Composite Materials Technology in Formula 1 Motor Racing.

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Abstract

If the pundits are to be believed, something approaching 10% of the world's population watches each Formula 1 race. Having said that, beneath its glamorous surface, few understand what exactly is involved and why it has evolved into "technological warfare". The strategy of Formula 1 will be discussed with a view to explain why the cars are so dependent on the use of advanced materials, in particular fibre reinforced composites. Any engineering structure, irrespective of its intended purpose, must be made of one or more materials. More often than not it is the choice and behaviour of those materials that determine its mechanical performance. The introduction of fibre reinforced composite chassis was one of the most significant developments in the history of Grand Prix motor racing. Technology advances gained from these advanced materials have produced cars that are lighter, faster and safer than ever before. A short introduction to the science of composite materials will be followed by a history of their use and development within the sport. Design manufacture and operation of composite structures will be reviewed. Reference will also be made to their energy absorbing properties that have contributed so significantly to the improved safety record of Formula 1 and the more specialist composite materials, such as carbon-carbon, used in brakes and clutches etc.

The design of Formula 1 racing cars

The general arrangement of single seat racing cars has remained the same since the early 1960s. The central component, which accommodates the driver, fuel cell and front suspension assembly, is the chassis (Figure 1).

Figure 1: The chassis is the central component of an F1 car.

This is a semi-monocoque shell structure which is more like a jet fighter aircraft cockpit, both in terms of shape and construction, than anything one would expect to find on the road. The engine, in addition to providing propulsion, has a structural function and is attached directly to the rear of this unit by high strength metal studs.

The assembly is completed by the addition of the gearbox and rear suspension assembly (Figure 2.).

Figure 2: Gearbox and rear suspension.

The car's primary structure of chassis, engine and gearbox (Figure 3) may be considered as a "box-beam" arrangement carrying the inertial loads to their reaction points at the four corners.

Figure 3: The "primary structure" of a formula 1 car consists of chassis, engine and gearbox.

The secondary structures (bodywork, undertray, wing configurations and cooler ducting etc.) are arranged around and attached to the primary structure at various points (Figure 4).

Figure 4: Complete car with secondary structures added.

A Formula 1 car is driven "on the limit", that is to say one aims to operate the car as close to the point where its longitudinal g is just about to be overcome due to the lateral g from cornering (Figure 5).

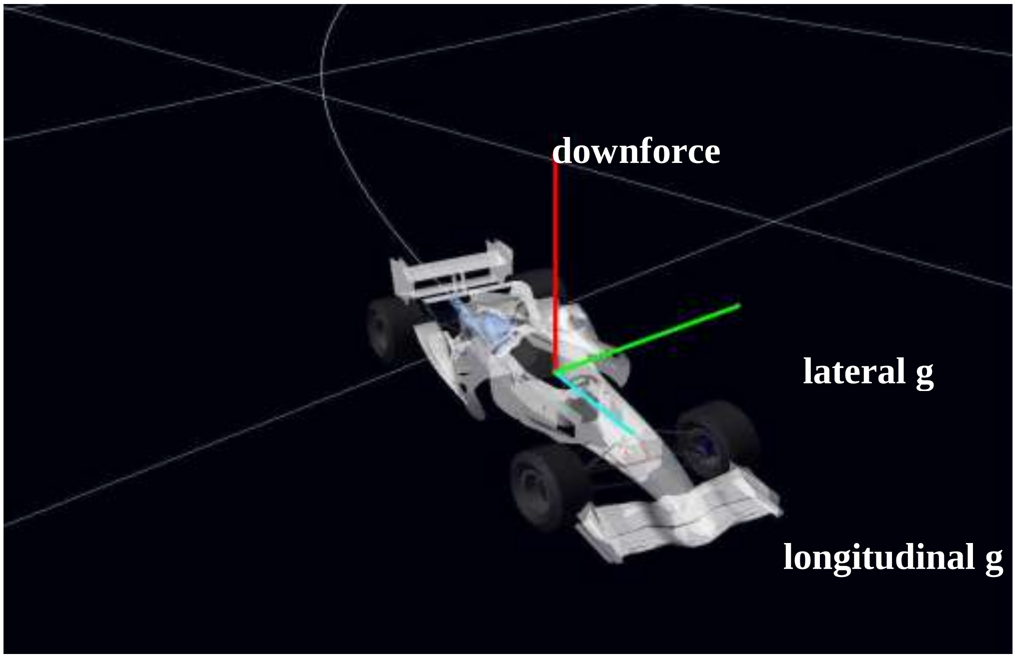

Figure 5: Driving "on the limit".

The car must be "set-up" for each individual circuit in order to optimise performance. Changes are made to the aerodynamic devices and the suspension elements (springs, dampers, anti-roll bars and so on) in an attempt to improve its lap time. Changes in the performance levels of the various sub-components must be manifest in the balance of the car. Clearly this will not occur if the structure transmitting the loads is not of adequate stiffness. In common with many other engineering disciplines, the designers of Formula 1 racing cars are required to comply with a stringent set of regulations. The rules are imposed by the FIA, the Sport's governing body. Constraints are laid down on geometry, strength and weight. Strict limitations are placed on the overall dimensions of the cars and the sizing of the driver envelope within the cockpit. A series of statutory regulations have been introduced over the years which are continually updated to improve safety. Consequently, the chassis has developed a secondary function of a "survival cell" to protect the pilot in the event of a crash. A number of tests must be performed in the presence of an official prior to the car being certified for Grand Prix usage. The regulation limiting the minimum weight of the car plus driver to 605kg is of great significance. Building a car to the weight limit is a vital task if it is to be competitive.

It has been estimated that a mass of 20kg above the weight limit equates to a loss of 0.4 seconds around a typical Grand Prix circuit. Less than half a second does not sound very much, but during a full race distance this amounts to half a lap or several grid positions during a qualifying session. With modern materials it is relatively easy to build a car which satisfies all of the statutory requirements whilst still being well under the minimum weight limit. As a consequence the majority of the cars are required to carry ballast (generally in the form of a heavy metal such as tungsten) in order to make up the deficit. At first glance therefore it may seem fruitless to continually aim to reduce the mass of components only to increase the amount of ballast carried. Lowering the weight of the chassis is still of benefit however when one considers Figure 6.

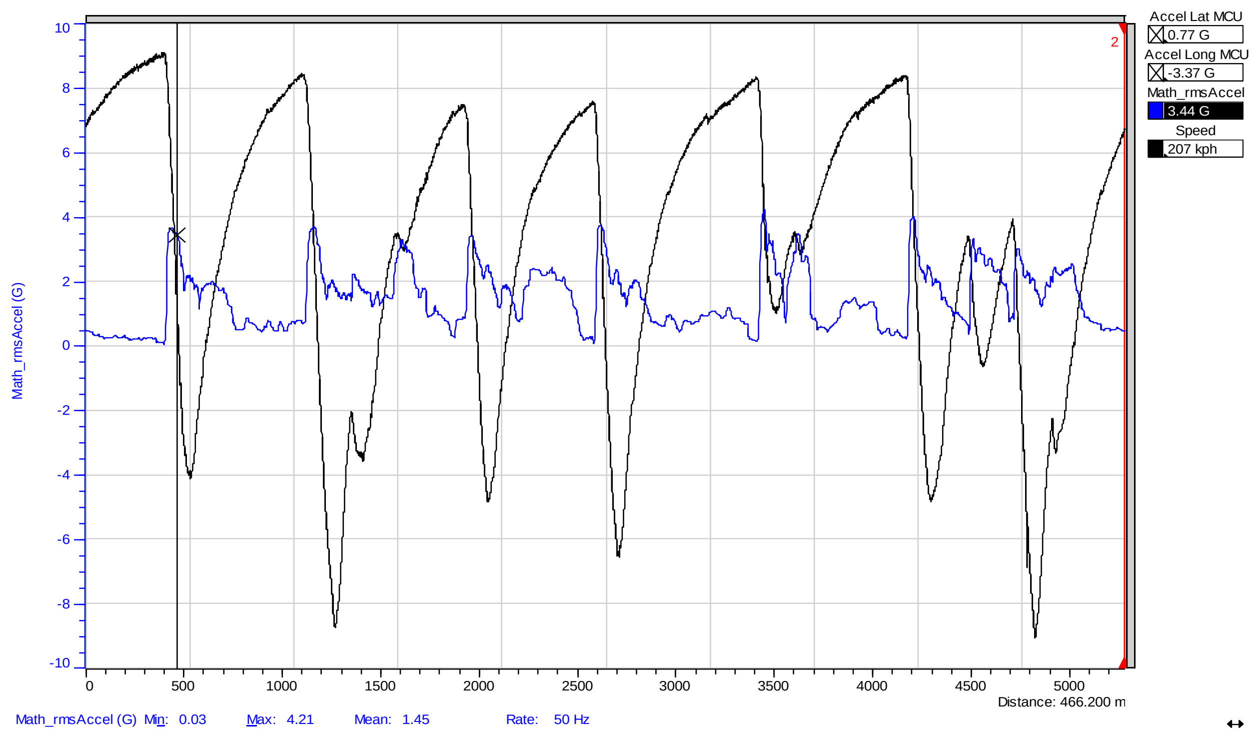

Figure 6: A Formula 1 car is always accelerating.

An F1 car is always accelerating, either positively under the influence of the engine or negatively under braking. Lower mass enables the engineers to alter the position of the car's centre of gravity and thus greatly influence its handling characteristics. The pursuit of lower weight and improved performance have both stimulated the introduction of new technology in both design and construction. The structural components of the car must be stiff, strong enough to satisfy the loading requirements, tolerant of and resistant to, impact damage and be of minimum weight. The solution to this problem is achieved by optimising the geometry, the quality of construction and by using the most appropriate materials. The quest for maximum structural efficiency has resulted in a progression of different technologies throughout the history of Grand Prix racing. Much of the development within Formula 1 has shadowed that taking place within the aerospace industry. This is not surprising when one considers the similarity of their objectives.

Composite Materials

Composites are defined as "materials in which two or more constituents have been brought together to produce a new material consisting of at least two chemically distinct components, with resultant properties significantly different to those of the individual constituents". A more complete description also demands that the constituents must also be present in reasonable proportions. 5% by weight is arbitrarily considered to be the minimum. The material must furthermore be considered to be "man made". That is to say it must be produced deliberately by intimate mixing of the constituents. An alloy which forms a distinct two phase microstructure as a consequence of solidification or heat treatment would not therefore be considered as a composite. If on the other hand, ceramic fibres or particles were to be mixed with a metal to produce a material consisting of a dispersion of the ceramic within the metal, this would be regarded as a composite.

