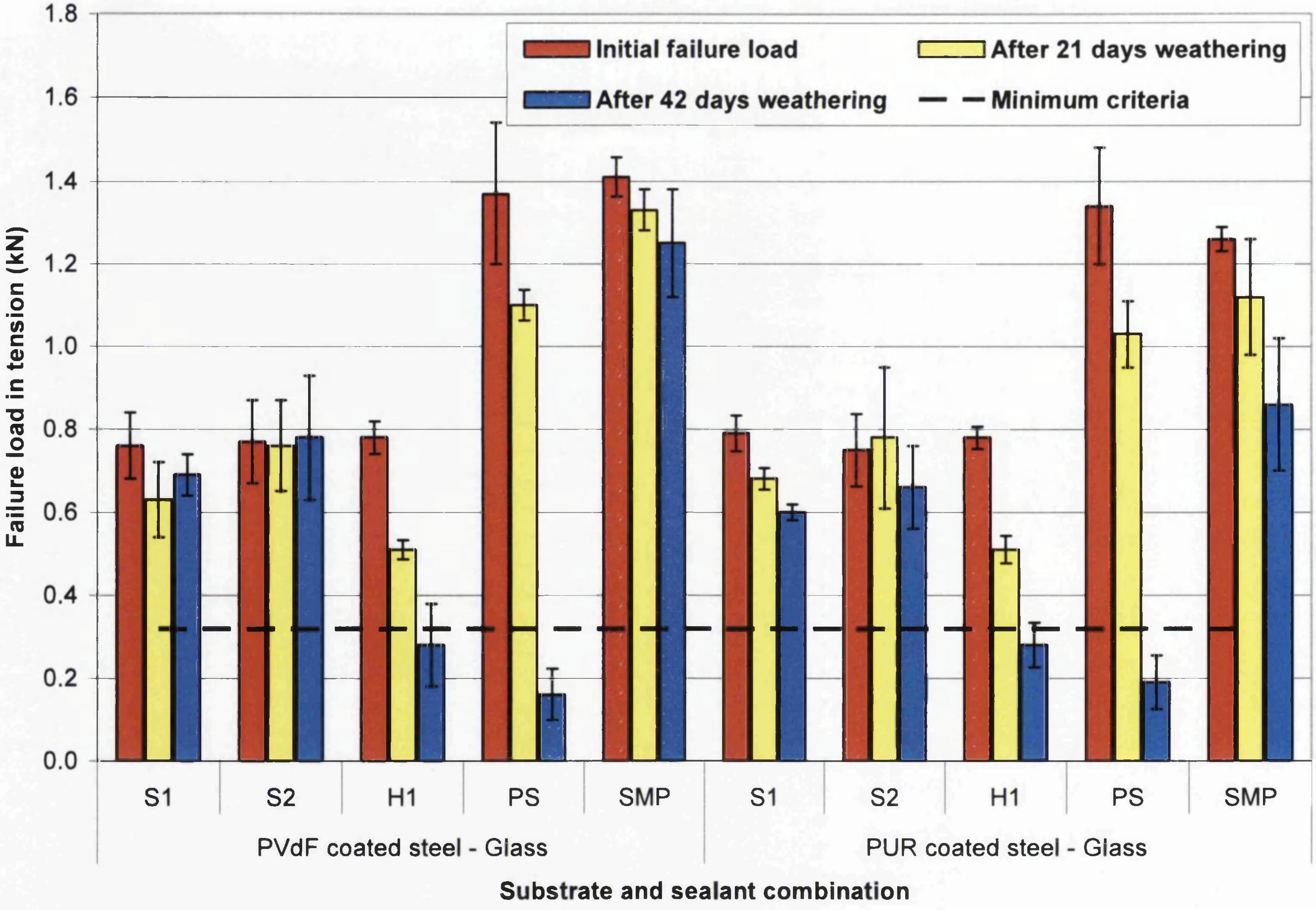


Figure 71 The durability performance of sealant bonded organic coated steel – glass H-joints.

5.4.7 Organic coated steel – Timber, Figure 72

Initial tensile loads ranged from 0.82 – 1.17kN with organic coated steel – timber joints. The highest failure load was obtained with PVdF coated steel – timber joints bonded with sealant SMP. All hybrid polymer sealants failed at similar tensile loads. Cohesive and surface cohesive failures (at all substrates) were the predominant modes of fracture.

After forty-two days of water immersion, all sealants failed to meet the minimum performance criteria. Tensile loads and strength retention values ranged from 0.11 – 0.2kN and 9 – 22% respectively. Strength loss was most rapid during the early stages of weathering. Surface cohesive failure near the timber substrate was the sole failure mode with both multi-material combinations.

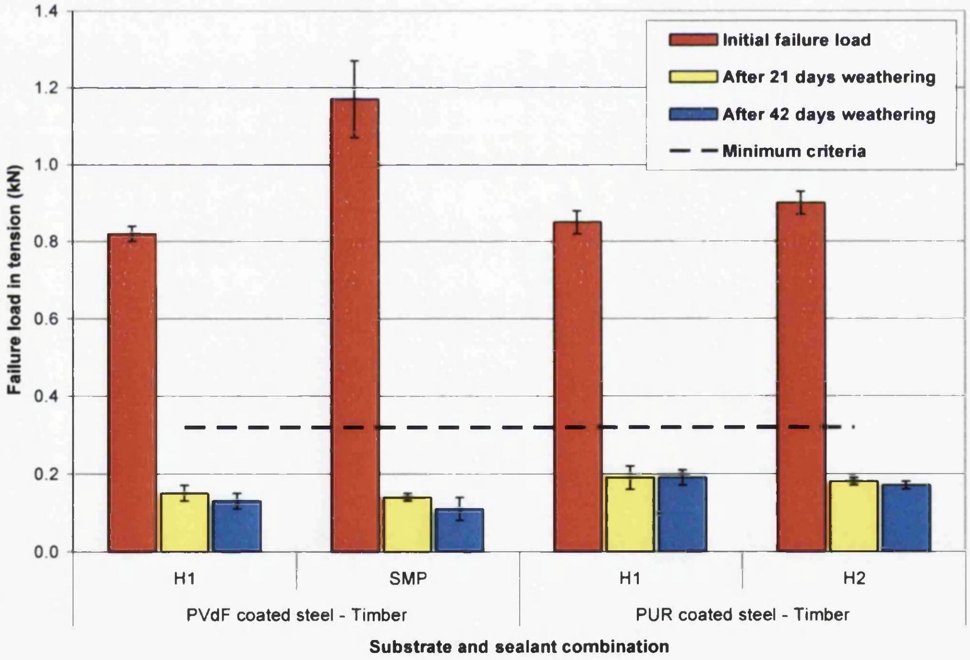


Figure 72 The durability performance of sealant bonded organic coated steel – timber H-joints.

6.0 DISCUSSION

The ability to fabricate joints between galvanised or organic coated steels and dissimilar materials expands the application opportunities for precoated sheet steels in new and novel applications in the construction sector. This is because synergy between appropriate dissimilar material combinations enables the achievement of function when design requirements demand for properties and performance levels unobtainable by a single material. As the basic nature of materials become more diverse, joining them together becomes increasingly more challenging. The 'dissimilar' construction materials chosen for this research project includes aluminium, glass, timber and mortar. Such materials possess a wide range of properties and can be used in structural load bearing applications. Hence, combining these materials with precoated steels enables the various issues associated with joining both dissimilar metal and fundamentally dissimilar materials to be studied.

A key enabling technology for precoated sheet steel – dissimilar material combinations is the development of robust joining processes that are tailored to the specific requirements of both the materials and the application. A review of the joining processes currently used to assemble sheet steel structures and components indicated that adhesive and sealant bonding has the most potential for joining both dissimilar metal and fundamentally dissimilar material combinations. Furthermore, unlike traditional joining processes such as welding, brazing and mechanical fastening, adhesive and sealant bonding has no adverse effects on the precoated steel products being joined. However, for adhesives and sealants to gain wider acceptance in the construction industry, it is necessary to demonstrate their resistance to high relative humidity and water. This is because the ingress of water into adhesive and sealant bonded joints often leads to joint failure.

Previous research has demonstrated that there are adhesives, sealants and, surface pretreatments available which provide high levels of bond strength and durability in a range of environments with precoated sheet steels, aluminium, glass, timber and mortar. However, due to the demand for longer functional performance guarantees against corrosion and photodegradation, the additives within precoated steels are continually being adjusted and modified. Such changes to the chemistry of a precoated steel product can significantly affect its surface properties and hence the ability to successfully bond it. Consequently, the results from earlier studies may no longer be valid. Therefore the initial objective of this research project was to re-evaluate adhesive and sealant bonding as a joining method for precoated sheet steels.

Furthermore, it must be noted that the vast majority of adhesive and sealant bonding studies (regardless of the material used) only considered the behaviour of uni-material joints; there was very limited literature available on the performance of multi-material joints. This highlighted the fundamental issue that at present there are no standard testing procedures for adhesive and sealant bonding sheet steels to dissimilar materials. Consequently, the second aim of this Eng.Doc research project was to establish test methodology procedures for the fabrication of adhesive and sealant bonded multi-material joints where high strength and long-term durability are key requirements.

6.1 ADHESIVE AND SEALANT JOINT TEST METHODOLOGIES

In terms of identifying appropriate adhesive and sealant systems for joining multi-material combinations there were two criteria that needed to be established. Firstly, the compatibility of the adhesive or sealant system, which was defined by the lap shear and tensile strength obtained prior to joint failure, and secondly, the level of strength retention after weathering. As water/high humidity was identified as the biggest concern with respect to bond durability, it was decided that this would be the most appropriate type of weathering environment. A variety of industry standard weathering procedures were selected to rapidly age joints in a manner that would be expected under normal service conditions. For adhesive bonded joints, this involved exposure to high levels of relative humidity, whereas a water immersion test was used with sealant bonded joints. Progressive monitoring of the joint failure load and primary mode of fracture enabled the critical mechanism of degradation to be interpreted.

The industry standard single lap joint and H-joint were chosen as the primary methods for assessing the performance of all structural adhesives and sealants with all construction materials. The H-joint configuration proved to be a very effective and versatile design for evaluating structural sealants on all types of substrate (and with multi-material combinations). However, there were issues with using the single lap shear joint to evaluate the compatibility of structural adhesives on brittle adherends such as glass and mortar. Initial studies showed that joint failure occurred at relatively low loads within the substrate with (outside of the overlap region), which was due to the inherent bending moments generated by a loaded lap shear joint. As a result, a series of tests were carried out to develop a new joint design which minimised the out of plane stresses in the adherends, and promoted failure within the adhesive bond area. Of the four alternative joint designs assessed, the constrained lap joint provided the best results in terms of high failure load and mode of fracture. This joint design was also simple to fabricate and could easily be adapted for multi-material combinations.

6.2 ADHESIVE BONDED UNI-MATERIAL LAP JOINTS

6.2.1 Galvanised steel

Overall, good chemical compatibility and high shear loads were demonstrated between the different galvanised steel substrates and both epoxy adhesives prior to weathering. The maximum failure load obtained by each epoxy adhesive was dependent on the galvanised steel substrate. With HDG and HDG_{Cr} steel joints, the high incidence of interfacial failures suggested that acetone degreasing the substrates prior to bonding was not an optimum surface preparation for these materials. (Such a failure mode can be caused by carbon contamination of the surface, which acts as a weak boundary layer. This is a common feature on metal and glass substrates exposed to the atmosphere). Whereas acetone degreasing proved to be a more effective surface preparation technique with HDG_V steel joints which failed at the highest shear loads with both epoxy adhesives with a predominantly cohesive mode of fracture. A comparison of the surface energy values of the three different zinc coated products showed that HDG_V steel had the highest surface energy value [**Table 11**]. This would enhance the adhesives ability to wet the surface of the substrate and establish the intimate bonds responsible for adhesion. The superior performance of vanadium passivated galvanised steel joints was obtained with a thinner steel substrate and should be considered for applications where weight reduction is a necessity.

All adhesive bonded galvanised steel joints, including those pretreated prior to adhesive application, indicated that the inherent durability of such products was inadequate (i.e. did not retain 70% strength retention). Interfacial and corrosion failures were predominant with all bonded joints after weathering. This indicated that the primary mechanism of joint degradation was associated with the ingress of moisture at the interface between the adhesive and the galvanised steel substrates. Contrary to Jones and Williams suggestion that cathodic delamination is responsible for the poor durability of adhesive bonded galvanised steel joints [57,58], it is proposed that anodic undermining is the critical failure mechanism. Although both mechanisms involve anodic and cathodic reactions [see section 3.1.1.1], the location of these regions differs. For cathodic delamination to occur, both water and oxygen must be absorbed into the adhesive layer and accumulate at the substrates surface to establish cathodic areas, which control the kinetics of failure. This failure mechanism is typically associated with the delamination of organic coatings on galvanised steel substrates. With anodic undermining, attack occurs because part of the metal surface is in a shielded or restricted environment (i.e. the bond area forms the anode), compared to the rest of the metal, which is exposed to oxygen and electrolyte and forms the cathode [**Figure 73**].

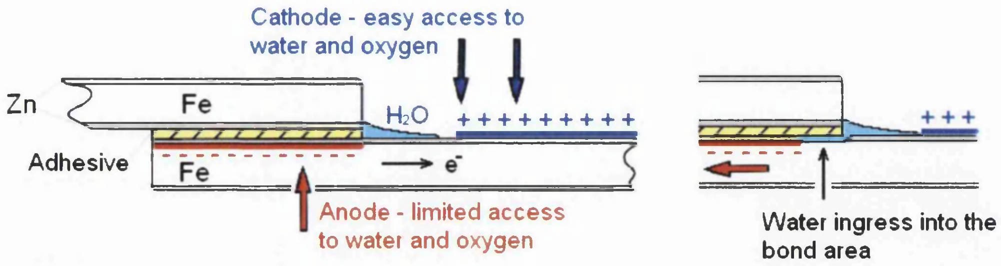


Figure 73 Anodic undermining on the surface of adhesive bonded galvanised steel joints

In most cases, the application of a surface primer or pretreatment to bare galvanised steel improved adhesive bond strength and durability. Scanning electron microscopy (SEM) images of the primed and pretreated galvanised steel substrates showed no significant changes in the surface topography when compared to the original galvanised steel surface [**Figure 74**]. This suggests that enhanced performance was either due to a higher surface activity, which increased secondary bond density or the formation of primary chemical bonds across the adhesive – adherend interface. Furthermore, previous studies have shown that the electrochemical activity of galvanised steels plays a vital role in the kinetics of degradation and failure mechanism [57]. Passivation coatings, primers and pretreatments generally inhibit such electrochemical activities on metallic surfaces and consequently improve adhesive bond durability.

