PRACTICAL ASPECTS OF FAILURE PREVENTION IN BONDED JOINTS ON PRIMARY LOAD BEARING STRUCTURES

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Abstract.Adhesive bonding is a particularly effective method of assembling complex structures, especially those made from different materials. Provided the joint is well designed, the adhesive bond ought to be one of the strongest aspects of the structure and most certainly should not be the life limiting factor. This of course pre-supposes that the joint has been correctly executed. The major factors determining the integrity of an adhesive bond are selection of the most appropriate adhesive, joint design, preparation of the bonding surfaces and strict quality control in production and condition monitoring in service. Adhesives have become increasingly important in assembling many of the multi-material structures which make up a contemporary Formula 1 racing car. Structural fibre reinforced composite materials were introduced into Formula 1 motor racing in 1980. Since that time the cars have become increasingly dependent on these materials such that a contemporary chassis may consist of up to 80% by weight of carbon fire reinforced epoxy resins and the appropriate adhesives to facilitate fabrication. One might argue therefore that a modern Formula 1 chassis consists of a series of "plastic" mouldings held together with glue! Many of these structures are very highly stressed and required to operate in aggressive environments, particularly high temperatures. The consequences of failure of "Class A" structures can be catastrophic to the operation of the vehicle and impinge on the safety of the driver. Although increasingly better understood, the science and engineering of adhesives is very much in its infancy. Consequently the design and operation of bonded components tends to be a constantly evolving, semi-quantitative process combining fracture and finite element analysis with practical experience. BAR have been particularly adept in the exploitation of adhesives over recent years. The process of "total quality management" (TQM) encompasses the whole operation from R&D and design through materials procurement, component manufacture and condition monitoring to ensure successful exploitation up to the point of withdrawal from service.

1. INTRODUCTION

Adhesives are being increasingly employed in the assembly of complex components within the Formula 1 industry. In particular they are used to replace or augment more traditional joining techniques such as welding, mechanical fastenings and interference fits etc. The driving force for the use of adhesives is the increasing use of composite materials, although this has precipitated an increasing number of other applications (1, 2). Adhesives may be quickly applied, possess excellent properties and are very cost effective. The many advantages of adhesives include:

1. The ability to join dissimilar materials.

2.The bond formed is continuous such that stronger and stiffer structures are often produced (Figure 1).

3.A more uniform stress distribution is achieved on loading, avoiding local stress concentrations (Figure 2).

4.Reduced weight and part count.

5.Small areas may be bonded accurately and large areas may be bonded without inducing stresses.

6.Little if any finishing is required.

7.With careful joint design, excellent fatigue resistance and vibration damping can be achieved.

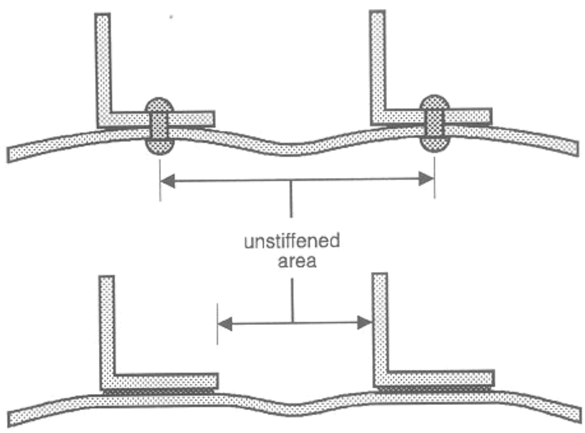

Figure 1. Stiffening with adhesively bonded joints

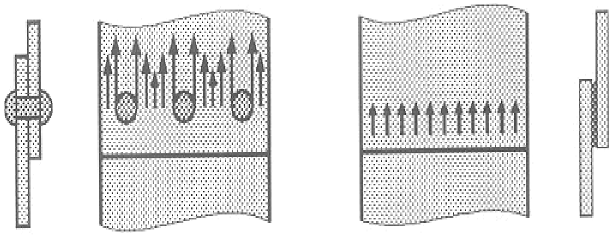

Figure 2. Stress distribution in a loaded joint.

It is very rare for the failure of a bonded joint to involve adhesive strength. Failures are generally due to poor design, inadequate preparation and poor production procedures. Successful exploitation of adhesives thus necessitates a thorough knowledge of all aspects of the materials science of the joint as a complete system. A large variety of products are available which may be engineered to suit individual applications. Nevertheless, the selection of adhesives can be overwhelmingly complicated due to this enormous diversity.

