Project 3
Environmental Durability of Adhesive Bonds

Report No 6

A Review of Industrial Case Histories.

Edited by AE Bond

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REPORT

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I FOREWORD

Many UK manufacturers are aware of the merits of adhesives in certain critical roles. However, the range of applications of adhesives is still limited largely due to the lack of consistent test methods and validated test data which the engineer needs in order to specify adhesives for a given application. In a recent survey the Centre for Adhesive Technology was commissioned by the DTI to establish specific areas where validated test methods could improve confidence in predicting joint life. The survey identified measurement methods for use in design, environmental durability and process control as priority areas and five projects were finally selected by the DTI for support through the Measurement Technology and Standards (MTS) budget. The projects started in December 1992 and are 100% funded by the DTI at the level of £5.4m over three years.

A key area that was identified in the survey was the need to provide a means for the quantification and prediction of the lifetime of bonded joints when exposed to a hostile environment, and forms the basis of Project 3 of the Adhesives programme. The project is being carried out through a collaboration of AEA Technology and Oxford Brookes University, together with important contributions from Imperial College, DRA (Holton Heath) and Loughborough University.

The basis of the project is that there still remains considerable uncertainty in predicting joint lifetime under typical operating conditions, despite the enormous prior investment in durability studies. This difficulty represents perhaps the single most significant impediment to the wider use of adhesive technology. The programme combines a fresh look at testing procedures and predictive methods with a rigorous examination of previous work. Together the two strands of the approach produce a work plan which has a strong industrial focus. In addition to the tasks on test methods and design, a series of forensic studies will be undertaken on examples of bonded structures which have seen extensive service life, in order to evaluate the reasons for their success. This will provide practical feedback into the other aspects of the programme as well as indicating to designers tangible evidence of the potential of bonding technology which they will be able to relate to their own particular application.

This project is divided into seven tasks:

- Appraisal of Test Methods and Durability Data
- Development of an Experimental Database
- Characterisation of the Moisture Absorption Process
- Forensic Studies
- Assessment of Microstructural Failure Mechanisms
- Development of Methodologies for Life Prediction
- Technology Transfer
II SUMMARY.

The merits of adhesives in certain critical roles are well known. The range of applications of adhesives is still limited, however, due largely to uncertainty in predicting joint lifetime under typical operating conditions. The DTI, through the Measurement Technology and Standards (MTS) budget, has supported a range of projects aimed at enhancing the understanding of adhesive technology. A key area identified for investigation was the need to provide a means for the quantification and prediction of the lifetime of bonded joints when exposed to a hostile environment, and this forms the basis of Project 3 of the Adhesives programme. The programme combines a fresh look at testing procedures and predictive methods with a series of forensic studies of bonded structures which have seen extensive service life.

A preliminary aspect of the forensic study was to identify suitable applications of adhesive jointing for investigation. This was done by carrying out a general review of applications where adhesive bonding technology has been successfully used in industry. These case histories are presented in this report. They have been selected to cover as broad a cross section of industrial sectors, and as wide a range of production environments as possible. They also serve to illustrate the fact that adhesive joints can, and do, survive for many years, even when exposed to particularly harsh service conditions. Of the examples described in this report, a number have been selected for further study and are presented in Report No. 8 of MTS project 3.

In almost all of the cases highlighted the use of adhesives has resulted in significant savings to the producer. In many instances the use of adhesives has reduced the production time for the particular component, through simplification of the processes, and a reduction in the number of fittings used. In other cases the primary savings have been a reduction in weight of the finished component and improved performance.

Many of the cases have illustrated that, even with a minimum of surface preparation, very reliable joints can be formed, when the loads in the joint are sufficiently low. By making use of some of the better surface preparation techniques, stronger and longer lasting joints can be formed, which allow the use of the adhesives to considerably greater proportions of their ultimate strength.

Adhesives are no longer new, uncharted territory. They have now been in use for some fifty years. Many of the examples cited in this review have been in regular service for 10 - 15 years, with some as long as 30 years. In this time, as long as adequate consideration was taken of the service duty and life expectancy of the adhesive joint during the design phase, there is little evidence of critical degradation of the joint performance.
1. INTRODUCTION.

Within industry, adhesives are increasingly recognised as offering an efficient means of joining components. As well as offering the designer greater flexibility, their use can result in lighter, cheaper and more aesthetically pleasing products. Given their potential benefits, however, the use of adhesives has not become as widespread as had been predicted. In part, this slow rate of growth has been due to the preconceptions about adhesive durability that have built up, based in many instances on domestic experience, where the adhesives used are often incompatible with the surfaces to be joined, and little or no care is exercised in the initial preparation of the surfaces. The ensuing failure of the joint leads to a lack of confidence in adhesive performance in general.

This lack of confidence is, in the main, not justified. In industry, by and large, far greater care is taken in selecting a suitable adhesive. The adherends are generally prepared in some way prior to bonding, albeit to a limited extent in some instances. As a result, in the vast majority of cases, the adhesive bonds perform well over many years, often outperforming conventional design solutions. In addition, the benefits associated with adhesive bonding, such as light weight and improved appearance, can be exploited to commercial advantage.

The durability of adhesive joints is in many ways more important than their initial strength. Past experience has shown that the mechanical properties of bonded joints often deteriorate under warm humid conditions, particularly if the joints comprise high surface energy substrates, such as metals, glasses and ceramics. Furthermore, an interfacial locus of failure, generally associated with low fracture energies, is commonly found after environmental exposure, and it is now widely appreciated that surface pre-treatments play a vital role in promoting the stability of adhesive bonds. Whilst there has been a considerable expenditure of effort in durability studies, there still remains a great deal of uncertainty in predicting lifetime under hostile environmental conditions.

Although the factors affecting joint performance are widely recognised, joint life prediction is frustrated by a lack of quantitative performance indicators and an appropriate methodology with which to forecast degradation and service life expectation. This "missing link" is largely responsible for the lack of confidence amongst design engineers, and is inhibiting the development and wider use of adhesives technology.

1.1 MTS Project 3.

The MTS series of projects is a DTI sponsored programme aimed at developing the required knowledge to facilitate the use of relatively high technology materials, and to pass the knowledge on to industry where it can be used to advantage. MTS Project 3 specifically addresses the concerns over the prediction of adhesive joint service lifetimes. A major component of this work, tying together experimental results and theory, is a series of forensic studies.

A preliminary aspect of this forensic study was a review of adhesives usage. By highlighting a number of real life case histories, where adhesive bonding technology has been successfully used in industry, it is hoped that the built-up prejudices of designers can be overcome. The cases presented have been selected to cover as broad a cross section of industrial sectors, and as wide a range of production environments as possible. They illustrate the fact that adhesive joints can, and do, survive for many years, even when exposed to particularly harsh service conditions. More detailed investigations have been carried out on a limited number of the products most exposed to the
environment and with higher service stress levels. These are the De Havilland Comet, Foden truck
door, footwear, LAW 80 rocket launcher, bridge plate bonding and GRP process piping. The
studies are reported fully in Report No 8 of the MTS Project 3, although brief descriptions of the
products are included in this report for completeness.

In order to structure the review, the case histories have been separated into three categories; those
where the adhesive is used primarily to enhance the appearance of the finished product and the
loading environment is relatively light, those where the use of adhesives facilitates production, and
finally those where the use of adhesives results in technical benefits. Clearly, as with any
classification system, the allocation of a particular product to a category is somewhat arbitrary, as
the boundaries of the groups overlap, with many applications being equally at home in more than
one. Within each category a number of case histories are presented, each of which is subjected to
different severities of service conditions, both in terms of loading, criticality and environmental
conditions.

