Institute of Materials

Adhesives Section

ADHESIVES IN TRANSPORT

One-day Symposium, 2 December, 1997

Society of Chemical Industries, Belgrave Square

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YOUNG J	VOSPER THORNACROFT
YU H	BRISTOL UNIV.
ZGOUL M	UNIVERSITY OF SURREY

Programme

1030	Registration and Coffee	
1055	Welcome	
1100-1125	***"Structural Adhesive Bonding in Civil Aircraft"*** A Higgins, AVRO	
1125-1150	***"Adhesives and Sealants: recent developments and their future implications for the transport industries"*** Dr W.A. Lees, Technical Director, Permabond	
1150-1215	***"Meeting EPA Regulations with Water-Borne Bonding Agents"*** R Woodcock, Metalastik Vibration Control Systems, Dunlop Ltd.	
1215	Lunch	
1355-1420	***"Adhesive Bonding in Marine Transport"*** Prof. M Cowling, Glasgow Marine Technology Centre, University of Glasgow	
1420-1445	***"Composite-to-Metal Joining for Transport Applications"*** RJ Lee, AEA Technology	
1445-1510	***"Modelling of Adhesive Joints for Automotive Body Structures"*** Prof A. Beevers Oxford Brookes University	
1510-1530	Tea	
1535-1600	***"Adhesive Bonding in Formula One"*** B. O'Rourke Williams Grand Prix Engineering	
1600-1625	***"Adhesives in the Rail Industry"*** D. Tooley, Bombardier Pro-rail	
1630	Close	

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STRUCTURAL ADHESIVE BONDING OF AIRCRAFT

by A.Higgins C.Eng.,B.Sc.,M.I.M

British Aerospace Regional Aircraft
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SUMMARY OF PAPER FOR IOM SYMPOSIUM "ADHESIVES IN TRANSPORT"

Adhesive materials used for metal structural bonding of aircraft fall into three distinct groups:-

a) Metal to metal - Hot cure
b) Metal to metal honeycomb - Hot cure
c) Metal to metal - Cold cure

The information given in this paper relates to the major aluminium alloys used in aircraft construction (2014A, 7075 and 7150). Other aluminium alloys and other metals could give rise to different properties although given the correct preparation most metals can be adhesively bonded to the same degree of bond strength. Adhesive bonding is used mainly for attaching stringers to fuselage and wing skin panels to stiffen the structure against buckling. It is also widely used for attaching skins and side members to metallic honeycomb core in the construction of ailerons, elevators and other flight control structures.

The main adhesives used by the aircraft industry are based on either epoxy or phenolic resins conforming to DTD 5577, MIL-A-24463 and MMM-A-132 specifications and to material specifications of the user OEM's. The materials in current use are described in the paper with regard to their constitution, characteristics, physical properties within the designed service operating temperatures, resistance to aircraft fluids and durability. Testing methods used to assess bond strength and durability will also be described. Properties of the various adhesives in use are compared and significant differences between them will be discussed.

The preparation of aluminium alloy surfaces for adhesive bonding will be detailed and the importance of correct processing and the effect on durability will be stressed.

The successful long term use of adhesive systems on aircraft structure at BAe, Saab-Scania, Fokker and other OEM's will be described as well as some of the problems encountered.

Qualification procedures for assessing new adhesive systems will be detailed and current work will be described.

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Adhesives & Sealants: Recent developments and their implications for the transport industries

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Background: Over the last few decades the use of structural, load-bearing adhesives - for both product assembly and sealing - has progressively accelerated to such a point that it is hard now to envisage how the engineering industries used to operate without them. It could be argued that the primary reason for this was, and is, that there has been no other practicable means available of meeting the engineers' increasing demands. In turn these have been driven by the need to provide lighter and more effective products more quickly and with greater economy than ever before. As a consequence, the use of traditional steel based assembly techniques has declined with the increasing employment of light alloys and plastics and with them the concurrent need to combine disparate materials. In effect, the science of materials is progressively beginning to affect every branch of engineering; without it the more demanding adhesive applications would be very difficult to satisfy successfully.

Such applications range in size from the minute to the immense. It is not just mechanically induced loads in the latter that need be borne but also the considerable stresses caused by say the thermal mismatch of electronic components fabricated from metal, ceramic and plastics that cannot be joined, or encapsulated, in any way other than by adhesives.

A few examples: Starting at one extreme there is the retention of the final twist of an electrical coil whose wire is so thin that it is barely visible. A trace of an acrylic based, UV cured adhesive secures the stability of the coil in a trice. This stability must be retained as the component endures the thermal cycling and shocks of its function. Similarly, the epoxy adhesives used to secure computer chip heat sinks must also be able to withstand the considerable stresses induced by the mismatch of the expansion ratios of the differing components. Correspondingly, potting materials and encapsulants must be able to minimize relative movement between thermally mis-matched components in order to prevent their being damaged during use - brake sensors are a case in point. Toughened epoxides, with carefully matched moduli, are used to bond carbon fiber reinforced plastic drive shafts to their respective steel end fittings. This latter is a particularly interesting application because it has been repeatedly shown that such bonded assemblies are much less prone to fatigue failure than riveted shafts and are capable of transmitting much greater loads in practice. This type of shaft is currently being used to drive cars, power station cooling fans, hover craft and deep, long shaft pumps. But, perhaps the most striking example of all is the use of both acrylic and epoxy adhesives to repair the cracked aluminum superstructures of both ocean liners and warships. The performance of these toughened adhesives has been followed over the years and has been the subject of detailed laboratory investigation and mathematical analysis. This background work has shown that bonding can outperform welding and is an excellent technique for joining dissimilar materials - especially metals to plastics.

Between them the various branches of engineering are forcing adhesive development down several clearly discernible routes. Increased emphasis is being place upon:-

- Faster reaction rates
- The formulation of multi-reaction-mode products (MRM)
- Rheological control
- Modulus matching
- Increased fracture toughness
- Surface interaction -

all while the adhesive formulators must cope with ever demanding legislative requirements.

Reaction rates and MRM products: For over three decades a fast reaction rate has axiomatically implied the use of a cyanoacrylate adhesive - especially of the methyl type since this version is probably the fastest of them all. Unfortunately, while recent work has boosted their performance - enhanced purity has enhanced consistency - there is still little justification for considering them to be true structural adhesives. Their fundamental characteristics really only lend themselves to the assembly of nominally loaded small parts. Immense efforts have been made to increase their shock and environmental resistance; but, little progress can be seen to have been made when judged against the performance of the toughened acrylic or toughened epoxy adhesives. Consequently, the focus has switched to the latter types whose reaction rates have increased dramatically as a result.

Materials have now been developed whose rate of cure effectively rivals that of the cyanoacrylates yet which also posses a significant level of toughness coupled with excellent adhesion.

As an example, the last decade has seen the introduction, withdrawal and replacement of the first wave of UV cured adhesives by the latest generation. These can be toughened, loaded bearing, resistant to both mechanical and thermal shock while being free of the more severe physiological restraints of their predecessors. Novel 'blue' light catalysts have been developed which enable the formulator to maintain speed and benefit from a greater depth of cure while avoiding the radiation hazards of the UV wavelength. This is particularly important for sealing and encapsulating work as well as glass bonding.

Unfortunately, only a number of materials are transparent to either, or both, UV and 'blue'. As a consequence, there is now considerable interest in creating adhesives where polymerisation is still possible once the relevant radiation can no longer gain access or is simply 'switched off'. The sophistry implied by this is both considerable and real.