Among the limitations of adhesives which must be considered are the following:

1.Durability is unpredictable and must be determined experimentally for each application.

2.Surface preparation is critical to the success of the operation and complete wetting of the substrate must be ensured.

3.Identification of defects by NDT requires a great deal of skill and experience and the tolerance to defects is impossible to predict in anything but a semi-quantitative manner, given the present level of understanding.

4.Increasing the service temperature decreases the bond strength.

5.Short term handleability is poor and bonded structures are often difficult to dismantle for in-service repair.

6.Environmental resistance depends on the integrity of the adhesive.

7.New and unfamiliar production and exploitation controls must be developed and implemented.

That aside, even materials which are traditionally difficult to join can be bonded with adhesives, although some substrates may give rise to lower bond strengths or limited durability.

2. DEFINING THE ADHESIVE BOND

Adhesion is defined as the holding together of two surfaces by interfacial forces that will resist separation (3). Good adhesion requires very close contact. For an adhesive to bond it is required to flow and wet the surface of the substrate. The surface energy (surface tension for liquids) of the adhesive must therefore be lower than that of the substrate to ensure good wetting, the first stage in forming an adhesive bond. The second stage is the generation of intrinsic adhesion forces across the interface. The various forces which may be acting are known as the *mechanisms of adhesion*. There are three primary mechanisms of adhesion proposed (Figure 3);

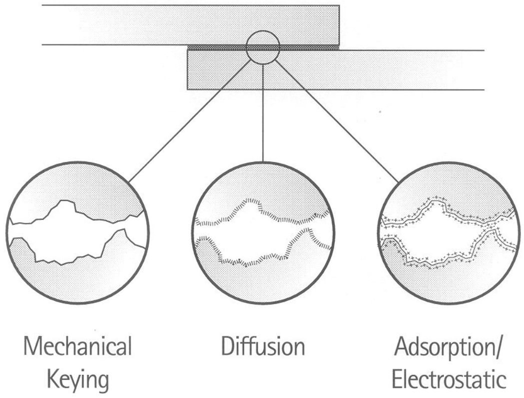

Figure 3. Mechanisms of adhesion.

1 .Mechanical interlocking or "*keying*" occurs when cured adhesive becomes trapped in the irregular surface of the substrate. It is however possible to show that the attainment of good adhesion is possible between optically smooth surfaces (4, 5). The frequently observed increases in measured joint strengths with increasing substrate surface roughness are therefore considered attributable to other factors such as the removal of weak surface material, improved wetting and a larger exposed surface area for bonding.

2. Adhesive and substrate may *diffuse* across the interface. Similarly the adhesive may diffuse into the surface of porous substrates and cure. The interdiffusion of the polymer chains of the adhesive requires the adhesive and substrate to be mutually soluble. Such conditions are thought to occur in the solvent welding of polymers, but are not considered capable of contributing significantly to the intrinsic strength of the bond. Interdiffusion can also be promoted in polymer/metal bonds via pores and other surface defects in the substrates. This effect tends however to enhance the bond by promoting adsorption of the adhesive rather than by the diffusion process.

3. Intimate contact between adhesive and substrate result in *adsorption*, electrostatic and molecular attraction processes established between the atoms and molecules in the surfaces of the adhesive and substrate. The most common of these are van der Waal's forces and, to a lesser extent, hydrogen bonding. These are referred to as

"secondary bonds". Additionally, chemical bonds may sometimes be formed across the interface. The establishment of ionic, covalent, or metallic bonds is known as "chemisorption" or "primary" bonds. The terms primary and secondary are fairly arbitrary descriptions of the relative strengths of their attractive forces.

Under specific circumstances, any or all of the mechanisms may be responsible for the adhesive strength of a particular joint. For the majority of engineering applications however it is the adsorption mechanism that dominates. Thus, providing there is intimate and continuous molecular contact at the interface of adhesive and substrate, a bond will be established due to the interatomic forces between the materials.