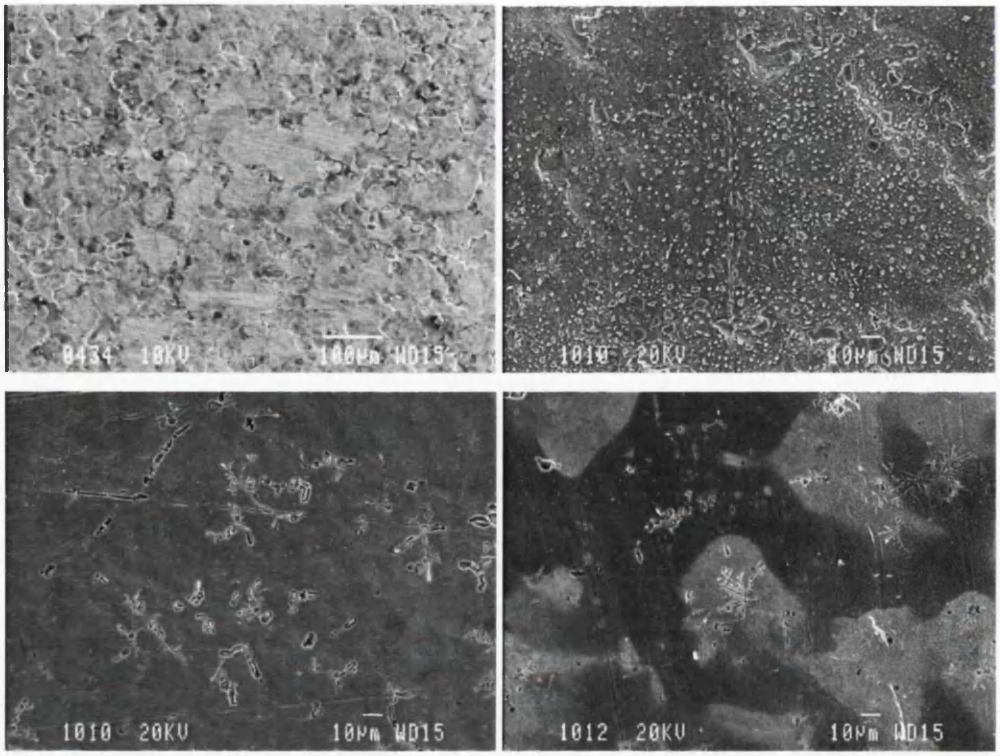


Figure 74 SEM images of bare galvanised steel (top left), chromium pretreated galvanised steel (top right), polymer pretreated galvanised steel (bottom left) and silane pretreated galvanised steel (bottom right).

The diffusion of water into adhesives is an activated process that obeys the Arrhenius equation, which means that the diffusion rate will increase with temperature [85]. The two weathering regimes used were compared and evaluated using the rule of thumb that the reaction rate doubles when there is a temperature increase of approx. 7 – 8 °C. Results showed that there was a close correlation between joint strength and mode of fracture after fourteen days weathering at 70°C and sixteen weeks at 46°C (the failure loads obtained after short-term tests have been superimposed onto the long-term weathering figures). However, further studies will be required to evaluate the potential of replacing undesirable long-term weathering procedures with appropriate short-term tests.

On further inspection of silane primed and chromate pretreated bond areas, it was visible that joint failure had not only occurred at the adhesive – pretreatment interface but also at the pretreatment – substrate interface and cohesively within the pretreatment layer. To provide more information on the exact locus of failure of silane and polymer pretreated galvanised steel joints, some FTIR studies were undertaken on samples that had failed at the interface. Although this surface analysis technique is not suitable for use on metallic substrates or coatings, it was used to indicate whether or not there was an organic pretreatment on the substrates surface. The transmittance spectra obtained showed no traces of these surface pretreatments which indicated that failure had occurred at the galvanised steel – pretreatment interface [**Figure 75**].

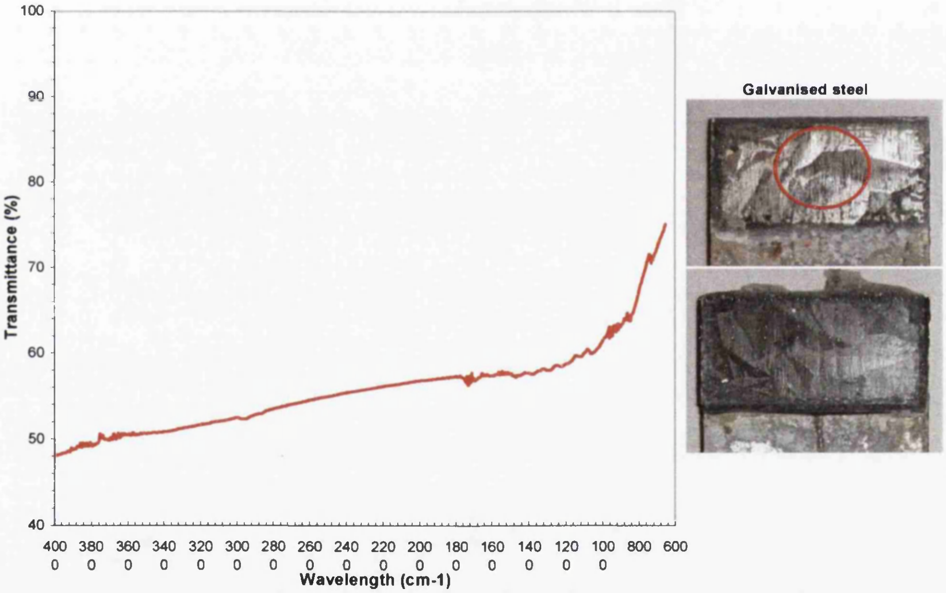


Figure 75 FTIR analysis of a fractured chromate pretreated galvanised steel joint.

6.2.2 Organic coated steel

Overall, the results indicated that there are epoxy, acrylic and polyurethane adhesive systems available to generate high levels of adhesive bond strength with all organic coated steels investigated. Initially, a variety of fracture modes were observed. This included interfacial failure, coating failure and cohesive failure. The maximum failure load obtained was dependent on the organic coating chemistry, steel base thickness, and adhesive selection. A larger range of shear failure loads was noted with thermoplastic coated steels when compared to thermosetting coated steels, which particularly highlights the importance of adhesive selection with these precoated steel products.

The highest failure loads were obtained with PVdF coated steel lap joints. The thicker steel substrate used with this product was considered to be largely responsible for this as a greater load had to be applied in order to bend the joint sufficiently to initiate failure as a consequence of peel and cleavage forces [36]. Similar failure loads were obtained with polyester (top coat) and black polyurethane coated steel lap joints. These organic coated products have a large variation in their surface free energies (i.e. 31.7 – 39.2mNm^{-1}), which suggests that surface energy is not a critical factor influencing adhesive bond strength. Overall, relatively similar performance levels were demonstrated by the different adhesive types on black, white and silver metallic effect polyurethane coated steels [**Figure 76**]. This indicates that neither the colour of the polyurethane coating nor the metallic effect (aluminium flake addition) affect the ability to bond this material. Overall, slightly lower failure loads were obtained with the green rough textured polyurethane coated steel. This could have been caused by poor penetration of the adhesive into the surface asperities of the coating and insufficient wetting.

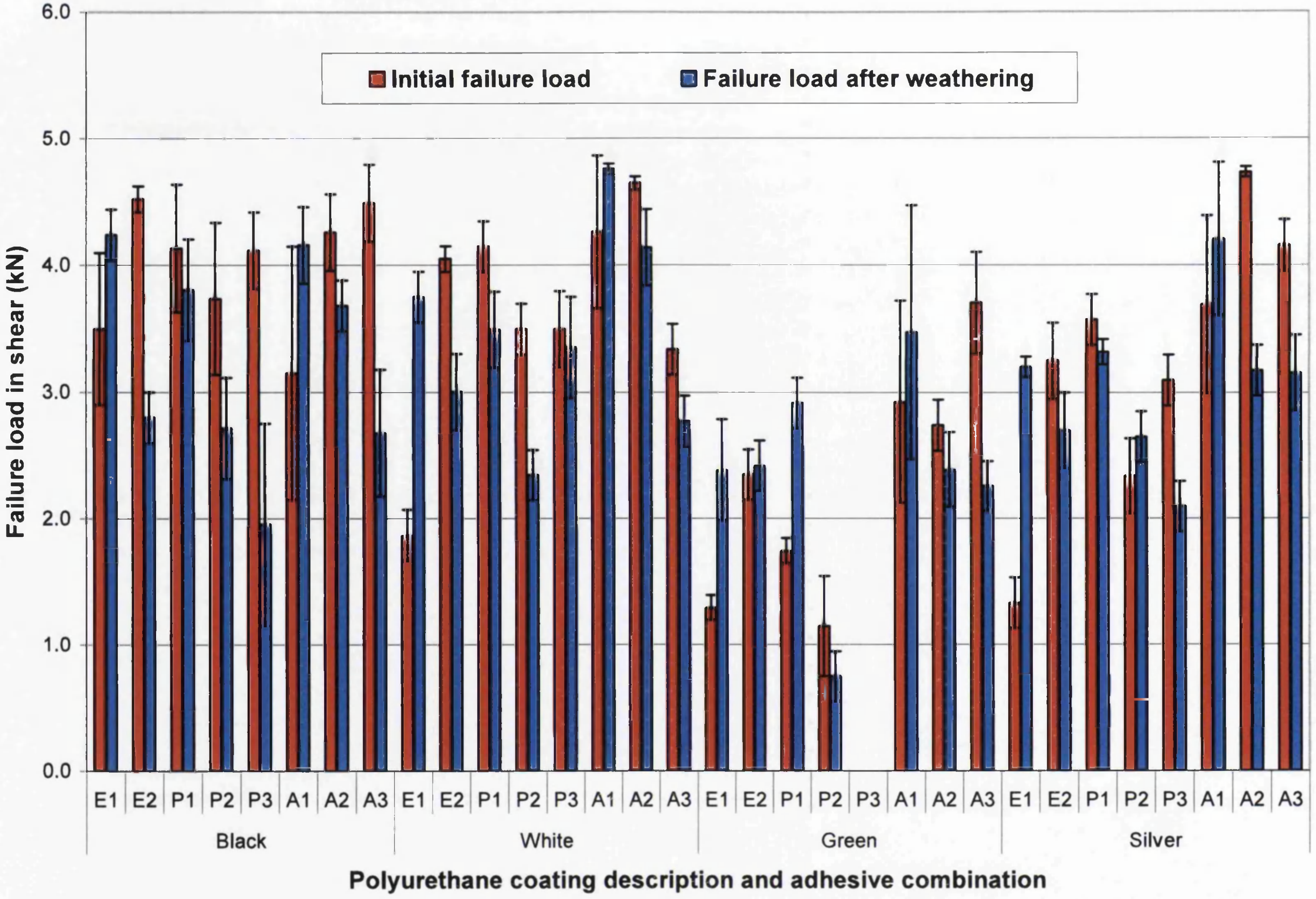


Figure 76 A comparison of the compatibility and durability performance of adhesive bonded polyurethane coated steels.

The lowest failure loads obtained with each adhesive type was noted with PVC-plastisol coated steel; four possible factors contributing to this are

1. Chemical incompatibility between the adhesives and PVC-plastisol coating resulted in poor adhesion and interfacial failure.
2. The thick porous topcoat is cohesively weaker than the other coatings and failed at much lower loads.
3. PVC-plastisol contains low molecular weight plasticizers that are highly mobile and can migrate to the surface prior to bonding, or to the interface after bonding, and thus act as a weak boundary layer [86]. Also, these plasticizers can migrate across the adhesive – coating interface into the adhesive layer, which results in a loss of mechanical integrity and softening of the adhesive material [86].
4. The absence of metal ions on the PVC-plastisol coating. With certain acrylic adhesives the presence of metal elements on the surface is essential to catalyse the curing mechanism [6].

A comparison of short-term and long-term weathering results indicated that at 100% relative humidity, the correlation between failure loads obtained after fourteen days weathering at 70°C and sixteen weeks at 46°C was dependent on the adhesive – coating combination. The modes of failure were always comparable, which indicated that the higher temperature used for short-term weathering did not introduce mechanisms of degradation that would occur under less destructive conditions. Again, further work is required to establish the potential of replacing undesirable long-term weathering regimes with appropriate short-term tests.

As a consequence of weathering, a variety of degradation mechanisms were identified from the changes that had occurred to the mode of fracture. All of these mechanisms were associated with the ingress of water into the adhesive bond line and include:

1. Water disbondment: an increase in interfacial failure indicates that water had accumulated at the interface and ruptured the adhesive bonds. This was considered to be the mechanism most detrimental to adhesive bond durability as it was generally noted with lower levels of strength retention.
2. Plasticisation of the adhesive: an increase in cohesive failure at lower shear loads indicates that water had absorbed into the adhesive and lowered it modulus. Plasticisation ceases to be a factor once water uptake has reached equilibrium.This was evident by epoxy adhesive E2.
3. Hydrolysis of the adhesive: this can also be identified by an increase in cohesive failure at lower failure loads. In general, hydrolysis requires much longer weathering periods than plasticisation.
4. Coating degradation: this was particularly evident with polyester coated steels.

FTIR analysis of selected samples was carried out to confirm interfacial failures and to establish the exact locus of failure within the various organic coated steel products. The results of the latter showed that with:

PVdF coated steel: coating failure occurred at the primer – chrome pretreatment interface **[Figure 77]**.

PVC-plastisol coated steel: analysis confirmed that coating failure occurred within the thick porous top coat.

Polyurethane coated steel (black): coating failure occurred at the chrome pretreatment – galvanised steel interface and cohesively within the primer layer **[Figure 78]**.

Polyurethane coated steel (white): coating failure occurred cohesively within the primer layer and at the chrome pretreatment – galvanised steel interface.

Polyurethane coated steel (green with rough texture): coating failure occurred at the chrome pretreatment – galvanised steel interface.

Polyurethane coated steel (silver metallic effect): coating failure occurred mainly within the top coat layer and at the top coat – primer interface.

Polyester coated steel (top coat): coating failure occurred cohesively within the polyester topcoat [**Figure 79**]. As coating failure was noted to increase as a consequence of humidity exposure, a selection of weathered samples were analysed. However, results showed that coating failure still occurred cohesively within the polyester coating.

Polyester backing coat: coating failure occurred cohesively within the polyester backing coat. Again, as coating failure was noted to increase as a result of ageing, a selection of weathered samples were analysed. Results indicated that failure still occurred cohesively within the polyester coating.

