EXPLOITING THE FRACTURE PROPERTIES OF CARBON FIBRE COMPOSITES TO DESIGN LIGHTWEIGHT ENERGY ABSORBING STRUCTURES

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Abstract. The survivability of a Formula 1 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. 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. In order to keep the weight of the car to a minimum, some of the energy absorbing devices are also required to perform a structural function in addition to their ability to absorb energy by controlled disintegration. The Rear Impact Structure (RIMP), for example, sits on the differential cover at the rear of the gearbox. The function of this device is to react the down force generated by the rear wing assembly as well as to provide protection in the event of a crash. Engineering structures are generally designed such that they do not fail. Producing a component, which is specifically intended to fail in a catastrophic, but controlled manner, presents a unique set of problems to the designer. When the same artefact is required to perform as a load-bearing member at the same time, the engineering problems are far more acute. The design process from materials selection to a finished component is discussed for an F1 RIMP. Particular reference is made to the design and analysis process and how it deals with the conflicting aspects of controlled fracture and load bearing durability. The analysis and testing process required to prove the piece fit for purpose and homologated for competition are also covered.

1. INTRODUCTION

During the 1960s the rate of fatal and serious injury within Formula 1 was 1 in every 8 crashes. The Sport's governing body (FIA.) took a number of measures to address this problem such that by 1980 the serious accident rate had been reduced by a factor of 5 to 1 in 40 [1]. 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 [2,3]. The greatly improved safety record of Formula 1 in the 1980s and beyond resulted from the co-operation between the FIA, the race organisers and participants in formulating the rules to enhance driver survivability. Having said that, it was facilitated by radical change in the materials from which the cars are made. Had it not been for the introduction of composite chassis in 1980, by the McLaren team, many subsequent safety regulations would simply not have been possible.

In common with aircraft, the majority of components of a Formula 1 car are stiffness critical. Carbon fibre reinforced composites exhibit the highest specific stiffness of any widely available engineering materials. As a consequence F1 teams strive to use them in more and more applications. The construction of all of the cars that will make up the 2003 grid will be completely dominated by composite materials, which are used to produce up to 85% of the structure [4].

The survivability of the driver 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 driver. 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 1).

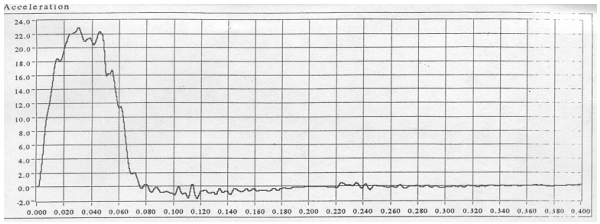


Fig. 1. Ideal load/deflection response by an energy absorbing structure

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 2003 season are summarised in Tables 1 & 2.

Table 1. FIA Static Test Requirements for Season 2003.

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)
Rear crash structure push off test	40.0 (load must be held for 30s)

Table 2. FIA Impact Test Requirements for Season 2003.

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

1.1. Survival Cell

The success of composite materials in providing stiffness efficiencies and weight reduction is well documented [5]. 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. 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. 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.

1.2 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.

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 [6].

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 racing 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" [7] 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.