Adhesive strength is described as the force required to pull the adhesive cleanly away from the surface of the substrate. A cured adhesive, in common with any other material, can also be characterised by its internal strength. Similarly, the third factor influencing the strength of the bond is the internal strength of the substrate(s). The term *cohesive strength* of adhesives and substrates is used to differentiate from adhesion (Figure 4). Preferred design practice is to ensure that the life-limiting factor of the joint is the cohesive strength of one or other of the substrates as this can be more accurately defined and guaranteed. During the execution of a bond adhesives typically follow a flow phase when they are applied, spread and wet the surface, followed by a hardening (cure) phase during which their cohesive strength develops. *Structural bonding* is the term used to define a bond where it performs a load bearing function. This allows the forces within a structure to be transmitted from one member to another through the joint. The purpose of the adhesive is to facilitate this load transfer. Despite an ever increasing amount of research aimed at defining the properties of the adhesively bonded joint, the majority of the data is qualitative at best, necessitating extensive testing and prototype evaluation.

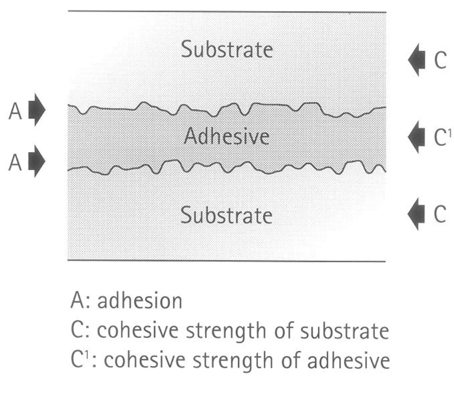

Figure 4. Forces operating in an adhesive bond

3. THE USE OF ADHESIVES IN FORMULA 1 CAR CONSTRUCTION.

Adhesives have been used on Formula 1 cars since the late 1970s. Their firs major usage was in the chassis, bonding initially aluminium and later carbon skins to honeycomb material (1). Further development saw extensive use of adhesives. One of the most exciting applications of adhesives was in the production of composite suspension members. These were originally introduced by McLaren (6) following an extensive period of testing and development but are now used by all of the teams (Figure 5). The most recent innovation on an F1 car is that of a composite gearbox (7). This device consists of a monolithic carbon fibre reinforced epoxy "maincase" into which are bonded a number of titanium bulkheads to carry the "internals" (gear cluster and selectors etc) and "inserts" such as suspension and engine mounts etc. This device illustrates very graphically the strength and versatility of adhesives, being a multi-material structure capable of transmitting in excess of 900bhp whilst reacting severe suspension loads, all at temperatures of up to (and sporadically exceeding) 150^{o}C (Figure 6).

Figure 5. Bonded composite suspension components

Figure 6. Composite gearbox

4. JOINT DESIGN

When considering an adhesively bonded joint it is important to appreciate that the optimum design will not be same as for traditional fixing methods such as welding or mechanical fasteners. The characteristics of adhesives dictate that their mechanical response to compression, shear and tensile loading regimes is far superior to peel and cleavage (Figure 7). It is paramount that a component be designed such that the bond will be strengthened by the geometry of the final artefact rather than be weakened or destroyed by it. The strength and durability of a joint is a complex function of the stress concentrations set up by the applied loads and operating conditions. In a simple lap joint made from thin metal sheets there are two types of stress: shear and peel. The shear stress varies along the length of the joint with concentrations at the ends. The peel stress acts at right angles to the lap joint and is also maximised at the ends (Figure 8). The peel stress tends to distort the joint and consequently weaken it. Similarly any deflections of the structure under load increase the peel component and may lead to premature failure. Unsupported lap joints are one of the weakest configurations and are seldom used in practise. A number of possible bond geometries, both good and bad, are illustrated in Figure 9. Such joints can be applied, either in isolation or combination, to more complex geometries. The best results are clearly achieved by designing the joint such that the forces experienced tend to compress the adhesive or induce shear loads whilst taking steps to eliminate or at least minimise peel and cleavage forces particularly at the vulnerable edges of the joint.