Adhesives are now on the market that continue to polymerise because they <u>have</u> been irradiated or, and perhaps more importantly in terms of ultimate development potential, because alternative curing processes have swung, or have been swung, into action. Thus, for example, components may have been fixed in place by the irradiation of an exposed adhesive fillet though the ultimate strength depends upon the sequential polymerisation of adhesive within the joint by either, or both, anaerobic or heat induced mechanisms.

Away from the limitations of irradiation techniques, novel cold cure catalysts can now support adhesives whose cure rates are phenomenal. Admittedly the adhesives are two part systems but 'bead-on-bead', or 'side-by-side' applications techniques are readily automated and, as a result, strong, environmentally stable joints can be formed in seconds. As a consequence, these adhesives are used in motor sub-components that must tolerate severe mechanical and thermal loads.

In acrylic systems reaction rate control has now reached such a level that is possible to get rapid polymerisation following joint closure without prejudicing the 'open' time required to actually put the components together. This is extremely convenient when parts are large or the assembly is complex. In effect, polymerisation is inhibited before joint closure - giving the time to assemble after adhesive mixing and application - and accelerated afterwards. This delayed action cure (DAC) is extremely effective and presents a fine example of MRM.

Although epoxy technology has not developed to quite the same degree effective reaction rates have improved of late. It's necessary to say 'effective' because it always was possible to cure epoxy resins rapidly. The issue is to affect rapid cure without degrading the toughness and shock resistance of the joint. Thus, it is now possible to complete thermal polymerisation in some fifteen to thirty seconds without inducing brittleness in the cured resins. Additionally, better equipment and handling techniques are enabling engineers to reach assembly and bonding rates of hundreds of piece parts per minute.

Rheology: Both large and small applications have always required a degree of viscosity control. However, increasing application rates, multiple application heads coupled with ever increasing reaction rates and component handling speeds means that the degree of control required is becoming ever higher. Simple concepts of viscosity are no longer enough - an in-depth knowledge of rheology is necessary. From the minute scale of electronic component assembly to the extreme of rail and truck construction the reproducible ability to accurately place adhesive swiftly, readily - without stringing - and have it flow when it should and stop when it shouldn't is becoming a commonplace requirement; not a 'wish' list. All manufacturers can be expected to devote much more effort to this particular area in future.

Modulus matching and fracture toughness: It is only in recent years that the importance of using an adhesive of an appropriate modulus has been recognised as making a significant contribution to the success, or otherwise, of the bonded assembly of highly stressed components. For the vast majority of the bonded components assembled to date careful analytical design has not been necessary - the empirical and well tried 'rules of thumb' have proved sufficient. However, with the automobile industry increasingly studying the use of load bearing adhesives, that are required to survive a crash at least as well as a weld, it is becoming ever more obvious that empiricism is no longer enough. And, herein lies a challenge. How to modify the modulus of an adhesive system so that not only are all the reaction and application (rheology) parameters met but so too are the other requirements. These are toughness, environmental performance, fatigue and creep resistance, a tolerance to welding together with an ability to bond 'as received' surfaces and yet demonstrate the maximum stress and strain capacity possible?

Surface interaction: Surface preparation can be expensive and is usually engaged in as a minimalist process. This is, of course, completely understandable especially when set in the context of recent environmental legislation. As a result adhesive manufacturers are producing products that will go at least part way to reducing the requirements for effective surface preparation. One could argue that they have been reasonable successful; especially so with some of the newer PU's which can cope readily with mould release agents. But, it would be very foolish to encourage the bonding of class one, safety critical components with the science at its present state of development. Because of this, parallel work is being undertaken in studies dedicated to the creation of simple, environmentally acceptable means of preparing surfaces at acceptable cost. New CEN standards are a reflection of this trend.

The impact of legislation: Government activity is driving both the development of safer adhesives and the creation of adhesives which enable safer parts and components to be designed. An excellent example of the latter is the requirement to construct rail vehicles which are not so susceptible to fire damage nor as likely to release toxic fumes and smoke in the event that there is a fire. Fire resisting, non-fuming adhesives are a must for the plastic based structures which need to be used.

Clearly, while environmental legislation is to be encouraged it needs be realised that is does reduce the formulating options for the adhesive manufacturer. And furthermore, new chemicals can no longer be offered without clearance. As this is very expensive only obvious 'winners' are becoming subject to study and thus ultimately gain a level of acceptance.

The Partnership concept: While the importance of recent technical developments must be recognised it is the concept of a 'Partnership' between the adhesive manufacturer and the user which is arguably the better measure of progress. Why? Because it is the closeness of the resulting teamwork that provides a better understanding of the application requirements which, in turn, drives the development needed. This, in a nutshell, is one of the primary objectives of the ISO quality system and in particular ISO 9001. To be understood the designers' needs must be clearly stated but their satisfaction results from the partnership which is developed between the client engineer, the adhesive formulator and the other suppliers involved. This supports either new processes, that significantly reduce unit costs, or the development of new designs which, for example, offer the automobile industry significant innovative advantages. These benefits simply could not be achieved were it not for the flexibility and consistency of current adhesive technology and the approach that responsible manufacturers take.

MEETING EPA REGULATIONS WITH

WATER BASED BONDING AGENTS (WBA'S)

ABSTRACT

All major manufacturers of bonding agents are now producing waterborne materials but new techniques must be developed by the end user if the traditional solvent based bonding agents are to be replaced. In the long term solvent elimination has advantages over incineration or arrestment systems.

Whilst WBA's are now being used in production quantities it is essential that manufacturers and end users work closely together to ensure the advantages are maximised.

This paper describes the key properties of three materials and the application techniques.

R. WOODCOCK

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ADHESIVE BONDING IN MARINE TRANSPORT

Professor M.J. Cowling,
Glasgow Marine Technology Centre, University of Glasgow

The presentation will include an overview of current practice with adhesive bonding in various forms of marine transport. Details of specific applications will be given, together with a range of future potential applications. The technical barriers to wider adoption of adhesive bonding in marine structures will be discussed.

Composite to Metal Joining for Transport Applications

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INTRODUCTION

Joining metallic materials with adhesives can result in reduced energy consumption when compared with more traditional welding techniques and also permits designers more scope to mix lightweight composite materials with more conventional metals in transport applications.

The use of lightweight composite materials in highly stressed transport applications is increasing. Adhesive bonding is particularly important as it is an effective means of joining. The introduction of improved adhesives, which are more tolerant to a production environment and having superior properties to earlier untoughened systems, may ensure that low cost assembly is possible. The current approach adopted covers :

Mathematical modelling to enable design engineers to predict overall stiffness of bonded structures.

Materials testing to produce design data for the models developed and investigate creep behaviour.

Component testing to focus the modelling work on application to realistic joint geometries.

MATHEMATICAL MODELLING

Stiffness prediction

The main objective of this work was to develop a software package capable of creating the stiffness matrix for a three dimensional finite element to represent an adhesive joint. The finite element technique is now widely used throughout the aerospace and automotive sectors for the analysis of deflections, stress/ strain, dynamic and thermal responses of structures. In order to accurately predict a structure's static deflection or dynamic response, attention must be paid to correctly modelling the joints between the component parts. Adhesive bonding can present a problem because the bondline is generally very small in comparison with the thickness and size of the adherend materials. Correct modelling of the bond therefore requires a large number of smaller elements, with a high aspect ratio, which are expensive in modeller's time to generate and expensive in computer time to solve. An element was created which permitted an accurate representation of the overall stiffness of thin shell structures. Its main requirements were to permit loads to be transferred between two adherends through an adhesive layer, allowing peaks in the adhesive strain at the ends of the joint, and the element should also be capable of deforming into a sufficiently complex shape to accommodate large peak edge strains. In addition some consideration was given to the compatibility of the joint element with other finite elements. Since the majority of bonded structures are modelled using shell elements it was decided that the bond element should have 6 degrees of freedom per node (i.e. 3 translation and 3 rotational). Five methods of generating the required stiffness matrix were investigated :

- using displacement data from an existing code
- using existing spring elements
- using existing laminate elements
- generating a new element formulation based on a layered solid.
- using a sub-structuring technique.