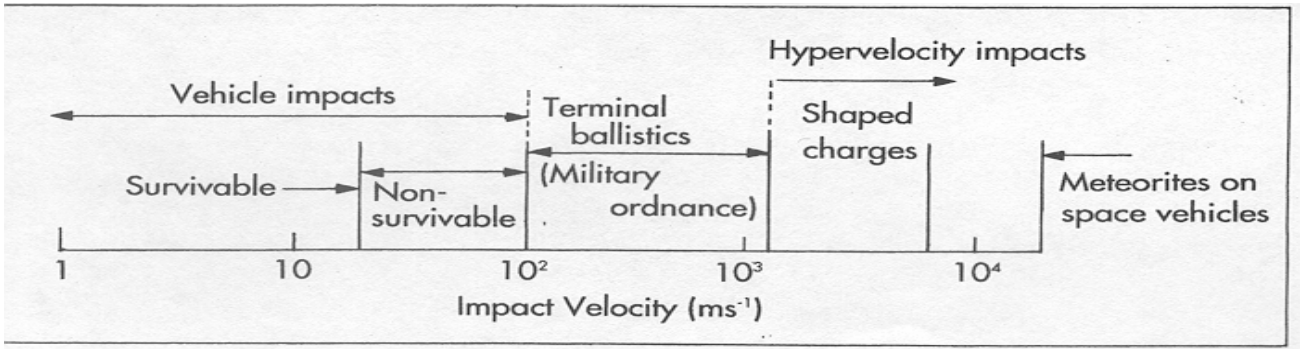


Fig. 2. Velocity regimes in impact analysis

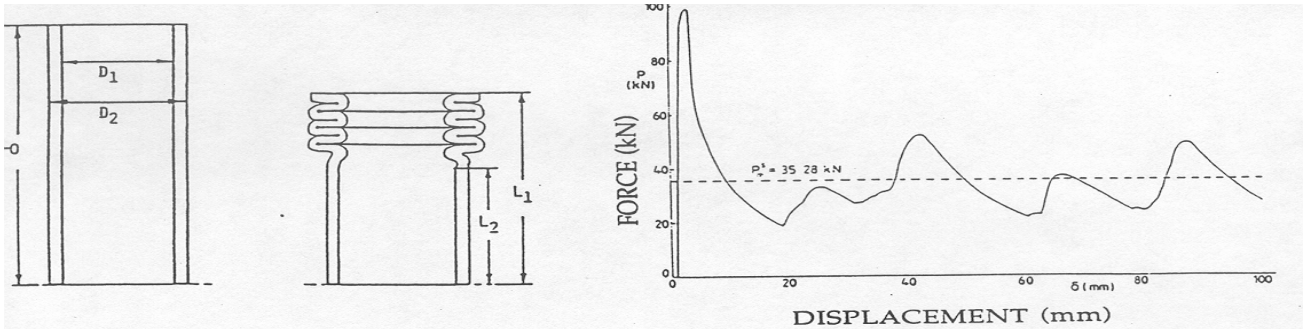


Fig. 3. Axial collapse by plastic buckling of a ductile metal tube with a typical load/deflection plot for the event.

1.3. 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.

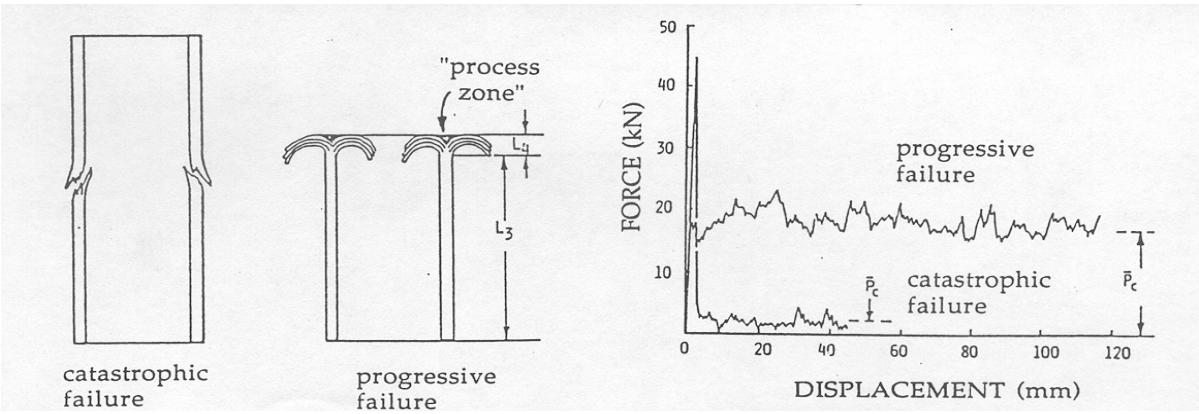


Fig 4. Axial crushing of composite tubes.