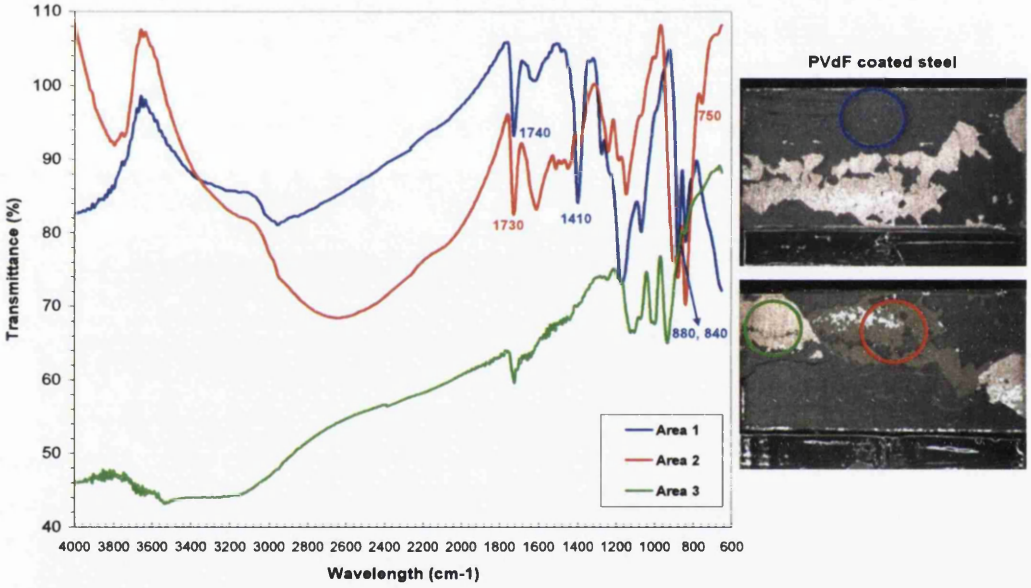


Figure 77 FTIR analysis of PVdF coating failure. The blue, red and green spectra were characteristic of the PVdF coating, the acrylic primer and the chrome pretreated galvanised steel substrate.

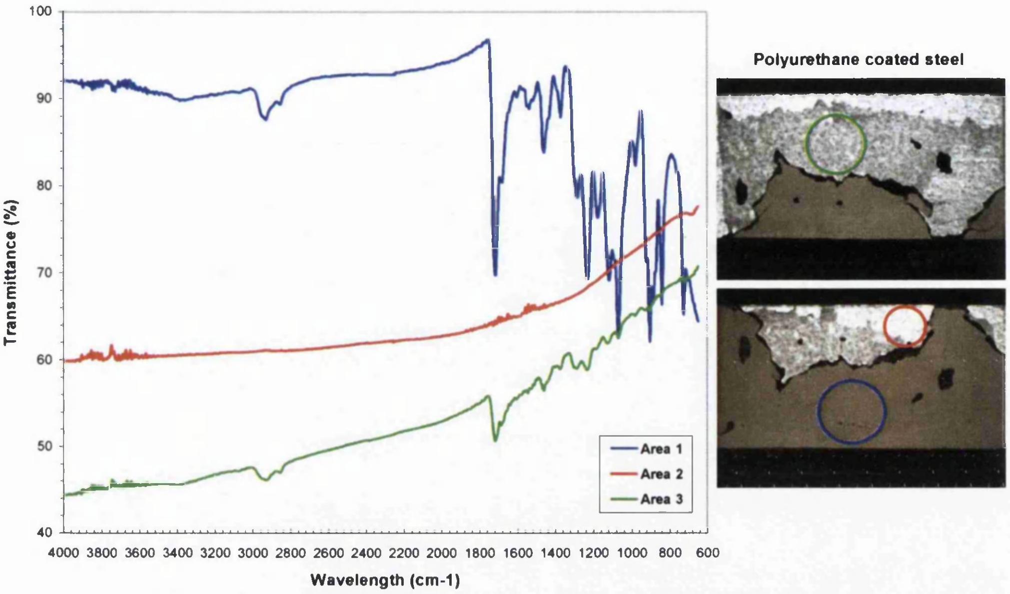


Figure 78 FTIR analysis of (black) polyurethane coating failure. The red, blue and green spectra are characteristic of the polyurethane primer and the galvanised steel substrate.

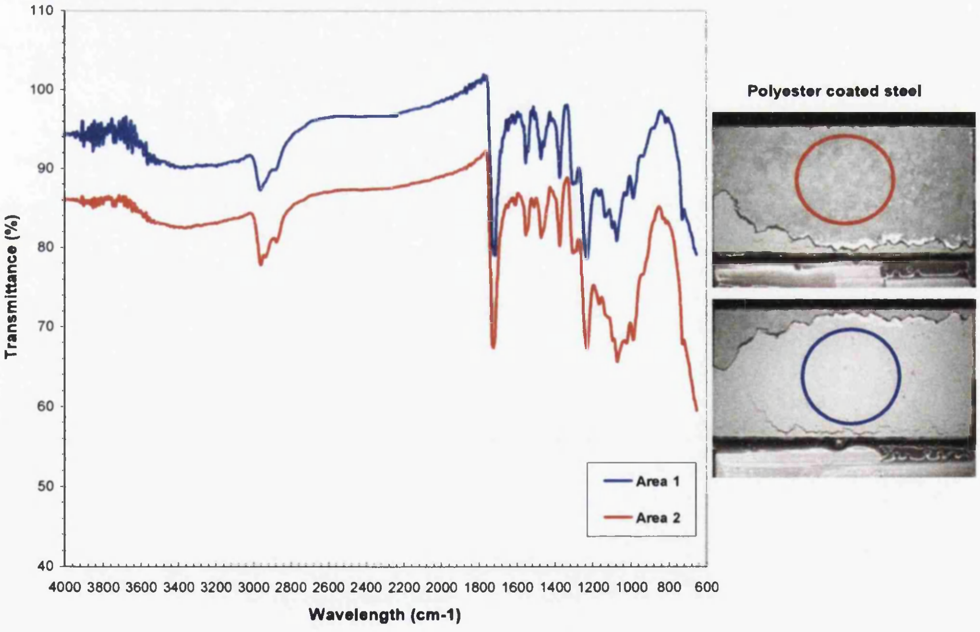


Figure 79 FTIR analysis of polyester coating failure (top coat). The red and blue spectra are characteristic of the polyester top coat.

The improved adhesion to the PVC-plastisol coated steel substrate after QUV weathering was noted with a change in its surface chemistry [**Table 15**]. X-ray photoelectron spectroscopy (XPS) analysis indicated that the surface chemistry of PVC-plastisol coated steel had undergone significant changes, with the most marked difference being the drop in the carbon content and a rise in chlorine. No sodium was detected on the surface, suggesting that the excess chlorine was not present as salt, so was presumably related to the chlorine present in the PVC matrix. It is speculated that during the QUV weathering cycle, plasticiser near the surface evaporates, thus removing a potential weak boundary layer and leaving more of the bulk PVC exposed. Pre-weathering PVC-plastisol coated steel did not change the material's surface energy.

Table 15 XPS analysis showing the changes in chemical composition of PVC-plastisol coated steel as a result of 1500 hours QUV weathering.

Treatment	Na	Ba	O	Sn	N	C	Cl	S	Si	Al
None	4.1	0.1	20.6	<0.1	0.5	72.5	1.4	0.8	<0.1	<0.1
QUV	<0.1	0.11	21.04	0.22	0.73	67.16	7.9	0.36	2.03	0.46

Both organic coated steel products that were pre-weathered prior to adhesive bonding demonstrated failure loads that were equal to and higher than the original failure loads. This indicates that the weathering cycle did not adversely affect the bonding ability of these materials and that they are suitable for recycling and re-using in applications that require attachment by either adhesive or sealant systems.

6.2.3 Aluminium alloy 6082T6

The results from this study have demonstrated that high levels of adhesive bond strength and durability can be obtained with aluminium alloy 6082T6 using a variety of epoxy, polyurethane and acrylic adhesives, and surface pretreatments. The initial failure loads and strength retention values were dependent on the condition of the aluminium surface and adhesive selection. The maximum failure loads obtained were comparable with precoated sheet steel results i.e. 5.8 – 6.0kN. This is due to the similar mechanical properties of the adherends. The tensile strength of aluminium alloy 6082T6 is 310N/mm^2, whereas a typical tensile strength of coil coating steel is 386N/mm^2.

In all cases, the application of a surface primer or pretreatment enhanced the shear strength and strength retention of joints. Excellent levels of durability were demonstrated by adhesives E1 and A3 without the need for chemical pretreating the aluminium surface. The durability of mechanically abraded aluminium was extremely poor. This type of surface preparation removes the protective oxide layer and exposes bare aluminium, which is almost instantaneously oxidised in the presence of oxygen. However, if the aluminium is bonded immediately after abrasion then the newly formed oxide layer does not have time to grow and is more easily hydrolysed when exposed to water [87]. Venables has suggested that upon exposure to moisture, the oxide on the surface of aluminium (Al_2O_3) converts to aluminium hydroxide with a chemical composition between that of boehmite (Al_2O_3 H_2O) and pseudoboehmite (Al_2O_3 $2H_2O$) [88]. Failure surface analysis reveals that the hydroxide layer is normally attached to the adhesive side, suggesting that adhesion of hydroxide to aluminium is very weak. Thus, once hydroxide is formed it is very easily separated from the substrate, causing failure of the joint.

Anodic undermining leading to interfacial and corrosion failure, and plasticisation of adhesive polymers were the key mechanisms of degradation identified from the mode of failure changes. To provide more information on the exact locus of failure with various pretreated aluminium joints, FTIR studies were undertaken on selected samples that had failed at the interface. The spectra obtained indicated the absence of organic materials at the aluminium surface and that failure had occurred at the pretreatment – aluminium interface.

6.2.4 Glass

The results from this study have demonstrated that high levels of adhesive bond strength and durability can be obtained with glass using a variety of epoxy, polyurethane and acrylic adhesives and surface pretreatments. The development of the constrained lap joint minimised the bending stresses in the adherends and prevented premature failure of the glass when applying load. Using this joint configuration, adhesive bond strength was approximately double that obtained with the standard lap shear joint, which highlights the importance of adhesive joint design. In most instances, fracture of the glass adherends in the proximity of the bond area was the initial failure mode with all adhesive bonded joints. Compared to organic coated steels, the maximum shear load of adhesive bonded glass joints was considerably lower due to failure of the glass adherend.

With regard to adhesive bond durability, it was imperative that the glass surface was pretreated prior to bonding to prevent hydrolysis of the silicon-oxygen bond on the material's surface. Both the silane primer and pretreatment assessed significantly enhanced the durability of adhesive bonded glass joints. The mechanisms of degradation identified from the changes in the mode of failure were hydrolysis of non-pretreated glass, water disbondment of adhesives on pretreated glass and plasticisation of the adhesive.

6.2.5 Timber

The results from this study indicated that adhesive bonding was an appropriate technique for assembling timber joints. Initially high failure loads were demonstrated by all types of adhesive. The large standard deviation values can be explained by the fact that timber is a natural material and is subject to variations in strength. A wide variation in strength retention values indicated that adhesive selection was critical to the durability performance. Both substrate and interphase failures were the primary modes of fracture before and after weathering. However, after weathering these modes of fracture were noted at lower a load, which suggests that the properties of the timber adherend had been adversely affected by the weathering cycle. Compared to precoated steel joints, the maximum bond strength of adhesive bonded timber joints was considerably lower due to failure of the timber adherend.

6.2.6 Mortar

Even though the maximum failure load obtained with adhesive bonded mortar joints was enhanced using the constrained lap joint, the results obtained in this study indicated that mortar was not a suitable substrate for structural adhesive bonding due to its friable nature. Although all bonded joints fractured within the mortar adherend (which is usually indicative of a high strength joint), failure loads were low compared to the capabilities of the epoxy adhesives used and results obtained with galvanised steel joints. After weathering, mortar failure occurred at lower loads, which suggests that the integrity of the surface had been adversely affected by the humidity exposure.

Despite mortar being an inappropriate material for structural adhesive bonding applications, it will still be further evaluated as part of the galvanised steel – dissimilar material studies to highlight the issues associated with joining such fundamentally dissimilar materials.

6.2.7 Adhesive selection and behaviour

A summary of the most compatible and durable adhesive – adherend combinations is shown in **Table 16**. On many occasions, adhesive bond strength was noted to increase after short-term weathering; this was particularly evident with adhesives E1 and A3. As all adhesive bonded joints were post cured prior to weathering, this increase in strength was not caused by the elevated temperatures of artificial ageing. It is considered that water absorbed into the bond line had increased the flexibility of the adhesive polymer, which consequently lowered the peak stresses at the edges of the overlap and enabled higher loads to be supported prior to joint failure.

The poor performance of acrylic A3 with aluminium, glass and timber joints was discussed with the manufacturers. No explanations were given as to why the adhesive was unable to bond these materials. A new batch of the same adhesive was offered for assessment, however due to time restrictions this was not possible.

Table 16 A summary of the most compatible and durable adhesive – adherend combinations

Substrate	Highest shear load	
	Before weathering	**After weathering**
Galvanised steel	E2	E1
Cr-passivated galvanised steel	E2	E1
V-passivated galvanised steel	E2	E1
PVdF coated steel	E2	E1 and A2
PVC-plastisol coated steel	P1	E2
Polyurethane coated steel (black)	E2 and A3	E1 and A1
Polyurethane coated steel (white)	A2	A1
Polyurethane coated steel (silver)	A2	A1
Polyurethane coated steel (green)	A3	A1
Polyester coated steel (top coat)	A3	E1
Polyester coated steel (backing coat)	P1	E1
Aluminium alloy 6082T6 (degreased)	A2	A2
Aluminium alloy 6082T6 (pretreated)	A3	E1
Glass (degreased)	E1	None
Glass (pretreated)	P1	E1
Timber	E1 and A2	E2
Mortar	E2	E1

6.3 SEALANT BONDED UNI-MATERIAL JOINTS

In general, structural sealants were less sensitive to adherend type and surface condition than structural adhesives. With the exception of mortar, the maximum tensile load obtained with each H-joint was dependant on the structural sealant used and was not affected by the different mechanical, chemical or surface properties of the adherends. Therefore similar failure loads were noted between galvanised steels, organic coated steels, aluminium alloy, glass, timber and mortar substrates. As structural sealants are designed to be flexible in order to accommodate large movements in bonded structures (due to thermal expansion), they are inherently weaker than structural adhesives and fail at much lower loads. Consequently, cohesive failure modes were dominant. In all instances, the cohesive strength of the structural sealant was the critical factor determining the maximum failure load.

With regard to sealant bond durability, the various substrates used did influence the performance. The highest levels of strength retention were noted with glass, unlike adhesive bonded joints hydrolysis of the silicon-oxygen bond was not an issue. Similar levels of strength retention were noted between metallic adherends i.e. galvanised steel and aluminium. Poor durability was observed with porous substrate joints i.e. timber and mortar. This can be explained by the fact that water can rapidly penetrate into the bond area via the porous adherends and degrade the sealant – substrate interface region. With organic coated steels, it was noted that with higher surface energy coatings more sealant bonded joints failed to meet the minimum performance criterion after weathering. For example, polyester has the highest surface energy of all organic coatings, and six of the sealants evaluated failed to maintain a minimum tensile load of 0.32kN. In contrast, with polyurethane coated steel, which has the lowest surface energy, only two sealants failed to meet the minimum performance criterion.