On a microscopic scale composites have two or more chemically distinct phases separated by a distinct *interface*. This interface has a major influence on the properties of the composite. The continuous phase is known as the *matrix*. Generally the properties of the matrix are greatly improved by incorporating another constituent to produce a composite. A composite may have a ceramic, metallic or polymeric matrix. The second phase is referred to as the *reinforcement* as it enhances the properties of the matrix and in most cases the reinforcement is harder, stronger and stiffer than the matrix (1).

The measured strengths of materials are several orders of magnitudes less than those calculated theoretically. Furthermore the stress at which nominally identical specimens fail is subject to a marked variability. This is believed to be due to the presence of inherent flaws within the material (2). There is always a distribution in the size of the flaws and failure under load initiates at the largest of these. Griffith derived an expression relating failure stress to flaw size (a).

$$\sigma_f = \frac{K_{IC}}{ya^{1/2}}$$

Where σ_f = failure stress, K_{IC} is the material's fracture toughness and y a geometrical constant.
As equation 1 shows, the larger the flaw size, the lower will be the failure stress (Figure 7).

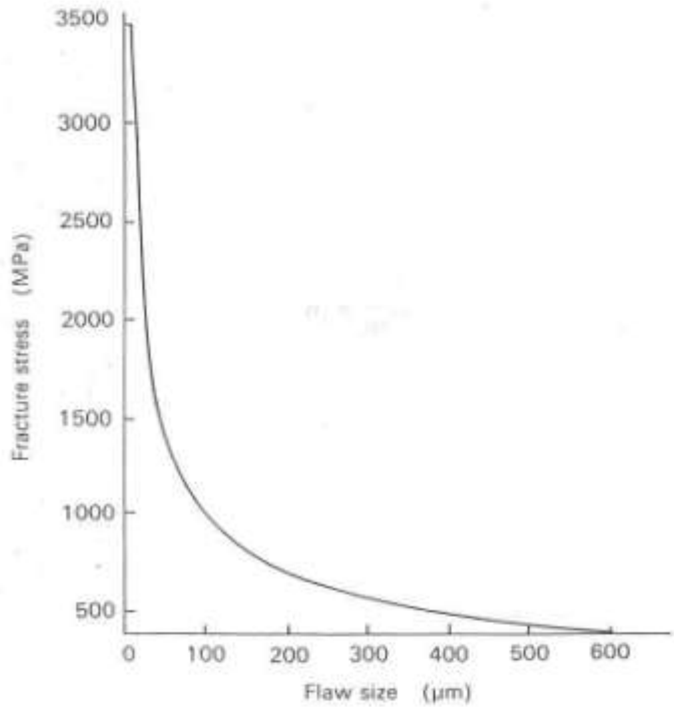

Figure 7: Relationship between flaw size and failure stress of a material (2).

It follows therefore that the strength of a material can be enhanced by eliminating or minimising such imperfections. Cracks lying perpendicular to the applied loads are the most detrimental to the strength. Fibrous or filamentary materials thus exhibit high strength and stiffness along their lengths because in this direction the large flaws present in the bulk material are minimised. Fibres will readily support tensile loads but offer almost no resistance and buckle under compression. In order to be directly usable in engineering applications they must be embedded in matrix materials to form fibrous composites. The matrix serves to bind the fibres together, transfer loads to the fibres and protect them against handling damage and environmental attack.
Composites can be divided into two classes: those with long fibres (continuous fibre reinforced composites) and those with short fibres (discontinuous fibre reinforced composites) In a discontinuous fibre composite, the material properties are affected by the fibre length, whereas in a continuous fibre composite it is assumed that the load is transferred directly to the fibres and that the fibres in the direction of the applied load are the principal load-bearing constituent. Polymeric materials are the most common matrices for fibre reinforced composites. They can be subdivided into two distinct types: thermosetting and thermoplastic. Thermosetting polymers are resins which cross-link during curing into a glassy brittle solid, examples being polyesters and epoxies. Thermoplastic polymers are high molecular weight, long chain molecules which can either become entangled (amorphous) such as polycarbonate, or partially crystalline, such as nylon, at room temperature to provide strength and shape. In common with all structural applications of polymer matrix composites, Formula 1 is dominated by those based on thermoset resins, particularly epoxies.

The driving force for the increasing substitution of metal alloys is demonstrated in Table 1.

Material	Density (gcm^{-3})	Tensile strength, σ (MPa)	Tensile Modulus, E (GPa)	Specific strength (σ/ρ)	Specific Modulus (E/ρ)
Steel	7.8	1300	200	167	26
Aluminium	2.81	350	73	124	26
Titanium	4	900	108	204	25
Magnesium	1.8	270	45	150	25
E glass	2.10	1100	75	524	21.5
Aramid	1.32	1400	45	1060	57
IM Carbon	1.51	2500	151	1656	100
HM Carbon	1.54	1550	212	1006	138

Table 1 - Comparison of mechanical properties of metallic and composite materials.

Contrary to many a widely held belief, composites are not "wonder materials". Indeed their mechanical properties are roughly of the same order as their metal competitors. Furthermore they exhibit lower extensions to failure then metallic alloys of comparable strength. What is important however is that they possess much lower densities. Fibre reinforced composites thus exhibit vastly improved specific properties, strength and stiffness per unit weight for example. The higher specific properties enable the production of lower weight components. The weight savings obtained in practice are not as great as Table 1 implies because the fibres are extremely anisotropic, which must be accounted for in any design calculations. In addition specific modulus (E/ρ) and strength (σ/ρ) are only capable of specifying the performance under certain loading regimes. Specific modulus is useful when considering materials for components under tensile loading such as, for example, wing support pillars (Figure 8).

Figure 8: Front wing pillars, loaded in tension.

The lightest component that will carry a tensile load without exceeding a predetermined deflection is defined by the highest value of E/ρ. A compression member such as a suspension push rod on the other hand is limited by buckling such that the best material is that which exhibits the highest value of $E^{1/2}/\rho$ (Figure 9).

Figure 9: Rear push rod – compression member.

Similarly, a panel loaded in bending such as a rear wing (Figure 10), will produce minimum deflection by optimising $E^{1/3}/\rho$. Nevertheless, weight savings of between 30-50% are readily achieved over equivalent metal components.

Figure 10: Rear wing, loaded in bending.

Designers of weight sensitive structures such as aircraft and racing cars require materials which combine good mechanical properties with low weight. Aircraft originally employed wood and fabric in their construction, but since the late 1930's aluminium alloys have been the dominant materials. During the last two decades composite materials have been increasingly employed for stressed members in aircraft. Composite structures are designed to have a precisely defined quantity of fibres in the correct location and orientation with a minimum of polymer to provide the support. The composites industry achieves this precision using "prepreg" as an intermediate product (Figure 11).

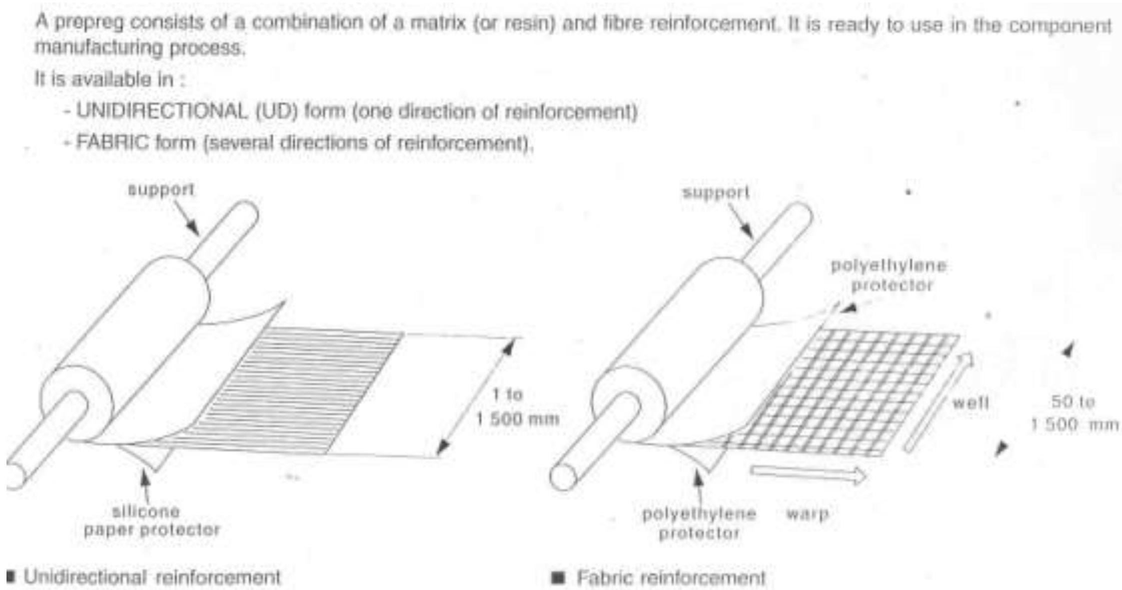

Figure 11: "Prepreg".

Prepreg is a broad tape of aligned or woven fibres, impregnated with polymer resin. A composite structure is fabricated by stacking successive layers of prepreg and curing under temperature and pressure. Many components consist of "sandwich construction"; thin, high strength composite skins are separated by, and bonded to, thick, lightweight honeycomb cores. The thicker the core, the higher the stiffness and strength of the component, for minimal weight gain (Figure 12).