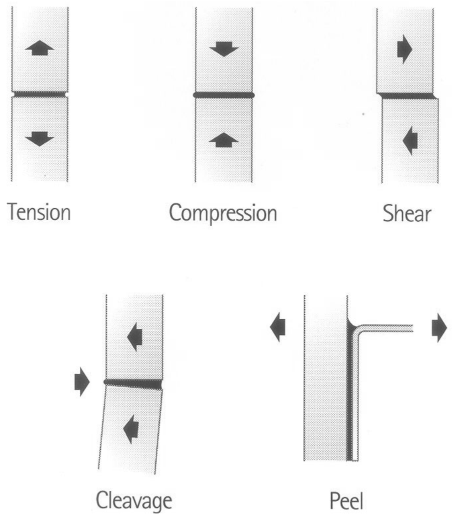

Figure 7. Types of loading endured by adhesive joints

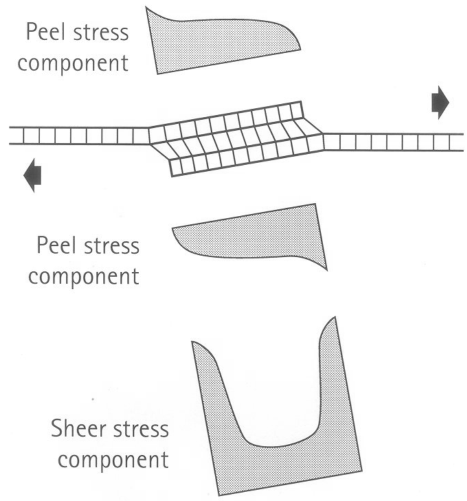

Figure 8. Stress distribution in a simple lap shear joint.

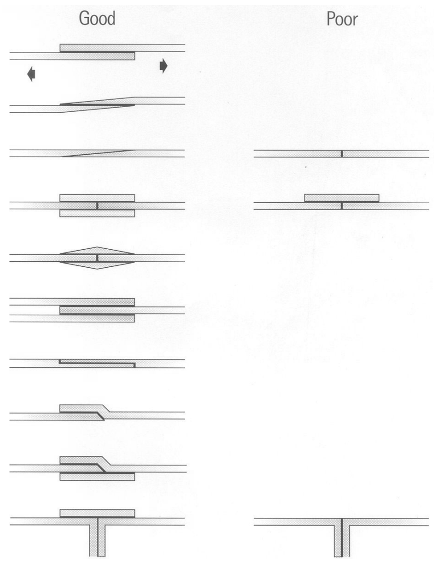

Figure 9. Basic joint geometries - in practice two or more may be used in conjunction.

Structural adhesive layers are at their most efficient in the thickness range 0.1-0.25mm. Too thin an adhesive layer will generally result in poor adhesion due to non-uniform wetting. Thicker bonds, although attractive from a theoretical point of view, are not practical because of the impossibility of executing them without inducing intolerable levels of flaws and porosity. Experience has shown that optimum wetting and relief of the stress concentrations at the edges is achieved by tapering the bonding faces and, wherever possible, machining them to the required tolerance. It is advisable to jig the assembly in such a way as to maintain a uniform bond line. It goes without saying that the design should maximise the area over which the load is distributed. Consideration must also be given to practical aspects such as ease and reproducibility of assembly. Non stressed components may be designed such that the adhesive bonds are self jigging but structural bonds must be assembled on purpose built jigs to ensure correct alignment throughout the curing process.

Estimation of the theoretical strength of a joint is relatively straightforward using data which may be obtained from the adhesive manufacturer or (preferably) determined experimentally. To a first approximation, the load capacity of a joint is simply the product of the bonded area and the shear strength of the adhesive. In practical applications, a number of variables must be factored in. These include substrates and surface finish, bond thickness (clearance), temperature, joint geometry and environment etc. Calculations must be verified by testing in the laboratory. This programme is particularly important in the eventual success of the application since it enables the identification of potential problems at an early stage. A variety of tests need to be considered in order to determine any possible problems and achieve the following objectives:

1. Compare the properties and suitability of a group of adhesives.

2. To act as a quality check for a batch of adhesives.

3. Verify the effectiveness and repeatability of the preparation techniques to be used.

4. Measure the environmental effects (temperature, fluids, moisture etc.)

5. Provide quantitative data on the joint and adhesive.

6. Analyse failure mechanisms.

Some important criteria of an adhesive joint may be determined by visual observation of the parts following a failure during a test. It is important to determine whether adhesive or cohesive failure has precipitated overall joint failure, or if the bonded parts (substrates) have been destroyed (Figure 10). In the case of *adhesive failure* the adhesive is observed to be completely separated from the face of one substrate. This is the "worst case" scenario in that the weakest aspect of the joint is the boundary layer between the bonded parts and the adhesive. This means that the joint is prone to failure without warning and at a load far lower than predicted. In such circumstances the causes are either that the material is unsuitable for bonding or the bonding surface was contaminated and therefore incorrectly prepared. In both cases the strength can be increased by devoting more attention to the pre-treatment of the surface. *Cohesive failure* occurs when the adhesive itself breaks. The failure is characterised by remains of the adhesive being found on both substrates. This occurs because the adhesive is over stressed through external action such as temperature, ageing or off-axis loading due to misalignment or deflection etc. It can be remedied by design changes in the bonding geometry, tightening of production procedures, and/or selection of an adhesive which is more suitable to the fine detail of the application. The preferred failure mode is *substrate failure*. In such instances the bond is not the life-limiting factor of the joint and should not therefore influence its long-term durability. It is recommended that all stressed joints are designed such that ultimate failure occurs in the substrate.