As a consequence of weathering, a variety of degradation mechanisms were identified from the mode of failure changes. These mechanisms were associated with the ingress of water into the adhesive bond line and UV light exposure and include:

1. Anodic undermining leading to interfacial failure [see section 6.2.1]. This mechanism is only associated with galvanised steel and aluminium alloy 6082T6.
2. Water disbondment [see section 6.2.2].
3. Plasticisation of the sealant [see section 6.2.2]. This mechanism of degradation was identified by an increase in cohesive failure and was more evident during the initial stages of weathering (i.e. after twenty-one days).

4. Hydrolysis of the sealant. An increase in surface cohesive failure suggests a different degradation mechanism to plasticisation. This was dominant with porous adherend joints i.e. timber and mortar.
5. Photodegradation. This mechanism of degradation was only observed with polyurethane bonded glass joints. After weathering, failure occurred at the surface exposed to the UV-A light source.

6.3.1 Sealant selection and behaviour

A summary of the most compatible and durable sealant – adherend combinations is shown in **Table 17**. Even though automotive sealant SMP frequently retained the highest tensile loads after weathering, this sealant was often noted to have the largest strength loss. When selecting an appropriate sealant system, consideration should be given to the strength retention and stability of the bonde system.

With regard to the assessment of multi-material combinations, it is anticipated that regardless of the substrates used, the properties of sealant polymer will still determine the maximum tensile load obtained. However, the selection of adherends is likely to have an influence on joint durability.

Table 17 A summary of the most compatible and durable sealant – adherend combinations

Substrate	Highest tensile load	
	Before weathering	**After weathering**
Cr-passivated galvanised steel	SMP	SMP and H3
V-passivated galvanised steel	SMP	SMP
PVdF coated steel	PS	SMP
PVC-plastisol coated steel	SMP	S2 and PS
Polyurethane coated steel (black)	PS	S2
Polyester coated steel (top coat)	SMP	SMP
Aluminium alloy 6082T6 (degreased)	SMP	SMP
Glass (degreased)	SMP	SMP
Timber (unprimed)	SMP	H1
Timber (primed)	SMP	H2
Mortar (unprimed)	SMP	SMP
Mortar (primed)	SMP	SMP

The sealant identity codes highlighted in red failed to retain a 0.32kN tensile load after weathering

6.4 ADHESIVE BONDED MULTI-MATERIAL JOINTS

6.4.1 Galvanised steel – organic coated steel

The results obtained from these studies have shown that high levels of adhesive bond strength can be obtained with HDG_V – organic coated steel joints. The maximum shear load was limited by both cohesive failure and interfacial failure at the organic coated steel surfaces. Following weathering, poor durability was noted with the development of interfacial failure at the galvanised steel substrate. This indicated that anodic undermining was the key mechanism of degradation with this dissimilar material combination.

The performance of HDG_V – polyurethane coated steel joints was as anticipated both before and after weathering. However, the maximum failure load obtained with HDG_V – PVdF coated steel joints was higher than expected. This was noted with PVdF interfacial and cohesive failures only. The unexpected absence of interfacial failure at the galvanised steel substrate suggests that the condition of the zinc coating was cleaner prior to bonding. In general, combining these dissimilar materials did not produce any unanticipated behaviours when compared to the performance of equivalent uni-material joints.

6.4.2 Galvanised steel – Aluminium alloy 6082T6

These results demonstrate that high shear loads can be supported with HDG$_V$ – aluminium alloy joints. Fracture of bonded joints initially occurred at the surfaces of both metallic adherends. Following short-term weathering low levels of strength retention were noted with an increase in interfacial failure at the galvanised steel substrate. Again, this indicated that anodic undermining at the galvanised steel surface was the primary mechanism of degradation.

With regard to predicting the optimum performance of HDG$_V$ – aluminium alloy joints, the results obtained in this study were as anticipated both before and after weathering. This implies that combining these two metallic adherends did not have any adverse affects on the behaviour of multi-material joints when compared to the performance of equivalent uni-material joints.

6.4.3 Galvanised steel – Timber

The results from this study have demonstrated that high levels of adhesive bond strength can be obtained between HDG$_V$ – timber joints. The maximum shear load was limited by failure of the timber substrate. As a consequence of weathering, corrosion of the galvanised steel resulted in failure occurring within this layer, such that white rust was visible on both substrate and adhesive sides of failure. This indicates that anodic undermining was the key mechanism of degradation.

The behaviour of HDG$_V$ – timber lap joints was different to that anticipated. Initially, failure loads were higher prior to fracture of the timber adherend. There are two possible explanations for this. Firstly, timber is a natural material and is susceptible to variations in strength. Secondly, a favourable change in the stress distribution occurred, which enabled a higher shear load to be supported by reducing the peak stress in the timber component [see section 3.7.1.1]. In addition, the failure loads after weathering were much lower than anticipated. This was also noted with 100% corrosion coverage of the galvanised steel surface. This could be due to the porous nature of timber enabling water to rapidly penetrate through the adherend and into the adhesive bond line, where a high concentration of water accumulated at the galvanised steel substrate and corroded the surface.

6.4.4 Galvanised steel – Mortar

The results obtained in this study have demonstrated that structural adhesives can be used to join HDG_V – mortar. Although, when compared to the load bearing capabilities of the epoxy adhesive used, joint failure occurred at relatively low loads due to the friable nature of mortar. Once again this indicates that structural adhesive bonding is not a suitable joining technique for mortar. Following short-term weathering, significant corrosion of the galvanised steel surface occurred. This weak layer fractured such that corrosion was visible on both substrate and adhesive side of failure. This indicated that anodic undermining was the key mechanism of degradation.

When compared to the performance of appropriate uni-material joints, the maximum shear load and mode of failure of HDG_V – mortar joints was as anticipated, where failure of the mortar occurred at 0.7kN. However, following weathering the mode of fracture was quite unexpected as failure occurred at the galvanised steel substrate. It is speculated that the porous mortar adherend has enabled water to rapidly migrate into the bond line where it accumulated at the high energy galvanised steel surface. Consequently, severe corrosion of zinc coating occurred.

6.4.5 Dissimilar organic coated steels

The results from this study have demonstrated that high failure loads can be achieved with dissimilar coating combinations using all types of adhesive (i.e. epoxy, polyurethane and acrylics). Initially, combinations of cohesive, coating and interfacial failure modes were evident. As a consequence of weathering, strength loss was typically noted with the development of polyester coating failure, which indicated that coating degradation was the critical mechanism controlling joint durability.

Overall, the behaviour of dissimilar organic coated steel joints was as anticipated. The dissimilar substrate thicknesses and organic coating chemistries did not have any adverse effects on the performance of multi-material joints.

6.4.6 Organic coated steel – Aluminium alloy 6082T6

The results demonstrate that high shear failure loads can be obtained with organic coated steel – aluminium alloy 6082T6 joints using a selection of adhesive types (i.e. epoxy, polyurethane and acrylics). Overall, higher failure loads were obtained with PVdF coated steel – aluminium alloy joints. This was partly attributed to better adhesive compatibility with the PVdF coating. Also the thicker steel substrate of this product would require larger loads to generate the peel and cleavage forces required to instigate joint failure. All adhesive types provided high levels of strength retention after weathering. The critical mechanisms of degradation identified from the mode of failure changes were anodic undermining, water disbondment, and plasticisation of the adhesive.

When compared to uni-material joints, the maximum performance of organic coated steel – aluminium alloy joints was as anticipated both before and after weathering. The dissimilar substrate thicknesses and mechanical properties did not have any adverse effects on the performance multi-material joints.

6.4.7 Organic coated steel – Glass

The results from this study have demonstrated that both high levels of adhesive bond strength and durability can be achieved with organic coated steel – glass joints using a variety of adhesives and a silane pretreatment. Higher failure loads were obtained with PVdF coated steel – glass joints than polyurethane coated steel – glass joints. As previously described, this was attributed to adhesive compatibility and a thicker steel substrate. To provide high levels of strength retention, it was essential that the glass adherend was pretreated. The key mechanisms of degradation identified from the mode of failure changes were water disbondment of the adhesive at both substrate surfaces and plasticisation of the adhesive.

The maximum shear load obtained with adhesive bonded organic coated steel – glass (in degreased and pretreated conditions) joints was considerably higher than anticipated. Again, this suggests a change in the stress distribution occurred, whereby the stress in the glass adherend was reduced and a higher stress concentration was located at the end of the higher modulus steel adherend [see section 3.7.1.1]. After weathering, failure loads were higher than expected with organic coated steel – pretreated glass joints, which is attributed to a change in the stress distribution.

6.4.8 Organic coated steel – Timber

The results from this study have demonstrated that high levels of adhesive bond strength can be obtained with organic coated steel – timber joints using a variety of adhesive types (i.e. epoxy, polyurethane and acrylic). Typically, fracture of the timber adherend was the factor controlling the initial failure load. Due to adhesive compatibility and substrate thickness effects, higher failure loads were obtained with PVdF coated steel – timber joints than polyurethane coated steel – timber joints. All adhesive bonded joints demonstrated low levels of strength retention. The critical mechanisms of degradation identified from mode of failure changes include timber degradation and water disbondment.

The maximum shear loads noted with adhesive bonded organic coated steel – timber joints were much higher than anticipated. There are two possible explanations for this; firstly, as timber is a natural material it is susceptible to variations in strength. Secondly, a favourable change in the stress distribution occurred, which reduced the stress in the timber adherend and enabled higher loads to be supported prior to failure of the timber substrate [see section 3.7.1.1]. Overall, the failure loads obtained after weathering were significantly lower than expected. This was also noted with occurrence of interfacial failure instead of the postulated timber or interphase failure. It is speculated that the porous nature of the timber adherend allowed water to rapidly penetrate into the bond area where it concentrated at the high energy surface of the organic coated steel substrates and promoted joint failure via water disbondment of the adhesive.

6.4.9 Summary

In conclusion, structural adhesive bonding is an appropriate joining technique for achieving high levels of adhesive bond strength and durability with dissimilar organic coated steels, organic coated steel – aluminium alloy and organic coated steel – glass joints. Therefore, such multi-material combinations should be considered for construction applications where high strength and durability are a necessity. The poor durability of organic coated steel – timber joints confines this multi-material combination to begin operating environments.

Galvanised steel – dissimilar material joints should only be used in benign environments until further research is carried out to establish robust surface pretreatments for the galvanised steel substrate. Structural adhesive bonding galvanised steel to mortar is considered impractical due to the friable surface of the mortar adherend.

6.5 SEALANT BONDED MULTI-MATERIAL JOINTS

The results from these studies have demonstrated that high levels of sealant bond strength can be obtained with all precoated steel – dissimilar mater joints using a variety of sealant types (i.e. polyurethane, hybrid polymers and silicone). Initial tensile loads obtained were dependent on the structural sealant used, which suggests that with sealant bonded multi-material joints each substrate is totally independent and unaffected by the other. In all instances, the cohesive strength of the structural sealant system was the critical factor determining the maximum tensile strength.

From the mode of failure changes noted after weathering, a variety of degradation mechanisms were identified with each multi-material combination. The key trends observed were:

1. With multi-metallic adherend joints (i.e. galvanised steel, organic coated steel and aluminium), the development of surface cohesive failure always occurred at the higher surface energy adherend i.e. surface cohesive failure preferentially occurred at galvanised steel > organic coated steel > aluminium alloy. This suggests that a higher concentration of water was present at the surface of these adherends, which reduced the cohesive strength of the sealant.
2. With organic coated steel – glass joints, surface cohesive failure also occurred at the higher surface energy glass substrate. However unlike opaque multi-material joints, the glass – sealant interface was additionally exposed to UV-A light and was susceptible to photodegradation.
3. Again, joints with timber and mortar adherends demonstrated poor levels of durability. With porous materials, water can rapidly penetrate into the bond line where it either ruptures bonds and displaces the sealant or weakens the cohesive strength of the sealant in this region.

The performance of all sealant bonded multi-material joints was as anticipated both before and after weathering. Unlike adhesive bonded joints, the performance of multi-material sealant bonded joints was not complicated by changes in stress distribution when joining fundamentally dissimilar materials.

For applications, where high tensile strength is a key requirement, the use of structural sealants should be considered for joining galvanised steels and organic coated steels to aluminium, glass, timber and mortar. However, where high levels of durability are a necessity the use of structural sealants should only be recommended for joining galvanised and organic coated steels to dissimilar materials that are non-porous i.e. aluminium and glass.

7.0 CONCLUSIONS

1. This project has demonstrated that the single lap shear joint is an ideal joint configuration for assessing structural adhesives with both uni-material and multi-material combinations with non-brittle adherends (i.e. precoated steels, aluminium and timber). For assessing structural adhesives with brittle materials (i.e. glass and mortar) in either uni-material or multi-material combinations, the constrained lap shear joint has proved to be a suitable joint design. The H-joint was an ideal configuration for evaluating structural sealants with non-brittle and brittle adherends in both uni-material and multi-material combinations.

2. There are a wide variety of structural adhesive and sealant systems and, surface pretreatments available that can be used to obtain high shear and tensile loads with galvanised steels, organic coated steels, aluminium alloy, glass and timber. The friable nature of mortar rendered it suitable for structural sealant bonding only. The selection of an appropriate adhesive system was far more critical to the performance of a bonded joint than the selection of a sealant. Overall, epoxy adhesive E1 (ScotchWeld DP190) and acrylic adhesive A3 (Arobond 812) demonstrated the highest levels of compatibility and durability with all materials investigated.

3. A comparison of the short-term and long-term weathering results obtained with galvanised steel indicated that at 100% relative humidity there was a good correlation between the failure loads obtained after fourteen days weathering at 70°C and sixteen weeks ageing at 46°C. However, with organic coated steels, the accuracy of this relationship varied and was dependent on the adhesive – coating combination. Further work is needed to establish if long-term weathering can be predicted from short-term weathering tests.

4. With adhesive bonded multi-material joints, high levels of durability were obtained between organic coated steel and, aluminium and glass adherends. The performance of galvanised steel – dissimilar material joints was restricted by the inherently poor durability of the galvanised steel substrate. Low levels of strength retention were also noted with multi-material joints with porous substrates due to a rapid ingress of water through the adherends. With sealant bonded joints high levels of durability were only noted with multi-material combinations with non-porous adherends. The water immersion environment was too severe for timber and mortar joints. This was demonstrated by the fact that all joints failed to retain the minimum tensile strength after forty-two days of weathering

5. The behaviour of adhesive bonded multi-material joints could be anticipated from uni-material results when the inherent properties of the dissimilar materials were relatively similar i.e. precoated steels and aluminium. However, as the nature of the multi-material combinations became more diverse i.e. steel – glass and steel – timber, unexpected behaviours were observed. It has been speculated that bonding fundamentally dissimilar material combinations produces a change in the stress distribution, whereby a higher load can be supported prior to joint failure. The behaviour of sealant bonded multi-material joints could be predicted from uni-material results regardless of the substrate combinations.