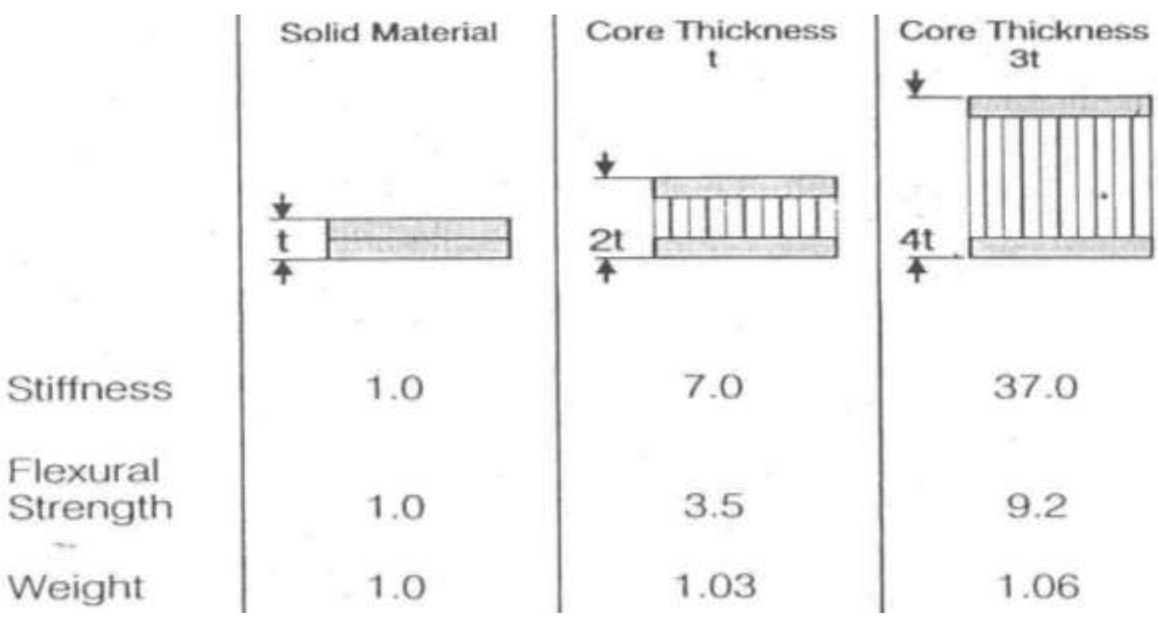

Figure 12: Optimising strength and stiffness using "sandwich structures".

Development of composite structures in Formula 1 racing.

The first documented uses of composite construction in racing cars date back to the late 1920’s and early 1930’s in the form of wood and steel chassis. These early vehicles tended to be home built and raced so there is very little documented data concerning their performance. It is most likely however that the use of wood as a chassis material was due in the main to cheapness and convenience rather than to enhance performance. Up until the early 1950’s the predominant method of formula 1 chassis construction consisted of a tubular aluminium space frame surrounded by hand worked aluminium body panels. At that time random orientation glass mat and polyester resins (Glass Reinforced Plastic) developed in wartime research became widely available. This material allowed the relatively cheap production of complex compound curvature bodywork which replaced aluminium. The use of GRP panelling continued right through to the late 1980’s.

The first truly composite chassis was built in the early 1960’s by Cooper cars. The structure consisted of a hand worked aluminium outer skin, an aluminium honeycomb core and a GRP inner skin. A single piece outer skin was produced from a number of panels to form the final aerodynamic surface of the car. The aluminium honeycomb core was then bonded to the inside of the outer skin using a phenolic resin film adhesive. The inner skin of GRP was similarly bonded to the structure in a separate operation. Although the car never actually reached the track, it was to become the basis of Formula 1 chassis design for the next two decades. In the mid-to-late 1970’s the preferred method of composite chassis construction used aluminium skinned, aluminium honeycomb material fabricated using the “cut and fold” method. The tubs were formed from pre-bonded sheeting which was routed, folded and riveted into the appropriate shape (Figure 13). The various teams involved later pre-formed the skins prior to bonding to the core using an epoxy film adhesive.

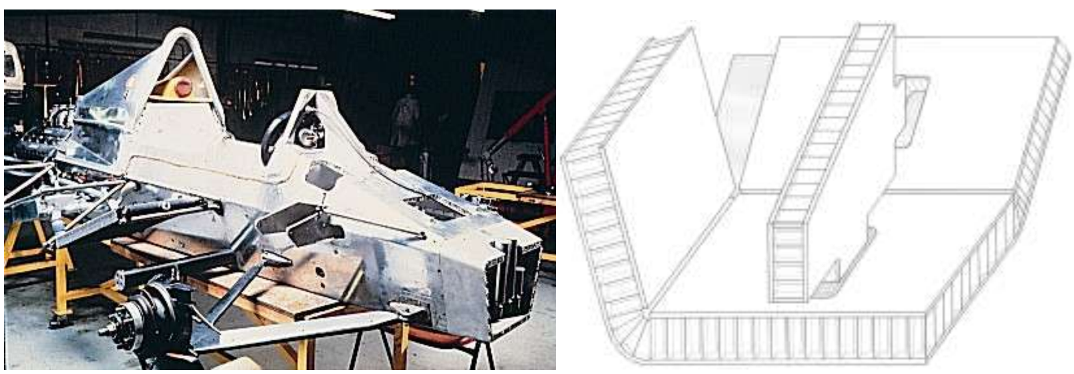

Figure 13: “Cut and fold” aluminium honeycomb chassis (late 1970’s).

Carbon fibre composite chassis were first introduced by the McLaren team in 1980 (3). They consisted of pseudo-monolithic arrangement laid up over a “male” mould or mandrel using unidirectional (UD) carbon fibre prepreg tape. The mandrel, made of cast and machined aluminium alloy, was dismantled for removal through the cockpit opening following an autoclave cure of the composite. A three stage cure was required: one for the inner composite skin, a second to cure the epoxy film adhesive which attached the honeycomb core and a third for a further adhesive layer and the structure’s outer skin. The basic design and manufacturing process remained essentially unchanged for a number of years and was still the basis of chassis construction at McLaren up until the 1992 season. There is some debate as to which team was the first to produce a fibre reinforced composite chassis since the Lotus team were carrying out similar research in parallel with McLaren. Unlike the former, the Lotus chassis followed the previous “cut and fold” methodology simply replacing the pre-bonded aluminium skins with a hybrid composite of carbon and Kevlar reinforced epoxy. As such they can be considered to have followed a “technological cul-de-sac” and the McLaren chassis must be recognised as the forerunner of those used today. In 1980 the reputation of composites with respect to impact loading was very poor as a result of problems experienced in aero-engine components in the early 1970’s and some dramatic in-service failures of early race car components. Indeed many designers of repute expressed grave doubts as to the suitability of such brittle materials in what is a highly stressed application. Despite the reservations of many of their competitors, the McLaren MP4/1, the first carbon fibre monocoque racing car (Figure 14) proved so successful that it was soon copied, in one form or another, by every other team.

Figure 14: The first carbon monocoque McLaren MP4/1 (1980).

The 1981 season became something of a "war of attrition" for McLaren with a number of cars being accidentally crashed several times during both testing and racing. It became clear that in addition to improved mechanical properties and lower weight of the composite chassis, the damage caused by accidents was constrained in the locality of the impact. Repairs could be executed quickly and effectively with little or no loss in performance. The ability to sustain and undergo repair to minor damage is all very well, but what concerned the designers most was the ability to withstand a major collision. At the 1981 Italian Grand Prix, John Watson lost control of his McLaren and smashed violently into the barriers. He was able to walk away from the debris unscathed (Figure 15). This incident went a long way to removing the doubts in the minds of those unconvinced of the safety of carbon fibre composites under high strain rate loading. As we shall see later, the energy absorbing properties of composites have made a great contribution to the safety record of the sport.

Figure 15: MP4/1 chassis following large impact.

The next major advance in chassis construction occurred in 1983 at one of the “lesser” teams. The German ATS team developed a tub fabricated inside female composite tooling. The two halves of the structure were made from woven fabric reinforced prepreg and joined at the centre line (Figure 16). Female moulding makes far more efficient use of the available aerodynamic envelope since only a minimum of secondary bodywork is needed to cover it. It also provides an opportunity to optimise the geometry and thus improve its structural efficiency. The BMW powered ATS was never a leading contender but generally considered to be one of the strongest and stiffest chassis on the circuit. This method of manufacture does however necessitate a join in the main shell and a great degree of laminator skill in order to produce a consistent, repeatable component. Developments in aerodynamic shaping, structural analysis and laminating techniques have ensured continuous development of the chassis and other composite pieces.

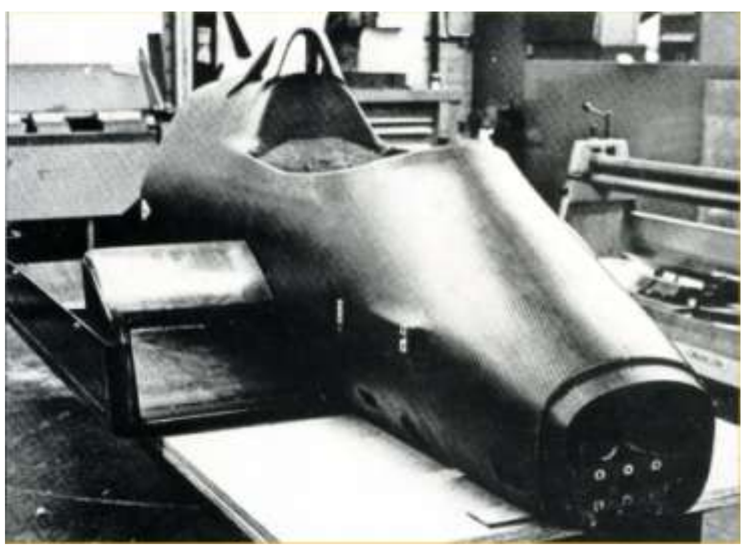

Figure 16: Female moulded ATS D6 (1983).

During the design of the MP4/1, McLaren used carbon composites wherever they offered advantages in mechanical properties or a reduction in complexity of design. Since that time there has been a continual process of metals replacement within the sport. In the early 1990's, Savage and Leaper from McLaren developed composite suspension members (4). Composite suspension components are now used by the all of teams (Figure 17).

Figure 17: Composite suspension.

In addition to the obvious weight savings, composite push rods and wishbones etc. have an almost infinite fatigue durability and so can be made far more cost effective than the steel parts which they replaced. The latest innovation was the introduction of a composite gearbox by the Arrows and Stewart teams in 1998 although the true potential of these structures was only fully realised from 2004 by the BAR-Honda team (5). Composite gearboxes (Figure 18) are significantly lighter than traditional alloy boxes, up to 25% stiffer, can be operated at higher temperatures and are easy to modify and repair. The design and logistics etc are not insignificant such that to this day they are not universally used on the F1 grid.

Figure 18: Composite gearbox.

Carbon fibre composites now make up almost 85% of the volume of a contemporary Formula 1 car whilst accounting for less than 25% of its mass. In addition to the chassis there is composite bodywork, cooling ducts for the radiators and brakes, front rear and side crash structures, suspension, gearbox and the steering wheel and column. In addition to the structural materials a number of "speciality" composites are also used. These include carbon-carbon brakes and clutches, and ablatives in and around the exhaust ports.