After initial investigations, the sub-structuring technique was selected as being the optimum method. A computer program was written to automatically generate the stiffness matrix of the element from data on adherend and adhesive materials and joint geometry. Two models were developed to validate the new element: one was based on a cantilever beam consisting of 20 of these elements joined together; the other was a top hat beam, modelled using shell elements with the adhesive element at the flanges. Results were compared with solid brick elements using the *ABAQUS* finite element program.

Strength prediction

To enable joint strength prediction it is necessary to make an analysis of stress and strain in the adhesive layer and in the adherends. The ***BISEPS-LOCO*** computer code developed in earlier work was capable of predicting the peel and shear stress/ strain distribution in a single lap joint. The code represented a significant advance on existing commercially available codes at that time because it accounted for plasticity in the adhesive layer. A number of additions to the capabilities of this program were identified to expand its usefulness to design problems and included the following features:

- single and double lap geometries
- profiled adherends
- variable adhesive bond thickness
- inclusion of spot welds in the bondline
- stepped lap geometries
- orthotropic adherends
- non-linear adhesive and adherends
- thermal effects in both adherends and adhesive accounted for
- pressure forces accommodated on the top and bottom surfaces of the joint
- prescribed displacements allowed.

Two main methods of extending the existing code were examined. These were refining the closed form solution or reformulation to a finite element technique. It was established that it was not possible to incorporate all of these effects into the closed form solution so a finite element route was pursued which could accommodate all the additional requirements. Pre- and post- processors were written so that data entry and results presentation were very similar to the original computer code.

MATERIALS TESTING

This had three main aims which were: to develop tensile property tests for adhesives in thin film and bulk form; to investigate the impact performance at low temperatures; and to examine the relationship between static creep and low frequency fatigue performance of bonded joints. Six adhesives were selected for study. These included a well characterised, toughened, heat cured epoxide (Ciba Araldite AV119) and a room temperature curing acrylic system (Permabond VOX 504). The former has a relatively high shear stiffness (> 1.1 GPa) whereas the latter is much more compliant. The adhesive testing was primarily to develop reliable testing techniques capable of measuring tensile property data which could be incorporated into the various computer design codes. It was anticipated that these measurements would be made on bulk samples cast into a suitable shape and also be inferred from tests on tensile butt joints. The bulk samples were expected to provide more useful information due to the complex constraint effects within thin bondlines. These techniques were interpreted using a laser moire interferometer (LMI) which enabled in-plane deformations to be recorded with a sufficiently high resolution to observe directly the onset of plasticity and the propagation of cracks near the adhesive/ adherend interface.

Bulk property measurements

Two methods were developed to produce good quality, low porosity, cast samples. One method was to inject the adhesive paste into a machined PTFE mould cavity and the other method used two glass sheets separated by a PTFE 'picture frame' to produce adhesive plates. The main problems encountered when casting large adhesive blocks were porosity due to air entrapment and the excessive exotherm during cure. Porosity was reduced by ensuring that all materials were vacuum degassed prior to casting and by heating the resin to reduce viscosity. The exotherm was reduced by casting thinner plates, approximately 2 mm thick, and by reducing the cure temperature. Cylindrical epoxide resin samples were also prepared by casting adhesive into etched aluminium alloy tubes and curing at 120 deg. C for 2 hours. The middle section was subsequently machined away to leave a bulk cylindrical specimen with circular end tabs.

Butt tensile testing

Square butt joints

HE30 aluminium alloy or steel adherends, measuring 12 x 12 x 90 mm, were degreased and etched. The nominal bondline thickness of 0.5 to 0.8 mm was controlled either by placing spacer wires at the centre of the specimen or by accurate clamping without wires. After curing the bonded area was polished and a moire grid was carefully mounted so that deformations within the bondline could be directly observed during loading.

Circular butt joints

These were prepared using steel adherends and a specially designed jig which provided accurate axial alignment.

Strain measurements

The strains in bulk specimens were measured using either 2 mm gauge length axial and transverse strain gauges or extensometers interfaced to a PC. The butt joint strains were monitored using 0.3 mm gauges centrally bonded onto the edge of the adhesive layer. Pairs of gauges were used throughout on opposite faces of the specimen to monitor bending. Figure 1 shows the longitudinal and transverse strains, measured by extensometers, as a function of applied stress for a bulk sample of Araldite 2007. Strain gauges gave similar results and showed that the adhesive becomes non-linear at 0.8% strain. The shear modulus of 1.22 GPa obtained from values of longitudinal modulus and Poissons ratio, agreed with an independently measured shear modulus obtained from thick adherend shear tests. The adhesive failure initiated from an internal void at approximately 62 MPa (2.7% strain). Poissons ratio also varied with strain and ranged from 0.33 at low strains to 0.435 at failure.

Laser moire interferometry

Validation of computer models requires a global strain distribution in both adherends and the adhesive layer. Zero gauge length extensometry, developed during previous work, enabled the successful measurement of shear displacement in a bondline at discrete points, but is not capable of providing full strain field information. Strain gauges are also of limited value as they are physically large compared to the rapidly varying strain distribution. A high resolution moire interferometry technique, developed at Virginia Polytechnic Institute (VPI) by Prof. Dan Post, was used to measure in-plane displacements with very high resolution. Deformations within adhesive bonds were measured together with their visco-elastic response.

Thick adherend shear testing

A limited number of thick adherend shear test specimens were manufactured and tested to provide shear property data on adhesives that were included in the programme.

Creep and fatigue effects

The effects of creep accumulation in structural joints were studied together with the variation of strain distribution along the bondline. Modified thick adherend shear specimens were produced using two batches of AV119 epoxide adhesive, cured at 120 deg. C. The bondline thickness was nominally 0.42 mm with bond lengths of 10 mm and 20 mm. The adherends used were either mild steel or high yield strength 20 carbon steel. Static and dynamic creep effects at ambient temperature were monitored using a combination of zero gauge length extensometry and laser moire interferometry. Stiffness data were obtained from load-deflection curves, which were corrected for adherend displacement, and ranged from 1.11 to 1.13 GPa. Marked non-linearity was observed at approximately 30 MPa. Static creep experiments were carried out in an Instron Model 1185 machine under load control and increases in deformation across the bondline monitored as a function of time. After an appropriate time period, up to a maximum of three days, specimens were unloaded and allowed to relax at zero load for up to 20 minutes, before reloading up to a higher creep load. This sequence of operations was repeated until failure occurred. The response of similar specimens to cyclic fatigue was also studied using similar extensometry.

COMPONENT TESTING

Three components were selected for testing with the objective of linking theoretical models and component testing. This involved the use of finite element analysis, mathematical modelling and component evaluation.

Metro A-pillar

This is a roof pillar between the windscreen and the front passenger window on a Rover Metro car. The adherends were mild steel sheet, pressed into a channel shape, and normally spot welded along the length of the flanges. Two adhesives were recommended for this application, one being a heat curing single component epoxide and the other a warm curing two part epoxide paste. The former would represent what could be used on an automatic assembly line and the latter could be used for vehicle repair. The primary load requirements for the pillar were torsional rigidity coupled with impact resistance. During the mechanical testing the torsional stiffness of spot welded and adhesively bonded beams was compared.