2. AESTHETIC AND LIGHTLY LOADED APPLICATIONS.

The first category that will be addressed is the aesthetic group of case histories. In this category,
the use of adhesives enables the elimination of, or reduction in the use of mechanical fasteners, thus
improving the appearance of the product. In many cases the adhesive joint is not subjected to a
particularly harsh loading regime, however as some of the later histories in this section will
demonstrate, this is not always the case.

2.1 Laminated Worktops.

A very common use of adhesives is in furniture making, where adhesives are used to apply
decorative laminates, such as veneered furniture tops, and domestic kitchen worktops, as shown in
Figure 1. Often the laminated surface is used to resemble a more expensive alternative surface, for
example stone or high quality timber. In these situations the use of alternative fastening techniques
would destroy the illusion of the original, more expensive material, and a less pleasing appearance
than can be achieved using adhesives. In most cases the surface is a coloured phenolic laminate or
thin wood veneer, which is applied to a cheap, relatively lightweight chipboard substrate.

In general the decorative surface being applied is lightweight, and the areas over which the adhesive
bonding takes place relatively large, hence a very low stress regime. Nonetheless, particularly in the
case of the kitchen worktop, the adhesive joint is subjected to a range of environmental conditions
which are not insignificant, such as when hot pans are placed on the top, and the regular wiping
down with detergents and bleaches which will affect the edges of the laminate, quite apart from the
generally high humidity environment of a kitchen.

Typically the adhesives used for these applications are either polyurethane adhesives, which can
easily be applied by brush, or film hot melts in commercial laminating facilities, and solvent based
contact adhesives for DIY use. All three types of adhesive have the advantage over other possible
adhesives that the component can be handled almost straight away after the joint has been
assembled, and there is little delay as the adhesive is allowed to cure. The polyurethane adhesive
however, does need to dry briefly once applied, before the joint is brought together, thus resulting
in slightly longer production times than can be achieved using hot melt systems. In contrast the hot
melt adhesives need more in the way of equipment to achieve a good level of bonding, particularly with large areas of laminate. Production is very simple, particularly when polyurethane adhesives are used, allowing quality joints to be formed, even in the simplest workshop.

Given the relatively low stress environment, the design of this sort of adhesive joint is fairly simple, indeed often little or no calculation is performed to qualify the design. In most cases no surface pre-treatment of the mating surfaces is necessary to achieve a good bond. In general, for DIY purposes, the surfaces to be joined are simply wiped down to ensure that there is no loose material, which would otherwise spoil the final appearance, rather than significantly weakening the joint. In industrial laminating processes, however an abrasion process is used to ensure that the surfaces are smooth, and to provide a key for the adhesive. Once assembled the joint typically has a life expectancy of upwards of twenty years, with relatively little evidence of premature failure, other than situations where adhesive starvation has occurred during manufacture, or the finished item has been abused.

2.2 Second Fixings.

Within the construction industry there is a growing trend towards the use of adhesives. Increasingly craftsmen on the building site are being paid by piecework agreements, and it is thus all the more important for the contractor to speed up the time taken to carry out a particular task. The example described here is that of the second fixing, that is the fixing of details such as skirting boards, picture rails, cornice and the like around a room, shown in Figure 2. Traditionally these boards have been nailed into wooden plug blocks which are firmly wedged into the blockwork of the building. Where a natural wood finish was specified, a more complex system of secret fixing was required so that the nail heads were not visible. The use of adhesives allows a significant reduction in the number of nails used, or in some cases the elimination of traditional fasteners altogether, thus reducing the amount of finishing that is required before the decorative finish can be applied, indeed in some instances now pre-finished boards can be bought, simplifying the job even further.

The areas over which the adhesive is applied are generally fairly large, but the components being hung can be relatively heavy, and they are likely to be knocked when in service. A further feature is that often the wall to which the board is being attached has a degree of ripple in it, which the board cannot follow because of its relative stiffness. The adhesive is therefore required to fill the resulting gap. There is no longer a requirement for immediate handling strength as by clamping and wedging the boards into place, the craftsman is left free to carry on working elsewhere whilst the adhesive reaches its full strength. This allows the use of cheaper, slower curing forms of adhesive. Typically single part polyurethane or solvent based contact adhesives are used, which can easily be applied using conventional low cost tooling.

The performance of the joint is in no way safety critical, and the adhesive stresses low, it is thus rare for any real design to go into the joint specification. By following a few simple rules a totally reliable joint can be formed. These rules are generally no more than common sense, for example do not bond to a damp plaster surface and follow the adhesive manufacturer's instructions. With modern constructions using plasterboard there is generally no need to pre-treat the surfaces, other than a light wiping down to remove loose material. In refurbishment situations where the boards are to be applied to traditional plaster finishes, it is often better to prepare the area to be bonded with a dilute coating of PVA to stabilise the plaster prior to bonding. The completed construction
is required to serve, with no maintenance, for typically upwards of fifty years. In that time, although protected from the worst environmental conditions, the joint is likely to be subjected to the very dry heat typical of modern living conditions.

2.3 Mk III and HST 125 - Window Surround.

The window frame surround on a railway carriage performs a similar function to the skirting board in the construction industry, in that it hides the join between two surfaces. This time, however the environment is considerably harsher.

Adhesive bonding technology has been used for many years in the railway industry for both traction and rolling stock, to produce structural joints that are both light and fatigue resistant. Railway coaches and locomotives typically have longer service lives than road vehicles and are also used more frequently. Their joints are subjected to track induced vibration, shock loading during shunting operations, as well as quite severe pressure surges on entry to and exit from tunnels.

This particular application, the window frame surround on the British Rail HST and Mk. 3 coaches, has been in regular service since 1978, Figure 3. The window frame trims are manufactured from GRP mouldings which are bonded to the steel framework of the carriage and the aluminium skin material using a two part toughened acrylic adhesive. In this case a major advantage of the removal of the fasteners, other than the improved appearance, is the reduced incidence of vandalism, as it had been found in the past that the visible screw heads were a great temptation to vandals.

In this application, the consequences of a failure of the adhesive are somewhat greater, with the potential for passenger injury, considerably more effort was expended in designing and evaluating the joint. An extensive programme of testing and development was carried out, as a result of which the two part acrylic adhesive used was developed, following some early trials where panels became detached due to the pressure surges. During these trials, a number of tests were carried out to identify the level of surface pre-treatment that was required to achieve a reliable joint. Taking cost considerations into account, the optimum performance was achieved by wiping the GRP with acetone, and lightly abrading the steel and aluminium followed by degreasing with 1,1,1-trichloroethane, and this was the process eventually used in production. More sophisticated pre-treatments, such as chromic acid etching had also been considered, but despite resulting in improved performance, the additional cost was not warranted in this situation. The trials also showed that the adhesive could frequently be used on oily and poorly prepared surfaces making it ideal for mating different materials under normal workshop conditions.

All of the HST 125 window surrounds built between 1978 and 1982 were bonded using a two part toughened acrylic adhesive, and in 18 years of service there have been no known failures of the joint which can be attributed to adhesive failure.

2.4 Foden Truck Cab.

Another industry that is making an ever increasing use of adhesives is the automotive sector. The particular case considered here is the Foden series 4000 truck cab, shown in Figure 4, in which adhesives have been used since 1978.
The cabs are constructed from a number of GRP and aluminium sections, many of which are bonded together. The area where the bonding performs in a more structural role is within the truck doors, where several aluminium pressings are bonded together to form the door. Two aluminium alloy stiffeners, one to resist bending of the door around the handle area as the door is opened and slammed closed, and the other to damp vibrations in what is a fairly large flat panel, are adhered to the outer door skin, as shown in Figure 5.