1.4 Impact structures

The Sport's technical regulations are written in order to ensure all-round protection for the driver in the event of a crash. This is achieved using the nose box for frontal protection, side impact structures either side of the cockpit and a specialist rear impact structure at the back of the car (Table 2).

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 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 5).

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.

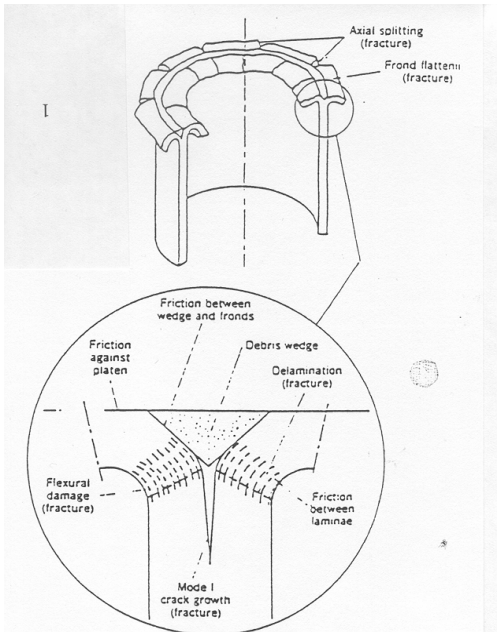


Fig. 5. Process zone development in axially crushed composite tube

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.

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 [8, 9]. For square sections, the greater the corner radius, the higher will be the efficiency of energy absorption [10]. Rounded corners prevent flat segments from failing by load plate buckling, with associated plate strip buckling and much lower specific energy absorption.

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 impact event.

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 an intermediate modulus carbon fabric reinforce composite, will have an efficiency of $\approx 80 Jg^{-1}$. In a more complex structure made from the same material, such as a side impact device, the efficiency drops to $\approx 60 Jg^{-1}$. When the component has a high axial ratio, a nose box 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 $\approx 35\text{-}40 Jg^{-1}$), because of a tendency towards plate strip buckling [6].

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 nose box 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 [11, 12]. At the time of writing however the quasi-numerical "heuristic" approach is favoured.

2. THE REAR IMPACT STRUCTURE

The process of designing one of the energy absorbing components on an F1 racing car may be illustrated using the BAR Honda 050 Rear Impact Structure (RIMP). The steps involved are typical for all of the energy absorbing structures on the car. Highlighted are the design constraints, their affect on the evolution of the component and methodologies for dealing with them. There is also some detail on the qualification of the components for service and condition monitoring once in service. The components of the system are shown in Figure 6.