Materials Selection

Carbon fibres may be produced from three different precursor feedstocks, namely rayon, polyacrylonitrile and pitch. In the market place those produced from acrylic precursors hold an overwhelming dominance. As a general rule of thumb the modulus of carbon fibre increases with increasing heat treatment temperature (HTT) and the application of tension during the processing. This occurs because the fibres' morphology approaches a more graphitic crystal structure, preferentially aligned along the fibre axis as the HTT increases. Theoretically their strength and ductility also ought to improve by the same principle. In practice however the strength of polyacrylonitrile (PAN) based carbon fibres tends to reach a peak at HTT$\approx$ 1500^{o}C (E_{11} $\approx$270GPa) and then begins to fall. The reason for this phenomenon is the presence of flaws on the surface of the fibres known as "Reynolds' sharp cracks" which develop from the surface morphology of the original polymer fibres when spun in solution. Fundamental fracture mechanics suggests that removing the flaws or, at the very least, minimising their effect, will result in increased strength. Spinning the fibres in air rather than solvent removes many of these defects resulting in a smooth rather than crenulated surface. This has led to the development of a new class of "ultra-high strength" fibres by the major manufacturers.

There are literally hundreds of different PAN based carbon fibres commercially available. It is possible however to simplify this bewildering array of products in terms of 4 distinct groupings according to their modulus. The interrelationship between fibre properties and heat treatment temperature is illustrated schematically in Figure 19 and numerically in Table 2 using commercial examples. By far the most widely used group of products are those which are heat treated in the 1000-1400^{o}C regime. These fibres have a diameter of approximately 7µm and are known as "standard modulus". The group, which includes the market leaders T300 from Toray and AS4 from Hexcel, is used in aircraft structures, marine, land transport and a whole host of other applications. In Formula 1, composites reinforced using these fibres are not generally used in structural applications. Rather they tend to be employed in body work, as "flat stock" for making inserts or as tooling prepregs. The HTT regime between $\approx$1400-1800^{o}C produces high strength ($\approx$5µm diameter) "intermediate modulus" fibres. IM composites are relatively new and are only just beginning to achieve prominence in the aerospace industry due to long qualification lead times and increased costs. This group of products is widely used in primary structures throughout the F1 grid. In particular this includes T800 and IM7 from Toray and Hexcel respectively.

Heat treatment of the fibres beyond 1800^{o}C leads to "high" and "ultra-high" modulus fibres with fibre diameters of around 4.4µm. Commercially this class of material tends to be used in lightly loaded, stiffness critical applications such as satellites and high quality sports goods (golf clubs, fishing rods etc.). The main drawbacks of these products, which include Toray's M46J, M55 and M60, and UHMS from Hexcel, are high cost and dramatically increasing brittleness with modulus.

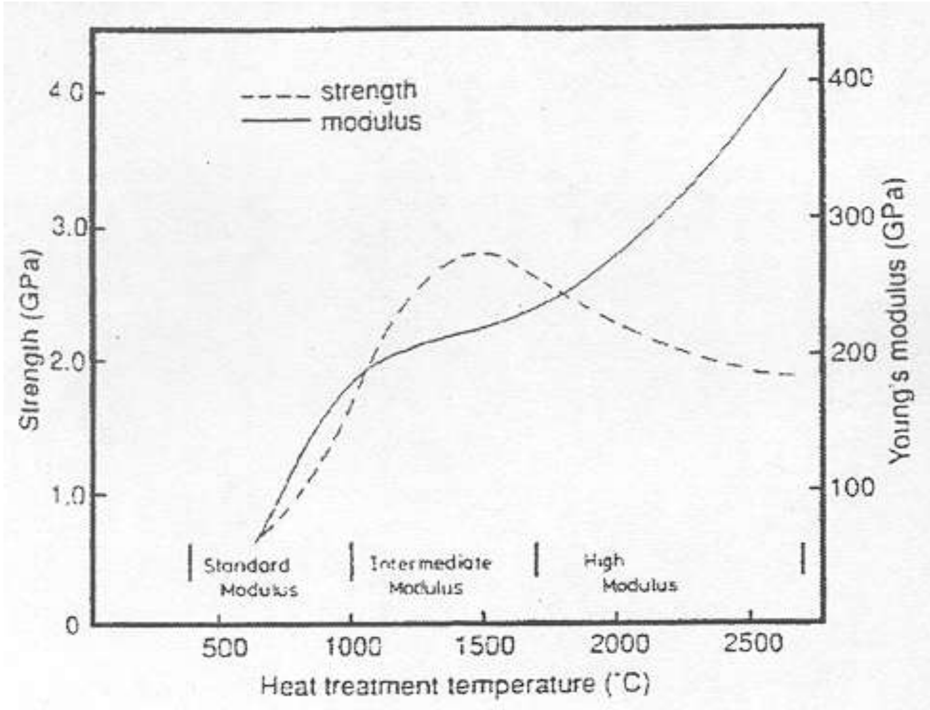

Figure 19: Relationship between heat treatment temperature and mechanical properties of PAN-based carbon fibres.

Fibre	Type	Fibre diameter (µm)	Approximate HTT (^{o}C)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Failure Strain (%)	Density (gcm^{-3})
T300	Standard modulus	7	1000-1300	3530	230	1.5	1.79
T800	Intermediate modulus	5	1500	5490	294	1.9	1.81
T1000	Intermediate modulus	4.5	1500	6370	294	2.1	1.80
M46J	High modulus	4.4	2350	4210	436	1.0	1.84
M55J	Ultra-high modulus	4.4	2500	3780	540	0.7	1.93
M60	Ultra-high modulus	4.4	2600	3920	588	0.7	1.94

Table 2 - Properties of carbon fibres.

"Ultra-high" strength fibres are a recently developed sub-division of the intermediate modulus grouping which have undergone a novel pre-treatment of the PAN precursor fibres. This results in a fibre diameter of 4.5µm rather than the 5µm more common to the normal IM grade. In this range Hexcel produce IM9 and Toray an equivalent fibre known as T1000. Both Fibres exhibit a failure strain in excess of 2%. The effect of using fibres of increasing strength and ductility is manifest as improved impact properties, in particular resistance to and tolerance of damage. Resistance to damage describes the ability of a material to sustain an "event" without resulting in damage. Damage tolerance alludes to the ability of the structure to maintain performance with damage present. This is a particularly important consideration with respect to driver safety. A car built in whole or in part from damage tolerant composites will be inherently safer since it is this property which contributes greatly to the integrity of the survival cell. The chassis must be able to sustain impact damage and protect the occupant, rather than disintegrate as is the case when high modulus, low strength fibres are used (6, 7).

The various heat treatments used in the manufacture of carbon fibres are extremely complex and those for different product groups tend to overlap. In that respect it is sensible to define the bands not in terms of HTT or individual products, but rather in terms of tensile modulus. We can thus define any carbon fibre as follows:

Standard modulus	up to 250GPa
Intermediate modulus	250-350GPa
High modulus	350-500GPa
Ultra high modulus	greater than 500GPa

Pitch based fibres differ from those made from PAN in that both strength and modulus increase with HTT throughout the range. Nevertheless, the modulus increases at a much higher rate such that ductility is significantly reduced as stiffness increases. Pitch fibres pass through a liquid crystal phase during pyrolysis (known as "mesophase") which aids crystallographic alignment. As a result they can achieve much higher modulus. They are however extremely expensive, very brittle and difficult to handle.

Three types of polymeric fibre have found use in racing car construction, these being "aramids", "Zylon" and highly oriented polyethylene filaments. Aramid fibres, known by their trade name "Kevlar", resemble inorganic fibres (carbon and glass) in terms of tensile properties but have much lower compressive strengths, lower density and considerably greater toughness. They can be formed into composites in the same way as carbon (hand lay up, filament winding, prepreg etc.) and have been traditionally employed to exploit their impact performance (particularly foreign object damage from stones etc.) and abrasion resistance. The development of higher strength intermediate modulus carbon fibres coupled with thermoplastic toughened epoxies, "stepped-bottoms" and wooden "planks" on the cars' floors caused Kevlar composites to become largely obsolete within Formula 1. The use of Kevlar is however compulsory within the structure of front wing end plates and other aerodynamic appendages at the front of the car. This is done with the aim of reducing the probability of tyre damage from sharp fragments of composite components damaged in impacts. Another aramid fibre in widespread use is the less oriented short fibre material known as "Nomex" which is employed in hexagonal core material. Zylon is an extremely strong fibre consisting of rigid-rod chain molecules of poly (p-phenylene-2, 6-benzobisoxazole) (PBO). An epoxy/Zylon appliqué armour panel must be fitted to the survival cell of each monocoque in order to prevent penetration and protect the driver from sharp-force injuries (Figure 20) (8).

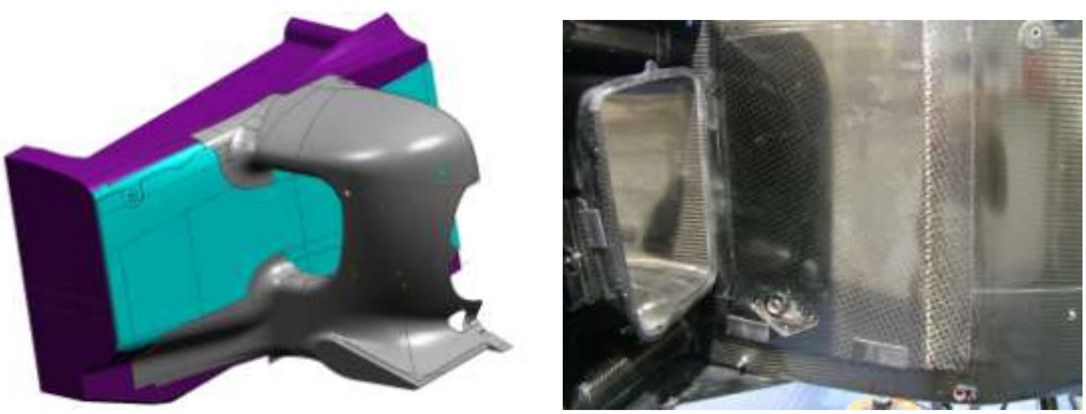

Figure 20: Zylon appliqué armour panel.