Model Top hat beam

This component is commonly used in experimental programmes and can be considered as a general component which is typical of the form of construction used in the automotive and aerospace industries for improving stiffness, strength and impact resistance of structures. Figure 3 shows a carbon fibre beam loaded in 3 point bending. The relatively simple shape was more amenable to detailed analysis than the more complex cross-section of the A-pillar. Components were assembled from steel, aluminium and carbon fibre composite and bonded at Harwell using three type of adhesives. Tests were performed in three point flexure and torsion to measure rigidity and strength. Several comparisons were made with more traditional ways of assembly including spot welding and seam welding. Load/ deflection curves were obtained for beams loaded in 3 point flexure.

Cut-out stiffener

This component was selected because it represents a general form of construction. In many composite structures access holes such as windows or inspection panels require edge stiffening or reinforcement to prevent failure. The adherends chosen were a woven [$\pm$45]s T300/ Fibredux 914 panel, approximately 2 mm thick, and aluminium alloy doublers. The adhesives selected were an epoxide film, Ciba-Geigy Redux 319A, which is used in production and a toughened acrylic, Permabond F245, used in repair. A total of 5 panels, each 300 mm wide and 450 mm long, containing a 100 mm square cut-out were tested in tension in a servo-hydraulic machine. Measurements of strains at various locations in the panel were recorded up to failure.

MAIN RESULTS & CONCLUSIONS

An improved finite element based analysis package, FELOCO, has been written to analyse stress/ strain distributions in single and double lap joints. This code allows profiling of the adherends, variable adhesive bond thickness, plasticity within the adherends and adhesive, stepped lap joints and inclusion of spot welds throughout the adhesive layer. The program operates on mainframe, mini- and microcomputers and makes extensive use of screen driven menus with associated help text. The output has been validated against other finite element codes and experimentally verified with the aid of laser moire interferometry.

A number of methods for creating an adhesive bond finite element have been investigated and required formulating a new element from first principles. It was concluded that the most appropriate method was a sub-structuring technique as it allowed a full 3 dimensional element to be formulated. This substructuring method has been successfully implemented in a computer program, written to generate the stiffness matrix of a 3 dimensional adhesive bond element for inclusion in a finite element model of a structure. The element may be connected to both 4 and 8 noded shell elements, and is generated from input data on bond length, adhesive and adherend thickness and materials properties.

Investigation of adhesive tensile properties using the butt tensile test highlighted the practical difficulties of obtaining sensible stiffness data because of the constraint effects of the adherends. Strain gauge data produced during these tests clearly showed these effects. It was found that bulk property measurements using both strain gauges and extensometry were more reliable provided that specimen porosity was minimised and axial alignment maintained.

Laser moire interferometry proved to be an extremely valuable diagnostic tool during the course of the programme as it was capable of providing the full field strain map of an adhesive bond. The measurements showed good agreement with the predictions from the mathematical models and it enabled them to be validated experimentally. It also provided a means of directly measuring adhesive properties, particularly creep, and was effective at studying the mechanisms of adhesion failure.

Component testing showed that the bonded Metro 'A' pillar and top hat beams exhibited approximately a 5 % increase in torsional stiffness compared to spot-welded beams. There was little difference, however, in the flexural stiffness of spot-welded and bonded beams used in the present testing programme. This observation is supported by independent findings. The orientation of the bonded beams (i.e. flange at top or bottom) appeared to affect the measured stiffness and is believed to be due to localised buckling near the central loading roller.

The load carrying capacity of the composite panel containing an aperture was found to be approximately doubled by the addition of bonded aluminium alloy stiffeners. The failure load for the epoxide film adhesive bonded stiffener was much higher than the acrylic bonded stiffener and it appeared to be more well bonded to the composite surface.

Modelling of Adhesive Joints for Automotive Body Structures

A. Beevers, S. Steidler, H. Hadavinia and J. Durodola

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The performance of a road vehicle is critically dependant on the stiffness of the vehicle body, which in turn is influenced by the nature of the joints in the vehicle structure. It is generally observed that adhesive bonded structures are stiffer than assemblies fabricated with fasteners or spot welds.

From the design perspective, it is desirable to predict the effects of joints from computer models. Various analyses have been carried out on body structures with different joint characteristics but the scale and complexity of FE models of a full vehicle body limits the detail of the joint properties. It is therefore necessary to model the joints at a micro-level and translate the characteristics into the full-body model.

In this study FEA techniques have been developed to predict the stiffness of lap and coach (T-Peel or flange) joints in terms of load-deflection characteristics. The models have been used in an extensive parametric study of the effects of adhesive and adherend properties and joint geometry. The FE predictions have been validated by experimental testing of equivalent joints using extensometric methods to measure component displacements under applied load.

The results summarised in Figures 1 and 2 show that joint configuration has a major effect on stiffness. Compared with a flat continuous sheet, the eccentricity of the load-path in lap joints introduces rotational deformation which causes a large loss in stiffness regardless of the adhesive modulus. Similarly for coach joints, the deflections in the flange bend area may be significantly higher than the adhesive deformation.

The effects of adhesive modulus on joint stiffness are shown in Figure 2. The graphs show that the joint stiffness is relatively insensitive to the elastic modulus, particularly for typical structural adhesions. This observation suggests that the bonded structure should be relatively tolerant to changes in adhesive properties which might arise from environmental exposure or from variability in processing conditions.

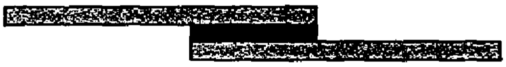
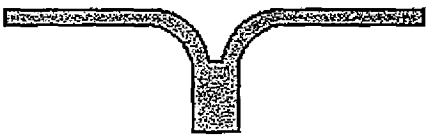
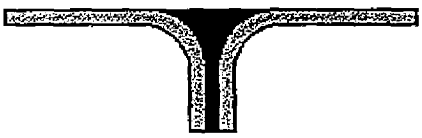
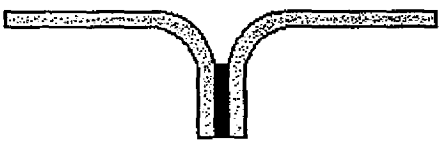
Joint Configuration *1mm thick mild steel* *0.2mm bondline in adhesive joints* *G = adhesive shear modulus*		**Stiffness** *N/mm.mm* *(50 mm gauge length)*	
Flat continuous sheet		**4200**	
'Solid' lap joint *15mm overlap*		**1691**	
Adhesive bonded lap joint *15mm overlap*	 **G = 0.6 GPa**	**1670**	
	G = 0.002 GPa		**144**
'Solid' coach joint *20mm flange* *5mm flange bend radius* *No fillet*		**122**	
Adhesive bonded coach joint *20mm flange* *5mm flange bend radius* *100% fillet*	 **G = 0.6 GPa**	**760**	
	G = 0.002 GPa		**41**
Adhesive bonded coach joint *20mm flange* *5mm flange bend radius* *No fillet*	 **G = 0.6 GPa**	**95**	
	G = 0.002 GPa		**25**