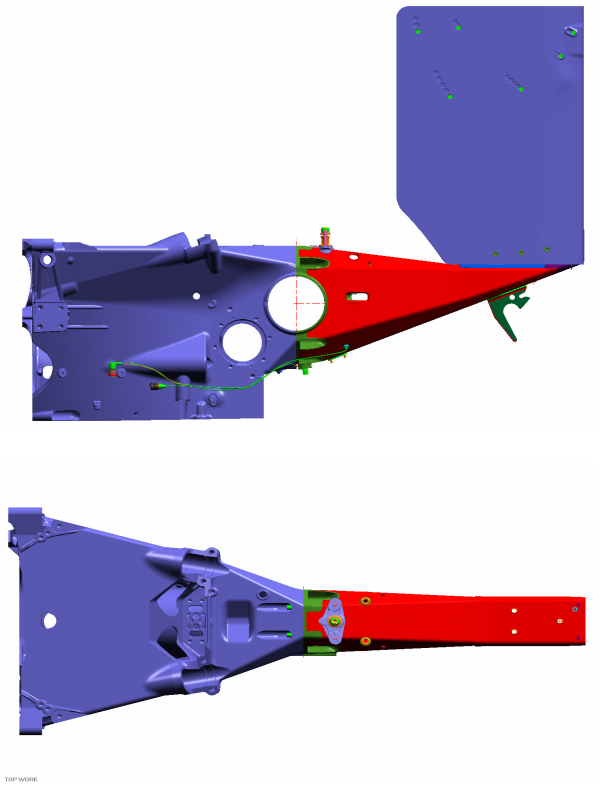


Fig. 6. BAR Honda 050, Gearbox and RIMP Structure

The RIMP, shown in red/green, is primarily an energy-absorbing component although it does perform several other functions at the same time. The gearbox main case, shown in mauve to the left of the RIMP, is attached directly to the engine, which is in turn attached directly to the chassis. The RIMP is also designed to transmit the rear wing and rear suspension loads to the chassis as well as supporting jacking loads and acting as a mount for the rear light. The compromise between making the RIS 'soft' in terms chassis/engine/gearbox for impact and strong and stiff for load bearing is taken care of largely by the magnitude of the forces and the components size. The RIS is physically the smallest component in the chassis/engine/gearbox system. The forces generated

under impact at peak g are in the region of 460kN. This force combined with the relatively small contact area generates large contact stresses ahead of the impact The resultant aero load is approx. 6.5kN and the rear top wishbone load is around 18kN, both being small in comparison. It is therefore the impact performance of the RIMP that drives the design.

Table 3 RIMP Design Constraints

Property	Requirement
Aero	Aerodynamic loading at maximum down force
FIA Impact	Homologation requirement
FIA Static Load	Homologation requirement
Suspension Loads	Max/min. Track rod and Top Wishbone Rear Leg.
Temperature	High thermal loading due to the proximity of the engine, gearbox and exhaust
Jacking	Operating condition
Packaging	Limits on length and volume (diff, rear light, suspension, wings.)
Geometry	Shape and taper has a large influence on efficiency
Mass	Minimum weight to reduce polar inertia of the car

2.1 Aero

For structural analysis aero loads are presented in the form of pressure fields generated from Computational Fluid Dynamics (CFD) models. These pressure fields feed directly to the FE model. The CFD load case is derived from the combination of wing elements and their relative maximum attainable speeds to achieve the maximum down force and hence the maximum load transmitted to the RIMP. Qualification of this component for service includes a static proof load and a durability test with the sinusoidal application of the maximum down force during 100,000cycles.

2.2 FIA Impact

An impact test on the RIMP is a "legal" requirement. The test specifies that the RIMP must to absorb the energy from the impact of a sled weighing 780kg and travelling at a speed of $12ms^{-1}$ (56kJ). The pass criterion specifies that there should be no damage to the gearbox forward of the axle centre line, that the peak g should exceed 60 for no more than 3ms and that the mean g should not exceed 35.

2.3 FIA Static load

A static load on the RIMP is a further legal requirement. The RIMP must sustain a 40kN lateral load for 30s. This load was introduced to improve the 'robustness' of rear impact structures to off-axis loading.

2.4 Suspension loads

There are two suspension-mounting points on the RIMP, the top wishbone (RTWB) rearward leg and the track rod (TR). The maximum individual member loads are derived from measured circuit data with appropriate factors of safety (FoS) added to determine the proof and design load cases. A durability test is also performed with the sinusoidal application of the max/min link loads during 100,000cycles.

2.5 Temperature

The rear of the car is particularly affected by temperature constraints. The combination of thermal conduction and convection from radiator, engine and gearbox pose particular problems in material selection. The impact properties of CFRP tend to be at odds with temperature performance. The higher temperature resin systems are inherently brittle with poorer G_{1c} (inter-laminar fracture toughness) properties.

2.6 Jacking loads

The rear of the car is lifted from the ground using a jacking point on the RIMP. The ballasted weight of the car plus driver and full fuel tank is 780kg and the RIMP has to resist repeated loading. The impact criterion usually drives the laminate however and consequently the laminate in this area is sufficiently strong to cope without further modification.

2.7 Packaging

There are various packaging constraints: aerodynamic, legality and design (differential, rear light, suspension pickups, fixation, diffuser, top body, etc).

2.8 Geometry

The efficiency of the RIMP is dominated by the geometry. Final tuning can be achieved through the laminate, however fundamentally the shape of the RIMP has the most influence on performance. A tapering structure with no re-entrant shape has the most predictable, stable crush.