Future work

Due to the diverse nature of this Eng.Doc project there are many possibilities for future studies of multi-material combinations. Below is a list of some suggestions:

1. Due to the poor durability performance of adhesive bonded galvanised steel joints, further research is required to establish robust surface

pretreatment that are capable of providing high levels of strength retention in severe weathering environments.

2. Identify application opportunities for precoated sheet steel – dissimilar material combinations where robust joining processes are a key element in further market development. Once established, the experimental programme can be tailored to the application and its operating environment.

3. Evaluate various combinations of mechanical fastener plus adhesive or sealant where the fastening element would speed up assembly, and enhance resistance to certain types of loading stress e.g. peel and cleavage.

4. Evaluate dissimilar metal combinations including novel high strength and ultra high steel grades and, structural aluminium alloys and stainless steels. Such multi-material combinations could be applicable in both the construction and automotive industry where higher levels of material performance capability would be an advantage. This research could include a comparative study between the performance of structural adhesives and other joining techniques that are currently used to assemble sheet steels i.e. resistance spot welding, friction welding, brazing, laser brazing and hybrid joining techniques.

BIBLIOGRAPHY

Below is a list of books that were frequently used during my four years of research into adhesive and sealant bonding. These provided a thorough grounding in theories and standard 'benchmark' test methods.

Books most relevant to section 2

Messler, R. W (2004) Joining of materials and structures: from pragmatic processes to enabling technology. Elsevier Butterworth – Heinemann.

Books most relevant to section 3

Comyn, J (1997) Adhesion science. Published by the Royal Society of Chemistry.

Lees, W. A., editor (1989) Adhesive and the engineer. Mechanical Engineering Publications.

Packham, D. E., editor (2004) Handbook of adhesion. Second edition. John Wiley and Sons.

Adams, R. D., and W. C. Wake (1984) Structural adhesive joints in engineering. Elsevier Applied Science Publishers.

Kinloch, A. J., editor (1983) Durability of structural adhesives. Applied Science Publishers.

Other sources of information that were often referred to include the following web sites:

The welding institute – www.twi.co.uk
National physical laboratory – www.npl.co.uk
The Adhesives design toolkit – www.adhesivestoolkit.com
Special chemistry for adhesives – www.specialchem4adhesives.com

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Appendix 1 – Surface energy calculation

The method used to determine the surface free energy of all substrates was based on the van Oss-Chaudhury-Good approach [1]. This method assumes that the long range interactions (called the Lifshitz-van der Waals interactions) and the acid – base interactions are the main interactions that affect surface free energy. Based on this, the surface free energy of a solid is equal to the sum:

$$\gamma_S = \gamma_S^{LW} + \gamma_S^{AB}$$

γ_S is the surface free energy of the substrate, LW corresponds to the Lifshitz-van der Waals interactions and AB to the acid – base interactions.

For a bipolar solid, the acid – base interactions can also be defined as:

$$\gamma_S^{AB} = 2(\gamma_S^{+} + \gamma_S^{-})^{0.5}$$

With γ_S^{+} and γ_S^{-} being the components corresponding to the interactions of the Lewis acid and base respectively. For an apolar or monopolar solid, the following equation is valid:

$$\gamma_S^{AB} = 0$$

Hence, the calculation of γ_S is dependent on the determination of the three unknown components: γ_S^{LW}, γ_S^{+} and γ_S^{-} . This requires contact angle measurements using three different liquids, two of them being bipolar and one apolar. The following general equation was then obtained:

$$(\gamma_S^{LW}\gamma_{Li}^{LW})^{0.5} + (\gamma_S^{+}\gamma_{Li}^{-})^{0.5} + (\gamma_S^{-}\gamma_{Li}^{+})^{0.5} = \gamma_{Li}(1+\cos\theta)/2$$

With i = 1, 2, 3 representing the three liquids.

The same relation can be represented in the form of a system of equations:

$$(\gamma_S^{LW})^{0.5} + g_1(\gamma_S^{+})^{0.5} + g_2(\gamma_S^{-})^{0.5} = g_3(1+\cos\theta_1)/2 \ldots\ldots\ldots (1)$$

$$(\gamma_S^{LW})^{0.5} + g_4(\gamma_S^{+})^{0.5} + g_5(\gamma_S^{-})^{0.5} = g_6(1+\cos\theta_2)/2 \ldots\ldots\ldots (2)$$

$$(\gamma_S^{LW})^{0.5} = g_7(1+\cos\theta_3)/2 \ldots\ldots\ldots (3)$$

Where θ_1, and θ_2 are the contact angles of the dipolar liquids while θ_3 is the contact angle for the apolar liquid. The values of surface energy (and its components) for water, glycerol and di-iodomethane are shown below:

Table 1 Surface free energy (γ_L) and its components (mNm^{-1}).

Liquid	γ_L	γ_L^{LW}	γ_L^{AB}	γ_L^{+}	γ_L^{-}
Water	72.8	21.8	51.0	34.2	19.0
Glycerol	64.0	34.0	30.0	5.3	42.5
Di-iodomethane	50.8	50.8	0	0	0

Using these surface energy values, the g_i coefficients were calculated and are given below:

Table 2 Values of g_i coefficients used in equations 1, 2 and 3.

g_1	g_2	g_3	g_4	g_5	g_6	g_7
0.93	1.25	7.80	1.12	0.39	5.49	3.56

Using equation 3, γ_S^{LW} was determined. This value was then used in equations 1 and 2, to calculate the two other unknowns. Equations 1, 2 and 3 were all set up in an Excel spreadsheet to calculate the surface energy value for each substrate using the measured contact angles of the three liquids.

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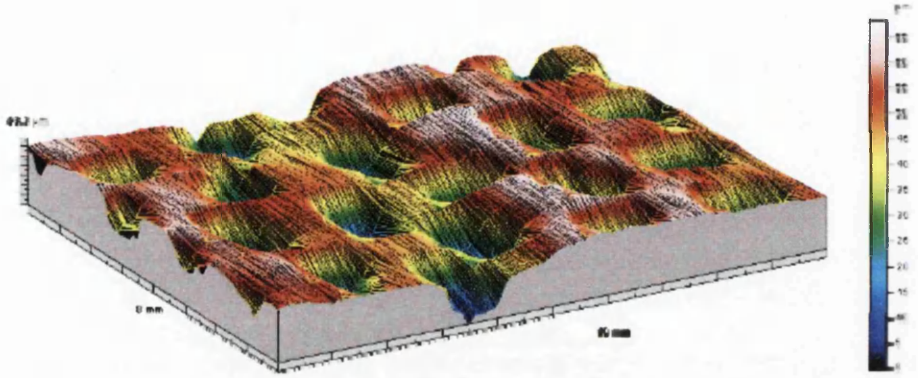
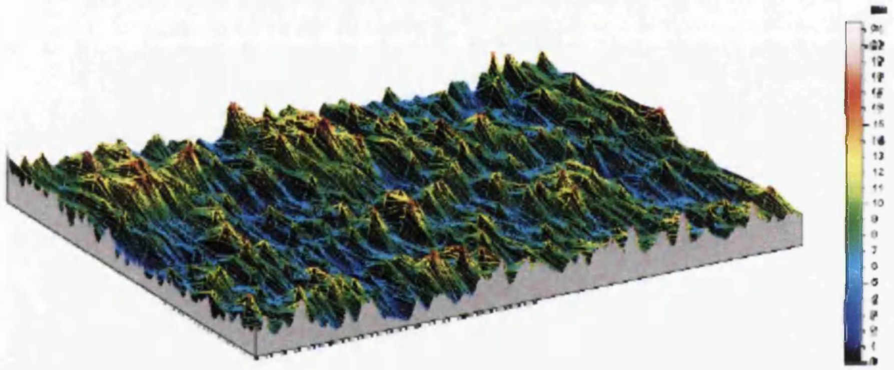
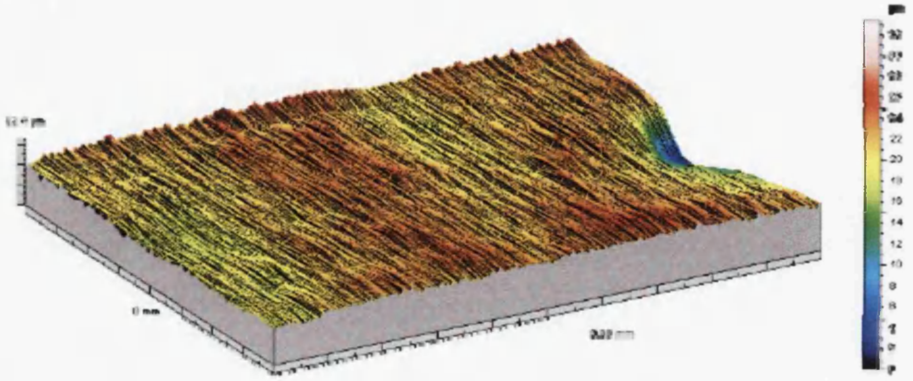
Appendix 2 – 3D surface texture images of precoated sheet steel products



PVC-plastisol coated steel embossed with the Colorcoat logo

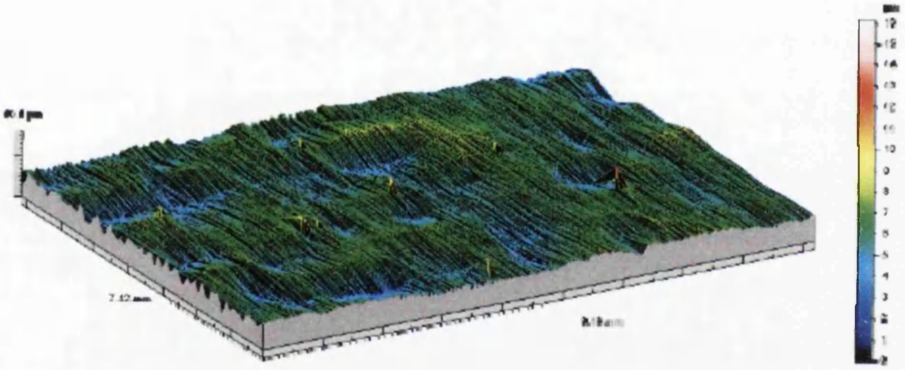


Polyurethane coated steel – smooth texture

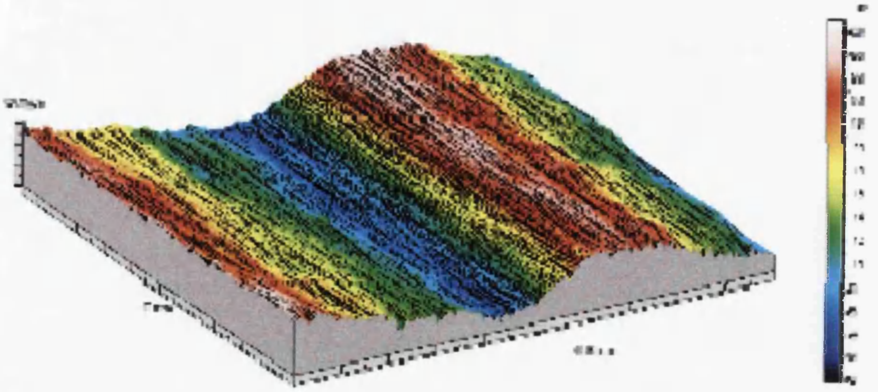


PVdF coated steel

Polyester coated steel – top coat



Chrome passivated galvanised steel



Vanadium passivated galvanised steel

Appendix 3 – The failure modes of adhesive and sealant bonded joints – Uni-material joints

The compatibility and short-term durability performance of adhesive bonded galvanised steel lap joints. Weathering conditions – 100% relative humidity at 70˚C for fourteen days.

Galvanised steel substrate	**Surface preparation**	**Adhesive system**	**Compatibility**			**Short-term weathered**			**Strength retention (%)**
			F (kN)	**σ (%)**	**Mode of failure**	**F (kN)**	**σ (%)**	**Mode of failure**	
Non-passivated galvanised steel	Acetone degrease	E1	3.0	7	100% interfacial	0.5	30	90% interfacial 10% corrosion	18
		E2	4.2	13	90% interfacial 10% cohesive	0	0	80% interfacial 20% corrosion	0
	Silane primer	E1	4.5	3	80% cohesive 20% interfacial	2.4	8	100% interfacial	53
		E2	4.6	5	100% interfacial	1.4	37	100% interfacial	30
	Chrome pretreatment	E1	3.1	17	90% interfacial 10% cohesive	2.1	22	100% interfacial	68
		E2	4.2	16	90% interfacial 10% cohesive	1.1	29	100% interfacial	26
	Polymer pretreatment	E1	3.5	7	70% interfacial 30% cohesive	0.7	20	100% interfacial	20
		E2	3.2	14	100% interfacial	0.5	22	100% interfacial	16
	Silane pretreatment	E1	4.0	8	100% cohesive	1.4	14	100% interfacial	35
		E2	3.8	3	90% interfacial 10% cohesive	1.1	11	100% interfacial	29
Chromium passivated	Acetone degrease	E1	3.6	12	100% interfacial	1.9	27	95% interfacial 5% corrosion	52
		E2	5.2	5	100% interfacial	0.2	26	90% interfacial 10% corrosion	4
Vanadium passivated	Acetone degrease	E1	3.8	11	80% cohesive 20% interfacial	2.4	7	95% interfacial 5% corrosion	63
		E2	5.9	3	80% cohesive 20% interfacial	0	0	80% interfacial 20% corrosion	0

The compatibility and short-term durability performance of adhesive bonded PVdF coated steel lap joints. Weathering conditions – 100% relative humidity at 70˚C for fourteen days.

Adhesive system	Compatibility			Short-term weathered			Strength retention (%)
	F (kN)	σ (%)	Mode of failure	F (kN)	σ (%)	Mode of failure	
E1	4.6	12	75% interfacial 25% coating	5.6	3	100% coating	122
E2	6.1	1	65% interfacial 20% cohesive 15% coating	3.7	9	90% cohesive 10% coating	61
P1	3.0	11	100% interfacial	0.8	21	100% interfacial	26
P2	4.0	12	100% interfacial	1.0	43	100% interfacial	24
P3	1.7	20	100% interfacial	1.8	19	100% interfacial	106
A1	2.0	33	100% interfacial	1.8	64	100% interfacial	90
A2	5.8	7	80% cohesive 20% coating	5.6	5	90% cohesive 10% coating	97
A3	6.0	4	60% interfacial 25% cohesive 15% coating	2.5	26	90% interfacial 10% coating	42

The compatibility and short-term durability performance of adhesive bonded PVC-plastisol coated steel lap joints. Weathering conditions – 100% relative humidity at 70˚C for fourteen days.