In order to meet the required production throughput, without the need for large stock piles, a simple bonding procedure was required. Both mating surfaces are degreased using 1.1.1-trichloroethane, and a toughened two part acrylic adhesive applied. The surfaces are brought together and clamped for around 6 minutes, while the adhesive cures. After this time, work on the door can immediately be continued, thus saving time compared to the use of slower drying, but possibly stronger adhesives. Prototype testing of cab doors using adhesive technology, prior to general release, indicated that this level of construction, relatively simple surface pre-treatment, and a rapid curing acrylic adhesive was fit for purpose, and more expensive improvements to the construction were not warranted. Now, with some 15 years in service, and no known cases of the adhesive failing under normal conditions, this compromise has been shown to have been valid. Indeed the door being used in the more detailed forensic study programme was involved in an accident in which the door was damaged. Although locally to the incident the adhesive had peeled back, more than 60% of the joint had remained intact.

For these components, the use of conventional spot welding techniques would have resulted in localised unevenness of the door skin, which would have affected the finished appearance of the cab. Through the use of adhesive bonding this problem was able to be eliminated. At the same time the cost of construction has been reduced due to the increased simplicity.

### 2.5 Summary of Aesthetic Advantages

One of the most common uses of adhesives currently is that of bonding decorative finishes to products. The adhesive is primarily used to enhance the aesthetics of the finished component, by eliminating or reducing the use of mechanical fastenings. In many cases the service loading of these joints is relatively low, and the consequences of failure minimal. As a result, the level of refinement of the joint is similarly low, and little effort is expended in the design of the joint. As the later cases have shown, however, this is not always the case, and with a little more care in the design of the joint, safety critical and structural aesthetic joints can reliably be made. None of the joints described in this section have required the use of tight tolerance precision fits or expensive pre-treatment of the mating surfaces. Nonetheless, each of the cases has been particularly successful, showing many years of service in difficult situations, with remarkably little incidence of premature failure due to problems with the adhesive joint.
Figure 1  Domestic Laminated Worktops.
Figure 2  Second Fixings.
Figure 1. Foden Series 4000 Truck.
(Reproduced by kind permission of Foden Trucks Ltd)
Figure 5  Door Stiffener Location.
3. PRODUCTION APPLICATIONS.

A second category of adhesive joints is those where the use of adhesive bonding technology results in simplified production. The following cases have all enabled their producers to reduce production costs compared with conventional designs, often improving the performance of the product at the same time.

3.1 Footwear - Sole to Upper.

Although outwardly, other than to meet the demands of fashion, footwear does not appear to have changed significantly over the last century, the techniques used in the manufacture of shoes have undergone revolutionary changes. These changes have resulted in a reduction in the production times for each item, as well as reducing the skill levels required for many of the operations. The construction of modern footwear involves a widespread use of adhesives, the major exceptions being the sewing of uppers and in some cases, the attachment of heels with nails. Figure 6 shows, in general terms, the various roles in which adhesives have been used in footwear construction. Of these, probably the most demanding joint is that between the sole and the upper material, and it is this joint that is considered here.

As with all adhesive joints, correct surface preparation is of paramount importance to achieve the level of performance required from the adhesive bond. In this case, the area of the leather uppers to be bonded is prepared by a process of mechanical roughing. This removes the surface finishes, as well as removing the weakly attached surface grain layer of the leather and reveals the stronger underlying fibres. The preparation of the soles depends on the material being used. The most common processes used are solvent wiping of PVC soles to remove surface plasticiser and a halogenation process which saturates the butadiene in rubbers, thus making the material more compatible with the adhesive.

The adhesive generally used is a one part polyurethane, containing approximately 20% solids in a solvent base, often methyl ethyl ketone (MEK), which has the desired properties of reasonable gap filling properties, combined with good spot strength (green strength). A layer of adhesive is applied to the perimeter of both components (approximately 10 mm wide) and allowed to dry. Prior to assembly the adhesive is heat activated, on at least one surface, by passing it under infra red heaters to raise the adhesive temperature to 80°C. The two components are then brought together and pressed for approximately 15 seconds to form the joint. Laboratory tests indicate that typically the sole/upper joint strength is around 5 N/mm.

For regularly used items of footwear, the life expectancy is on average one year from purchase. During this time, the adhesive joint is subjected to a range of chemical and environmental conditions, depending on the nature of the shoe. The joint is often subjected to moisture, both from the environment, and perspiration from the wearer. Results from a number of wear trials, carried out over this length of time, indicate that the majority of failures that occur are due to errors in the original bonding process, for example insufficient or over enthusiastic surface preparation, rather than environmentally provoked failure of the adhesive. This is borne out by laboratory tests performed on polyurethane adhesive joints typical of the sole to upper joint, which have indicated that water saturation of the joint at temperatures below the glass transition temperature for the adhesive has little effect on the medium term strength of the joint.
3.2 Speaker Cones.

The assembly of modern loudspeakers, Figure 7, typically involves a number of different adhesive bonds. These are primarily to do with the bonding of the speaker cone, made from stiffened fabric or compressed paper, to the passivated steel chassis or to the suspension rubber, and the bonding of the ferrite magnet to the chassis. Prior to the early eighties, the majority of speaker manufacturers used low cost, solvent or two part mixed adhesives which are relatively slow curing, for these joints. Faced with increasing competition, and a desire to expand production in the light of a major increase in demand from the automotive industry, a major UK manufacturer decided to replace these low cost adhesives with faster curing, but more expensive, adhesives such as cyanoacrylates and UV curing and two part acrylics.

By changing the adhesives used, the assembly time of the speakers was considerably reduced, as was the number of units on the line at any one time. As a result of no longer needing large areas in which to hold stock whilst the adhesive cured, increased production volumes could be achieved from the same factory space. A further benefit, resulting from the reduced stock levels, was a reduction in the capital tied up as work in progress, thus saving the company money.

The loudspeakers, particularly those used in automotive applications, are subjected to wide temperature fluctuations and humidity levels, from dry to near condensing humidity. The speakers are expected to survive for the lifetime of the vehicle in which they are installed, ie ten years or more.

This case clearly illustrates how important it is to consider all of the cost implications of the use of adhesives. Although more expensive adhesives were used, the overall manufacturing costs were reduced. The benefits associated with the use of adhesives are not necessarily apparent if one merely considers the cost of a bottle of adhesive against the cost of a handful of rivets or bolts.

3.3 Coaxial Engineering Fittings - Lotus Engine.

The use of anaerobic adhesives to secure coaxial engineering components is nowadays common place. Almost every assembled part of the modern engine makes use of an anaerobic adhesive or sealant to retain non moving pieces whilst the engine is assembled, Figure 8. The service environment within the engine is particularly harsh, with relatively high temperatures, and oil or water immersion for much of the time, coupled with a fair degree of vibration.

It is well known that, under these conditions, adhesive properties can drop to significantly below short term static test values, and the adhesive is therefore rarely used in a long term structural capacity. Nonetheless, by designing the joints such that the stress levels in the adhesive in service remain relatively low, the joint remains intact, retaining and sealing the components, thus facilitating subsequent maintenance operations. Anaerobic sealants, which are incorporated to accommodate movement between components such as the engine block flanges, are designed so as to retain flexibility and adhesion at the high engine temperatures of 150 °C. It is not only the relatively small components found in engines that are bonded, as Figure 9 shows, some considerably larger bearings are also fixed in their housings using adhesives.

