EXPLOITING THE FRACTURE PROPERTIES OF FIBRE REINFORCED COMPOSITES TO ENHANCE THE SURVIVABILITY OF FORMULA 1 RACING CARS

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Abstract. The changeover from aluminium alloy to carbon fibre chassis precipitated a degree of anxiety within Formula 1 with respect to the ability of such brittle materials to protect the driver in the event of a crash. The reality of the situation however was that composite racing cars afford vastly improved crashworthiness with compared to their metallic predecessors. Much of the sport's improved safety record in recent years derives from the controlled fracture behaviour of composite materials. Research and understanding of the impact and fracture behaviour of these materials has enabled the designing of a sophisticated driver protection system into the vehicles' structure at minimum weight penalty. The chassis itself has evolved into a "survival cell" capable tolerating damage from minor incidents and preventing intrusion of foreign objects, whilst at the same time being capable of protecting the driver in the event of a major impact. Coupled with this are specialised structural devices designed to absorb vast amounts of energy by controlled fracture and disintegration.

1. INTRODUCTION

Despite motor sports being just over 100 years old, until the late 1960s little was done to protect the participants from serious or fatal injury (1). Up until that time the drivers raced largely as amateurs and the major automobile manufacturers considered the sport to be an R&D rather than a marketing exercise. As a consequence, death and injury were considered and acceptable risk of participation. Towards the end of the 1960s the changing attitude of the public towards road safety coincided with the drivers becoming highly paid professionals, precipitating a campaign for greater safety in all forms of motoring. If we define "serious injury" as one that prevents a driver from finishing a race, in the 1960s the rate of fatal and serious injury within Formula 1 was 1 in every 8 crashes. The first steps taken were to reduce the risk of fire, the introduction of circuit safety structures such as run-off areas and safety barriers, protective clothing and 6-point harness systems, and the standardisation of signalling and marshalling procedures. Throughout the 1970s a constant string of safety measures were introduced including structural specifications for chassis, specialist medical trauma centres at the circuits and graded driver licences. The effect of these measures was to reduce the ratio of serious injury by a factor of 5, to 1 in 40 crashes. The period between 1980-92 saw a further impressive (6-fold) decline in fatalities and serious injuries per accident to less than 1 in 250 (2). Achieving this large reduction required research into all aspects of motor sport influencing safety so that action could be taken to minimise the threat to participants and spectators. The greatly improved safety record of Formula 1 in the 1980s and beyond is a great credit to the co-operation between the sport's governing body, the FIA. and the race organisers and participants. Having said that, had it not been for a radical change in the materials from which the cars are made in 1980, many subsequent safety regulations would simply not have been possible.

McLaren first introduced carbon fibre reinforced chassis in 1980 (3). At the time a number of designers expressed concern as to the suitability of such brittle materials in a dynamic loading application. Indeed, some even went so far as to attempt to have them banned on safety grounds (4). An incident at the 1981 Italian Grand Prix at Monza went a long way to dispelling those fears and removing the doubt as to the safety of carbon fibre structures under impact conditions. During the race John Watson lost control of his McLaren MP4/1, smashing heavily into the Armco barriers. The ferocity of the impact was sufficient to remove both engine and transmission from the chassis. The remains of the monocoque were catapulted several hundred metres along the circuit until finally coming to rest. Watson was able to walk away from the debris completely unscathed. The wrecked chassis clearly demonstrated the ability of the composite structure to both absorb and dissipate kinetic energy. The high stiffness of the chassis allowed the impact to be transmitted to the structure as a whole rather than being concentrated at the point of impact. Furthermore, the composite material was able to absorb the energy of impact by a controlled disintegration of the structure. By contrast, the forces generated from the impact of a vehicle constructed from a ductile metal such as aluminium are sufficient to exceed the material's elastic limit. Had Watson been driving such a car the chassis would have remained in one piece but collapsed until all of the energy had been absorbed. As a consequence he would undoubtedly been killed.