Adhesive system	Compatibility			Short-term weathered			Strength retention (%)
	F (kN)	σ (%)	Mode of failure	F (kN)	σ (%)	Mode of failure	
E1	0.6	14	100% interfacial	0.9	23	100% interfacial	152
E2	1.8	11	95% interfacial 5% coating	2.2	7	50% interfacial 25% coating 25% cohesive	120
P1	2.4	4	80% coating 20% interfacial	1.5	34	95% interfacial 5% coating	61
P2	1.1	9	80% interfacial 20% cohesive	0.6	33	100% interfacial	56
P3	1.8	17	50% coating 50% interfacial	1.3	33	90% interfacial 10% coating	71
A1	0.1	31	100% interfacial	1.3	26	90% interfacial 10% coating	1023
A2	1.9	14	90% coating 10% cohesive	1.7	19	100% cohesive	87
A3	0.4	12	90% interfacial 10% cohesive	1.0	9	80% interfacial 20% cohesive	228

The compatibility and short-term durability performance of adhesive bonded (black) polyurethane coated steel lap joints. Weathering conditions – 100% relative humidity at 70°C for fourteen days.

Adhesive system	Compatibility			Short-term weathered			Strength retention (%)
	F (kN)	σ (%)	Mode of failure	F (kN)	σ (%)	Mode of failure	
E1	3.5	16	100% interfacial	4.2	6	100% interfacial	120
E2	4.5	2	100% coating	2.8	9	100% cohesive	62
P1	4.1	12	90% cohesive 10% coating	3.8	12	100% cohesive	93
P2	3.7	16	80% cohesive 10% interfacial 10% coating	2.7	15	60% cohesive 40% interfacial	73
P3	4.1	7	50% interfacial 50% coating	2.0	43	100% interfacial	49
A1	3.1	33	70% interfacial 30% coating	4.2	8	80% coating 20% interfacial	135
A2	4.3	7	100% cohesive	3.7	4	100% cohesive	86
A3	4.5	6	75% interfacial 25% cohesive	2.7	18	50% cohesive 50% interfacial	60

The compatibility and short-term durability performance of adhesive bonded (white) polyurethane coated steel lap joints. Weathering conditions – 100% relative humidity at 70°C for fourteen days.

Adhesive system	Compatibility			Short-term weathered			Strength retention (%)
	F (kN)	σ (%)	Mode of failure	F (kN)	σ (%)	Mode of failure	
E1	1.9	12	100% interfacial	3.8	6	90% interfacial 10% coating	197
E2	4.1	3	100% interfacial	3.0	10	90% cohesive 10% interfacial	73
P1	4.1	5	90% cohesive 10% coating	3.5	8	100% cohesive	85
P2	3.5	6	90% cohesive 10% coating	2.4	10	100% cohesive	67
P3	4.1	7	100% coating	3.4	11	100% coating	82
A1	4.3	13	40% coating 30% cohesive 30% interfacial	4.8	1	75% coating 25% interfacial	112
A2	4.7	1	90% coating 10% cohesive	4.1	7	95% cohesive 5% coating	89
A3	3.3	7	80 cohesive 15% interfacial 5% coating	2.8	8	85% cohesive 10% interfacial 5% coating	83

The compatibility and short-term durability performance of adhesive bonded (green) polyurethane coated steel lap joints. Weathering conditions – 100% relative humidity at 70˚C for fourteen days.

Adhesive system	Compatibility			Short-term weathered			Strength retention (%)
	F (kN)	σ (%)	Mode of failure	F (kN)	σ (%)	Mode of failure	
E1	1.3	8	80% interfacial 20% coating	2.4	19	90% coating 10% interfacial	185
E2	2.3	7	100% coating	2.4	7	55% cohesive 40% coating 5% interfacial	104
P1	1.7	8	100% coating	2.9	7	95% cohesive 5% coating	171
P2	1.1	39	80% cohesive 20% coating	0.7	24	100% cohesive	64
A1	2.9	28	80% interfacial 20% coating	3.5	28	90% interfacial 10% coating	121
A2	2.7	8	70% cohesive 30% coating	2.4	13	85% cohesive 15% coating	89
A3	3.7	12	90% coating 5% cohesive 5% interfacial	2.3	7	95% cohesive 5% interfacial	62

The compatibility and short-term durability performance of adhesive bonded (silver metallic) polyurethane coated steel lap joints. Weathering conditions – 100% relative humidity at 70˚C for fourteen days.

Adhesive system	Compatibility			Short-term weathered			Strength retention (%)
	F (kN)	σ (%)	Mode of failure	F (kN)	σ (%)	Mode of failure	
E1	1.3	13	100% interfacial	3.2	2	100% coating	246
E2	3.2	8	100% coating	2.7	11	90% cohesive 10% coating	84
P1	3.6	6	100% coating	3.3	4	60% coating 40% cohesive	92
P2	2.3	12	100% coating	2.7	7	80% coating 20% cohesive	117
P3	3.1	8	100% coating	2.1	8	90% coating 10% interfacial	68
A1	3.7	18	80% coating 20% interfacial	4.2	15	50% coating 50% interfacial	114
A2	4.7	1	90% cohesive 10% coating	3.2	6	100% cohesive	68
A3	4.2	5	100% cohesive	3.2	10	100% cohesive	76

The compatibility and short-term durability performance of adhesive bonded polyester coated steel (top coat) lap joints. Weathering conditions – 100% relative humidity at 70°C for fourteen days.

Adhesive system	Compatibility			Short-term weathered			Strength retention (%)
	F (kN)	σ (%)	Mode of failure	F (kN)	σ (%)	Mode of failure	
E1	4.2	1	50% cohesive 50% interfacial	4.2	2	100% coating	100
E2	4.3	1	100% interfacial	3.0	8	80% cohesive 20% coating	70
P1	4.2	2	100% cohesive	3.7	10	80% coating 20% cohesive	88
P2	4.3	5	100% cohesive	1.6	17	50% coating 50% interfacial	37
P3	4.2	1	50% coating 50% interfacial	3.5	19	50% coating 50% interfacial	83
A1	3.9	8	60% interfacial 40% coating	0.9	27	90% coating 10% interfacial	23
A2	4.2	3	80% coating 20% cohesive	3.3	11	100% coating	79
A3	4.4	1	50% coating 25% cohesive 25% interfacial	2.8	12	100% coating	64

The compatibility and short-term durability performance of adhesive bonded polyester coated steel (backing coat) lap joints. Weathering conditions – 100% relative humidity at 70°C for fourteen days.

Adhesive system	Compatibility			Short-term weathered			Strength retention (%)
	F (kN)	σ (%)	Mode of failure	F (kN)	σ (%)	Mode of failure	
E1	2.2	25	100% interfacial	4.1	10	60% coating 40% interfacial	186
E2	4.3	16	100% coating	3.3	8	40% coating 60% interfacial	77
P1	4.7	1	95% cohesive 5% coating	3.2	9	80% cohesive 20% coating	68
A3	4.3	11	90% cohesive 10% interfacial	1.2	14	70% interfacial 30% coating	28

The compatibility and short-term durability performance of adhesive bonded aluminium alloy 6082T6 lap joints. Weathering conditions – 100% relative humidity at 70˚C for fourteen days.

Surface preparation	**Adhesive**	**Compatibility**			**Short-term weathered**			**Strength retention (%)**
		F (kN)	**σ (%)**	**Mode of failure**	**F (kN)**	**σ (%)**	**Mode of failure**	
Acetone degrease	E1	4.0	13	70% interfacial 30% cohesive	2.8	26	60% interfacial 30% corrosion 10% cohesive	70
	E2	3.7	3	80% interfacial 20% cohesive	0.4	25	85% interfacial 15% corrosion	11
	P1	2.6	18	100% interfacial	0	0	100% interfacial	0
	A2	5.9	5	100% cohesive	4.8	1	80% cohesive 20% interfacial	81
	A3	0	0	100% interfacial - adhesive not compatible	/	/	/	/
Mechanical abrasion	E1	4.4	1	50% interfacial 50% cohesive	0.9	38	90% interfacial 10% corrosion	20
	E2	4.9	4	90% cohesive 10% interfacial	0.1	36	40% interfacial 60% corrosion	2
	P1	3.7	10	90% interfacial 10% cohesive	0.1	87	100% interfacial	2
Acid etched and chrome pretreated	E1	4.1	8	70% interfacial 30% cohesive	4.0	13	70% cohesive 30% interfacial	96
	E2	5.7	5	100% cohesive	0.7	10	100% interfacial	13
	P1	2.0	16	100% interfacial	1.2	17	100% interfacial	61
	A3	5.1	7	80% cohesive 20% interfacial	4.5	5	100% cohesive	89
Acid etched and polymer pretreated	E1	6.1	4	100% cohesive	4.8	1	90% cohesive 10% interfacial	79
	E2	6.0	6	80% cohesive 20% interfacial	2.2	22	50% cohesive 50% interfacial	37
	P1	4.9	9	70% cohesive 30% interfacial	2.9	13	90% interfacial 10% cohesive	58
	A3	6.0	4	100% cohesive	4.9	6	100% cohesive	82
Acid etched and silane pretreated	E1	5.7	3	100% cohesive	5.3	5	100% cohesive	92
	E2	5.8	10	100% cohesive	1.6	21	80% interfacial 20% cohesive	28
	P1	5.6	6	100% cohesive	4.8	7	100% cohesive	85
	A3	1.5	22	100% interfacial	0.6	31	100% interfacial	43

The compatibility and short-term durability performance of adhesive bonded glass lap joints.

Weathering conditions – 100% relative humidity at 70˚C for fourteen days.

Surface preparation	Adhesive system	Compatibility			Short-term weathered			Strength retention (%)
		F (kN)	σ (%)	Mode of failure	F (kN)	σ (%)	Mode of failure	
Degreased	E1	1.6	18	Upper substrate	0	0	100% interfacial	0
	E2	1.4	13	Upper substrate	0	0	100% interfacial	0
	P1	0.8	24	100% interfacial	0	0	100% interfacial	0
	A2	1.5	15	Upper substrate	0	0	100% interfacial	0
	A3	0	0	100% interfacial	/	/	/	/
Silane primer	E1	1.6	15	Upper substrate	1.6	3	Upper substrate	99
	E2	1.4	5	Upper substrate	0.6	16	100% interfacial	43
	P1	1.9	2	Upper substrate	0.7	10	100% interfacial	37
	A2	1.5	14	Upper substrate	1.0	12	100% interfacial	65
Silane pretreatment	E1	1.4	20	Upper substrate	1.1	17	Upper substrate	80
	E2	1.4	8	Upper substrate	1.1	14	Upper substrate	79
	P1	1.8	10	Upper substrate	1.3	20	100% cohesive	72
	A2	1.6	12	Upper substrate	1.1	15	Upper substrate	71

The compatibility and short-term durability performance of adhesive bonded timber lap joints.

Weathering conditions – 100% relative humidity at 70˚C for fourteen days.

Adhesive system	Compatibility			Short-term weathered			Strength retention (%)
	F (kN)	σ (%)	Mode of failure	F (kN)	σ (%)	Mode of failure	
E1	2.6	33	60% timber 40% interphase	1.7	24	50% timber 50% interphase	65
E2	1.7	7	25% timber 75% interphase	1.8	16	30% timber 70% interphase	106
P1	1.4	18	100% cohesive	0.4	28	80% cohesive 20% interfacial	29
A2	2.6	5	50% timber 50% interphase	0.2	13	100% interfacial	8
A3	0	0	100% interfacial	/	/	/	/

The compatibility and short-term durability performance of adhesive bonded mortar lap joints.

Weathering conditions – 100% relative humidity at 70˚C for fourteen days.

Adhesive system	Compatibility			Short-term weathered			Strength retention (%)
	F (kN)	σ (%)	Mode of failure	F (kN)	σ (%)	Mode of failure	
E1	0.6	23	100% mortar	0.5	30	100% mortar	76
E2	0.7	21	100% mortar	0.4	20	100% mortar	65

The compatibility and durability performance of sealant bonded galvanised steel H-joints. Weathering conditions – water immersion at 45˚C for periods of twenty-one and forty-two days.

Galvanised steel substrate	Sealant system	Compatibility			Weathered for 21 days			Weathered for 42 days			Strength retention (%)
		F (kN)	Ext. (mm)	Mode of failure	F (kN)	Ext. (mm)	Mode of failure	F (kN)	Ext. (mm)	Mode of failure	
Chromium passivated	H1	0.78	15	100% cohesive	0.42	49	100% cohesive	0.44	13	90% cohesive 10% interfacial	56
	H2	0.84	12	100% cohesive	0.42	29	90% cohesive 10% interfacial	0.33	10	60% cohesive 40% interfacial	39
	H3	0.67	8	100% cohesive	0.47	52	100% cohesive	0.47	12	80% cohesive 20% interfacial	70
	SMP	1.63	12	100% cohesive	0.81	14	80% cohesive 20% interfacial	0.47	8	80% cohesive 20% interfacial	31
Vanadium passivated	H1	0.67	9	100% cohesive	0.42	29	90% cohesive 10% interfacial	0.41	11	90% cohesive 10% interfacial	61
	H2	0.77	11	100% cohesive	0.42	13	90% cohesive 10% interfacial	0.39	10	85% cohesive 15% interfacial	51
	H3	0.69	15	100% cohesive	0.42	30	100% cohesive	0.41	12	100% cohesive	59
	SMP	1.42	12	100% cohesive	0.58	9	80% cohesive 20% interfacial	0.62	11	80% cohesive 20% interfacial	45

The compatibility and durability performance of sealant bonded PVdF coated steel and PVC-plastisol coated steel H-joints. Weathering conditions – water immersion at 45°C for periods of twenty-one and forty-two days.

Organic Coated steel	Sealant system	Compatibility			Weathered for 21 days			Weathered for 42 days			Strength retention (%)
		F (kN)	Ext. (mm)	Mode of failure	F (kN)	Ext. (mm)	Mode of failure	F (kN)	Ext. (mm)	Mode of failure	
PVdF	S1	0.65	18	100% cohesive	0.54	10	70% cohesive 30% interfacial	0.56	11	70% cohesive 30% interfacial	86
	S2	0.75	32	100% cohesive	0.53	18	90% cohesive 10% interfacial	0.47	19	60% cohesive 40% interfacial	63
	H1	0.81	11	100% cohesive	0.43	51	80% cohesive 20% interfacial	0.36	20	60% cohesive 40% interfacial	45
	H2	0.68	9	100% cohesive	0.28	8	60% cohesive 40% interfacial	0.18	5	40% cohesive 60% interfacial	26
	H3	0.53	5	100% cohesive	0.41	46	100% cohesive	0.35	11	70% cohesive 30% interfacial	66
	PS	1.24	9	95% cohesive 5% interfacial	1.09	45	80% cohesive 20% interfacial	0.66	30	60% cohesive 40% interfacial	53
	SMP	1.16	8	95% cohesive 5% interfacial	0.97	23	80% cohesive 20% interfacial	0.72	15	80% cohesive 20% interfacial	62
PVC-plastisol	S1	0.67	20	95% cohesive 5% interfacial	0.17	5	50% cohesive 50% interfacial	0.11	2	40% cohesive 60% interfacial	16
	S2	0.70	24	100% cohesive	0.64	32	80% cohesive 20% interfacial	0.66	35	90% cohesive 10% interfacial	84
	H1	0.74	11	90% cohesive 10% interfacial	0.39	11	100% cohesive	0.28	7	70% cohesive 30% interfacial	31
	H2	0.79	9	95% cohesive 5% interfacial	0.25	6	30% cohesive 70% interfacial	0.13	4	10% cohesive 90% interfacial	16
	H3	0.55	6	100% cohesive	0.34	22	70% cohesive 30% interfacial	0.30	10	60% cohesive 40% interfacial	54
	PS	0.63	4	60% cohesive 40% interfacial	0.64	18	20% cohesive 80% interfacial	0.66	22	20% cohesive 80% interfacial	105
	SMP	0.87	16	80% cohesive 20% interfacial	0.45	11	70% cohesive 30% interfacial	0.25	3	30% cohesive 70% interfacial	29

The compatibility and durability performance of sealant bonded (black) polyurethane coated steel and polyester coated steel (top coat) H-joints. Weathering conditions – water immersion at 45˚C for periods of twenty-one and forty-two days.