Figure 1 Comparitive stiffness of different joint configurations

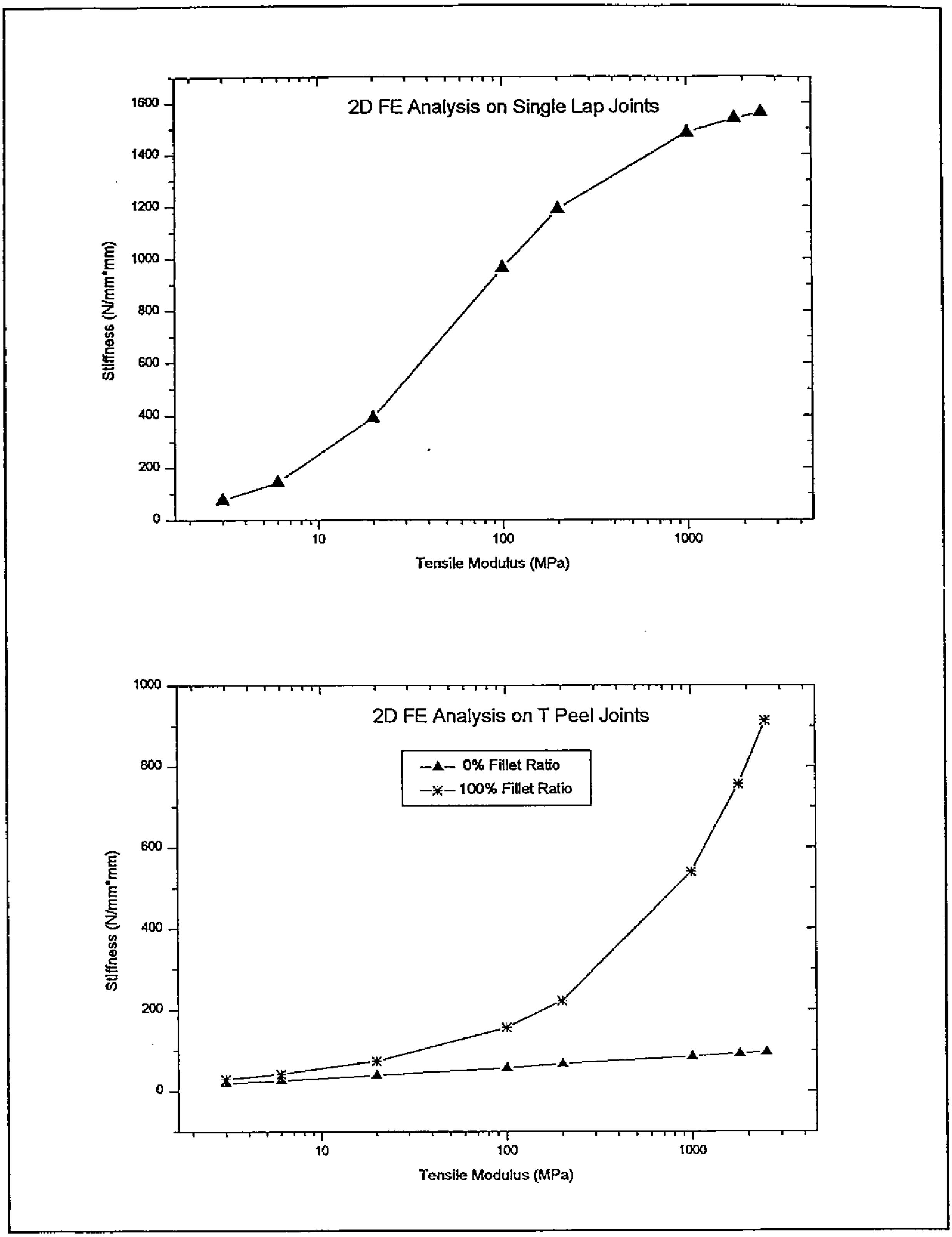


Figure 2 Effect of adhesive modulus on joint stiffness

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Composite Materials and Adhesively Bonded Structures in Grand Prix Racing Cars.

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Abstract.

The contemporary Formula 1 racing car makes extensive use of advanced composite materials and adhesive bonding in its construction. The high loadings encountered by, and the durability demanded of, its components when competing successfully in Grand Prix require the application of materials having excellent mechanical property performance. This paper describes the processes used in the design and manufacture of a current, successful Formula 1 racing car through the experiences gained at Williams Grand Prix Engineering Ltd.

Introduction.

Formula 1 World Championship motor racing is an activity that is always ready to exploit the potential of any emerging new technology and supplies a demanding environment in which to demonstrate any advantages that it may provide. One such technology is the application of advanced composite materials to primary load–bearing applications. The composite used is that of carbon fibre reinforced epoxy polymer, the initial interest in which was driven by the need to find a material which offered greater specific stiffness advantages over the aluminium alloy previously used and which would allow greater freedom in its application to the manufacture of more adventurous shapes.

In the decade since the introduction of composites design solutions have evolved which successfully meet the engineers' original expectations. At the same time strength design has become ever more important whilst the complexity of component geometry has developed rapidly.

Vehicle general arrangement

It is important before discussing the general subject further to explain the constituent parts of a current Formula 1 racing car's structure. In simple terms the general configuration of the vehicle is as shown in Fig. 1 and may be described as follows:

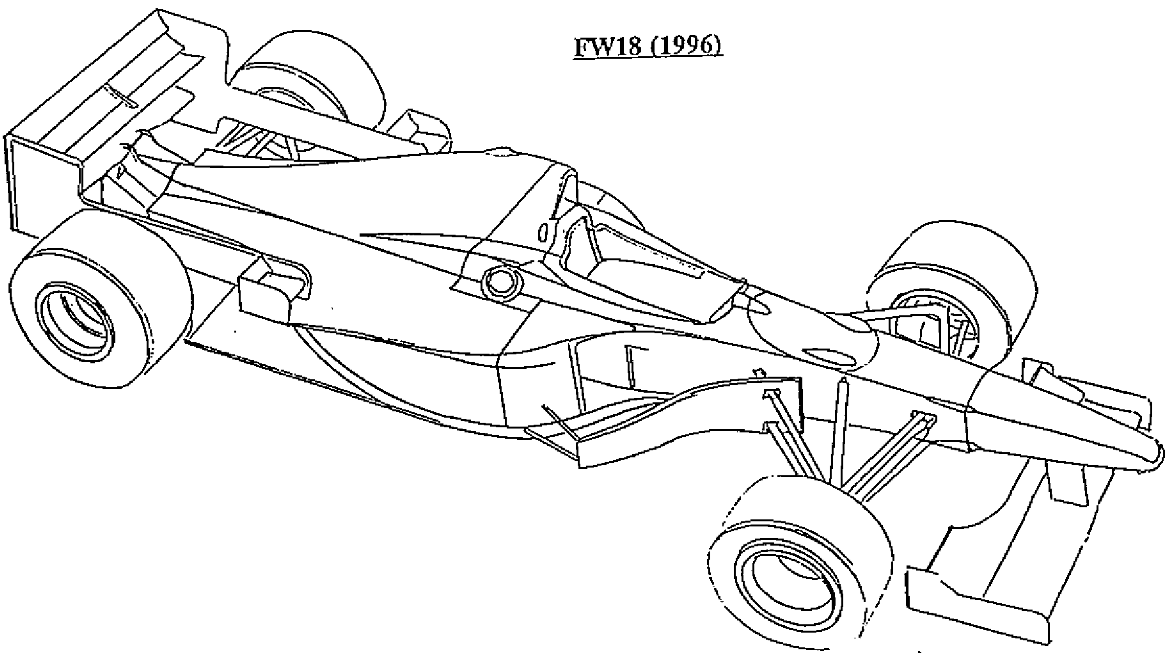

Fig. 1 Vehicle general arrangement

A central load–bearing structure connects the front and rear suspension systems together. It is made up of three main elements; the chassis, the engine and the gearbox casing. The 'chassis' (or 'tub' or 'monocoque') accommodates the driver, the fuel tank and the front suspension components. The engine is joined to the back of this, semi–monocoque shell, assembly on four studs and the structure is completed by the attachment of the gearbox casing to the rear face of the engine. The chassis, engine and gearbox, therefore, form a 'box–beam' structure which carries the inertial loads to their reaction points at the four corners of the car. Arranged around, and attached to, this are the remaining components – wing structures, underbodies, cooler ducting and bodywork.