In the case of bearings and free running studs, the primary benefit derived from the use of an anaerobic adhesive is that interference fits are no longer required to hold the component in place. This relaxes the tolerance on size for these items, reducing manufacturing costs, as well as
eliminating the forces generated by interference fits in the housing, allowing the sections of the mountings to be reduced, thus reducing the weight. In addition the assembly of relatively loose components is far quicker and simpler than press fitting.

3.4 Differential Gear.

The automotive industry forever strives to make savings, both in terms of costs and weight. The component shown in Figure 10 is a ring gear and its hub. As can be seen from the diagram, the original design consists of three components which are bolted together to form the completed shaft. To ensure that the bolts did not loosen during service, thus potentially causing significant damage, an anaerobic adhesive was used to retain the bolts. At the end of the day a fairly elaborate item to manufacture, and therefore costly, as well as being heavy.

The manufacturer recognised that significant improvements over this original design could be achieved. In order to meet the required production cost savings, improve reliability and reduce weight, it was important that the bolts were eliminated. It had originally been intended that the gear ring be heat shrunk onto the shaft, but in testing it was found that the component was not able to transmit the required level of torque (nearly 35000 Nm). Increasing the initial interference fit would have resulted in increased hoop stresses in the ring gear, requiring an increase in its thickness, and hence an increase in unit costs, as well as weight. The capital cost of the electron welding equipment required to weld the components together was very high, and thus this option was discarded.

The solution adopted in the end merely consists of two items, the gear and a single hub shown in Figure 11. The two components are held together using an anaerobic adhesive, coupled with a slightly increased interference fit. This solution resulted in the desired reduced component count, thus resulting in cost savings estimated at around £1.10 for each unit, without requiring large capital expenditure on equipment, as well as a weight reduction of some 15% compared with the original design.

3.5 Headlamp Bonding.

The bonding of lenses for headlamp assembly was developed in the late 1960s as a successor to the sealed beam lamp unit. In the early two component bonded assemblies the glass lenses were adhesively bonded to the bright aluminised surface of the reflector unit, Figure 12. In addition to meeting the severe service conditions of the joint (temperature, salt spray and high g-forces), the bonding process had to satisfy demanding product manufacturing requirements of flexible automation and optical clarity of the lens and reflector.

For many years the adhesive used was a 1-component mineral-filled epoxy which was cured at 180°C for 15 minutes. The joint was formed in a tongue and groove configuration around the perimeter of the lamp: the adhesive was extruded into the groove at the edge of the reflector by means of a nozzle guided by a cam profile plate. The lens was then placed on to the extruded bead and the assembly transferred through the curing oven on a continuous conveyor.

Extensive testing during the early development programme included accelerated ageing, typically in a salt spray environment at 35°C. Most headlamps survive for the life of the car and many early bonded units still "on the road" exceed 20 years in service.
Headlamp design has continuously evolved to accommodate improved performance. During the 80s a polypropylene outer case was introduced to enclose the lamp reflector unit, making a three component assembly, as shown in Figure 13. The glass lens is now bonded to the polypropylene box instead of the reflector and this allows easier beam adjustment. Several different adhesives and bonding arrangements are used in current products, including polyurethanes and hot melts. No pre-treatments are applied to the glass or the polypropylene, and these adhesives exhibit good substrate tolerance and environmental durability. All finished units are pressure tested to check the integrity of the bond.

The general joint design and assembly process are similar to early bonded units, but most products now include additional spring clips for rapid handlability and supplementary support. In some more recent designs the polyurethane bead is pre-cured prior to assembly to form a foam gasket, and the spring clips provide the mechanical retention of the lens. This permits dismantlability in the event of lens breakage. Another recent development is the introduction of polycarbonate to replace the glass in the lens unit.

3.6 Speedboat.

Adhesives are increasingly being used in marine environments. The obvious cases are the lightweight GRP boats, dinghies and the like, even of course many of the modern mine hunters which are built with an extension of the same technology, where the hulls are bonded to the deck structures. The case study presented here is that of an aluminium-hulled speedboat, Figure 14.

Traditionally this sort of boat has been assembled using conventional welding technology. The use of adhesives within the main load bearing structure, however, results in a number of savings. To understand how these savings are achieved one must look at the construction of the hull.

In the majority of aluminium construction hulls, an aluminium framework is first built up, which will take much of the loading, Figure 15. The frame is then stiffened and rendered watertight by attaching a lightweight aluminium skin, normally using rivets rather than welding, because of the dissimilarity in thickness of the spaceframe sections and the skin material.

The first set of savings which can be achieved through the use of adhesives lie within the framework construction. In some modern constructions, the aluminum tubes are bonded into aluminum node castings using toughened epoxy systems, which allows the manufacturing tolerances of the various sub-components can be opened up, thus offering considerable savings in costs. As heat is no longer applied there is no longer a danger of melt through with thin sections, and section profiles can thus be reduced, making further savings in cost and also weight.

Further savings can then be achieved by bonding the skins to the space frame. Here two-part toughened acrylic systems have been used, because of their ductility, and ability to bond relatively unprepared metal surfaces. In this particular case the adhesive has been used in conjunction with intermittent riveting, which eliminates the need for additional jiggling during construction. The rivets also provide additional support to the joint and prevent peel stresses from building up in the adhesive, which can lead to premature failure of the joint. This combination of bonding and riveting significantly stiffens the whole structure, as well as sealing the join, without the need for
additional caulking. The net result is a boat which is cheaper to produce and whose performance is improved through reduced weight and increased stiffness.

3.7 Bridge Refurbishment.

Over the last decade there has been a rapid and to some extent unpredicted growth in the volume of traffic using the world's road networks. This, and in this country the EC directive regarding the use of 40-tonne articulated lorries, has resulted in a number of bridges requiring upgrading. In this country it is estimated that some 40,000 road bridges will need to be strengthened, replaced or subjected to restrictions by the year 1999.

Clearly the costs associated with replacing all of these bridges would be astronomical. Fortunately a technique has been developed which allows certain types of bridge to be upgraded, relatively simply. This technique, shown in Figure 16 and known as plate bonding or external reinforcement, makes use of steel plates bonded to the tension side of the existing reinforced concrete beams. The technique has been widely and successfully exploited in Europe, South Africa and Japan, since the late sixties. The first use in this country was on the M5 interchange at Quinton where the technique was used in 1975, and is still performing to specification. The latest project undertaken in the UK is the A23 Bolney flyover in East Sussex, where some 38 tonnes of steel was bonded to the underneath of the bridge deck.

The major advantages of this technique over other methods, is the fact that the reinforcement can be carried out whilst the structure is still in use. In addition the technique has relatively little effect on the headroom under the bridge.

In simple terms the technique involves grit blasted steel plates, generally around 300 mm wide and 6 mm thick, being bonded to the prepared surface of the concrete bridge, using a heavily filled cold curing epoxy adhesive. Typical bondline thicknesses are between 1 and 6 mm thick to allow for irregularities in the concrete surface. Once hardened the dynamic loads from the bridge structure are transmitted into the steel plates through the adhesive. In order to reduce the amount of support required during the assembly of the joint the steel plates are generally also bolted to the underlying concrete, whilst the adhesive cures. Not only does this provide an important second line of defence, but it acts to inhibit peel stresses, and transmits any tensile loads which might otherwise develop in the adhesive where the structure goes into reverse bending, at supports for example.