2. DESIGNING WITH COMPOSITE MATERIALS

In common with aircraft, the majority of components of a Formula 1 car are stiffness critical. Carbon fibres exhibit the highest specific stiffness of any widely available engineering materials. Since stiffness is the major design criterion one might therefore expect materials selection to be a simple matter of choosing fibres with the highest modulus. Unfortunately, producing fibres of increasing modulus involves a corresponding increase in brittleness.

As a general rule of thumb the modulus of carbon fibre increases with increasing heat treatment and the application of tension during the processing (5). 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≈ 1500°C (E_{11} ≈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".

There are literally hundreds of different PAN based carbon fibres commercially available. Having said that, it is possible 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 1 and numerically in Table 1 using commercial examples. By far the most widely used group of products are those which are heat-treated in the 1000-1400°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, 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 bodywork, as "flat stock" for making inserts or as tooling prepregs (6).

The HTT regime between ≈1400-1800°C produces high strength, ≈5µm diameter "intermediate modulus" fibres. This group of products is widely used in primary structures throughout the F1 grid, in particular this includes Toray's T800 and T1000. Heat treatment of the fibres beyond 1800°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, are high cost and dramatically increasing brittleness with modulus.

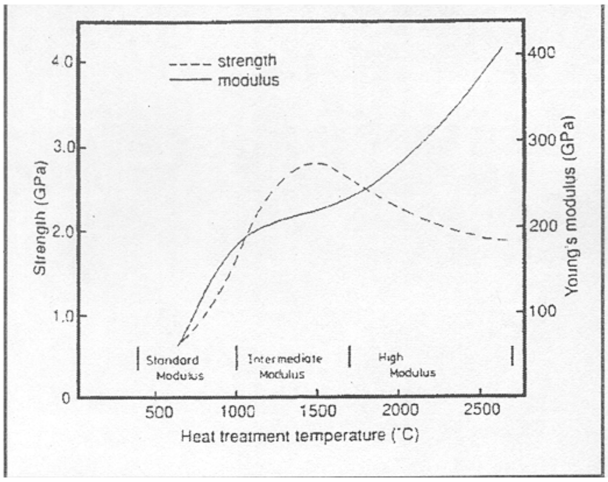

Figure 1. The relationship between the mechanical properties and heat treatment temperature of PAN based carbon fibres

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 (Table 2).

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. Prepreg is a broad tape of aligned unidirectional (UD) or woven fibres, impregnated with a partially cured polymeric resin. The primary mechanical properties of composites (strength, stiffness and failure strain) are governed primarily 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).

Table 1 Properties of Commercial Carbon Fibres

Fibre	Type	Fibre diameter (μm)	Approximate HTT (^oC)	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 Defining Carbon Fibres According to Modulus

Fibre Type	Modulus Range
Standard modulus	up to 250GPa
Intermediate modulus	250-350GPa
High modulus	350-500GPa
Ultra-high modulus	greater than 500GPa

There are generally 3 reasons cited 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.

3. ENERGY ABSORPTION

When designing a racing car capable of protecting its occupant in a collision, it must be remembered that both energy and momentum will be conserved. The task of the engineer is to arrange for dissipation of those commodities in such a way that as little as possible is passed onto the driver. Vehicle crashworthiness requires an understanding of the response of both structures and materials to dynamic loading. Furthermore the effect of this loading on the driver must also be considered. It is not speed that injures or kills people, it is the sudden loss of it. The designer must consider the deceleration that will be transmitted to the driver and must consult with medical specialists as to what "g" levels are survivable. It is becoming increasingly necessary to include impact resistance in the design of a great many engineering systems. Examples include the safety of industrial plant (7), crashworthiness of aircraft (8), ground vehicle transport (9) and armoured protection (10,11).