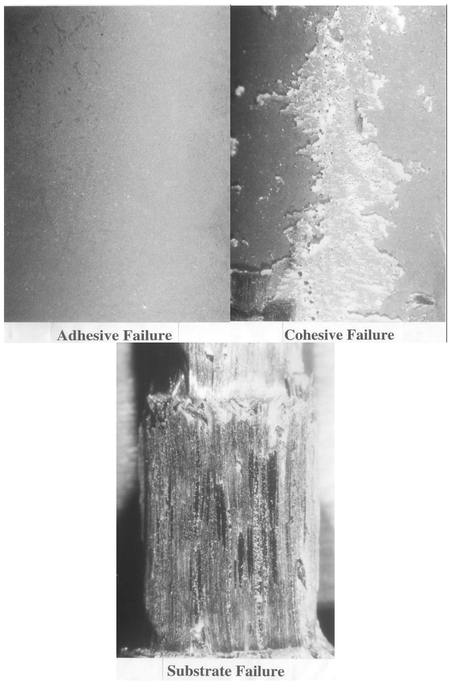

Figure 10. Possible failure modes in adhesively bonded structures.

5.SURFACE PREPARATION

The advantages gained through good design can only be exploited if the surfaces to be bonded are properly prepared. The surface thermodynamics of the majority of materials used on the race cars are extremely favourable to the adhesive bonding process and those few which are not may be treated with a primer with a modicum of success. This presupposes of course that the bonding surfaces are free from contaminants. To ensure maximum strength in structural bonds it is necessary to remove all traces of paints, oxide films, dust, mould release agents and all other debris. There are four principal ways of preparing surfaces, which are used in combination:

1.Solvent degreasing. This process removes any contaminants that would adversely affect the adsorption mechanism

2. Mechanical abrasion (grit blasting etc.), removes any weak surface layers from the substrates and increases the bond area.

3. Chemical etching and anodising. Promotes primary and secondary bonding mechanisms.

4. Use of primers and activators. Promotes primary and secondary bonding mechanisms and can be used to modify the cure kinetics of the adhesive.

Provided the appropriate adhesive and surface preparations are used, almost any substrate can be bonded as long as the operating conditions are not too extreme

6.DURABILITY OF ADHESIVE JOINTS

Structural joints are required to perform under a combination of service conditions, which include both static and dynamically applied loads and exposure to hostile environments, particularly temperature, moisture and solvents. It is paramount therefore to design a bonded structure capable of operating under such conditions and to develop processes to guarantee integrity over the entirety of their service life. Adhesives generally exhibit superior fatigue properties in comparison with competitive joining technologies as a consequence of a more even distribution of stress. Nevertheless, the consequences of failure are such that a great deal of work is necessary to minimise the probability of such an event. When evaluating the fatigue performance of a joint one must consider a wide range of variables (9) (stress amplitude, mean stress, frequency, waveform, ambient and internal temperature of the system etc.). Thus there are potentially more unknowns to consider than with a more "traditional" joining technique. The complex fatigue conditions must be approximated to much simpler laboratory test conditions in which many of the parameters are held constant. This presents a formidable task in that it is vital to identify those service conditions which directly influence the life of a particular joint. Failure to do this will render the test useless and any results not merely of no value, but may present too optimistic (or pessimistic) a prediction of the durability of a particular component.