2.9 Mass

The further away from the centre of gravity (CoG) of the car that the mass is, the higher will be the polar moments of inertia ($\int r^2 da$). This is manifested in a slowing of the response of the car in pitch and yaw. To reduce the mass of the RIMP we need to optimise its efficiency, the measure of which is it's specific energy absorption, Jg^{-1}. Several tests were carried out on standard crush tubes to determine material and laminate efficiency, which was then used as the basis of the RIMP laminate.

3. RIMP DESIGN PROCESS

Layout

- Basic design, philosophy and principals.
- Basic sizing, length, volume, attachment.
- Stress analysis, FE and classical calculation.
- Bond area calculations.
- Fastener type, number and dimensioning.

Shape Study

- Quasi-static crush test.

Material Selection

- Std tube impact tests
- Temperature evaluation
- Std RIS impact tests

Laminate Optimisation

- Std RIS impact tests

Qualification

- FIA Impact and static tests.
- Internal Proof and Durability Tests
- Non-destructive Testing (NDT)

Condition Monitoring

- Proof tests
- Stiffness monitoring
- NDT

3.1 Stress Calculations

An energy balance is used to calculate the minimum theoretical crush distance, KE=PE. Since the mean g is regulated to 35, the potential energy (PE) can be resolved to mgl, 'l' being the crushable length. This is further reduced to give $l=v^2/2a$. The min. theoretical crush distance is therefore 209mm. A further factor is then added to account for structural inefficiencies to determine the length of the structure for design. To size the laminate the specific energy absorption from a simple crush tube is applied to discrete sections of the RIMP, at 25mm intervals for example. The surface area is measured from CAD (initial RIMP scheme) at each interval and a thickness applied to determine a volume and hence the energy absorption potential. This process is repeated until the energy is reduced to zero at which point the estimated crush distance is noted and introduced as a design constraint.

An FEA model is produced on the initial RIMP scheme. The purpose of the model is to perform static strength and stiffness analyses to verify the general integrity of the design as a load bearing structure. The software used is Patran for pre and post processing and Nastran for the numerical solution. Internally within the Company, the RIMP is classified as a "Class-A" structure since an in-service failure of this component would result in the driver losing control of the car. As such it must to be signed of by a Stress Analysis Engineer and the Chief Engineer as "fit for service" once the analysis, design and testing processes have been successfully completed. This testing also extends to condition monitoring throughout its service life.

The first use of the FE model is to determine the attachment loads, which in this case are the bolt reaction loads and the carbon impact structure to the differential cap bond area.

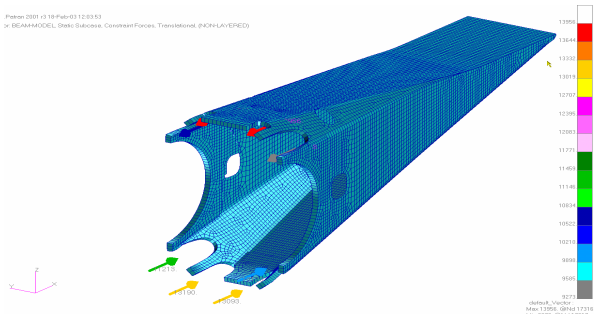


Fig 7 Initial FEA model of RIMP

Finite element analysis (FEA) is used to calculate the structural response to statically applied loads. There are explicit codes being developed to model impact and composites however the number of failure mechanisms available in CFRP materials renders this process much more involved than that with elastic-plastic materials like steel. At this time the effort involved in modelling and validation renders these methods unsuitable for F1 timescales

The load case in Figure 8 models the FIA lateral push test. An extract from an element showing through the thickness ply failure indices and stresses, top to bottom respectively, is shown in Figure 9. The forces and displacements of a particular element of interest are exported to Laminate Analysis Program (LAP) to do this. The plot in Figure 8 shows the Margin of Safety (MoS), which is a reflection of reserve strength MoS > 0 = SAFE!