3.7 IBM Redwing Disk Drive.

IBM makes use of adhesives in the assembly of the core for its Redwing disk drives, shown in Figure 17. The disk head runs on a pair of ceramic guide shafts, which are bonded to a sintered iron core, Figure 18. These ceramic guides provide the wear resistance required to allow the disk drive to operate reliably over many thousands of cycles. By using adhesives, the assembly of the guides into the core with the required accuracy is considerably simplified, and the part count can be kept down.

The core is made from a nickel plated, resin impregnated sintered iron core. The location holes for the ceramic guides are produced to tight tolerances within the core. As delivered, the cores are
covered with a light protective oil film. The 8 mm diameter ceramic guide shafts, on which the disk head runs, are made of sintered zirconia ceramic.

Prior to bonding, both components are solvent degreased in 1.1.1-trichloroethane. A modified methacrylate adhesive is then applied to both surfaces, and the components brought together. The assembled core is held in a jig with a spring force of 100 N for 15 minutes at room temperature, to allow the adhesive to gain handling strength. Any excess adhesive is then cleaned from the core assembly using 1.1.1-trichloroethane before completing the adhesive cure cycle at 100°C for one hour.

On completion the assembled cores are visually checked to ensure that adhesive has not spread onto the running surfaces, key dimensions are checked, as well as non-destructively tested by applying a proof load of 2000 N, and samples are destructively tested, and failure loads compared with development test values. Once in service the conditions are relatively benign. The units are normally fully protected from damp conditions, and major temperature fluctuations, although the ambient temperature is generally marginally above typical room temperature. The main value of the use of adhesives in this situation is that it is significantly cleaner than alternative techniques, such as tapping for screws, where there is a risk that debris such as swarf would contaminate or damage the surface of the data storage disk.

3.8 Summary of Production Advantages

This set of case histories was selected to illustrate the beneficial effects that the correct use of adhesives can have on production costs. In many cases the cost reductions are immediately apparent, through reduced raw material costs, reduced production times and reduced skill levels of production workers. The use of adhesives can also result in a reduction in the part count, resulting in simpler assembly, and time consuming assembly procedures such as press fitting and machine stitching can often be eliminated. The cost benefits are not always immediately apparent, however. With careful consideration of the use of adhesives from an early stage in the design process, it is possible to reduce the volume of work in progress in the factory, allowing a greater production rate from a given production floor area and reduced stock levels. In realising the potential production benefits, the end product is also often enhanced through improved reliability or performance, and reduced weight.
<table>
<thead>
<tr>
<th>Application</th>
<th>Adhesive Type</th>
<th>Typical peel strength (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Topline folding</td>
<td>Hot melt - polyamide</td>
<td>-</td>
</tr>
<tr>
<td>2. Linings</td>
<td>Latex - natural rubber</td>
<td>0.2 - 0.5</td>
</tr>
<tr>
<td></td>
<td>Hot melt - polyamide, EVA</td>
<td></td>
</tr>
<tr>
<td>3. Toe puff</td>
<td>Hot melt coating - EVA</td>
<td>0.5 - 1.0</td>
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<tr>
<td>Heel stiffener</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Lasting</td>
<td>Hot melt - polyamide, polyester</td>
<td>0.5 - 1.0</td>
</tr>
<tr>
<td>5. Shank</td>
<td>Hot melt - EVA, polyamide</td>
<td>-</td>
</tr>
<tr>
<td>6. Sole attachment</td>
<td>Solvent based polyurethane, polychloroprene</td>
<td>3 - 7</td>
</tr>
<tr>
<td>7. Heel Covering</td>
<td>Solvent based latex - polychloroprene</td>
<td>0.5 - 1.0</td>
</tr>
<tr>
<td>8. Insock</td>
<td>Latex - natural rubber, acrylate</td>
<td>0.2 - 0.5</td>
</tr>
</tbody>
</table>

Figure 6. Use of Adhesives in Footwear.
Figure 7  Loudspeakers.
AUTOMOTIVE PRODUCTION APPLICATION

Ring Gear Locked To Differential Case

Bolt locked in ring gear with Loctite adhesive

Figure 10  Automotive Ring Gear Design.
Figure 12. Early Two Component Headlamp Assembly.

Figure 13. Recent Three Part Headlamp Assembly.
Figure 15  Speedboat Internal Spaceframe.
Figure 16  Bridge Plate Reinforcement.
Figure 17  IBM Redwing Disk Drive.

Figure 18  Disk Drive Core Assembly.
4. TECHNICAL APPLICATIONS

The final category of adhesive joints is where adhesives are used primarily for the technical benefits, for example reduced weight and improved performance. In many instances the use of adhesives offers the only practical solution, and the product would not be possible without their use.

4.1 Retortable Laminate.

Retortable laminates are used in the packaging of long life ready made foods. The laminates are designed for a shelf life of around two years as well as ultimately surviving being cooked at between 120 - 130°C for 30 to 45 minutes. In this case the packaging is not designed to be frozen. It has been found that if a simple polymer packaging is used, there can be a two way diffusion of molecules through the polymer. In order to prevent this a laminated construction is used. The laminate under consideration here is a three-layer laminate, consisting of an outer layer of reverse printed nylon or PET, 12 - 20 µm thick. This is bonded to a layer 9 - 12 µm thick of near-pure aluminium foil, which acts as a transmission barrier. Finally, and in contact with the food stuff, is a layer of polypropylene, or high density polyethylene with a minimum concentration of slip additives, approximately 70 µm thick.

As with all adhesive joints, correct surface preparation is of paramount importance to achieve a satisfactory bond. The outer and inner polymer faces of the laminate are prepared by corona discharge. This is done both at the initial manufacture of the polymer film, and topped up in the laminate production line, just prior to bonding. The near chemically pure aluminium foil is bonded directly with no surface preparation, as it has been found that the polyurethane adhesives are relatively tolerant of small amounts of contaminant, and thus in the interest of cheap, efficient production, the aluminium is bonded through any remaining process oil.

The adhesive generally used is a two part polyurethane, containing approximately 30% solids in a solvent base. Clearly as the laminate is to package food substances, the adhesive used must not present a health hazard. For this reason, the isocyanate used is normally either MDI or aliphatic. More recently there has been a move towards the replacement of solvent based adhesives with water borne adhesives.

A schematic diagram of a typical assembly line is shown in Figure 19. Typical production rates are around 200 m/min of film. On entering the plant, the polymer film is corona discharge treated, followed directly by the application of the adhesive. The adhesive is applied at a rate of approximately 3-5 g/m². The film is then passed through an oven at 70°C to drive off the solvent carrier from the adhesive. The aluminium layer is then brought in and the joint nipped closed between rollers. After the initial bond is formed the joint is left to cure for 24 hours at 50°C, after which the final layer of the laminate is added in a similar process to that described above. This is followed by a further five days cure time before the completed laminate is released to the food distributors.

Laboratory tests performed on the laminate joints have indicated that the peel strength of the outer joint is typically 10 N/25 mm with that of the inner joint typically >25 N/25 mm. Other tests have been performed subjecting the joints to saturation in water, alcohol, olive oil, tomato and curry solutions, these foodstuffs having been found to present an increasing severity of test environment.
These tests have shown little or no deterioration in the joint strength over time. Similar tests following a typical cooking cycle have shown joint strength reduction to be of the order 10%.