"Dyneema" and "Spectra" are the trade names for continuous filaments made of highly oriented polyethylene. Its high strength and very low density ($0.97gcm^{-3}$) give it specific properties far superior to most other structural fibres. The fibres cannot however be used at high temperatures. They melt at 133-136^{o}C and there is a progressive loss of preferred alignment, from which the advantageous properties are derived, above $\approx$90^{o}C. Furthermore, the oily surface finish associated with polyolefines often results in poor adhesion between fibres and matrix in composites. These are used on F1 cars from time to time in the form of hybrids co-woven with carbon fibres for use in the statutory impact structures. The aim is to exploit their high tensile strength to maintain the components' integrity during the event and thus optimise the controlled disintegration of the carbon and honeycomb which facilitates energy absorption. A carbon/Kevlar hybrid would perform a similar function but be less weight efficient.

The primary mechanical properties of composites (strength, stiffness and failure strain) are governed for the most part by the properties of the fibres, their volume fraction, orientation to the applied stress and their “architecture” within the structure. UD tapes offer the best translation of fibre properties because the fibres are not crimped or otherwise distorted as in fabric prepregs. Furthermore the resin content is by necessity higher in woven prepregs thus reducing mechanical properties due to a lower fibre volume fraction (V_f).

There are generally 3 reasons for the employment of woven products in composite structures: their ease of conformance to complex geometries (drapability), reduced manufacturing time and improved damage resistance. Unidirectional fibre tapes have negligible strength in the direction normal to the fibres. Any attempt to stretch them in that direction to conform to double curvature tooling would therefore lead to tape splitting. The answer to that problem is to select a woven product with sufficient “drape” to conform to the contoured surface. Fabric prepregs are generally significantly wider than UD tapes. It is thus possible to lay up larger areas without seams. If the fabric is close to being balanced, a single fabric ply will replace two orthogonal tape plies, thereby further reducing the amount of lay-up time.

A great number of variations in the properties of woven composites are possible by combining different yarns and weaves, allowing the designer a wide range of laminate properties. The fabric pattern, or construction, is an x-y co-ordinate system. The y axis represents the long axis of the fabric roll and is known as the warp direction. The x axis in the width of the roll is known as the fill or weft direction. A weave is described as “balanced” if the same yarn and weight are used in both directions. There are basically three styles of weave used in the composites industry. They are the plain, twill and satin weaves. The plain weave consists of the warp and weft yarns going over and under one another, resulting in an equal amount of each on either side of the fabric. The curvature, or deformation, arising as a result of the weaving is known as crimp. The application of a tensile load in the plane of the fabric will tend to straighten out the crimp, manifesting itself as a reduction in strength and stiffness when compared to a unidirectional tape of the same material. An obvious way to increase the fabric’s stiffness is to reduce the amount of crimp by having the fibres as straight as feasible. Twill weave is a variation of the plain weave in which the warp and weft yarns are paired, 2 up and 2 down (or 4 up and 4 down). Satin weaves are a family of constructions with a minimum of interlacing. In these weaves the weft yarns periodically skip over several warp yarns. The length of yarn between the crimped intersections is known as the float. The numerical value preceding the “HS” descriptor is always one greater than the number of warp yarns over which the weft yarn passes before crimping under a single warp yarn. The weaves obviously appear different depending on which side is viewed. When laying them up in laminates it is necessary to make a complete description to include whether each ply is laid warp or weft face up. A schematic diagram of some of the more commonly used weaves is given in Figure 21.

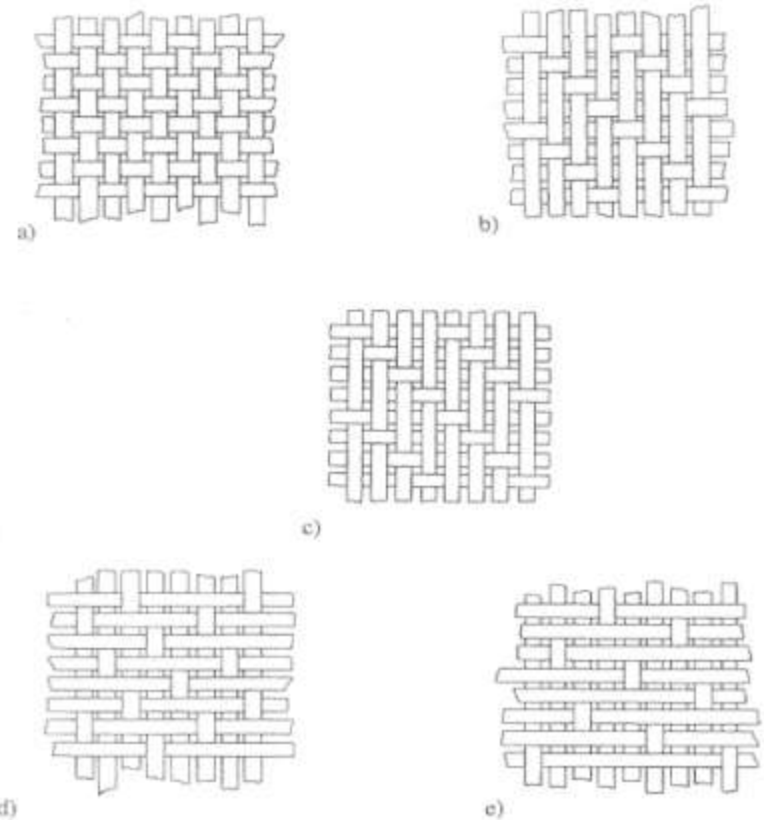

Figure 21: Fabric styles commonly used in composites:
a) plain weave; b) 2x2 twill; c) 4x4 twill; d) 5-harness satin; e) 8-harness satin.

Great care must be taken to ensure that composite structures are laid up in such a way as to balance the laminate as near as possible about its neutral axis to prevent pre-stressing. This is particularly true of laminates employing UD materials either in whole or in part. Honeycomb structures should be designed in such a way that the skins themselves are balanced in addition to the entire structure being symmetrical about the core. Despite their widespread use, the mechanics of woven fabrics is very poorly understood irrespective of the weave style. The plain weave exhibits the greatest degree of stability with respect to yarn slippage and fabric distortion. High harness satin weaves on the other hand possess improved mechanical properties as a consequence of there being fewer fibre distortions at cross-over points. Also, since the movement of fibres is less restricted, satin weaves are more drapable but at the expense of reduced energy absorption and fabric stability. This is because the greater the number of cross-over points, the greater will be the energy transference to adjoining fibres. High harness satin fabrics (i.e. greater than 5) can only be produced using 1 and 3K fibre tows (yarns) i.e. 1000 and 3000 fibres per bundle. IM fibres are only produced in 6 and 12K tows thus restricting the styles of fabric into which they can be woven. As a reasonable generalisation, the 2x2 twill weave offers the best compromise between the various conflicting factors which govern choice of weave.

The resin matrix phase serves to bind the fibres into the structure and protect them from mechanical and environmental damage. The primary mechanical properties are dominated by the reinforcement (fibres) whereas the matrix contributes significantly to secondary properties. Laminated structures are typified by poor out of plane performance. As a result they are particularly sensitive to impact damage. Toughened resin systems have been developed in order to increase the work of fracture in the interply region. This is achieved using a blend of resins which bring about enhancement of the fracture process zone. Essentially tough thermoplastic polymers and oligomers are used to blunt and deflect cracks propagating in the interply region. Toughening of low temperature (120^{o}C) curing resins is relatively simple whereas improving 180^{o}C curing resin systems is extremely difficult without adversely affecting mechanical properties and/or processability. 120^{o}C curing resins are cheaper and easier to process than the 180^{o}C curing systems which are used to allow higher component operating temperatures by virtue of their increased glass transition temperature (Tg). Recently a number of prepreg suppliers have developed 135^{o}C curing prepregs which combine the ease of processing of the 120^{o}C curing systems with more than adequate temperature performance and are therefore ideal for Formula 1 use.

In the production of the race cars the aim is to keep the number of composite materials to a minimum. This enables a tighter control on logistics and quality control, and allows for a more complete understanding of their properties. Materials selection is defined by a "rolling specification". The incumbent in each materials class is used to define the property requirements. Should a new material prove superior, following extensive testing and trials, it will simply replace the old one. The aim is for the highest possible stiffness and strength whilst maintaining an acceptable minimum value of impact related properties (strain to failure, damage tolerance, matrix toughness etc.) as defined by testing and experience. Anisotropy of fibre composites means that a complete structural characterisation of a composite material requires far more property definition and data collection (Table 3) than is necessary for metals and alloys. The properties of fibre reinforced composites are also statistically complex such that one measures a distribution of properties rather than a discrete value. Unlike metals, composite production requires the carrying out of a complex chemical reaction, the cure. The successful execution of the cure is vital in determining the properties of the composite. Finally the properties of the composite are particularly sensitive to fibre alignment.

E_{11T} E_{11C}	Tensile, Compressive Modulus, Fibre Direction
E_{22T} E_{22C}	Tensile, Compressive Modulus, Transverse Direction
G_{12} G_{23} G_{31}	Shear Modulus
ν_{12}	Poisson's Ratio, In-Plane
σ_{11T} σ_{11C}	Tensile, Compressive Strength, Fibre Direction
σ_{22T} σ_{22C}	Tensile, Compressive Strength, Transverse Direction
τ_{12}	In-Plane Shear Strength
ILSS	Interlaminar Shear Strength
σ_b	Bearing Strength
ρ	Density
t	Ply Thickness
T_g	Glass Transition Temperature
G_{1C}	Strain Energy Release Rate
SEA	Specific Energy Absorption

Table 3 - Mechanical properties required to fully characterise a fibre reinforced composite material.

Design Process

The media will often refer to the "designer" of the car as though it were the product of a single individual. In reality it is more likely the result of the combined efforts of 30 or more people, each having responsibility for a particular specialisation. Aerodynamicists are sometimes singled out because the external shape of the car is its most obvious feature. Arguably the most difficult job is that carried out by the Team's Technical Director who must lead the design team towards the best compromise on what are often conflicting requirements. The design of a new car begins with concept studies. Nowadays this is an ongoing iterative process involving constant wind tunnel testing. The project definition phase usually occurs during the late summer and involves finalising the general configuration of the major car components. Computer Aided Design (CAD) facilities are used to generate the "electronic master" of the external geometry, optimise the suspension dynamics and organise the internal packaging of the layout. Computer Aided Manufacturing (CAM) software uses this geometry database to produce cutter path information for the machining of metal components and production of the master patterns for composite parts. When they are complete, moulds are taken from the patterns ready for the start of component production. While these activities are in progress, detail design of the structures and bodywork will continue.