Organic coated steel	Sealant system	Compatibility			Weathered for 21 days			Weathered for 42 days			Strength retention (%)
		F (kN)	Ext. (mm)	Mode of failure	F (kN)	Ext. (mm)	Mode of failure	F (kN)	Ext. (mm)	Mode of failure	
PUR	S1	0.68	20	100% cohesive	0.54	16	100% cohesive	0.43	12	80% cohesive 20% interfacial	63
	S2	0.81	42	100% cohesive	0.62	27	100% cohesive	0.59	28	80% cohesive 20% interfacial	73
	H1	0.79	12	100% cohesive	0.39	20	80% cohesive 20% interfacial	0.37	17	80% cohesive 20% interfacial	47
	H2	0.73	12	100% cohesive	0.28	7	70% cohesive 30% interfacial	0.22	5	40% cohesive 60% interface	30
	H3	0.61	4	100% cohesive	0.36	14	100% cohesive	0.34	10	70% cohesive 30% interfacial	56
	PS	1.15	7	100% cohesive	0.96	53	40% cohesive 60% interfacial	0.52	14	20% cohesive 80% interfacial	45
	SMP	1.13	22	100% cohesive	0.42	8	50% cohesive 50% interfacial	0.20	3	50% cohesive 50% interfacial	18
Polyester	S1	0.75	23	100% cohesive	0.30	9	80% cohesive 20% interfacial	0.07	2	20% cohesive 80% interfacial	9
	S2	0.86	48	100% cohesive	0.45	16	90% cohesive 10% interfacial	0.31	11	80% cohesive 20% interfacial	36
	H1	0.75	12	90% cohesive 10% interfacial	0.17	2	40% cohesive 60% interfacial	0.13	2	40% cohesive 60% interfacial	17
	H2	0.83	9	90% cohesive 10% interfacial	0.07	1	100% interfacial	0.05	1	100% interfacial	6
	H3	0.61	4	100% cohesive	0.11	2	100% interfacial	0.11	1	100% interfacial	24
	PS	0.93	17	90% cohesive 10% interfacial	0.45	9	70% cohesive 30% interfacial	0.17	2	80% cohesive 20% interfacial	18
	SMP	1.30	35	100% cohesive	1.21	54	100% cohesive	0.43	7	60% cohesive 40% interfacial	33

The compatibility and durability performance of sealant bonded aluminium alloy 6082T6 H-joints. Weathering conditions – water immersion at 45˚C for periods of twenty-one and forty-two days.

Sealant system	Compatibility			Weathered for 21 days			Weathered for 42 days			Strength retention (%)
	F (kN)	Ext. (mm)	Mode of failure	F (kN)	Ext. (mm)	Mode of failure	F (kN)	Ext. (mm)	Mode of failure	
H1	0.76	13	100% cohesive	0.46	52	80% cohesive 20% interfacial	0.40	13	70% cohesive 30% interfacial	50
H2	0.83	9	100% cohesive	0.43	10	70% cohesive 30% interfacial	0.26	7	80% interfacial 20% cohesive	33
H3	0.74	12	100% cohesive	0.46	52	70% cohesive 30% interfacial	0.39	20	60% cohesive 40% interfacial	56
SMP	1.42	10	100% cohesive	1.14	21	100% cohesive	0.73	14	100% cohesive	52

The compatibility and durability performance of sealant bonded glass H-joints. Weathering conditions – water immersion at 45˚C for periods of twenty-one and forty-two days.

Sealant system	Compatibility			Weathered for 21 days			Weathered for 42 days			Strength retention (%)
	F (kN)	Ext. (mm)	Mode of failure	F (kN)	Ext. (mm)	Mode of failure	F (kN)	Ext. (mm)	Mode of failure	
S1	0.69	21	100% cohesive	0.57	14	100% cohesive	0.61	14	100% cohesive	88
S2	0.74	31	100% cohesive	0.69	28	100% cohesive	0.67	23	100% cohesive	91
H1	0.64	13	100% cohesive	0.47	44	100% cohesive	0.46	27	100% cohesive	72
PS	1.54	16	100% cohesive	1.00	18	100% cohesive	0.62	23	70% cohesive 30 interfacial	39
SMP	1.63	13	100% cohesive	1.11	22	100% cohesive	1.30	21	100% cohesive	80

The compatibility and durability performance of sealant bonded timber H-joints. Weathering conditions – water immersion at 45˚C for periods of twenty-one and forty-two days.

Timber substrate	Sealant system	Compatibility			Weathered for 21 days			Weathered for 42 days			Strength retention (%)
		F (kN)	Ext. (mm)	Mode of failure	F (kN)	Ext. (mm)	Mode of failure	F (kN)	Ext. (mm)	Mode of failure	
Unprimed	H1	0.68	8	100% cohesive	0.19	7	100% cohesive	0.20	6	100% cohesive	29
	H2	0.64	5	100% cohesive	0.22	6	100% cohesive	0.18	7	100% cohesive	28
	H3	0.71	11	100% cohesive	0.19	6	100% cohesive	0.18	5	100% cohesive	25
	SMP	1.39	11	85% cohesive 15% substrate	0.18	3	100% cohesive	0.16	3	100% cohesive	12
Primed	H1	0.82	9	100% cohesive	0.13	2	90% interfacial 10% cohesive	0.11	1	100% interfacial	13
	H2	0.84	6	100% cohesive	0.16	2	70% interfacial 30% cohesive	0.15	3	90% interfacial 10% cohesive	18
	H3	0.85	12	100% cohesive	0.10	1	100% interfacial	0.09	1	100% interfacial	11
	SMP	1.37	9	75% cohesive 25% substrate	0.14	2	70% cohesive 30% interfacial	0.08	1	50% cohesive 50% interfacial	7

The compatibility and durability performance of sealant bonded mortar H-joints. Weathering conditions – water immersion at 45˚C for periods of twenty-one and forty-two days.

Mortar substrate	Sealant system	Compatibility			Weathered for 21 days			Weathered for 42 days			Strength retention (%)
		F (kN)	Ext. (mm)	Mode of failure	F (kN)	Ext. (mm)	Mode of failure	F (kN)	Ext. (mm)	Mode of failure	
Unprimed	H1	0.43	4	70% interfacial 20% cohesive 10% substrate	0.20	2	100% interphase	0.09	1	100% interphase	23
	H2	0.56	4	50% cohesive 30% interfacial 20% substrate	0.18	2	100% interphase	0.16	2	100% interphase	27
	H3	0.45	4	70% cohesive 30% substrate	015	2	100% interphase	0.11	1	100% interphase	22
	SMP	0.63	3	70% cohesive 30% substrate	0.28	2	100% interphase	0.20	1	100% interphase	33
Primed	H1	0.74	10	90% cohesive 10% substrate	0.15	2	100% interfacial	0.13	2	100% interfacial	18
	H2	0.75	8	70% cohesive 30% substrate	0.19	2	100% interfacial	0.14	1	100% interfacial	19
	H3	0.73	11	80% cohesive 20% substrate	0.15	2	100% interfacial	0.08	1	100% interfacial	11
	SMP	0.94	6	60% cohesive 40% substrate	0.41	3	100% interfacial	0.27	2	100% interfacial	29

MULTI-MATERIAL JOINTS

The anticipated performance of E1 bonded vanadium passivated galvanised steel – dissimilar material lap joints; these results were postulated from relevant uni-material results. Any deviations between predicted and actual results will be indication that something unexpected has occurred.

Multi-material combination	Compatibility		Short-term weathered	
	F (kN)	Mode of failure	F (kN)	Mode of failure
HDG$_{V}$ – PVdF coated steel	3.8	Cohesive and interfacial at both surfaces	2.4	HDG$_{Va}$ interfacial
HDG$_{V}$ – PUR coated steel	3.5	Polyurethane interfacial	2.4	HDG$_{Va}$ interfacial
HDG$_{V}$ – Aluminium	3.8	Cohesive and interfacial at both surfaces	2.4	HDG$_{Va}$ and aluminium interfacial
HDG$_{V}$ – Timber	2.6	Timber	1.7	Timber
HDG$_{V}$ – Mortar	0.6	Mortar	0.5	Mortar

The compatibility and short-term durability performance of vanadium passivated galvanised steel – organic coated steel, aluminium, timber and mortar lap joints. Weathering conditions – 100% relative humidity at 70°C for fourteen days.

Multi-material combination	Compatibility			Short-term weathered			Strength retention (%)
	F (kN)	σ (%)	Mode of failure	F (kN)	σ (%)	Mode of failure	
HDG$_{V}$ – PVdF coated steel	4.9	7	60% cohesive 40% PVdF interfacial	2.4	8	85% HDG interfacial 10% cohesive 5% HDG corrosion	49
HDG$_{V}$ – PUR coated steel	3.6	15	100% PUR interfacial	1.8	6	90% HDG interfacial 10% HDG corrosion	50
HDG$_{V}$ – Aluminium	3.9	8	50% Al interfacial 30% HDG interfacial 20% cohesive	2.5	18	55% HDG interfacial 30% Al interfacial 10% cohesive 5% HDG corrosion	64
HDG$_{V}$ – Timber	3.9	5	90% timber 10% HDG interfacial	0.1	0	100% HDG corrosion	3
HDG$_{V}$ – Mortar	0.7	23	100% mortar	0.5	21	40% HDG interfacial 60% HDG corrosion	80

The anticipated performance of adhesive bonded dissimilar organic coated steel lap joints

	PVdF top coat – polyester backing coat		Polyurethane top coat – polyester backing coat	
	Most compatible	Most durable	Most compatible	Most durable
Adhesive	A3	E1	A3	E1
Max shear load	4.3kN	4.1kN	4.3kN	4.1kN
Fracture mode	Cohesive	Polyester coating	Cohesive	Polyester coating

The compatibility and short-term durability performance of adhesive bonded dissimilar organic coated steel lap joints. Weathering conditions – 100% relative humidity at 70°C for fourteen days.

Organic coated steel combination	Adhesive system	Compatibility			Short-term weathered			Strength retention (%)
		F (kN)	σ (%)	Mode of failure	F (kN)	σ (%)	Mode of failure	
PVdF top coat – polyester backing coat	E1	6.0	1	80% PVdF interfacial 10% cohesion 10% PVdF coating	4.9	17	100% polyester coating	82
	P1	4.2	9	100% cohesive	2.7	14	50% polyester coating 30% PVdF interfacial 20% cohesive	64
	A3	4.9	2	90% cohesive 10% polyester coating	2.7	20	80% polyester coating 10% polyester interfacial 10% PVdF interfacial	55
Polyurethane top coat – polyester backing coat	E1	4.5	1	90% polyester interfacial 10% polyester coating	4.5	2	40% polyester coating 30% PUR interfacial 20% PUR coating 10% cohesive	100
	P1	3.9	3	90% cohesive 10% PUR coating	2.8	16	80% cohesive 20% PUR interfacial	72
	A3	4.4	2	80% polyester interfacial 20% cohesive	1.3	14	100% polyester interfacial	30

The anticipated performance of adhesive bonded PVdF coated steel – aluminium alloy 6082T6 lap joints.

	PVdF coated steel – Aluminium (degreased)		PVdF coated steel – Aluminium (pretreated)	
	Most compatible	Most durable	Most compatible	Most durable
Adhesive	A2	A2	E2	E1
Max shear load	5.8kN	4.8kN	5.8kN	5.3kN
Fracture mode	Cohesive	Cohesive	Cohesive	Cohesive/coating

The compatibility and short-term durability performance of adhesive bonded PVdF coated steel – aluminium alloy 6082T6 lap joints. Weathering conditions – 100% relative humidity at 70°C for fourteen days.

Aluminium surface preparation	Adhesive system	Compatibility			Short-term weathered			Strength retention (%)
		F (kN)	σ (%)	Mode of failure	F (kN)	σ (%)	Mode of failure	
Acetone degreased	E1	3.5	9	90% aluminium interfacial 10% cohesive	3.3	13	90% aluminium interfacial 10% cohesive	94
	E2	4.2	16	100% aluminium interfacial	0	0	100% aluminium interfacial	0
	P1	2.4	20	100% aluminium interfacial	0	0	100% aluminium interfacial	0
	A2	6.1	3	100% cohesive	4.6	5	80% cohesive 20% aluminium interfacial	75
Acid etched and silane treated	E1	5.4	5	90% PVdF interfacial 10% cohesive	4.1	4	50% PVdF coating 50% cohesive	76
	E2	6.0	7	80% cohesive 10/10% PVdF coating/ interfacial	2.1	15	70% aluminium interfacial 30% cohesive	35
	P1	4.0	13	50% cohesive 50% PVdF interfacial	2.5	11	90% PVdF interfacial 10% cohesive	62

The anticipated performance of adhesive bonded polyurethane coated steel – aluminium alloy 6082T6 lap joints.

	PUR coated steel – Aluminium (degreased)		PUR coated steel – Aluminium (pretreated)	
	Most compatible	Most durable	Most compatible	Most durable
Adhesive	A2	A2	P1	E1
Max shear load	5.3kN	3.7kN	4.1kN	4.2kN
Fracture mode	Cohesive	Cohesive	Cohesive	Polyurethane interfacial

The compatibility and short-term durability performance of adhesive bonded polyurethane coated steel – aluminium alloy 6082T6 lap joints. Weathering conditions – 100% relative humidity at 70˚C for fourteen days.

Aluminium Surface preparation	Adhesive system	Compatibility			Short-term weathered			Strength Retention (%)
		F (kN)	σ (%)	Mode of failure	F (kN)	σ (%)	Mode of failure	
Acetone degreased	E1	2.8	15	100% PUR interfacial	3.4	8	60% aluminium interfacial 30% PUR interfacial 10% cohesive	121
	E2	5.2	7	50/15% PUR interfacial/ coating 25% aluminium interfacial 10% cohesive	0.9	31	100% aluminium interfacial	17
	P1	1.3	9	100% aluminium interfacial	0.1	18	100% aluminium interfacial	5
	A2	5.6	6	100% cohesive	3.9	6	50% cohesive 50% aluminium interfacial	70
Acid etched and silane treated	E1	2.9	10	50% cohesive 50% PUR interfacial	3.9	7	100% cohesive	138
	P1	4.2	3	90% cohesive 10% aluminium interfacial	3.0	2	80% cohesive 20% aluminium interfacial	72

The anticipated performance of adhesive bonded PVdF coated steel – glass lap joints.