A number of loading methods and specimen geometries have been reported in the literature (10, 11) for fatigue testing of adhesive joints. In practical applications however, the life limiting factor of many joints is the stress concentration set up by the geometry of the design. Consequently, there is a tendency to test full-scale structures rather than standard test pieces (12). Whilst this approach provides the designer with confidence about a particular item, it does not generate basic materials data apposite to other applications. The extreme competitive drive within Formula 1 ensures that engineers use the very latest materials in novel applications as they strive for improved performance. Thus, despite great advances in computer stress analysis and materials science, our ability to produce components more often than not leads our ability to fully understand them. The dynamic performance and long-term durability of such structures, particularly those involving adhesive joints with their inherent variability, can only be demonstrated by means of experiments with complete components and simulation of actual operating conditions. The validity of accelerated durability tests depends on how closely the extrapolation follows service conditions an as such relies very strongly on the experience of the team's technical staff. Durability testing may be carried out using calculated loads or service data collected from the test track to drive servohydraulic actuators which stress the components on purpose built jigs (Figure 11) (13, 14). The digital operation of the equipment such as that manufactured by Instron, enables the programming of safety factors with relative ease. The effect of increased temperature on durability is to increase the rate of strength loss. This can be modelled by incorporating some form of heating chamber into the test rig. The time constraints imposed due to the nature of the sport make more long-term environmental effects such as moisture uptake difficult to simulate. Given time one would carry out tests using relative humidity cabinets etc. Instead environmental testing tends to be an "over-kill" such as a 24 hour condition exposure to, for example, hydraulic fluid prior to the durability tests. One has to be very careful when interpreting the results from this type of test. In the interests of expediency there is a great potential to produce misleading results. Too harsh an environment compared to reality may result in premature failure (and subsequent anxiety) over a mechanism which would never occur in practice. Similarly, if the environment is not simulated in such a way as to at least provide subjective results, there is likely to be a degree of over-confidence in the component. There is a tendency therefore for bonds to be over designed but this is obviously preferable to a failure.

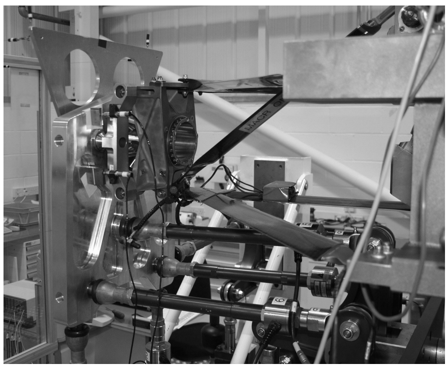

Figure 11. 6-axis test rig used to test a complete corner suspension assembly

7.FATIGUE MECHANISMS

Fatigue is generally considered to involve initiation of a crack and its subsequent propagation. Most studies however tend to neglect the initiation phase and focus upon growth of a crack of microscopic proportions, since it is this portion of the failure mechanism which actually determines the fatigue life. This is an acceptable practice since the initiation of a crack is difficult if not impossible to model, and any calculated lifetime will be somewhat conservative which is generally preferred by designers. Studies on carbon fibre composites bonded using epoxy adhesives show fatigue failure to occur due to crack growth within the adhesive (15). A similar process is observed when bonding composite to metal (Figure 12). The concept of fatigue crack growth in adhesive joints is a great concern, but little work has been has been reported to enable a fundamental understanding of the mechanisms involved. It is therefore very difficult establish design criteria and develop quantitative methodologies for predicting service lives. The nature of the damage which accumulates at the crack tip, and causes the loading/unloading cycle to be so deleterious, has not been identified. Furthermore, the affects of changing the various loading and environmental parameters upon the rate of crack growth is all but unknown.

Figure 12 Fatigue failure in metal to composite joint

Despite a lack of hard evidence, a number of studies have suggested an endurance or fatigue limit in adhesive systems (analogous to observed with ferrous alloys) of 35-45% of ultimate strength (16). Experimental evidence suggests that a safety factor of 3 or more to a joint will all but eliminate purely mechanical fatigue problems (this does not of course negate environmental degradation and the effect of defects). Regardless of anecdotal evidence, the work of Lewis et al is considered to over-simplify the problem and make far too many assumptions such that any agreement between calculated life and general design practice is far more likely to be a fortunate coincidence and is certainly not an established phenomenon (17).

A further complication in understanding the fatigue behaviour of bonded joints arises from the nature of the adhesives themselves. A perfectly elastic material will remain at the temperature of the test environment throughout a fatigue test since no energy is dissipated within the specimen. Polymeric materials however are viscoelastic and exhibit mechanical hysteresis even at relatively low applied strains. Under cyclic loading some of this deformation energy will be dissipated as heat during each loading cycle. The adhesive’s temperature will rise as a consequence, until the heat generated per cycle is equal to the heat dissipated by conduction and radiation. It is theoretically possible for the adhesive to heat up quite quickly to relatively high temperatures. The affect, if any, is difficult to predict; the elevated temperature may soften the adhesive causing blunting of the crack tip, hence act as a toughening mechanism, or may result in a loss of strength by wakening the adhesive. Thermal effects resulting from fatigue loading may well be very significant in determining the long term performance of a joint under load, but are frequently far too complex to interpret. This then is yet another factor making the fatigue response of adhesives difficult to quantify.