The design of the monocoque is extremely complex as a consequence of the multitude of forces acting upon it. As the central element of the car all of the other load bearing structures are directly attached to it. Forces are fed in through the front suspension as the car responds to circuit perturbations and driving manoeuvres; loads are similarly fed in through the engine and gearbox/rear suspension assemblies. Aerodynamic loads are fed in via the wings and floor and there are even forces from within due to the g-forces from the driver on his seat and safety harness mountings. The car must resist the various forces effectively if it is to contribute to the overall performance of the car. It is necessary therefore to design sufficient stiffness into the chassis to minimise deflection under load. The prerequisite is for torsional rigidity to resist twisting loads (3). At the same time there is a requirement for beam stiffness to resist lateral or longitudinal bending loads, and local reinforcement at the points where loading feeds in directly (suspension pick-ups etc.). A further design obligation is impact resistance. The chassis needs to be strong enough to protect the driver in the event of an accident, and must be proved so by passing the FIA's statutory safety tests (7).

The complexity of its geometry and the materials used result in the chassis structure being difficult to analyse. The present designs are semi-quantitative combining of experience and evolution with Finite Element Analysis (FEA). Breaking down the structure into a finite number of elements on a computer enables analysis of its behaviour under the influence of a wide variety of loading regimes. Once an analysis has been completed the results are displayed in graphical form, with values colour co-ordinated to aid interpretation (Figure 22). The deformations of a component under load can be represented in such a way that extremely small movements are artificially exaggerated, making it easier to identify the areas where reinforcement is required. However sophisticated the computer analysis however, the software makes a number of assumptions and estimations on the true behaviour of the structure and materials behaviour. It is paramount therefore that the FEA is carried out in parallel with mechanical testing of representative coupons and components to verify the results before committing to final lay up (9).

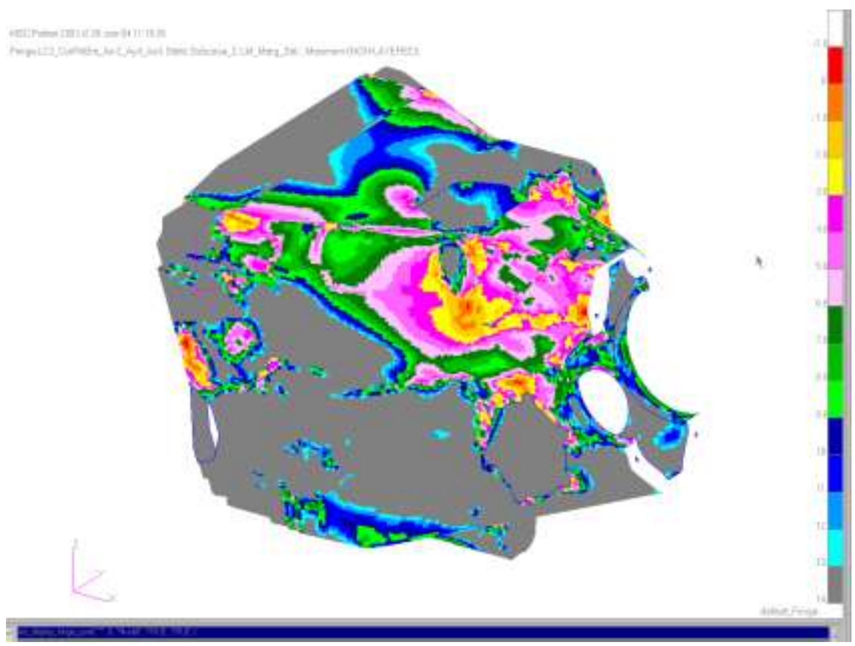

Figure 22: Gearbox finite element analysis.

The loading on a Formula 1 car is now better understood than ever before. On-board data logging equipment linked to transducers provides a sound basis for the data to be used in the design of the structure. These, together with the FIA test loads define the basic requirements for strength and stiffness. Beyond this it is always necessary to design for the highest strength situation. One certainty in motor racing is that cars will at some time crash. The use of FEA enables a reduction in weight of the various components by lowering the margin for error needed in the design procedure. Furthermore stress concentrations likely to result in structural failure can be identified and eliminated. It cannot be emphasised too strongly however that whilst the computer stress analysis is a very useful tool, its results must be backed up with a reliable test programme to overcome any of the technique's shortcomings (Figure 23). Failures are generally down to small aspects of detail design and materials selection rather than inadequacies in the overall concept.

Figure 23: Strength, stiffness and durability testing on a composite gearbox and rear suspension assembly.

There is a potential conflict between the need for stiffness and the requirement for impact resistance since the higher the stiffness of the fibres used the less resilience they have. This conflict is resolved by using a combination of fibre types and, where possible, defining a smoothly flowing shape avoiding sharp corners and joggles which act as stress concentrations. A further potential conflict arises because aerodynamic considerations play a key role in defining the shape of many of the cars' components, so a design compromise must be reached. The chassis' inner and outer skins typically consist of a number of "general plies" oriented at $\pm 45^{o}$ to provide torsional stiffness. In regions where greater strength or rigidity are required there may be significantly more material with fibres oriented so as to most efficiently react the loads. The lay up of the area directly surrounding the driver is required to afford protection from "sharp-force penetration". As such it must correspond to the lay up of a control panel which has passed an official test (8).

The structural arrangement of the chassis is such that the outer shell is reduced to the minimum number of parts. Generally this consists of two: a top and bottom section. Bulkheads are positioned so as to feed suspension point-loads into the structure and enclose the cockpit bay. Engine mounting studs fit into solid inserts bonded within the honeycomb shell. The gearbox may be considered as the "rear chassis" such that the same design considerations as for the monocoque apply (except for the anti-penetration requirement). Composite gearboxes are generally thin monolithic shells with metallic or composite transverse bulkheads which impart stiffness and carry the "working parts". Bodywork components, the engine cover and side-pods, and the cooling ducts, require good, accurate aerodynamic surfaces, moderate stiffness and minimum mass. Sandwich construction and low density materials such as carbon composites provide an ideal solution for these parts. The floor presents a greater design challenge in that it is required to fulfil a range of different tasks. It forms the mandatory bottom of the car between the wheels whilst performing as an aerodynamic device generating sizeable quantities of down-force. Impact is also an obvious criterion as is vibration tolerance. In common with the chassis, wing structures need to exploit the specific stiffness and strength characteristics of carbon/epoxy laminates, minimum deflection under load being required and tolerance of a high degree of vibration. The accuracy of a wing's profile is crucial to its performance. Prepreg moulding techniques accomplish this very well. Suspension components undergo loading in predetermined directions and so are ideal for exploiting the anisotropy of composites.

Linking design to production.

When designing a component from composites it is never sufficient to consider the finished item alone. It is always necessary to think about how it will be manufactured in terms of the lay-up through the mould design stage and back as far as the configuration of the master pattern. It is very often necessary to seek a compromise between the simplest way to produce a part and the most elegant design configuration. Components are formed by stacking layers of oriented prepreg into a mould prior to curing under heat and pressure in an autoclave (Figure 24). Composites are particularly demanding with respect to optimisation and process control since there are so many potential variables. Parameters such as ply thickness, fibre type, ply orientation, matrix materials and the number of plies present F1 teams with an almost infinite variety of possible combinations for achieving a wide range of mechanical performance.

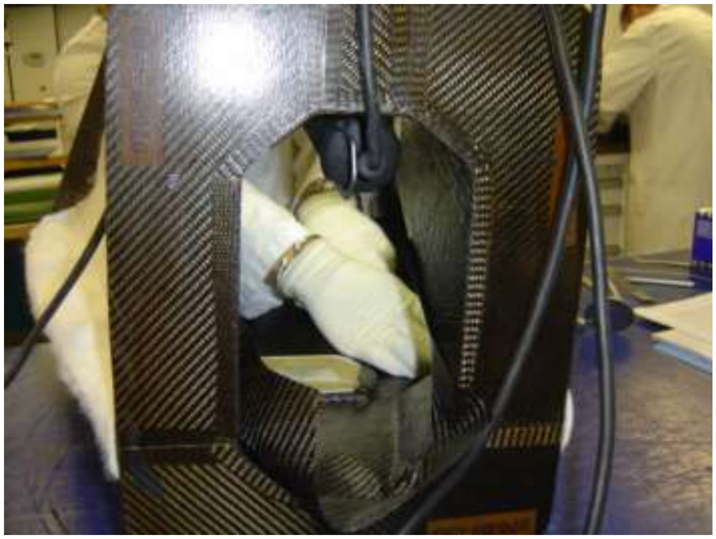

Figure 24: Hand laminating with pre-preg.

One of the most difficult tasks facing the composites design engineer is creating accurate design documentation to enable the conversion of flat-sheet raw material into a complex double curvature component. This becomes even more challenging as changes are made to the design. A recent trend has been the use of optimisation software tools which augment the CAD software to provide a seamless link from the 3D CAD model to the manufacturing floor. Composites application software is able to automatically generate material tables, sequence charts, ply lay-up protocols and lay-up diagrams. As changes are made to the design, the documentation can be automatically updated to accommodate those changes, shortening lead times and preventing mistakes. The overall aim is to simplify the production of components essentially providing a simple set of instructions akin to those used to assemble a hobby model kit in order to guarantee continuity and reproducibility of manufacture. The software allows for the direct translation of compound curves into flat patterns and is able to drive CNC cutting machines which produce a kit of parts ready for assembly (Figure 25).

Figure 25: Pre-preg cutting and materials management.

It is also able to provide manufacturing “alerts” during the design phase. Potential problems which may arise include regions where material deformation will cause wrinkles or a ply exceeds available material width etc. Such practical feedback during design supports a concurrent engineering methodology and enables fast and efficient re-design long before the production phase. One particularly beneficial aid is the use of what are known as “ply books”. Complex constructions are broken down into simple ply by ply steps presented, as the name suggests, in a book format. Each page of the book represents a single ply in the lay up and contains all the information required (material, shape details, start and finish points etc.) to enable an efficient sequential assembly. An example page from a ply book for the manufacture of a composite engine airbox is shown in Figure 26. Originally these books were produced by a separate operation once the design was complete. Nowadays they tend to be produced (and updated automatically when necessary) by the optimisation software package. A recent innovation in the aircraft industry uses laser projection equipment to visually indicate the position of each ply or insert on the surface of the mould tool (Figure 27).