	PVdF coated steel – Glass (degreased)		**PVdF coated steel – Glass (pretreated)**	
	Most compatible	**Most durable**	**Most compatible**	**Most durable**
Adhesive	E1, E2 or A2		All	All
Max shear load	1.4 – 1.6kN	0kN	1.4 – 1.8kN	1.1 – 1.3kN
Fracture mode	Glass	Glass interfacial	Glass	Glass or cohesive

The compatibility and short-term durability performance of adhesive bonded PVdF coated steel – glass lap joints. Weathering conditions – 100% relative humidity at 70˚C for fourteen days.

Glass surface preparation	**Adhesive system**	**Compatibility**			**Short-term weathered**			**Strength retention (%)**
		F (kN)	**σ (%)**	**Mode of failure**	**F (kN)**	**σ (%)**	**Mode of failure**	
Acetone degreased	E1	3.0	17	40/10% PVdF coating/ interfacial 30/20% glass interfacial/ substrate	0	0	100% glass interfacial	0
	E2	3.2	14	40/10% PVdF interfacial/ coating 30/20% glass substrate/ interfacial	0	0	100% glass interfacial	0
	P1	2.4	5	100% glass interfacial	0	0	100% glass interfacial	0
	A2	3.1	6	30/10% glass substrate/ interfacial 30/10% PVdF interfacial/ coating 20% cohesive	0	0	100% glass interfacial	0
Silane pretreated	E1	3.1	13	40/20% PVdF coating/ interfacial 40% glass	2.9	7	100% glass interfacial	94
	E2	3.4	16	40/10% glass substrate/ interfacial 30/20% PVdF interfacial/ coating	2.9	5	100% cohesive	84
	P1	2.9	10	100% PVdF interfacial	0.9	17	100% PVdF interfacial	31
	A2	3.2	9	30/10% PVdF interfacial/ coating 30% glass 30% cohesive	2.8	9	60% glass interfacial 40% cohesive	88

The anticipated performance of adhesive bonded polyurethane coated steel – glass lap joints.

	PUR coated steel – Glass (degreased)		PUR coated steel – Glass (pretreated)	
	Most compatible	Most durable	Most compatible	Most durable
Adhesive	E1, E2 or A2		All	All
Max shear load	1.4 – 1.6kN	0kN	1.4 – 1.8kN	1.1 – 1.3kN
Fracture mode	Glass	Glass interfacial	Glass	Glass and cohesive

The compatibility and short-term durability performance of adhesive bonded polyurethane coated steel – glass lap joints. Weathering conditions – 100% relative humidity at 70˚C for fourteen days.

Glass surface preparation	Adhesive system	Compatibility			Short-term weathered			Strength retention (%)
		F (kN)	σ (%)	Mode of failure	F (kN)	σ (%)	Mode of failure	
Acetone degreased	E1	2.2	17	40/20% PUR interfacial/ coating 40% glass interfacial	0	0	100% glass interfacial	0
	E2	2.8	11	60% PUR coating 40% cohesive	0	0	100% glass interfacial	0
	P1	0.8	22	100% glass interfacial	0	0	100% glass interfacial	0
	A2	2.6	14	50% cohesive 50% PUR coating	0	0	100% glass interfacial	0
Silane pretreated	E1	2.6	15	100% PUR interfacial	2.5	12	50% PUR interfacial 50% glass interfacial	98
	E2	3.0	6	50% PUR coating 50% cohesive	2.2	10	80% cohesive 20% glass interfacial	72
	P1	2.9	12	100% cohesive	2.3	8	100% cohesive	80
	A2	3.0	9	100% cohesive	2.3	7	80% cohesive 20% glass interfacial	78

The anticipated performance of adhesive bonded PVdF and polyurethane coated steel – timber lap joints.

	PVdF coated steel – Timber		PUR coated steel – Timber	
	Most compatible	Most durable	Most compatible	Most durable
Adhesive	E1 or A2	E1 or E2	E1 or E2	E1 or E2
Max shear load	2.6kN	1.7 – 1.8kN	2.6kN	1.7 – 1.8kN
Fracture mode	Timber and interphase	Timber and interphase	Timber and interphase	Timber and interphase

The compatibility and short-term durability performance of adhesive bonded PVdF coated steel – timber and polyurethane coated steel – timber lap joints. Weathering conditions – 100% relative humidity at 70˚C for fourteen days.

Lap joint substrates	Adhesive system	Compatibility			Short-term weathered			Strength retention (%)
		F (kN)	σ (%)	Mode of failure	F (kN)	σ (%)	Mode of failure	
PVdF coated steel – Timber	E1	4.4	11	50/50% timber/ interphase	1.4	23	80/20% timber /interphase	32
	E2	3.3	8	60/40% timber/ interphase	1.0	23	50% timber interphase 40% PVdF interfacial 10% cohesive	29
	P1	2.2	18	50% PVdF interfacial 30% cohesive 20% timber interphase	0.0	/	100% PVdF interfacial	0
	A2	3.2	16	50/50% timber/ interphase	0.2	186	100% timber interfacial	6
PUR coated steel – Timber	E1	1.2	11	100% PUR interfacial	0.0	/	100% PUR interfacial	0
	E2	3.2	12	30/35% timber/ interphase 35% PUR interfacial	0.0	/	100% PUR interfacial	0
	P1	2.0	18	15/35% timber/ interphase 50% cohesive	0.0	/	100% coating	0
	A2	2.5	8	50/50% timber/ interphase	0.0	/	100% timber interfacial	0

The anticipated performance of sealant bonded chromium passivated galvanised steel – organic coated steel, aluminium alloy 6082, timber and mortar H-joints.

Multi-material combination	Optimum performance	Most compatible	Most durable
HDG_{Cr} – PVdF coated steel	Sealant	SMP	H1 or SMP
	Max tensile load	1.2 – 1.6kN	0.4 – 0.5kN
	Fracture mode	Cohesive	Primarily cohesive with some interfacial failure on both surfaces
HDG_{Cr} – PUR coated steel	Sealant	H1	H1
	Max tensile load	0.8kN	0.4kN
	Fracture mode	Cohesive	Predominantly cohesive with some interfacial failure at both surfaces
HDG_{Cr} – Aluminium alloy	Sealant	SMP	SMP
	Max tensile load	1.4 – 1.6kN	Approx. 0.5kN
	Fracture mode	Cohesive	Predominantly cohesive with some interfacial failure at the HDG_{Cr} surface
HDG_{Cr} – Timber	Sealant	SMP	H1 or SMP
	Max tensile load	1.4 – 1.6kN	0.2kN
	Fracture mode	Predominantly cohesive with some timber failure	Cohesive
HDG_{Cr} – Mortar	Sealant	SMP	SMP
	Max tensile load	0.9kN	0.3kN
	Fracture mode	Cohesive and mortar (interphase)	Cohesive and mortar (interphase)

The compatibility and durability performance of sealant bonded chromium passivated galvanised steel – organic coated steel, aluminium alloy 6082T6, timber and mortar H-joints. Weathering conditions – water immersion at 45˚C for periods of twenty-one and forty-two days.

H-joint substrates	Sealant system	Compatibility			Weathered for 21 days			Weathered for 42 days			Strength retention (%)
		F (kN)	Ext. (mm)	Mode of failure	F (kN)	Ext. (mm)	Mode of failure	F (kN)	Ext. (mm)	Mode of failure	
HDG_{Cr} – PVdF coated steel	H1	0.82	9	100% cohesive	0.29	6	90% cohesive 10% HDG interfacial	0.30	5	90% cohesive 10% HDG interfacial	37
	SMP	1.44	10	100% cohesive	0.59	9	80% cohesive 20% HDG interfacial	0.68	16	90% cohesive 10% HDG interfacial	47
HDG_{Cr} – PUR coated steel	H1	0.85	10	100% cohesive	0.25	4	90% cohesive 10% HDG interfacial	0.31	5	80% cohesive 10% HDG interfacial 10% PUR interfacial	35
	H3	0.84	11	100% cohesive	0.35	9	80% cohesive 10% HDG interfacial 10% PUR interfacial	0.31	5	90% cohesive 10% PUR interfacial	36
HDG_{Cr} – Aluminium	H1	0.65	10	100% cohesive	0.35	7	90% cohesive 10% HDG interfacial	0.31	5	70% cohesive 30% HDG interfacial	48
	SMP	1.39	10	100% cohesive	0.68	9	70% cohesive 30% HDG interface	0.66	11	60% cohesive 40% HDG interfacial	47
HDG_{Cr} – Timber	H1	0.85	10	100% cohesive	0.10	1	70% cohesive 30% timber int.	0.14	2	80% cohesive 20% timber int.	16
	SMP	1.46	10	100% cohesive	0.19	2	70% cohesive 30% HDG interfacial	0.15	2	60% cohesive 40% HDG interfacial	10
HDG_{Cr} – Mortar	H1	0.72	5	100% cohesive	0.16	1	100% cohesive	0.13	1	100% cohesive	18
	SMP	1.35	8	90% cohesive 10% mortar	0.29	2	100% cohesive	0.21	1	100% cohesive	16

Int. – interfacial failure

The anticipated performance of sealant bonded organic coated steel – aluminium alloy 6082T6 H-joints.

	PVdF coated steel – Aluminium		PUR coated steel – Aluminium	
	Most compatible	Most durable	Most compatible	Most durable
Sealant	SMP	SMP	H3	H1
Max tensile load	1.2 – 1.4kN	0.7kN	0.7kN	0.4kN
Fracture mode	Cohesive	Predominantly cohesive with some PVdF interfacial	Cohesive	Primarily cohesive with interfacial failure at both substrate surfaces

The compatibility and durability performance of sealant bonded PVdF coated steel – aluminium alloy 6082T6 and polyurethane coated steel – aluminium alloy 6082T6 H-joints. Weathering conditions – water immersion at 45°C for periods of twenty-one and forty-two days.

H-joint substrates	Sealant system	Compatibility			Weathered for 21 days			Weathered for 42 days			Strength retention (%)
		F (kN)	Ext. (mm)	Mode of failure	F (kN)	Ext. (mm)	Mode of failure	F (kN)	Ext. (mm)	Mode of failure	
PVdF coated steel – Aluminium	H1	0.81	9	100% cohesive	0.39	9	90% cohesive 10% PVdF int.	0.37	9	80% cohesive 20% PVdF int.	46
	SMP	1.18	5	90% cohesive 10% Al int.	0.83	18	90% cohesive 10% PVdF int.	0.50	9	90% cohesive 10% PVdF int.	42
PUR coated steel – Aluminium	H1	0.73	5	100% cohesive	0.37	8	90% cohesive 10% PUR int.	0.28	5	90% cohesive 10% PUR int.	38
	H3	0.73	8	80% cohesive 20% Al int.	0.33	7	80% cohesive 20% PUR int.	0.28	6	80% cohesive 20% PUR int.	38

Al – aluminium, int. – interfacial failure

The anticipated performance of sealant bonded organic coated steel – glass H-joints.

	PVdF coated steel – Glass		**PUR coated steel – Glass**	
	Most compatible	**Most durable**	**Most compatible**	**Most durable**
Sealant	PS or SMP	SMP	PS or SMP	S2
Max tensile load	1.2 – 1.6kN	0.7kN	1.1 – 1.6kN	0.6kN
Fracture mode	Cohesive	Predominantly cohesive with some PVdF interfacial	Cohesive	Primarily cohesive with some polyurethane interfacial

The compatibility and durability performance of sealant bonded PVdF coated steel – glass and polyurethane coated steel –glass H-joints. Weathering conditions – water immersion at 45˚C for periods of twenty-one and forty-two days.

H-joint substrates	**Sealant system**	**Compatibility**			**Weathered for 21 days**			**Weathered for 42 days**			**Strength retention (%)**
		F (kN)	**Ext. (mm)**	**Mode of failure**	**F (kN)**	**Ext. (mm)**	**Mode of failure**	**F (kN)**	**Ext. (mm)**	**Mode of failure**	
PVdF coated steel – Glass	S1	0.76	23	100% cohesive	0.63	15	70% cohesive 30% PVdF int.	0.69	13	80% cohesive 20% PVdF int.	91
	S2	0.77	33	100% cohesive	0.76	26	100% cohesive	0.78	29	80% cohesive 20% PVdF int.	101
	H1	0.77	8	100% cohesive	0.51	25	80% cohesive 10% PVdF int. 10% glass int.	0.28	3	100% cohesive	38
	PS	1.37	8	100% cohesive	1.06	13	100% cohesive	0.16	2	100% cohesive	15
	SMP	1.41	8	100% cohesive	1.33	17	100% cohesive	1.25	20	100% cohesive	92
PUR coated steel – Glass	S1	0.79	24	100% cohesive	0.68	14	100% cohesive	0.60	12	100% cohesive	76
	S2	0.75	28	100% cohesive	0.78	24	100% cohesive	0.66	23	100% cohesive	88
	H1	0.78	10	100% cohesive	0.51	31	100% cohesive	0.28	4	100% cohesive	36
	PS	1.34	22	100% cohesive	1.03	17	100% cohesive	0.19	2	100% cohesive	14
	SMP	1.31	18	100% cohesive	1.10	21	100% cohesive	0.91	19	100% cohesive	68

The anticipated performance of sealant bonded organic coated steel – timber H-joints.

	PVdF coated steel – Timber		PUR coated steel – Timber	
	Most compatible	Most durable	Most compatible	Most durable
Sealant	SMP	H1 or SMP	H1 or H2	H1 or H2
Max tensile load	1.2 – 1.4kN	0.2kN	0.6 – 0.8kN	0.2kN
Fracture mode	Predominantly cohesive with some timber failure	Cohesive	Cohesive	Cohesive

The compatibility and durability performance of sealant bonded PVdF coated steel – timber and polyurethane coated steel – timber H-joints. Weathering conditions – water immersion at 45˚C for periods of twenty-one and forty-two days.

H-joint substrates	Sealant system	Compatibility			Weathered for 21 days			Weathered for 42 days			Strength retention (%)
		F (kN)	Ext (mm)	Mode of failure	F (kN)	Ext. (mm)	Mode of failure	F (kN)	Ext. (mm)	Mode of failure	
PVdF coated steel – Timber	H1	0.82	11	100% cohesive	0.15	2	100% cohesive	0.13	2	100% cohesive	16
	SMP	1.17	8	100% cohesive	0.14	2	100% cohesive	0.11	2	100% cohesive	9
PUR coated steel – Timber	H1	0.85	10	100% cohesive	0.19	3	100% cohesive	0.19	3	100% cohesive	22
	H2	0.90	8	100% cohesive	0.18	2	100% cohesive	0.2	3	100% cohesive	19