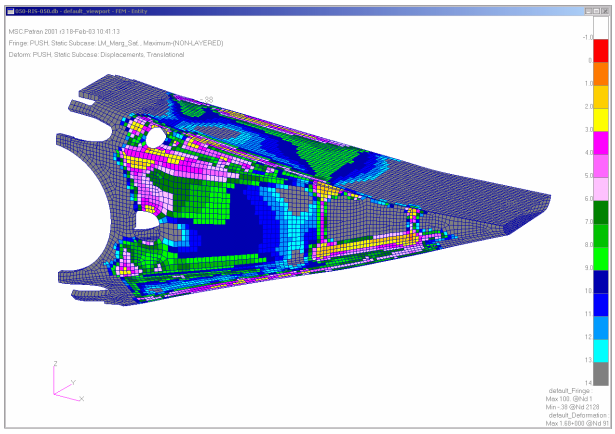


Fig 8 FEA model of FIA lateral RIMP static test

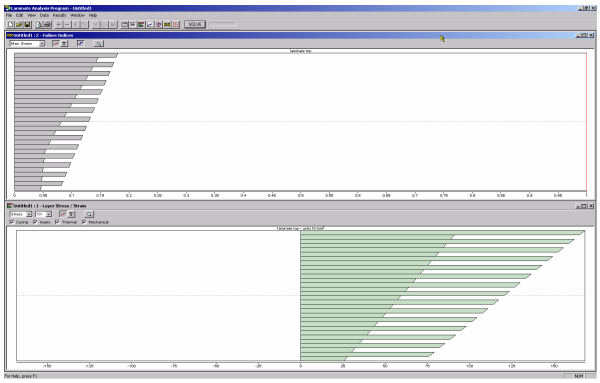


Fig 9 Laminate analysis of RIMP elements.

4. TESTING PROGRAMME

4.1 Materials selection

The measurement of primary mechanical properties of composites is relatively straightforward and well documented [13]. BAR generally have this information by our technical partner for the supply of composite materials, Cytec Engineered Materials Ltd. Temperature measurements in service on previous cars show that the RIMP is required to operate at temperatures of up to 125°C. It is paramount therefore that the properties of the material chosen for manufacture remain unaffected in this temperature regime. Composite materials generally exhibit a constant elastic modulus with increasing temperature until they approach the glass transition temperature (Tg) of their resin matrix [14]. At this point the modulus of the composite can fall by an order of magnitude or more, with drastic consequences for the component. A number of candidate composite materials were screened using the Dynamic Mechanical Analysis (DMA) technique [15]. DMA works by impressing a small sinusoidal varying stress on to the material and transducing the strain. The time-dependent response is shown in Figure 10. For a completely elastic material the strain is in phase with the stress, and for a purely viscous material the strain will be 90° out of phase. Polymers are viscoelastic to a greater or lesser extent, depending upon the temperature at which they are measured. It is therefore convenient to resolve this behaviour into an in-phase (elastic) component governed by the "storage modulus" E′ and an out of phase (viscous component) defined by the "loss modulus" E″. The lower curves in Figure 10 show the stress response broken down into the two components with respect to the strain response.

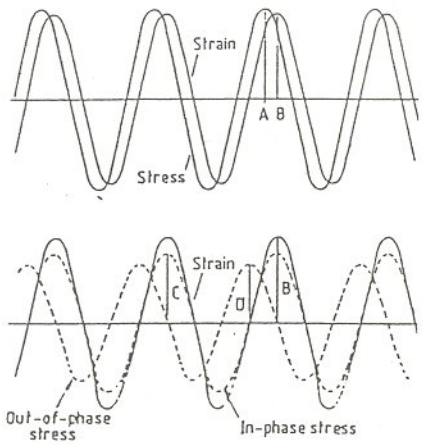


Fig. 10. Viscoelastic stress/strain behaviour

The storage and loss modulii may now be defined by;