Functions of the structure

The behaviour of the structure is of major importance to the performance of the car when it is in motion. During the course of 'setting up' a racing car at a circuit changes are made to the suspension elements (springs, dampers, anti–roll bars) with the intention of modifying its handling. Ideally, any small change in a component stiffness should be felt in the balance of the car. This will not occur if the structure transmitting the loads is of an insufficient stiffness. The chassis member must, therefore, possess good stiffness characteristics or the handling will suffer and speed around the circuit will be lost.

Designers of Grand Prix cars must comply with a set of regulations when arriving at their solutions. These, the 'Formula 1', are defined by the F.I.A., the governing body for motor sport world–wide. The key parameters affecting structural design are those of geometry, strength performance and weight. Constraints are placed on the overall dimensions of the car's bodywork and the sizing of the driver envelope within the cockpit. Load cases are specified for the design of key elements of the structure and tests are defined which must be performed and passed in the presence of an appointed witness. Of major significance also is the regulation which limits the minimum weight of the car (with driver) to 595 kg. All of the car's components must be of minimum mass. It is estimated that 10 kg. of excess weight is equivalent to a time difference of at least .1 seconds around a typical circuit – a significant amount in motor racing terms.

The need for structural efficiency.

Summarizing, for the structure to fulfil its required functions correctly it should exhibit the following qualities. It must:–.

- have good stiffness
- be of sufficient strength to carry the loads applied to it
- be of a damage–tolerant and impact–absorbing construction
- be of minimum mass

In short, the structure must be efficient. Structural efficiency may be maximised by considering a number of factors but most effectively by:–

- optimising the structure's geometry
- improving its construction
- using the most efficient materials

The adoption of composite materials.

The search for these qualities resulted in a progression of different technologies being employed in racing car construction during their evolution. Composite materials are the latest of these and were attractive to Formula 1 designers because their specific mechanical properties showed improvements over the available metals. Their use has also been extended to a full range of components covering secondary as well as primary structural duties as is shown in Fig. 2.

The 'monocoque' chassis structure is an adhesively bonded assembly of five principal components and is shown in diagrammatic form in Fig. 3.

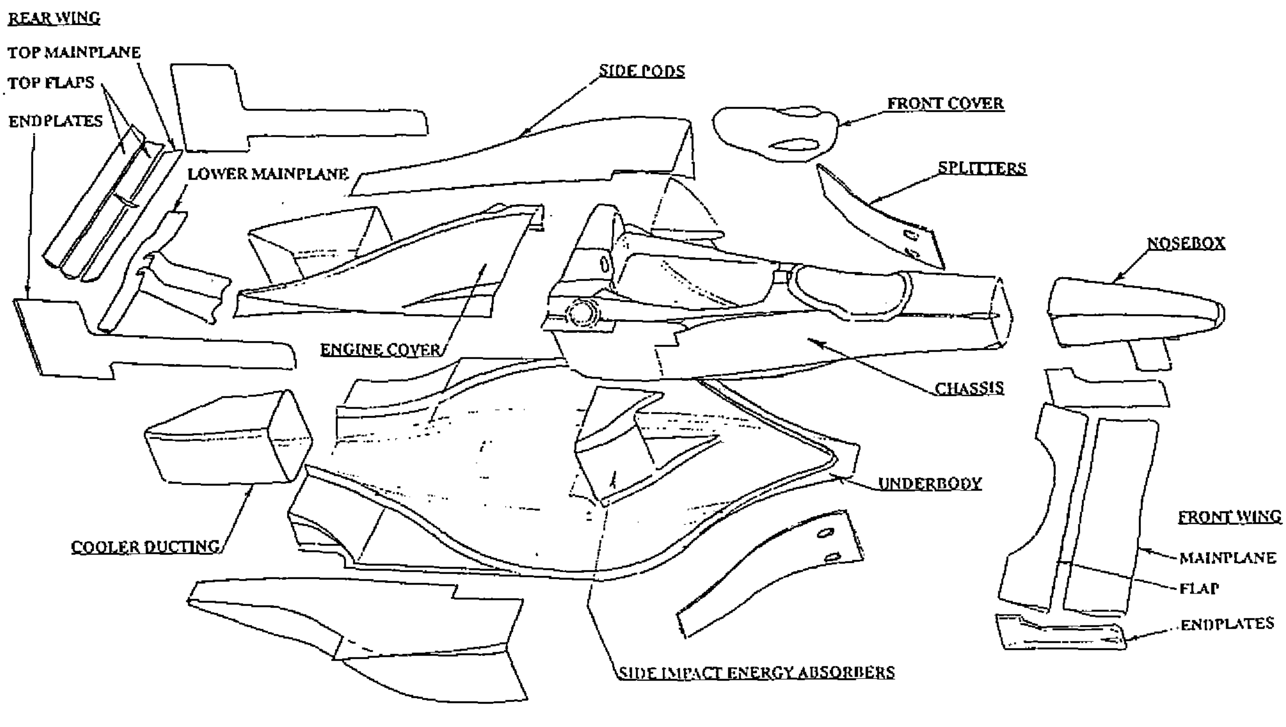

Fig. 2 Components manufactured from composite materials.

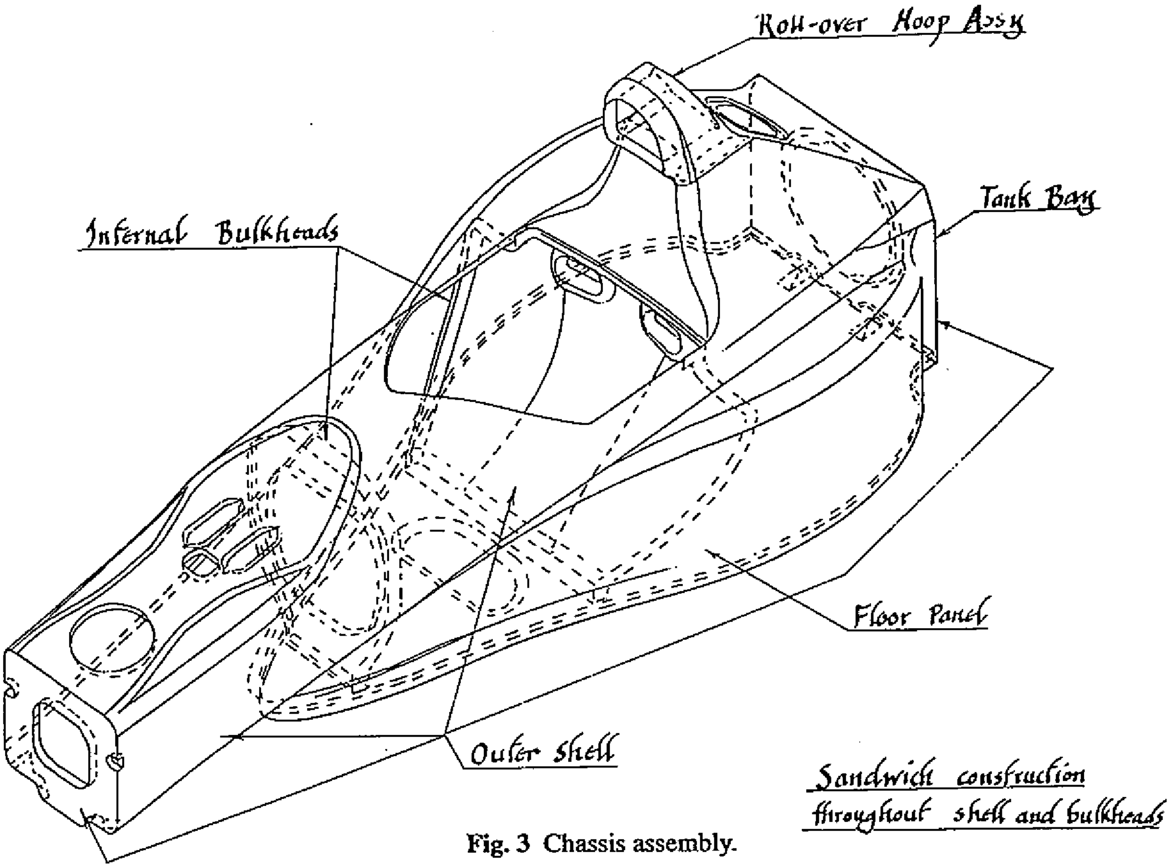

Fig. 3 Chassis assembly.