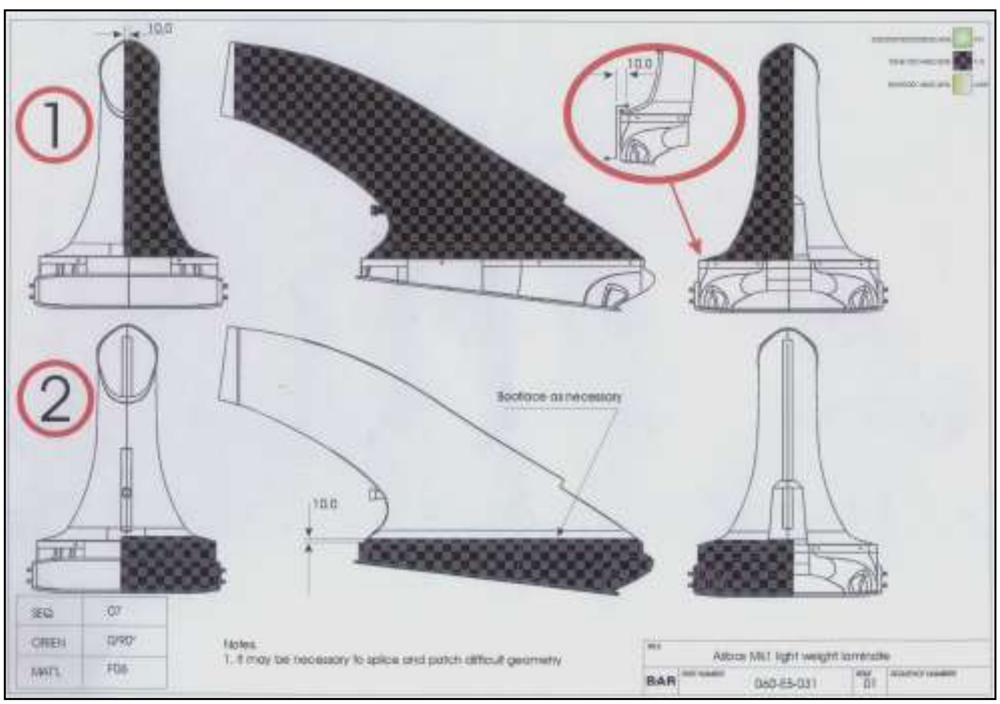

Figure 26: Example page from a ply book.

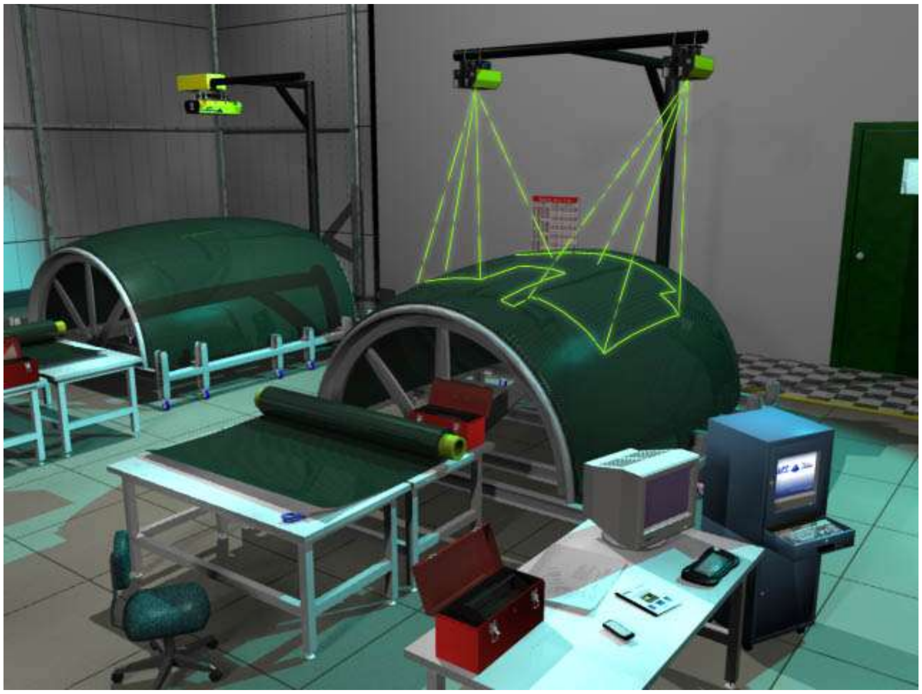

Figure 27: Laser projections to aid ply placement.

Component manufacture

Before the components can be produced, a full sized pattern must be produced for each part. The patterns are used to make moulds into which the composite plies are laid up. The most common method for the production of the patterns begins with the appropriate data from the CAD system being fed into a 5-axis CNC milling machine. The milling machine cuts the patterns from a tooling block material (generally a solid epoxy resin containing glass micro-spheres) (Figure 28).

Figure 28: Cutting master patterns.

As supplied the slabs of tooling material are only 50mm deep so the larger patterns must be made by stacking and gluing several slabs together. When the cutting process is complete the patterns are rubbed down by hand using “wet or dry” silicon carbide abrasive paper. This operation, known as *shaping*, ensures that the interfaces between adjoining patterns are blended together and removes any machining marks left by the mill. A coat of epoxy paint is then applied to the moulding surfaces to seal and protect them (Figure 29). Finally the patterns are checked for accuracy using a 3-axis digitising machine.

Figure 29: Finished patterns prepared for moulding.

The moulds from which the composite components are made are produced by laying up a carbon epoxy “tooling prepreg” on the patterns to form a reflected image of the final part (Figure 30). The laminating process followed for the moulds is identical to that employed when making components except that they are always single skins unlike many of the parts made from them which are often honeycomb structures. The tooling prepregs contain a specially formulated epoxy resin which cures at a relatively low temperature of 60°C or less. This is done in order improve the accuracy of reproduction by avoiding heat expansion and distortion in the patterns. Moulds are conventionally made 10 plies thick. The outer and inner skins (i.e. the moulding surface) are made from a 200gm^{-2} 2x2 twill weave fabric (T300 fibres) whilst the bulk of the mould (8 plies) is made from a 650gm^{-2} 2x2 twill weave fabric. Larger moulds, such as those for the chassis and the bodywork, require stiffeners and must be supported in fabricated metal cradles to prevent them from distorting under their own mass. Following the cure, the moulds are post cured in a programmable oven to increase the glass transition temperature of the resin. A typical post cure cycle would involve heating the mould from ambient to 200°C at a rate of 20°Chr^{-1} followed by a 15 minute dwell. The oven is then cooled to 190°C and the mould held at that temperature for 8 hours. It is then allowed to cure back down to ambient at a rate of 3°Chr^{-1} maximum. It is important to note at this point one of the most significant advantages of composite fabrication; the tooling is extremely quick to produce (3 days or less if time scales are tight) and, more often than not, is less expensive than a single unit of the parts made from it. This is particularly advantageous when the production run is small. In certain applications CNC machined aluminium moulds are used for expediency or a one-off component may be taken directly from tooling block, but composite moulds are generally preferred because their resistance to distortion and expansion during the curing cycle produces a more accurate component.

Figure 30: Composite engine cover mould.

Prepreg lay-up of the composite parts is accomplished by hand and follows accepted practices and procedures. Plies are laminated to the orientations specified in an appropriately configured mould, a vacuum bag is applied and curing takes place in an autoclave to the recommended cycle. The laminating operation is carried out in a controlled environment under *clean room* conditions. The laying up of the prepregs within the moulds is a meticulous process, in which highly skilled and experienced operators must closely follow the documentation provided by the design engineer. The labour intensive nature of the laminating process is one of the main drawbacks of composite materials. Large aircraft panels, of relatively simple geometry, are often laid up automatically using CNC tape laying machines but small, intricate F1 pieces can only be done by hand. It is essential, when laying up the prepreg, that the material conforms to the contours of the mould and does not bridge any of the corners or other surface features. To achieve this it is sometimes necessary for the laminators to warm the prepreg with hair dryers to lower the viscosity of the resin and improve its drapability. In addition to hair dryers, the tools of the laminators' trade include surgical scalpels and spatulas to work the materials into and around the features of the mould or tooling block, taking care to minimise any air trapped between the plies. Adjoining pieces of prepreg are overlapped to create a completely integrated structure. The kit of prepreg pieces supplied to the laminators is generally cut slightly oversized so that they can be trimmed to create precisely the correct amount of overlap.

After the first two or three plies of the component have been laid up in the mould, steps are taken to ensure that they are compacted together and that they follow the contours of the mould. This process, known as *consolidation and de-bulking* is carried out by applying a carefully tailored vacuum bag and subjecting the work piece to a combination of vacuum and a moderate temperature rise in the autoclave. A layer of polyester fabric, with a consistency rather like cotton wool, known as *breather* is sandwiched between the outer layer of prepreg and the bag to allow for controlled removal of the trapped air. A non-stick film known as the *release layer* is placed between the breather and the prepreg to prevent the two from sticking together. The process is repeated several times as the laminate is built up, with a final de-bulk carried out under pressure prior to curing. An aluminium plate, known as a *caul plate,* is some times used to bring a more direct and uniform pressure onto the lay up, although this is optional.

When all of the plies have been laid up and the final pressure de-bulk completed, the assembly is enveloped in a new vacuum bag and returned to the autoclave for curing. A schematic representation of the various layers in the "curing assembly" is shown in Figure 31.

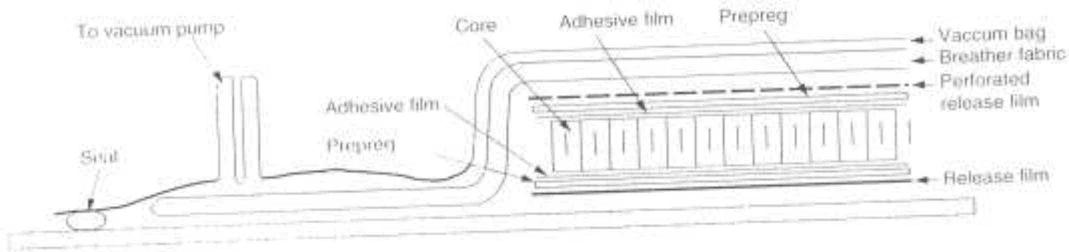

Figure 31: Composite curing assembly.