The impact energies of interest in the study of energy dissipation may be divided into three distinct groups (Figure 2), At speeds of 0 to 150ms^{-1}, impact behaviour is governed by both a materials response and that of the structure as a whole. This velocity regime includes the survivable vehicle impacts with which Formula 1 engineers are concerned. Impact behaviour in the range 150-1500ms^{-1} is covered by the science of ballistics and is most appropriate to military ordnance. The response of structures in this regime is generally materials dominated and usually confined to the locality of the impact. At velocities in excess of 1500ms^{-1}, materials are vaporised and solids flow as liquids. This type of behaviour is known as "hypervelocity impact" and is apposite to the penetration of heavy armour by shaped explosive charges and foreign object damage to spaceships and satellites (12).

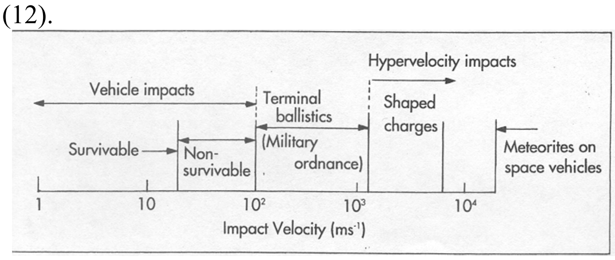

Figure 2. Velocity regimes in impact analysis

The large forces generated during major impacts of vehicle structures are sufficient to exceed the elastic limit of the materials from which they are made. 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 consequence of the work done in forming "plastic hinges" (6) which develop progressively along the tube. A load deflection curve typical of such an event is shown in Figure 3, as is the plastic buckling typical of a metal energy-absorbing device. By contrast, the failure of a composite chassis, comprising brittle carbon fibres in a brittle epoxy matrix, 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 the point of impact further into the structure so that higher load 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 laminate progressively tears itself to pieces.

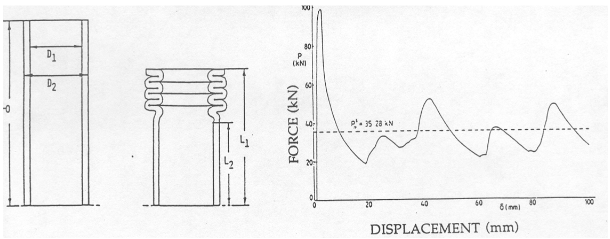

Figure 3. Axial collapse by plastic buckling of a ductile metal tube with a typical load/deflection plot for the event.

4. IMPACT RESPONSE OF COMPOSITE MATERIALS AND STRUCTURES

The energy absorbing capability of composite materials is a consequence of the "work of fracture" arising from the mechanisms occurring during catastrophic fracture. The inherent brittleness of composites ensures that they do not undergo the yield processes 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:

- cracking and fracture of the fibres
- matrix fracture
- de-bonding (pull-out) of fibres from the matrix
- delamination of the layers making up the structure.

A composite body thus disintegrates both structurally and microscopically during impact. A typical load/deflection response for a composite tube is shown in Figure 4. After the initial peak load the curve is much flatter than the plastically deforming metal tube in Figure 3. The area under the curve, i.e. the amount of energy absorbed, is therefore much greater. This combined with the lower density of the composite makes it far more efficient.

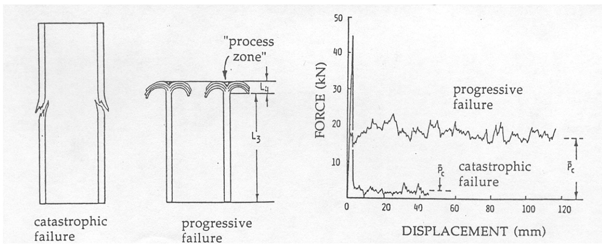

Figure 4. Axial crushing of composite tubes.

Figure 5. Measuring the energy absorption efficiency of a composite material.

The energy absorbing efficiency of composite material is a function of the combination of fibres and resins from which it is made. A numerical value for any material can be measured by axially impacting) or crushing (Figure 5) a simple tube.

$$\textit{Specific Energy Absorption} = E_a/M_c \quad (1)$$

$$= (M_0/L_0)L_c \quad (2)$$

Where E_a = energy absorbed by tube during test, M_c = mass of crushed length of tube, M_0 = mass of tube prior to testing, L_0 = original length of tube and L_c = length of tube after testing.