4.2 De Havilland Comet.

The aircraft industry has been at the forefront of the use of adhesives for many years. In many cases the bonds are used in light duty regions where aesthetics is the primary reason for the selection of adhesive bonding, eg trims around windows. In other locations the adhesive is used to form lightweight sandwich panels, where adhesive bond stresses are relatively low. The industry, however, has also been amongst the first to use adhesives in safety and functionally critical areas to form lightweight, fatigue-resistant structures.

The de Havilland Comet, shown in Figure 20, which first flew in July 1949 made very extensive use of adhesives in its construction, and is a living proof of the longevity of adhesive joints. Many aircraft are still flying in the form of the Nimrod reconnaissance plane. Adhesives were used throughout the aircraft to bond profiled aluminium alloy stiffeners to the aluminium alloy skins, both in the wings and in the fuselage, Figure 21.

The Comet was one of several aircraft developed during the early post-war years which exploited the Redux bonding process. Redux 775 exists in several forms as a bonding system, but essentially consists of a phenol formaldehyde resin and polyvinyl formal (formvar) toughening agent. In the Comet application the Redux materials were used in a liquid / powder form. In this technique the resin is applied to the surface to be bonded and the coarse powder is then sprinkled onto the wet resin surface. Surplus powder is shaken off and in some process specifications a second liquid resin layer is applied to cover the powder. The two surfaces are then brought together under heat and pressure. The curing process is a condensation reaction and high pressures are needed to prevent the formation of steam from the reaction moisture. In the early years of Redux bonding the complete assembly was carried out in a heated platten press. The manufacturers' literature specifies a glue line temperature of 150 °C for 30 minutes at a pressure of at least 0.7 N/mm² (7 bar). It is reported that De Havilland used curing conditions of 145 °C for 20 minutes at 2.8 - 5.0 N/mm² (28 - 50 bar).

The importance of surface treatment of aluminium was well appreciated during the early Redux development period. Initially a chromic/sulphuric acid etch, used for paint pre-treatment, was found to be effective; chromic acid anodizing after etching was introduced by De Havilland to increase resistance against long term ageing and was used on the Comet. On thicker sections the aluminium surfaces were grit-blasted with 120-220 alumina grit at 5.6 bar before etching and anodizing. In order to prevent a build up of peel stresses within the joint, and to hold the components together during curing, the adhesive joints were backed up by rivets, although a considerably reduced number compared to a purely riveted structure.

The total process bonding specification was the result of extensive development and testing, and the quality assurance was based on visual checks and mechanical tests on witness samples. Visual inspection consisted of checking the amount and colour of spew which, in correctly cured Comet materials, was a magenta / purple colour.

There have been some reports of corrosion problems in the belly areas which are attributed to spillage of aggressive liquids in the passenger compartment being trapped in the top-hat stringers,
however, in general, Redux 775 has proven to be one of the most durable adhesive bonding systems and is still used in essentially the same formulation today.

The recent forensic analysis of bonded airframe stringers from a 30 year old Comet shows that the Redux 775 has retained its original strength properties and the adhesive exhibits little evidence of degradation.

4.3 Fokker Fellowship - F28

A second example from the aircraft industry is that of a series of lap joints in the pressurised fuselage of the Fokker F28 civilian aircraft, amounting to some 90 running meters in length, Figure 22. Clearly this structure is subjected to repeated cyclic loading as the fuselage is pressurised and depressurised for every flight, as well as take off and landing shocks and in flight and taxiing vibrations.

To ensure the maximum safety, preparation of all components to be joined is extremely thorough. All items to be bonded are chromic acid/ sulphuric acid pickled and subsequently chromic acid anodized. Within two hours of rinsing, a phenolic primer is applied, to a thickness of 2-5 µm. In order to protect the faces to be bonded during subsequent assembly operations, a strip of clean aluminium foil is applied to the bond area. The primer is cured in an autoclave at 155°C, which also bonds the protective foil to the skin. Directly before the application of the adhesive, the aluminium foil is removed. The adhesive used is a two part, room temperature curing epoxy resin. The components are brought together, and pressure applied to the joint using either spring loaded clamping devices or magnets, resulting in a void free bond line, approximately 0.2 mm thick. After 24 hours the clamping devices are removed and backup rivets added along the bond line.

The approach used to determine the suitability of the selected adhesive for long term service was to subject single lap shear specimens to condensing humidity at 70°C for 30 days. Typical strength retention of between 75 and 95% gave confidence of a twenty year service life. This testing procedure is the accepted industry standard, European Norm EN 2243-5.

Over 200 Fokker F28 aircraft have been sold to customers in 36 countries over the last 25 years. Each aircraft contains over 900 adhesive bonded assemblies. Of these the earliest craft have completed over 65,000 flights, amounting to some 40,000 flying hours. During this time there have been no reported problems associated with the adhesive bonds. Recently the fuselage lap joints were non-destructively inspected during routine maintenance, and no sign of delamination of the joints could be found.

4.4 Stainless Steel Plumbing.

Many hundreds of metres of austenitic stainless steel water tubing are used each year for carrying hot and cold water, and occasionally gases, in both domestic and commercial installations. Stainless steel is frequently chosen in preference to traditional materials because of its attractive and hygienic appearance, its easy cleaning and its high corrosion resistance. The most common methods of joining have involved the use of conventional fittings or capillary fittings with soft solder and a phosphoric acid based flux. However, these fittings are made of copper, or copper
alloys, and for aesthetic and corrosion reasons a wholly stainless system is desirable. Stainless steel compression fittings are more bulky and expensive than stainless steel capillary fittings, which are readily available at a reasonable price. Unfortunately, stainless steel is very difficult to soft solder to itself by reason of its very protective oxide film, which makes fluxing difficult, and also its low thermal conductivity. The elegant answer is adhesive bonding and this has been developed by British Steel in conjunction with Lancashire Fittings Limited and examples have now been in service for many years.

Lancashire Fittings have been using an acrylic anaerobic adhesive to bond their stainless steel fittings for the past 24 years. These fittings have to withstand mains water pressure and stresses due to freezing. In addition, in certain circumstances they must withstand temperatures of up to 80°C for long periods in hot water supply and heating applications. They must also have sufficient strength to withstand stresses imposed during installation and minor knocks in service.

To ensure a good joint, the stainless steel surfaces are degreased and then abraded, both operations that can be carried out on a building site. The adhesive is cured at room temperature using an activator so that handling strength is achieved in around 60 seconds.

Long term tests simulating a domestic central heating system have shown that adhesives based on polyethylene and methacrylic acid were found to be satisfactory. Lancashire Fittings have been operating a system with water at 80°C for over 10 years without any leakage. Tensile tests of these joints, carried out by the manufacturers, have shown that they are stronger than both compression fittings and soldered copper joints, and can accommodate a reasonable degree of flexing without leakage and the burst strength is exceedingly good.

4.5 Honeycomb Sandwich Panels.

Although the stress levels in joints between rigid adherends are not uniform and care has to be taken in their design to avoid localised failure, where the adherends are flexible, or where there are many small joints adhesives are able to distribute loads more uniformly throughout the joint than many alternative joining technologies. This uniformity has been exploited in the next application of adhesives to be considered here, that of sandwich structures, such as honeycomb sandwich panels shown in Figure 23.

Without the advent of adhesives these high stiffness, lightweight structures would not have become viable, as adhesives are the only convenient way of bonding the lightweight core material, typically foam or honeycomb, to the stiffer high strength outer skins. The design of the sandwich panel can be tailored to the requirements of the particular application by varying the materials of the skins and cores to provide particular desired properties. With many such panels it is common practice to incorporate blocks to facilitate the fixing of additional fastenings, for example catches for access panels. The blocks are bonded into the construction as the assembly proceeds, thus they become an integral part of the finished panel. These laminated sandwich panel structures are now widely used in the aerospace, marine and construction sectors; Figure 24 shows the extent to which these sandwich panels are used in the construction of civil aircraft, in this case the Fokker Friendship.