8.DEFECTS IN BONDED STRUCTURES

A number of possible sources of weakness have been identified within adhesively bonded joints. These occur within the adhesive itself, at the adhesive/substrate interface and progressively due to in-service degradation. The strength of the joint depends on how successfully the loads are transmitted by each part of the structure. Any weak link will therefore lead to premature failure. The most common defects found in adhesively bonded joints are shown schematically in Figure 13 (18). Porosity results from trapped gasses (perhaps during mixing) and volatiles associated with the curing process. Voids may be formed by the coalescence of porosity, entrapment of air during application of the adhesive or by insufficient adhesive being applied. Incorrect cure is caused by the presence of contaminants, bad formulation, or poor mixing of the adhesive. It may occur locally in small pockets but is more likely to occur throughout the whole of the bond line. Cracks within the adhesive are generally associated with curing and thermal shrinkage during manufacture, particularly when using high temperature adhesives which can sometimes be quite brittle at room temperature.

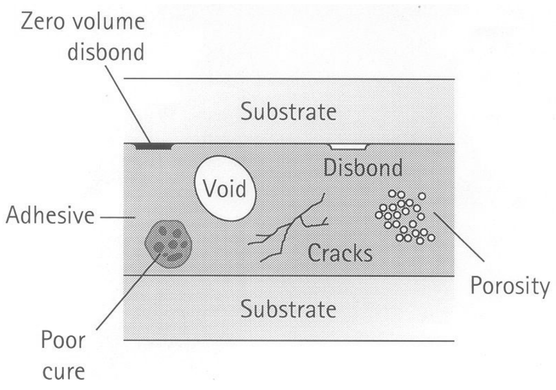

Figure 13 Potential defects in adhesive bonds (18)

A weak or non-existent bond generally results from a contaminated substrate surface or if the adhesive is used too long after mixing. The resulting total lack of bond, or disbond of zero volume at the interface, can be detected using NDT techniques albeit with a degree of difficulty. Their significance on the performance of the joint is however very difficult to predict. Specific bonding problems can arise with the "peel plies" (19) which are frequently used when joining composite materials. In practice these consumables are not removed until just prior to bonding. It is not uncommon for the release agents used in formulating the peel ply to migrate into the surface of the composite substrate which may lead to a weakening of the subsequent bond. Hot cured epoxy adhesives offer an advantage in such applications in that they can dissolve some of the surface contamination. In the long-term, dispensing with peel plies in favour of the "wet blasting" preparation technique offers many advantages.

As previously discussed, adhesively bonded joints are particularly susceptible to attack by aggressive chemicals and moisture. The mechanical properties of the adhesive may be progressively degraded by solvent or other damage, but a far more severe problem is degradation of the bond interface. Not only is the bond strength reduced, it may lead to weakening of the substrate(s) due to corrosion. Chemical etching of metallic substrates is particularly useful in preventing or, at the very least, slowing this process by reducing the electrochemical potential. The nature of the loading regime also affects the durability of the joint. Adhesive bonds, like composite materials, rely on a perfect stress transfer between their constituents. High frequency (shock) loading may result in local stress concentrations, especially in the presence of flaws and other inhomogeneities, which exceed the bond strength and lead to a progressive failure in a manner analogous to metal fatigue. Defects within bonded joints can be detected by a number of techniques, but there is insufficient data and understanding to allow a quantitative analysis of their affect on durability. Clearly the presence of defects can only have a negative influence on the service life of a bonded component. Any lifing predictions will thus have to be qualitative based upon experience and laboratory testing.

9.TOTAL QUALITY MANAGEMENT

There are clearly a number of distinct advantages offered by the extensive use of adhesive bonding. Nevertheless, there are also a significant number of problems which arise from their seemingly unpredictable long-term behaviour. This inability to accurately quantify the durability of adhesives arises from a relatively poor understanding of their materials' science, particularly with respect to the affect of environmental variables. This can be circumvented however by the introduction of Total Quality Management (TQM). TQM is a process of controlling all aspects of the technology from inception through exploitation to eventual obsolescence. Whenever an adhesive is used process quality control is vital since once the joint has been made it is very difficult to inspect and rework. For many tasks it is sufficient to dispense product directly from its container onto the surfaces to be joined. Other cases require very precise mixing and application. It is very easy to execute a poor bond whereas the production of complex structures of dissimilar materials requires very careful processing by well trained, skilled and highly disciplined staff. The operator must wear gloves at all times and under no circumstances touch the bonding surfaces with a foreign object except for any tools with which the adhesive is applied. Where appropriate, the adhesives must be mixed thoroughly in the correct proportions, and the cure carried out correctly. These latter two factors may be monitored using thermochemical analysis techniques such as Differential Scanning Calorimetry (DSC) as part of the quality control procedure (20).