The results obtained for generic types of composite are shown in Table 3. As a general rule, the higher the strength of the fibres and the higher the toughness of the resin, the better will be impact performance of the composite. Figure 6 shows a comparison of data obtained for the same material using both the stable static crush and impact methodologies. The results show the energy absorption of advanced composite materials to be insensitive to strain rate.

Table 3 Comparison of specific energy absorption by composite materials.

Fibre	Reinforcement	Resin Type	Specific Energy Absorption (Jg^{-1})
T800	Fabric	120^{o}C curing rubber toughened epoxy	81
T300	Fabric	135^{o}C curing oligomer toughened epoxy	54
T800	Fabric	135^{o}C curing oligomer toughened epoxy	62
M46J	Fabric	135^{o}C curing oligomer toughened epoxy	47
M55J	Fabric	135^{o}C curing oligomer toughened epoxy	34
T800	UD	135^{o}C curing oligomer toughened epoxy	110
M46J	UD	135^{o}C curing oligomer toughened epoxy	69

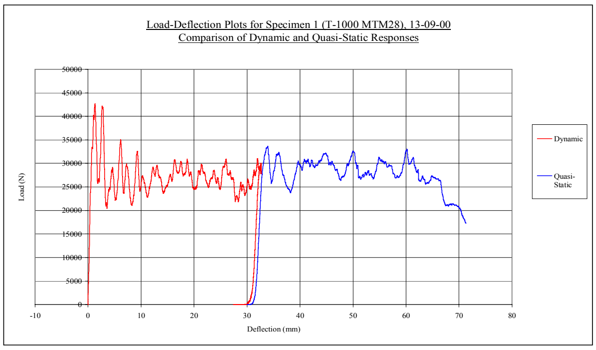

Figure 6 Comparison of static and dynamic response to axial compression.

It should be remembered however that this is not always true for components. Components that perform well under static loading do not necessarily do the same under dynamic conditions and vice versa. This can lead to embarrassing results if not taken into account!

5. SURVIVABILITY

The survivability of the pilot in an accident is achieved by a combination of the crash resistance of the car and its ability to absorb energy. This has been achieved by providing a survival cell (the chassis), which is extremely resistant to damage, around which energy absorbing devices are placed at strategic points on the vehicle. The energy absorbing devices operate to enable maximum deformation up to a specified limit. The devices used are designed to dissipate energy irreversibly during the impact, thereby reducing the force and momentum transferred to the survival cell and hence the pilot. They are “one-shot” items, being partially or totally destroyed so as to act as a load limiter. They are proportioned so as to posses a more or less rectangular force/displacement characteristic (Figure 7).

Since the late 1980s the controlling body of Formula 1 (FIA.) has introduced a series of regulations to ensure that the cars conform to stringent safety requirements and build quality. Each vehicle must satisfy a list of requirements, in the form of officially witnessed tests, before it is allowed to race. There are two groups of tests that must be passed. The first is a series of static loads applied to the chassis, which guarantees the strength and integrity of the survival cell. The second series defines the position, and effectiveness of the energy absorbing structures. Each year the number and severity of the tests increases in line with ongoing research and development into survivability, or in response to track “incidents”. The regulations for the 2001 season are summarised in Tables 4 & 5 and examples are shown in Figures 8 & 9

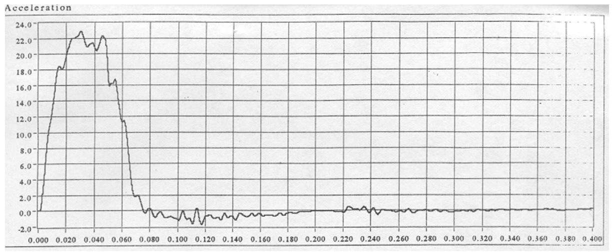

Figure 7. Ideal load/deflection response of energy absorbing structure.

Figure 8. FIA static roll hoop test.