$$E' = C/B \qquad (1)\ \&$$

$$E'' = D/B \qquad (2)$$

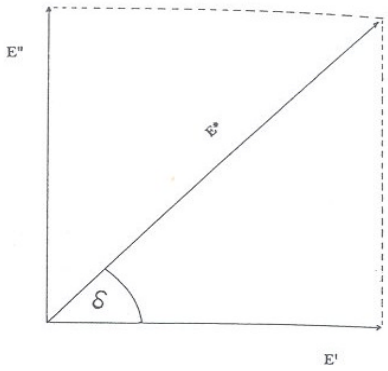


Fig. 11. Argand diagram representation of viscoelastic behaviour

These relationships can be summarised in an Argand diagram with the total response governed by the complex modulus E* as shown in Figure 11. The phase lag is also clearly defined in the Argand diagram and a convenient dimensionless parameter is the loss tangent (tan δ);

$$\tan\delta = E''/E'' \qquad (3)$$

This is physically the ratio of energy lost to energy stored per deformation cycle. A peak in tan δ occurs when the impressed frequency matches the frequency of molecular relation through thermally activated processes. The peak in tan δ represents the "true" value of Tg, but the structure will clearly be useless well below this temperature. At BAR, the standard technique used to characterise the temperature performance of a resin system is to use the storage modulus. The onset of loss in stiffness is measured and a safety factor of 10°C applied, such that;

Maximum use temperature = (onset in E′ –10)°C (4)

Figure 12 shows the thermal analysis of the material chosen to produce the RIMP (2020 epoxy resin system from Cytec, cured at 180°C). The onset occurs at 153°C, giving a maximum use temperature of 143°C, significantly above that required.

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 a simple tube (Figure 13) using a universal test frame of the "Instron genre" [4].

$$SpecificEnergyAbsorption = E_a / M_c \quad (5)$$

$$= \left(M_0 / L_0 \right) L_c \quad (6)$$

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 material selected to manufacture the RIS consisted of a 200gsm 2x2 twill weave T800 intermediate modulus carbon fibre fabric in a 2020 epoxy resin matrix, cured at 180°C and had a specific energy absorption of 64Jg^{-1}.

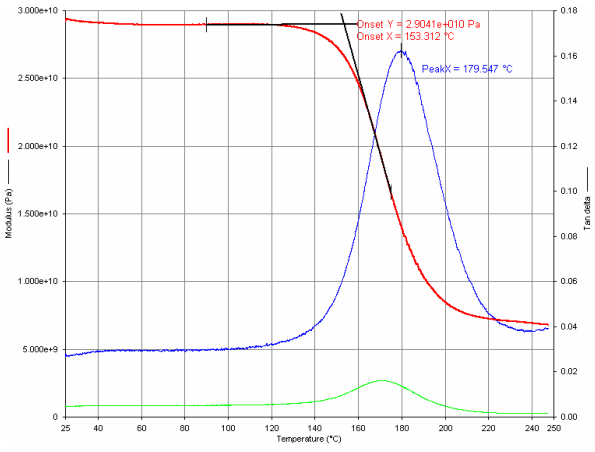


Figure 12. DMA curve for Cycom 2020 resin system



Fig. 13. Measuring the energy absorption efficiency of a composite material.

4.2 Component Testing

Once the initial laminate has been determined from the FEA analysis, a RIMP is manufactured and tested quasi-statically as the first step in an iterative optimisation programme. Testing was carried out on a 600kN Instron servo-hydraulic test frame (Figure 14).

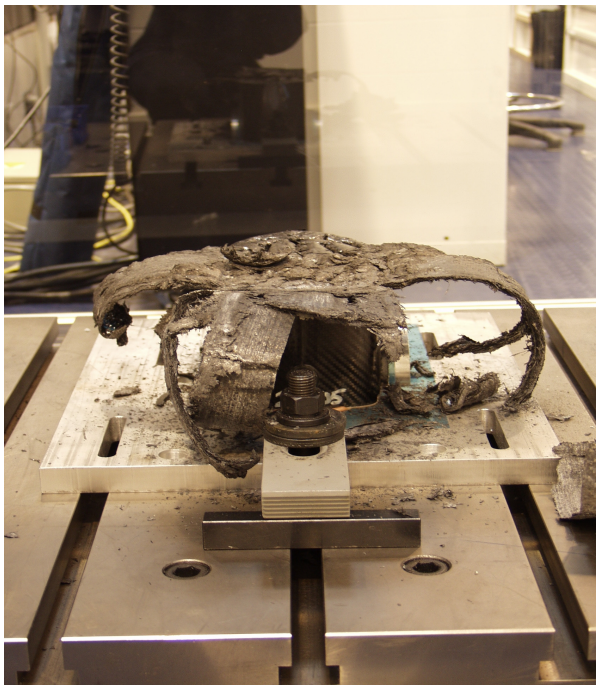


Fig. 14. RIMP following successful quasi-static test.