Design criteria

The chassis structure is subject to inertial loading. Currently a fully laden Grand Prix car may be subjected to sustained loads of 4.5 'g' laterally, at least 4 'g' under braking and as much as 10 'g' as instantaneous 'bump' loading at one or more of the corners. Aerodynamic downforce from the front wing is input to the structure at the nose attachment points. This may be as much as 5kN. Additionally, the chassis must be designed to cope with the impact test and strength demonstration cases. These loads are summarised in the diagrams Figs. 4 & 5. The structure that results from the criteria detailed here weighs approximately half that of a Formula 1 driver.

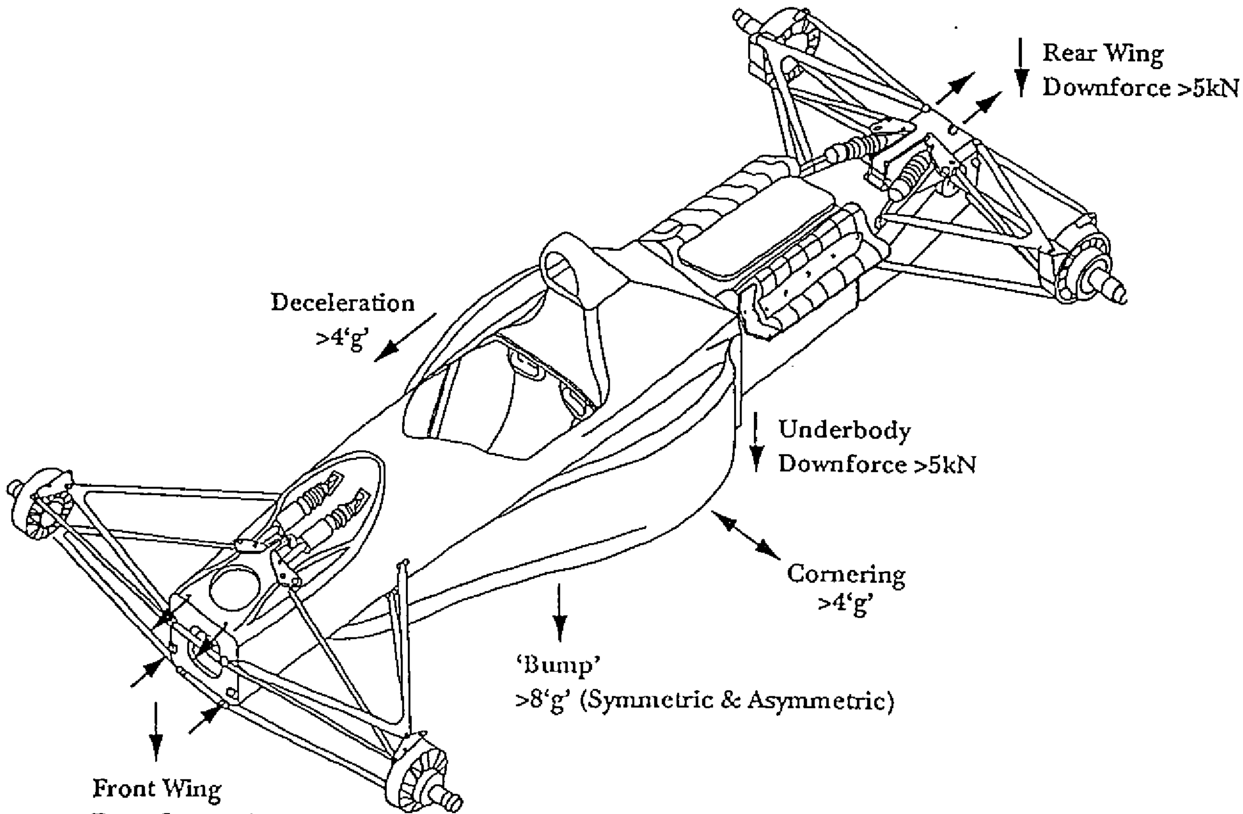

Fig. 4 Chassis inertial load cases.

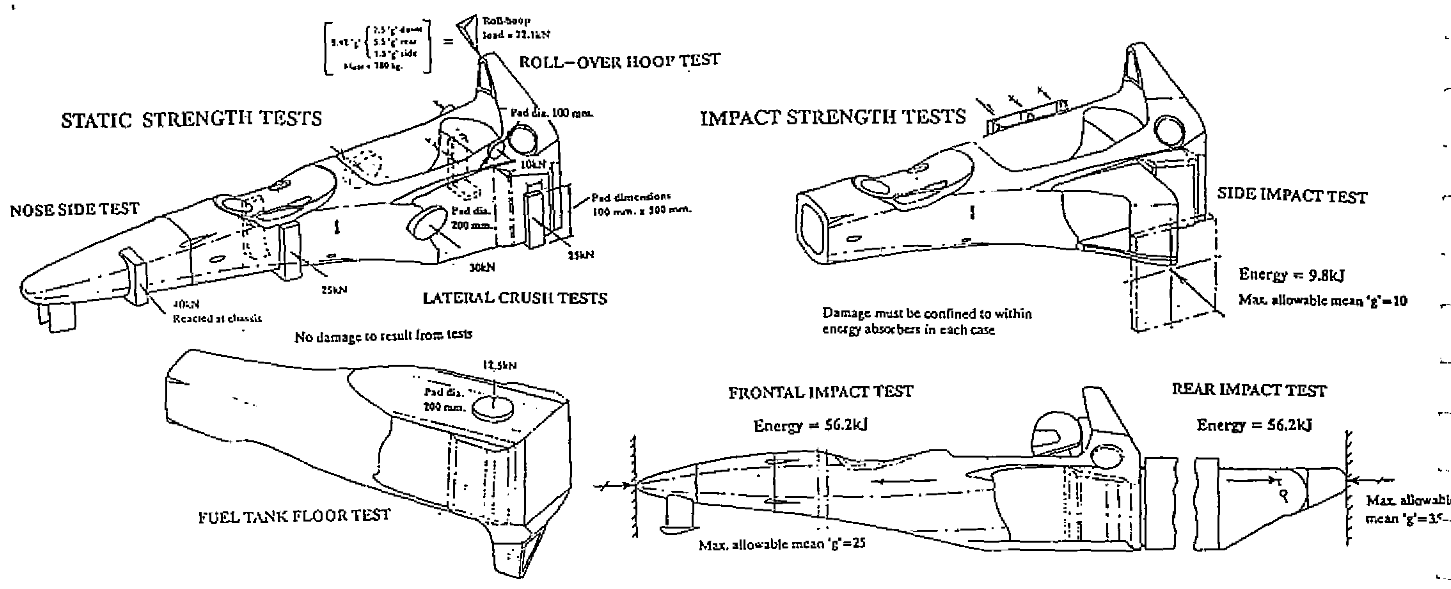

Fig. 5 Structural testing load cases

Design processes

The design of a Formula 1 car makes extensive use of Computer Aided Engineering. This covers aerodynamic design, geometry definition, drawing production, structural and fluid dynamics analysis, and master pattern machining. The production moulds are taken directly from these patterns.