6, THE SURVIVAL CELL

The success of composite materials in providing stiffness efficiencies and weight reduction is well documented (6). There has always been a minimum weight criterion within the Technical Regulations since weight is recognised as a powerful controller of ultimate performance. Furthermore the governing body believed that it would remove the incentive for designers to strive for absolute minimum component weight at the expense of strength.

Table 4. FIA Static Test Requirements.

Structure	Applied Load (kN)
Primary (rear) roll over hoop	120.0
Secondary (dash board) roll over hoop	75.0
Cockpit side	30.0 (load must be held for 30s)
Fuel tank floor	12.5 (load must be held for 30s)
Cockpit rim	10.0 (load must be held for 30s)
Nose box push off test	40.0 (load must be held for 30s)

Table 5. FIA Impact Test Requirements.

Structure	Impact Mass (kg)	Velocity (ms^{-1})	Energy (kJ)	Peak Force Permitted	Maximum Mean Deceleration (g)
Nose box	780	14	76.44	60g for 3ms	40g (must be <5g for initial 150mm)
Side	780	10	39.0	80kN for 3ms	20
Rear	780	12	56.16	60g for 3ms	35
Steering column	8	7	0.196	80g for 3ms	na

Figure 9. FIA rear impact test.

The introduction of mandatory safety tests has resulted in its design becoming increasingly dominated by strength considerations. The static proof loads and dynamic impact requirements mean that the necessary stiffness levels are not difficult to achieve with the materials thicknesses necessary to provide the required strength. One would consider that once a design had produced a result that was close to the minimum weight limit, there would be little point in developing it to achieve further weight reduction for the same performance. On the contrary, studies of vehicle dynamics have shown the benefits in controlling the vehicle's mass distribution upon its handling. As a consequence every component on an. F1 car must be engineered to the absolute minimum weight. The more ballast that is needed to return the car to the legal minimum weight, the more scope is provided to achieve optimum performance by tuning its balance by appropriate positioning of said ballast. There is therefore an incentive to use weight efficient materials such as composites wherever possible.

The design procedure used is "semi-quantitative" combining finite element stress analysis with trial and error. The application of a purely theoretical numerical analysis is not practicable since detailed structural and materials data are not generally available. Instead the FE engineers arrive at a "best guess" initial composite lay-up capable of resisting the applied loads of the static safety tests and those induced by the impact scenarios (Figure 10). Tests are then carried out on prototype representative sections to check the validity of the model and to provide more accurate input data. The final design of the survival cell is an iterative process of mathematical modelling and laboratory testing which aims to produce a chassis capable of meeting the test requirements at minimum weight within the available timescale.

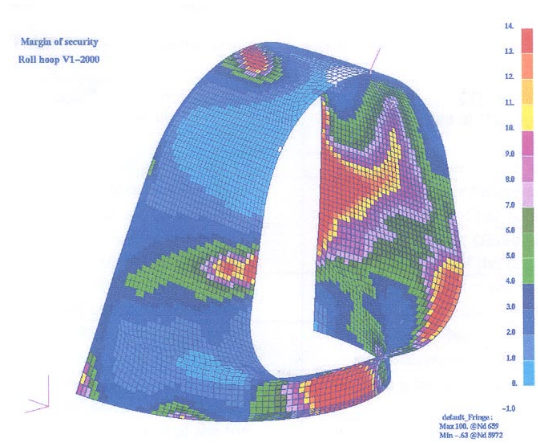

Figure 10. FEA analysis of roll hoop under FIA test configuration.