Hollow sectioned components such as wings and suspension pieces are consolidated using the *internal pressure bag* technique. Pressure bags also involve the use of vacuum but are more complex, applying additional pressure to the assembly through an elastomeric bag. The bag is open to the autoclave gas ensuring isostatic pressure on the mould tool. A variation on this theme involves the use of a solid metallic or elastomeric mandrel. Consolidation pressure is generated by the thermal expansion of the mandrel against the mould and laminate. Great care must be taken with this method since the pressure generated is not the same as the autoclave gas. It is very easy to make the mandrel too small and have poor consolidation, or too large creating a huge pressure which can damage the mould. Single skin components are cured at 7 bar pressure at the recommended temperature for 1 to 2 hours. Sandwich constructions are cured in two or three stages, the first skin being cured at full (7 bar) autoclave pressure and the subsequent film adhesives, honeycomb core, inserts and inner skin cured at a pressure safe for the core (typically 3.5 bar) (Figure 32).

Figure 32: Autoclave cure.

Points where bolts and other fasteners pass through the honeycomb core are locally reinforced using *inserts*. Inserts are solid composite or metallic pieces which are supplied to the laminators pre-cut and are positioned in predetermined cut outs in the honeycomb core. The inserts serve to spread point loading over a larger surface of the composite and thus reduce stress concentrations. They also prevent the bolts etc. from moving under load which crush the honeycomb core and ultimately fracture the composite skin. The layer of aluminium or aramid ("Nomex") honeycomb material sandwiched between the two skins varies in thickness depending on the structural design. A film adhesive is applied between the skins and the core creating a strong bond when cured.

The majority of structures are assembled by adhesively bonding a number of parts together. Adhesive bonding is a particularly effective method of assembling complex structures, especially those made from different materials. Provided the joint is well designed, the adhesive bond ought to be one of the strongest aspects of the structure and most certainly should not be the life limiting factor. This of course pre-supposes that the joint has been correctly executed. The major factors determining the integrity of an adhesive bond are selection of the most appropriate adhesive, joint design, preparation of the bonding surfaces and strict quality control in production and condition monitoring in service. Adhesives have become increasingly important in assembling many of the multi-material structures which make up a contemporary Formula 1 racing car (10). Before the main chassis is "closed" by bonding the top and bottom, the two internal bulkheads are bonded in with an epoxy paste adhesive. One is the "seat back", a sculpted sandwich panel located directly behind the driver's seat, forming a partition between the fuel cell and the cockpit, and the other is the "dash" bulkhead positioned slightly forward of the cockpit aperture, through which the driver's legs pass (Figure 33). *Finishing* of the components generally involves drilling and tapping etc. the various holes used for attachments. The holes are drilled on a 5-axis CNC milling machine using data supplied by the CAD model and are used, in the case of the monocoque for example, for the fitting of suspension pick-ups and bodywork etc.

Figure 33: Chassis assembly.

Design and production resources

Over the years teams have increased in size as a reflection of the greater amount of engineering fed into the project. A competitive team such as Honda employs a total of around 650 staff to cover all aspects of car design construction and operation, with the exception of the engines and other bought-out items. The workforce engaged in composites design and production amounts to around 140. Factory floor space given over to composites is of the order of 1100m^2 while curing facilities include 3 autoclaves and 5 air-circulating ovens. In the past the car was designed by a small number of people in a short period of time and, by necessity, decisions were made more upon instinct than lengthy analytical investigation. Time-scales remain the same but the larger number of people involved indicates the increased extent to which science forms the basis of the design. Parts have become more complex and of higher quality. As a consequence the workload in both design and production has grown in volume. The time period from project definition to the first running of the complete vehicle is around 5 months and requires in excess of 80,000 man hours of design time. The need for good project management is therefore self explanatory. The quantity of parts produced varies according to the anticipated rate of attrition for individual components either through obsolescence as the car develops or damage. Outside of the initial "panic" period leading up to the first race, the aim is to produce a steady flow of parts as and when they are required. Having said that, the production staff need to be extremely flexible in their ability to react to unpredictable events. Whilst the Grand Prix calendar and circuit test programme impose a periodicity upon development and production, unforeseen accidents at either could result in the need to organise a very rapid programme of repair and replacement (11).

Safety and survivability

The area of crash safety allows us to explode another of the myths surrounding composite materials, that they have poor impact performance. The mechanisms which would occur during the destruction of a metallic race car chassis may be illustrated by considering the axial collapse of a thin walled metal tube under impact. Following an initial peak load, which initiates the process, energy will be absorbed as a result of the work done in the formation of plastic hinges which develop progressively along the tube (Figure 34). This may be demonstrated quite simply by stamping on top of a soft drinks can and then trying to imagine what it would be like to be in it at the time!

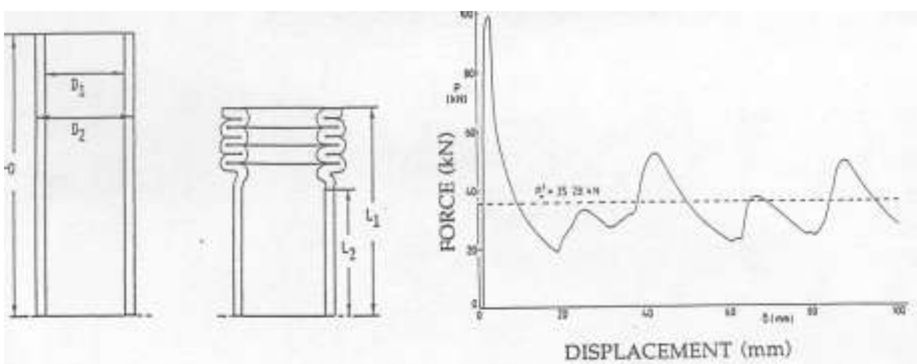

Figure 34: Energy absorption by metallic structures.

In contrast the failure of a composite chassis does not involve plastic deformation. The immense stiffness of a carbon fibre monocoque is such that its elastic limit will not be exceeded. This high stiffness serves to transmit the load from point of impact further into the structure with the result that higher loads can be absorbed without permanent damage Once the load in the locality of the impact has exceeded the absolute strength of the laminate, failure in that area is total as the composite progressively tears itself to pieces (Figure 35).

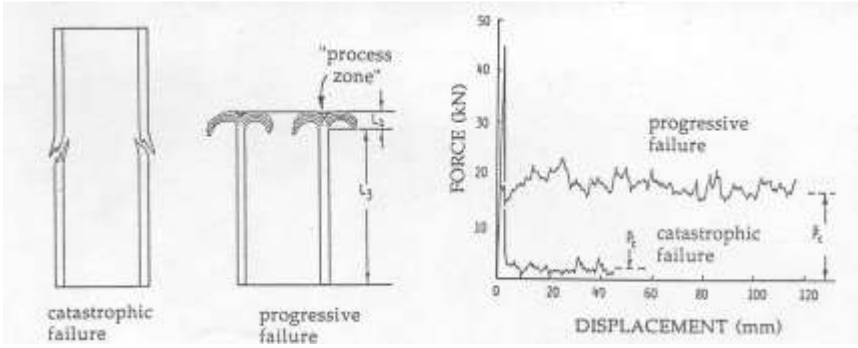

Figure 35: Energy absorption by composite structures.

The energy absorbing properties of composite materials may be described in terms of "work of fracture" which arises from the mechanisms occurring during failure. The inherent brittleness of composites ensures that they do not undergo the yield process characteristic of ductile metals, but, on the application of load, deform elastically up to the point of fracture. A number of modes of deformation are available to complex multiphase composite materials.
The primary energy absorbing mechanisms in fibre reinforced plastics are:

1. Cracking and fracture of the fibres
2. Matrix fracture
3. Debonding (pull out) of fibres from the matrix, and
4. Delamination of the layers making up the structure.

A composite body thus disintegrates both structurally and microscopically during an impact event. The core material in aluminium honeycomb cored sandwich structures also adds to the energy absorbing mechanism. Referring to our original analogy, metal honeycombs may be considered as a large array of small soft drinks cans which squash and absorb energy on impact. Once the mechanisms by which composites dissipate energy have been discerned, steps may be taken to engineer the structure to improve driver survivability. The energy absorption properties of composite cars have dramatically improved the safety record of Formula One. It is now fairly commonplace to see drivers survive crashes that previously would almost certainly have claimed their lives. The fatal accidents of the 1994 season showed however that the sport can never be made 100% safe. In order to minimise the risk to drivers and spectators, the FIA require that each car built by the teams must pass a stringent set of safety tests. The tests are upgraded every year as the knowledge of structural design improves and following survivability research carried out by the governing body's medical team. The tests consist of a number of static loads applied to the survival cell to verify its integrity, and impact tests on mandatory front (nose box) rear and side impact structures (Figure 36). The tests must be carried out in the presence of an FIA official. There must be no damage to the survival cell and, in the case of the impact tests, the magnitude of deceleration must be within the limits set by the medical experts as being survivable. Driver survivability relies upon the chassis behaving as a survival cell (essentially a suit of armour) protecting the driver from the impact whilst the energy absorbing structures dissipate the kinetic energy and limit the load transmitted into the monocoque and driver (7).

Figure 36: FIA nose crash test.

Summary

From the outset, motor racing teams have striven to exploit leading edge technology in their quest for victory. Formula 1 stands at the very pinnacle of the sport in terms of popularity, funding and technology. Over the last three decades the sport has developed into a multi-billion dollar business commanding immense global coverage. The major teams now operate on budgets of the order of several tens of millions of dollars as they prepare to "do battle", via the global media, witnessed by a significant proportion of the world's population. An increasing percentage of the teams' budgets are invested in new technology. The extent of this investment has been so great that cynical observers have dubbed the sport "the search for the unfair advantage". Joking aside, the aura of state-of–the-art science and engineering adds much to the allure and increasing appeal of the races. The introduction of fibre reinforced composite chassis was one of the most significant developments in the history of Grand Prix motor racing. Technological advances gained from these advanced materials have produced cars that are lighter, faster and safer than ever before. Composite materials can only be exploited to their full potential if one understands the complete process from raw materials until components are withdrawn from service. The key to success is the ability to obtain the optimum solution to the package of pilot, engine, tyres, aerodynamics, technical innovation and reliability. Composites materials science and engineering has had a significant, often pivotal, roll in the development of Formula 1.

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