Bonding of components whether they are polymeric, composite or metallic has increased in both quantity and complexity in the construction of Formula 1 vehicles over the last few years. The use of adhesives within the industry was originally the exclusive domain of composite materials and all of the work carried out by that specialist department. Introduction of bonded metallic and multi-material structures has resulted in these techniques becoming interdepartmental involving additionally the joining of fabrications and monolithic (machined) components. The manufacturing process requires all of the constituent parts to be scheduled to arrive at the right place at the right time given the restrictions of the bonding process. Efficient management of this production is vital to prevent bottlenecks from occurring. The time elapsed between preparation and assembly must be kept to a minimum in order to minimise contamination. The working environment must be controlled in terms of temperature and relative humidity coupled with general standards of cleanliness. The volume of work will inevitably increase and necessitate a purpose built facility to provide a clean room environment. Such a unit requires the specialist equipment needed for cleaning and pre-treatment, and to be large enough for assembly and storage of components during curing.

Tracability of components and operations is of paramount importance. A "zero defects" operation is employed in which each component is documented throughout the entirety of its manufacture, testing and service life. All aspects of manufacture must be fully documented and follow procedures developed during the R&D phase of component design. Complex assembly operations are broken down into more manageable segments which can be efficiently managed. Each stage of the operation must be verified using non-destructive testing (NDT) techniques in order to ensure that all finished components meet specification. Once passed for exploitation, a condition monitoring programme should be employed to illuminate any potential problems before they become serious. Condition monitoring in the BAR team involves the setting of a service interval after which each component is returned to the factory for proof testing (to verify strength and stiffness characteristics, Figure 14) and NDT etc.

Figure 14. Proof testing a bonded composite wishbone

In the BAR system, "Class A" components are defined as "those parts, which if they were to fail, would cause the driver to lose control of the car". The TQM process operated by BAR for such pieces is;

1. All aspects of manufacture and exploitation must be fully traceable (a process known as "lifing").

2. A representative sample of parts must be fully tested in the laboratory in order to prove that they meet design criteria for load bearing and other properties.

3. A representative sample of parts must be fully tested in the laboratory in order to prove that they are capable of surviving a simulation of a season's operation without deterioration in any way.

4. A car set of parts must complete a minimum of 1000km of trouble free operation on a test car.

5. Following a service interval of 2500km (an arbitrary figure chosen to approximate to 2 tests or 3 races) parts must be returned to the factory for full proof and NDT inspection.

6. Only those components that show no deterioration may be returned to service.

TQM procedures are developed during the prototyping phase of a new components or subassembly. They tend to be periodically modified and improved as the technology develops, newer more specialised applications are introduced and through feedback from operators. It is important understand the concept of a "process" in this context: A process is a series of operations which is developed such that it represents the "best practice" for the task involved. It will therefore have no end (unlike a programme or project) since it will constantly evolve along with the technology.

10.CONCLUSION.

There has been traditional reluctance amongst engineers to use adhesives primarily due to the fear of catastrophic failure. The widespread application of bonded joints in performance critical applications on Formula 1 racing cars shows just how useful adhesives can be. It would not be unreasonable to suggest that components manufactured using bonded joints are generally superior to those assembled using more traditional joining technologies. Indeed, many of the assemblies common on contemporary F1 cars simply could not be made any other way. There is however a very significant "price of conformity" which must be paid. The lack of numerical design and durability data demand a very sophisticated TQM process is in operation if the integrity of highly stressed joints is to be guaranteed. Production controls are paramount if the advantages of adhesives are to be successfully exploited. Attention to detail in manufacture is vital to ensure enhanced mechanical performance, improved durability, and increased service life of components. The integrity of adhesive joints can only be guaranteed by observing a "zero defects" approach to quality control. Whilst this may well be acceptable in Formula 1 and "high end" aeronautical applications, it will preclude the technology from more cost sensitive theatres of engineering. What is required is a far greater understanding of the materials science of adhesives and the need to consider the design, production, testing and service of the joint as integral components of a complete system.

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