Recently there have been a number of safety issues raised by injuries caused to pilots by Foreign Object Damage. This has generally involved penetration of their survival cell by broken pieces of their own or other competitor's vehicles (Figure 11). In an attempt to combat this potentially very dangerous occurrence, a "side intrusion" test has been introduced. Each team is required to submit a panel for testing which is representative of the construction of their monocoque. The centre of the panel is loaded in a universal test frame at a rate of 2mm.s^{-1} by a special loading device, which simulates a rigid, truncated nose box (Figure 12). The load is recorded until the crosshead has moved 150mm. The maximum load reached over the first 100mm of deformation must be recorded and presented along with the energy absorbed during that same period and graphs of load and energy vs. displacement. The pass criteria for season 2001 is that there must be no damage to the fixture or border of the panel, that the maximum load shall exceed 150kN and the energy absorption shall exceed 6000J. In subsequent seasons this test will be made more stringent requiring greater loads and energy absorption. The net result on chassis design is that it forces the use of high strength (T800 & T1000) rather than high modulus fibres, the increasing use of woven rather than unidirectional architectures and high toughness resin systems (6).

7. IMPACT STRUCTURES

From the numerous experimental studies that have been carried out on composite energy absorbing devices, it is generally accepted that thin-walled tubes offer the most weight efficient solution. The tubular devices have been shown to to perform at their best when global Euler column buckling and local wall buckling, with corresponding bending collapse modes, has been precluded (Figure 4). That is to say when geometric, material, and loading conditions are such that axial failure of the tubes is characterised by the progression of a destructive zone of constant size at the loaded end. This is called the crash "process zone" or "crash frond" (Figure 13).

The challenge of design is to arrange the column of material such that the destructive zone can progress in a stable fashion. The energy absorption must be as high as possible by allowing the development of a sustained high level crushing force, with little fluctuation in amplitude as the process zone travels along the component's axis. Furthermore, the destruction should be initiated smoothly by avoiding large initial peak resisting forces that might cause global wall or column buckling rather than the beneficial load wall destruction mode.

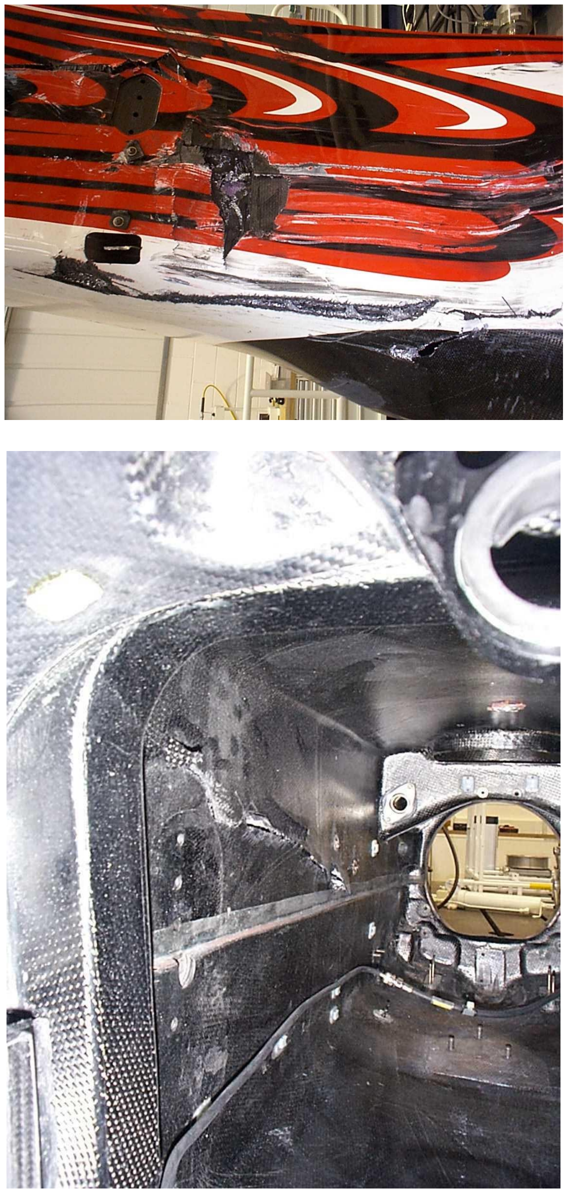

Figure 11. Impact resistance of the survival cell is of great importance, in this example penetration by a broken wishbone injured the pilot's leg.