The design solution for the chassis is illustrated in Fig. 3. It consists of 5 principal components. The outer shell of the structure is reduced to two; a separate, largely flat, floor panel being joined to the remainder at its base. Bulkheads are positioned so as to feed suspension point loads into the structure and enclose the cockpit bay, and assembly of the whole is effected by means of adhesive bonding. Attachments fit into solid inserts bonded within the shell honeycomb.

Since one of its primary functions is that of the driver's 'survival cell', when considering the design of the chassis structure a balance must be found between the goals of weight, stiffness and strength. In terms of the author's own philosophy, the process should be: i) determine as part of the specification what are the permissible maximum weight of component and minimum levels of stiffness required for adequate handling characteristics, ii) produce a design solution which satisfies these whilst including the best combination of material properties, geometry and manufacturing details to provide the maximum possible strength. The point of the exercise is not merely to to satisfy the mandatory strength demonstration cases but to design for the real cases which cannot be so easily quantified.

Wing structures, similarly, must embody damage–tolerant thinking since they are also safety–critical components. Whilst aerodynamic variations due to deflection must be minimised, strength considerations should not be neglected when choosing materials or a manufacturing route. The more recent extension of composites to use in selected suspension elements has provided the first examples of components which are strength–designed as a primary requirement. The choice of an appropriate manufacturing method in combination with careful analysis of the structural function involved considerable effort to evolve a suitable design solution.

Manufacturing processes

Master patterns of the component geometries to be built are constructed by the machining of epoxy–based pattern block on a 5–axis router via a CAD/CAM link from the designed surface data. Moulds are taken from the patterns using low temperature–curing carbon/epoxy 'prepreg' tooling techniques. Component manufacture is accomplished by the hand lay–up of uni–directional and woven pre–impregnated ('prepreg') carbon/epoxy materials onto appropriately configured moulds and curing using vacuum bag and autoclave techniques. Curing temperatures are either 120^{0}C or 175^{0}C depending upon the requirements of the component and type of resin matrix chosen.

Wing structures are mostly assembled from carbon/epoxy monolithic laminate components but many of the other parts – including the monocoque components and nosebox – are made by a sandwich construction method. In these cases a skin of prepreg material is first laminated and cured on the mould face. A film of epoxy adhesive is then applied to the pre–cured skin followed by a honeycomb core material (typically of aluminium or Nomex foil), a further film of adhesive and a mirror–image inner skin prepreg laminate. This assembly is then bagged and autoclaved to produce the finished sandwich panel.

Joining of components to form structural assemblies is carried out using a secondary bonding process. This most usually employs room–temperature–curing paste epoxy adhesives. Those currently in use are chosen for their ease of use, temperature duty, and toughness in combination with strength.

Conclusions and future developments

Advanced composites and adhesives are the standard materials chosen for the primary structural as well as the secondary components of all contemporary Grand Prix cars. They provide an effective and efficient solution to many of the problems presented by the demanding environment of World Championship motor racing.

Considering structural performance, stiffnesses are currently achieved which adequately meet the requirements necessary for vehicle handling whilst allowing acceptable component weight. Strength characteristics are also obtained which are adequate for the loads induced while the car is in motion and during the mandatory strength demonstration tests. The aim of future study is to further understand material and structural behaviour so as to further improve strength performance, and hence safety, wherever possible.

INSTITUTE OF MATERIALS SYMPOSIUM

"ADHESIVES IN TRANSPORT"

THE USE OF ADHESIVES IN THE RAILWAY INDUSTRY

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1) Introduction

This paper will give an overview of the use of non structural (contact) adhesives, thread bonding adhesives, semi structural adhesives and structural adhesives in Railway Rolling Stock applications.

It will consider the service environmental limitations of different adhesive families and make suggestions on future development topics required before further applications will be considered by Rolling Stock designers, especially in the newly privatised operating industry.

2) Objectives of Using Adhesives

- To attach 2 materials together, either with or without supplementary mechanical fasteners.
- The application must give a competitive advantage over other methods of substrate attachment.
- The bonding process must be suitable for the application and any subsequent post assembly processing.
- The bonding process must survive the service environment for the designed life of the product (Physical, Chemical and Mechanical limitations may apply).
- The bond must be easily detachable if service requirements dictate.
- The process **MUST** meet current and anticipated Health and Safety requirements.

3) Applications for Non Structural Adhesives

The interiors of Railway Vehicles have successfully used non structural adhesives for many years.

Contract adhesives were used a generation ago to bond melamine laminate or cloth to wood or metal substrates. These product types are still being used today as Vehicles are refurbished. Thermosetting adhesives are now used more extensively to overcome internal stresses in melamine - aluminium and melamine - wood bonds.

Development in these product types have been the adoption of non flammable solvents and improved resins which contribute to assemblies meeting the latest fire performance regulations.

Water based adhesives have been offered in recent years, but there have been resistance to their use and some problems in service.

4) Applications for Anaerobic Adhesives

The use of anaerobic adhesives to aid thread locking or sealing has lagged behind other industries. Following privatisation, this situation is changing and I believe their use will reach similar levels to other transport industries in the near future.

5) Application For "Semi Structural" Adhesives

Vehicle Interiors

The major driver towards the use of "semi structural" adhesives for vehicle interiors was the need to improve aesthetics and to present a vehicle interior without visible fasteners.

Products used include 2 part acrylics, adhesives and high strength double sided tapes.

These have been used successfully in service applications for over 5 years. This followed some detailed process development, successfully carried out with the aid of the adhesive suppliers.

Vehicle Exteriors

There have been a number of examples of the use of bonded external "shear" panels on light rail vehicle designs.

There have also been extensive applications of bonded glazing on all types of rail vehicles.

The majority of these applications have used moisture curing single part polyurethane adhesive sealant.

The technology employed has successfully “crossed-over” from the motor industry. Problems to date have been linked to ensuring satisfactory priming of substrates, and satisfying operators that repair cure times will not interfere with service schedules.

6) Applications for Structural Adhesives

Structural Adhesives have been used successfully in only one UK trial to my knowledge. A suburban commuter car design was slightly modified to allow the use to a single pack heat curing adhesive. After extensive laboratory testing a section was built into a prototype and put into passenger service in the late 1980's. This has been totally successful, demonstrating the concept and associated inspection processes. The use of this design has not been progressed to series production orders for a variety of reasons, one of which is detailed below.

7) Barriers to Future Specification of Adhesives

The railway industry is rightly a very well regulated one. It's aim is to ensure that the railway's safety record remains at the current levels.

There are very strong barriers to the use of new technology unless it can be proved that it is as safe as existing design solutions.

This is particularly so in terms of fire performance and structural strength.

It is a challenge to designers to ensure any fully bonded joints satisfy the fire performance requirements of current legislation, but with the help of adhesive suppliers we have succeeded to date.

However I believe there is a lot more work to be done in the supply of standardised design codes which will be accepted by adhesive suppliers, designers and regulators alike.

Analysis of bonded structures by FEA is relatively new and confidence in results limited.

Basic materials property data is rarely available, especially fatigue data.

For welded steel joints the accepted design code is BS 5400 part 10, and for aluminium constructions it is BS 8118. There is no equivalent, to my knowledge, for bonded joints. I believe it should be a major priority that work begins (or continues?) on such a code. Until it does, there will be no major development of structurally bonded rail cars even though on economic case could be made for them.

8) Summary

Adhesives have been used for many years in the rail industry.

The products used have changed in the last 5-10 years. They are now much more likely to be semi structural adhesives, rather than contact adhesives.

Restrictions to further developments, such as the use of adhesives in fully structural applications are the lack of suitable design codes.

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25th June 1997

Acknowledgements

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