A particularly harsh environment for the use of these honeycomb structures is in jet engine cowl doors, in this case from the Rolls Royce RB 211-524 engine, developed in the late seventies. The lightweight cowl doors for this engine are formed from carbon fibre reinforced epoxy composite
skins, bonded to aluminium alloy honeycomb. These replacement doors achieve a 25% weight reduction compared with a conventional aluminium design. An important aspect of the specification of the doors was that they were to be fireproof to prevent penetration by flames onto the engine mounting pylon. This led to the specification of the aluminium honeycomb core material, in preference to alternative non-metallic materials. As a result, the specification of the bonding processes was particularly important in order to reduce the possibility for galvanic corrosion between the skins and the core. Various corrosion protection features were incorporated into the design. The exposed surfaces of the aluminium honeycomb were conversion coated, and primed with an epoxy primer, BSL 122. In addition the adhesive used was a supported film type adhesive, with a nylon fabric carrier, thus preventing direct electrical contact between the aluminium and the carbon fibre. Normal practice when bonding composite materials is to vacuum-blast all surfaces to be bonded, a maximum of eight hours before bonding. It was shown, however, that the use of a nylon peel-ply material in the composite manufacture eliminated the need for blasting, thus reducing the manufacturing costs.

As a part of the development programme, a number of durability tests were carried out, and the effects of 1000 hours exposure to engine oil, fuel, hydraulic fluid, salt spray and humidity were assessed. In addition thermal cycling tests were performed, between -55 and +110°C. Results from these tests indicated that the joints would retain satisfactory strength under service conditions. Further doors were flight tested for 5795 flying hours, over 2663 flight cycles, before being assessed for degradation. Although in places, the door skin had been damaged, thus allowing ingress of water and oil into contact with the adhesive bonding, there was no indication of debonding or reduction in strength of the bonds. Following this work the cowl doors went into service with the Lockheed 500 Tristar, and derivatives of the doors are still in service.

4.6 GRP Process Plant Piping.

The use of glass fibre reinforced composite piping has been gaining favour in a number of industries, Figure 25. These systems offer benefits in the form of reduced weight, improved corrosion resistance and longevity, as well as reduced costs. Unlike conventional metallic pipework, it is not possible to weld the composite pipe. Conventional compression, or gasketed flange connections are less desirable in view of the increased potential for leakage. As a result the preferred method for joining composite pipes is by adhesive bonding.

Most systems available make use of bell and spigot type joints. Pipes and fittings are formed with bell ends into which is inserted a mating tapered section of pipe. The spigot end is either formed in the factory or prepared on site using a mechanical shaving device. The surfaces of both the spigot and the bell end are then abraded to expose the fibre reinforcement using a flapper sander. Surfaces are wiped clean with a dry cloth, prior to mixing and applying the adhesive. The pipes are brought together and pulled tight using winch pullers if necessary.

Curing of the adhesive is typically accelerated by the use of heating blankets, which are wrapped around the pipe, and covered with insulation. The cure cycle required depends on the size and rating of the pipes used, however a typical cure cycle would be a minimum of 1 hour at 90°C.

GRP piping has been in service in the form of fire water mains piping on boats and offshore installations for several years. In general there have been few problems associated with the
longevity of the adhesive bonding. Most problems are identified during the initial pressure testing, and can be traced back to haphazard preparation of the joint prior to bonding.

4.7 Peugeot 205 Rally Car.

Considerable demands are placed on the drive shafts of motor vehicles, particularly those used for rallying purposes. Since the early eighties, several of the bigger rally teams have been using carbon composite drive shafts because of their increased stiffness and reduced weight. The example used here is that of the Peugeot 205 rally car, which won the world rally in 1985,6 and 7, Figure 26.

These shafts typically have metallic end fittings bonded into the shaft using a toughened adhesive system to transfer the engine power, shown in Figure 27. This is probably one of the most demanding applications for which adhesives have been used, as in order to keep weight to an absolute minimum, there is no subsidiary mechanical support whatsoever, and the full engine torque is transmitted through the adhesive.

For connections of this sort, very careful consideration is given to the design of the adhesive joint. In most instances finite element analysis is performed to optimise the joint design, and most will incorporate techniques to optimise the joint strength, such as careful profiling of the steel sections so as to match stiffnesses, and localised thickening at the ends of the joint to reduce peak stresses. Clearly in these applications, where only limited numbers of the components are being made, the additional costs involved in meeting tight tolerances on fits and careful profiling of the adherends are less significant than in a mass production environment. Again in view of the limited numbers of these composite drive shafts being made, greater care is generally taken over the assembly of the joint, with all possible steps being taken to ensure that the bond performs at its best.

The technology involved in the production of composite drive shafts has, however begun to find a place within the more conventional market place. A somewhat simpler system is now in use on the Renault Espace, Figure 28. In this case the composite shaft incorporates a mechanical interlocking feature to back up the adhesive, but nonetheless it is still a very demanding application, less in the way of vibration and peak loading, but issues of longevity and reliability come to the fore.

4.8 LAW 80 Rocket Launcher.

The LAW 80, lightweight anti-tank weapon was designed to be carried easily by one person into battle, be simple and quick to operate, and to be discarded after the missile has been fired, Figure 29. Weighing only 9 kg in total, the weapon is light and compact enough to be carried over the shoulder. The basic design of the weapon was for two concentric tubes which can slide apart. The tubes are compressed together to a length of 0.9 m for storage and transportation. The launcher can be quickly extended to its full length of 1.5 m for firing.

The main criteria for material selection were weight and cost. The tubes were constructed from kevlar fibre reinforced epoxy resin, using a filament winding process. The tubes were also coated with polyurethane paint which was co-cured with the matrix resin. At early stages of design it was apparent that a variety of fittings, such as tube end rings, sight, tracer housing, housing ring, harness clips, shoulder rest, trigger mechanism and handle would have to be attached to the tubes. It was decided at the outset that these attachments would be bonded, because drilled holes for
mechanical fastenings would be detrimental to the strength of the tube. The majority of the fittings were manufactured from appropriate grades of nylon. For example the end rings were constructed of impact modified nylon - 6,6, whilst the sight and its cover were made from nylon - 11.

The use of adhesive bonding instead of mechanical fastenings resulted in both weight and cost savings. Adhesive bonding was also believed to be more consistent. Overwinding of external components was also considered, but the location tolerances could not be met by the process, and there would have been a weight penalty due to the increased layers of filaments.

Extensive laboratory tests were conducted to select appropriate adhesives and surface pre-treatments. A two-part acrylic adhesive was chosen because it was tough and flexible, and could allow for expansion and movement under load, which was vital to withstand the pressure pulse generated by the launch. The adhesive also had a rapid cure time, and could be dispensed robotically. Durability studies of the adhesive bonds were also undertaken to ensure that the joints could withstand storage in a wide range of operating conditions.