For tubes with structures other than circular, i.e. "real structures" crushing behaviour has been shown to be influenced favourably when the corners of polygonal thin-walled sections are rounded so as to represent segments of circular tubes (13, 14). For square sections, the greater the corner radius, the higher will be the efficiency of energy absorption (15). Rounded corners prevent flat segments from failing by load plate buckling, with associated plate strip buckling and much lower specific energy absorption.

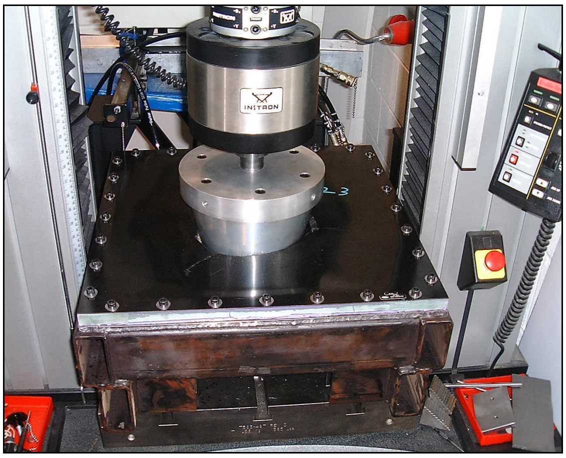
Figure 12. Intrusion panel test set-up.

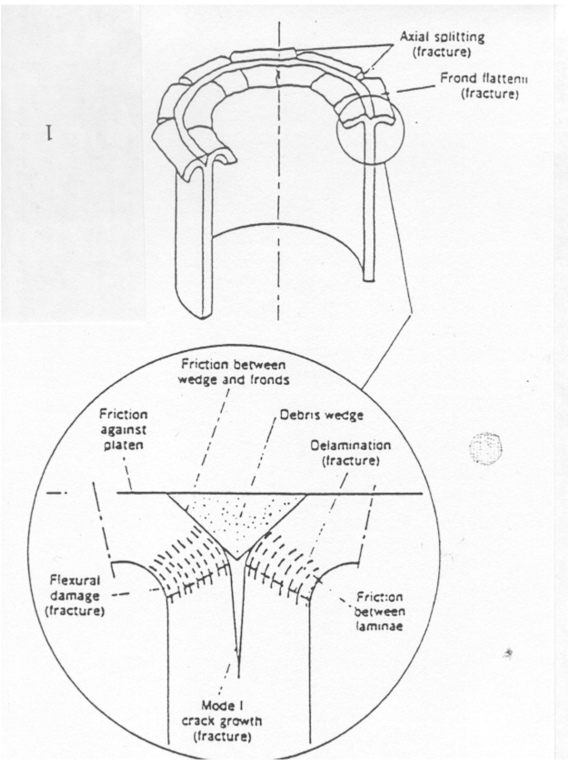

Figure13. Process zone development in axially crushed composite tube.

The successful axial crushing of composite structures hinges on the necessity to trigger the respective highly energy absorbing progressive failure mechanism. In practice, the "trigger" is designed into the structure by tapering its geometry and lay-up within the confines of the envelope defined by the car's aerodynamic performance, the sport's technical regulations and the basic physics governing the event. To illustrate the philosophy behind the design of one of the cars' impact devices we may consider the 2001 side impact test. The survival cell must be rigidly fixed to the ground and a solid object, with a mass of 780kg (representing a car, driver and full fuel cell) projected into it at a velocity of $10ms^{-1}$ (Figure 14). The impact axis must be perpendicular to the car centre line and parallel to the ground. Furthermore, the car must be impacted in the area of the pilot as defined in the regulations. The resistance of the test structure must be such that during the impact the average deceleration of the impactor does not exceed 20g and the force applied to any one of the four impactor segments does not exceed 80kN for more than a cumulative 3ms. In addition, the energy absorbed by each of the four impactor segments must be between 15 and 35% of the total energy absorption and all structural damage must be contained within the impact absorbing structure.

The minimum crash distance (s) may be calculated as follows,

$$E = \frac{1}{2}mv^2 = Fs \tag{3}$$

Where E = impact energy, m= mass, v =impact velocity, F the force generated by the event and s the distanced travelled from the point of impact until the impactor is brought to rest.
At equilibrium,

$$F = ma \tag{4}$$

Therefore,

$$s = \frac{v^2}{2a} = \frac{10^2}{2x20x9.81} = 255mm \tag{5}$$


Figure 14. FIA side impact test.

To pass the test, the side impact structure must be at least 255mm in length. In practice it is necessary to add at least 15% to this length in order to accommodate the debris produced in the impact, to take into account any "non-ideal" fracture behaviour and to ensure that the impactor does not impinge on the monocoque. The minimum mass requirement is calculated from the total energy of the impact test (39J). For a T800 fabric reinforced epoxy composite, we can assume an energy absorption efficiency of ≈ $60Jg^{-1}$. Therefore the minimum mass of composite required to pass the test is given by;

$$\frac{39x1000}{60} = 650g \qquad (5)$$

The design of the component follows an iterative process. An initial test piece is produced by conservatively fitting the correct amount of material into the laminate's fracture zone. A "remote" or practise test is then carried out, to FIA specification, on the component fixed to a solid metal plate (rather than a monocoque, for obvious reasons!) in order to test the theory. The design then follows a trial and error process, changing the lay-up and modifying the geometry in order to arrive at the most weight efficient solution. Wherever possible one aims to use a monolithic structure for the composite as this is the most efficient way of absorbing energy.

As one moves away from a simple tube to a more complex geometry, the energy absorbing efficiency is reduced. For example, a tube made from a T800 fabric will have an efficiency of $\approx 80Jg^{-1}$. In a more complex structure made from the same material, such as a side impact device, the efficiency drops to $\approx 60Jg^{-1}$. When the component has a high axial ratio, a nosebox for example, it is necessary to use a honeycomb-stabilised structure in order to increase the wall thickness at minimum weight penalty in order to prevent catastrophic failure. In a situation such as this, where the axis of the honeycomb cells is perpendicular to the impact, the energy efficiency is significantly reduced (to $\approx 35\text{-}40Jg^{-1}$), because of a tendency towards plate strip buckling.

When choosing the material from which the device will be made one aims to use intermediate modulus fibres and the toughest resin systems. This is not always possible, particularly in honeycomb structures where it can sometimes be preferable to use a higher modulus fibre to promote fibre fracture rather than plate buckling as the primary failure mode. Similarly, some of the impact structures (that at the rear for example), require a degree of heat resistance necessitating the use of a more brittle, high temperature matrix material. Despite UD composites being more efficient in energy absorption, fabric reinforced materials tend to be preferred in impact structures in order to ensure a stable crush failure. The effect of these considerations is to reduce the efficiency of the component. Nevertheless a nosebox weighing of the order of 3kg, is capable of absorbing in excess of 76kJ. There are moves to introduce specialist, finite element crash simulations into the design process (16, 17). At the time of writing however the quasi-numerical "heuristic" approach is favoured. Once the remote test has been passed and the team is happy that it has produced the optimum design, an Official test is carried out to homologate the car. Fixing the component to a chassis tends to be a less harsh test than when attached to a rigid plate due to the increased compliance of the system. As a consequence the impact devices generally perform better in a "real" rather than practice test. This does not however prevent the many nervous hours spent before it is all over and the car certified for the season!

8. CONCLUSION

The nature of Formula 1 racing, with cars propelled around the congested circuit at enormous speeds by highly motivated pilots, is such that collisions are an inevitable consequence. Advances in technology and stringent safety rules have combined to significantly reduce the risk of death and injury resulting from such incidents. The automotive industry has acquired much from motor racing. At the present time the impact absorbing devices used in F1 are made from what are essentially "exotic" and expensive materials produced by an inefficient multistage batch process. Having said that, the basic principles of specific energy absorption are equally apposite to road cars and with careful process and materials engineering, similar devices could be used to significantly improve the crashworthiness of a host of transportation systems.

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