4.9 Glued Laminated Timber - Glulam.

Glued-laminated timber, glulam, is a well established structural material and some significant roof arch and bridge members survive to this day which have been in service for nearly 100 years. Glulam consists of parallel laminations of wood bonded together to produce members that act as single structural units, Figure 30. Glulam has at least two principal advantages over non-composite, or solid timber. Firstly, member cross sections and lengths are not dependent on the sawn log size. The size of completed units is governed only by considerations such as industrial workshop size and jig layout, transport and handling facilities, and by design considerations. In addition, since the speed at which timber is dried is dependent on thickness, and individual laminations are generally between 12 and 45 mm thick, the required optimum 12% moisture content is more rapidly achieved than with solid members. Secondly, greater consistency in strength and stiffness over solid timber is achieved by the use of graded laminates and the omission of natural strength reducing features, thus enabling higher design stresses to be used than in an equivalent solid member. Glulam represents a lightweight form of construction and spans up to 70 m for both bridges and buildings are quite feasible. It possesses excellent resistance to corrosive environments and glulam structures are often favoured for chemical storage, swimming pool enclosures and similar structures. In common with solid timber, it also exhibits excellent fire resistance.

Structural glulam is usually laid up with the laminations parallel to the horizontal axis, with their grain essentially parallel. Following drying and checks on moisture content, laminations are invariably planed to thickness before fabrication, no more than 48 hours before bonding; with hardwoods, it is considered to be important to both plane and bond within the same shift. Straight members may utilise laminations up to 45 mm thick, whilst curved work entails thinner laminates for ease of bending. End jointing to obtain full length laminations is usually obtained by using finger joints.

The urea formaldehyde (UF), resorcinol formaldehyde (RF) and phenol formaldehyde (PF) adhesives recommended by BS 4169 for glulam are designated by their environmental resistance in BS 1204. Performance types designated WPB, weather and boil proof, are available among certain of the phenol formaldehyde or phenol- resorcinol formaldehyde types and these adhesives are now
widely used and recommended for glulam structures in both interior and exterior environments. Structurally the adhesive must have a strength sufficient to provide a joint at least as strong as that of the timber in shear parallel to the grain; this implies a shear strength of around 1 MPa for most softwoods.

Adhesive spreading and assembly clamping must be accurately and rapidly carried out, as the adhesives used possess limited pot-life and assembly times. To achieve a consistent application, laminates are generally coated with rollers and jigs are then used to assemble the laminations. They are clamped under pressure to achieve a thin bondline and maintained at a steady temperature until the adhesive is fully cured. Finishing operations, such as planing, trimming and additional carpentry may then take place, followed by the application of preservatives or water repellents.

4.10 Car Body Bonding.

The early use of adhesives in car body construction evolved from the use of sealants in spot-welded seams and lap joints. The substitution of oil-based mastics with reactive resins such as PVC plastisols and nitrile phenolics provided supplementary stiffening to panels and assemblies, resulting in improved vehicle characteristics. Developments of adhesives and sealants for body applications have continued to enable the opportunities for enhanced structural performance to be exploited and at the same time to reduce the number of spot-welds in body construction.

While many manufacturers observe that the primary functions of these newer adhesives are still to seal and prevent corrosion, they are being used increasingly in applications where structural strength is required and durability is important. In typical bonded details, design features such as compression joints and clinched flanges/hems are commonly employed to avoid the risk of failure.

The application of the adhesive bonding process in body assembly is constrained by the total manufacturing operation. As it is not possible to pre-clean bonded joint surfaces, the adhesives used must be tolerant to a wide range of oily surface contaminants. It is also desirable that they should have a cure profile which matches the subsequent paint-stoving cycle.

A number of different generic adhesive/sealant materials have been developed to meet these requirements. They are formulated to satisfy individual manufacturers specifications which include strength properties, rheological characteristics and durability performance. Epoxide based adhesives are occasionally specified where high strength requirements dominate, and current developments are concerned with the provision of high toughness and durability.

An early application of epoxide adhesives in structural joints was developed in the late 70's for the attachment of roofs on the Triumph Acclaim and subsequently the Austin Maestro. In this assembly a bead of thixotropic one-component epoxide adhesive is deposited into a groove in the cantrail section, shown in Figure 31. When the roof is placed into position the adhesive in effect forms a lap joint with the flanged edge of the panel, shown diagrammatically in Figure 32. The adhesive is cured during the paint stoving process, and this heating cycle also enables the adhesive to penetrate and absorb the oily contaminants. The development work leading to this process demonstrated the effective tolerance of the adhesive to the surface residues, and extensive accelerated ageing tests (including salt spray and high temperature wet exposure) were used to establish durability performance. Many 15 year old Triumph Acclaims are still on the road. The joint concept has subsequently been applied in Maestro construction, and the use of structural
Epoxy bonding is gradually being adopted in other areas of vehicle assembly. Applications where the structural requirements are less demanding include attachments of stiffeners to panels to provide enhanced anti-flutter properties. The evolution of materials and techniques for this type of assembly has led to the use of a semi-structural elastosol based on polybutadiene in the construction of body side panels for vans.

4.11 Summary of Technological Advantages.

In a number of situations, the use of adhesives offers the best technological solution to a particular joining design problem. The use of adhesives allows loads to be transmitted between members more uniformly than many alternative techniques, thus making their use ideal in composite material constructions. The absence of perforations in the adherends eliminates the stress raisers that are associated with many forms of mechanical joining techniques. This also leaves the outer face of the component smooth, with resultant improvements in aero or hydro dynamic coefficients of friction, and hence improved product performance.

The second area where adhesives offer technological advantages is in their corrosion resistance. As the majority of adhesives are formed from polymers, their electrical resistance is relatively high, thus reducing the likelihood of galvanic corrosion occurring between dissimilar materials.
Figure 19  Retortable Laminate Production.
Figure 20   De Haviland Comet Aircraft.
Figure 21  Use of Adhesives in the Comet.
Figure 22  Structural Breakdown of the Fokker F28.
Figure 25  GRP Process Piping.
Figure 26  Peugeot 205 Rally Car.
Figure 29  LAW 80 Rocket Launcher.
Figure 30  Glulam Swimming Pool Enclosure Structure
Figure 32    Automotive Roof Cantrail Assembly.
5. CONCLUSION

It is hoped that this series of case histories has conveyed the incredibly wide range of applications in which adhesive bonding has been used. In almost all of the cases highlighted the use of adhesives has resulted in significant savings. In many instances the use of adhesives has reduced the production time for the particular component, through simplification of the processes, and a reduction in the number of fittings used. In other cases the primary savings have been a reduction in weight of the finished component. In all cases the use of adhesives has resulted in cost savings, or increased product performance. Indeed the cost savings attributable to the conversion to adhesives from traditional jointing techniques is key to their specification. The cost savings, as has been highlighted by some of the case studies, are not purely a matter of the comparison of direct materials costs; the full production and service life of the component must be considered. More efficient use of factory space, reduced capital expenditure, reduced labour and maintenance costs as well as in service cost savings all enhance the marketability of products, and can be achieved through the judicious use of adhesives.

Many of the cases have illustrated that, even with a minimum of surface preparation, very reliable joints can be formed, when the loads in the joint are sufficiently low. By making use of some of the better surface preparation techniques, stronger and longer lasting joints can be formed, which allow the use of the adhesives to considerably greater proportions of their ultimate strength.

Adhesives are no longer new, uncharted territory. They have now been in use for some fifty years. Many of the examples cited in this review have been in regular service for 10 - 15 years, with some as long as 30 years. In this time, as long as adequate consideration was taken of the service duty and life expectancy of the adhesive joint during the design phase, there is little evidence of critical degradation of the joint performance. Clearly there are a number of examples of applications where premature failure of adhesive joints has occurred. In the main, however, these failures can be attributed to procedures being incorrectly followed during production, or insufficient account being taken of the service duty during the design process.
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