The equipment is capable of carrying out what is effectively a "slow motion" impact test. The purpose of the test is ensure that the failure is stable and progressive, measure the peak load which will be fed into the supporting structure (in this case the gear box) and ensure that the RIMP is capable of absorbing all of the energy from the FIA impact. Once the team were

happy with the quasi-static results, a practice FIA impact (in which the RIMP was mounted on a fixed plate rather than the gearbox) was carried out to verify the results of the research programme. The Official FIA test (Figure 15) requires that the RIMP be fitted with all components that could possibly interfere with the impact event such as rear wing and light and suspension brackets etc. Weighing the component before and after the test enabled the specific energy absorption to be recorded, which was $60Jg^{-1}$. This is very close to the theoretical value measured for the simple tube, clearly demonstrating the efficient geometry of the RIMP.

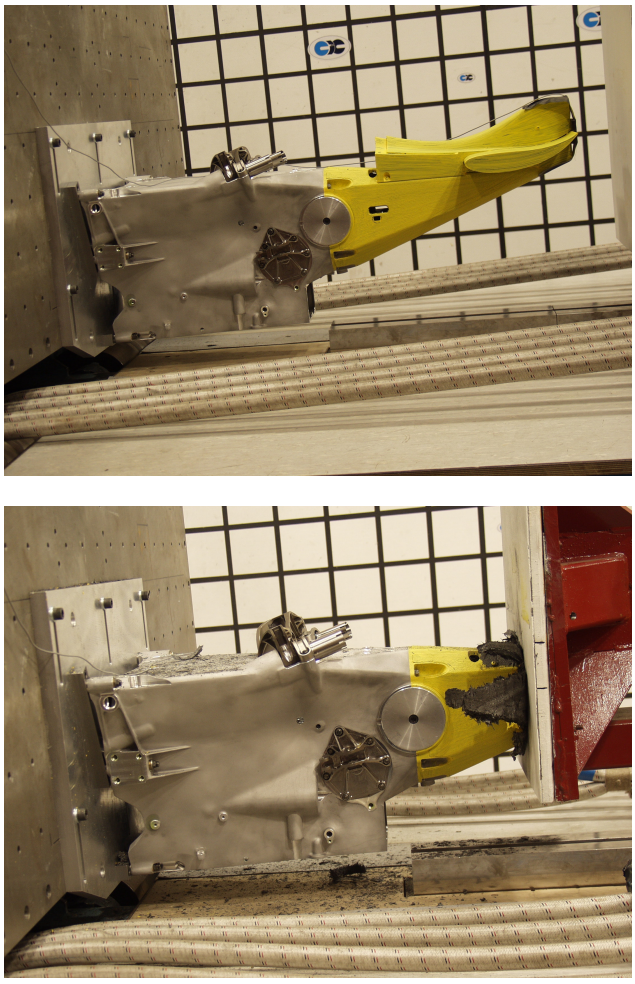


Fig.15. Oficial FIA RIMP test

Prior to being passed "fit for service", Class A parts must pass a further series of tests, imposed by BAR, which involves static proof testing and fatigue testing simulating service conditions. The design load is defined as the lowest load at which a component is permitted to fail. The RIMP was subjected to a proof test by the application of a load simulating that produced by the wing assembly on the circuit. The proof load is lower then the design load, but higher than the largest calculated service load, by a safety factor of 1.3. Proof testing is carried out on a custom built rig, using a hydraulic actuator to apply the load in the direction of the centre of pressure of the rear wing (Figure 16). At the same time, a transducer is used to measure the global stiffness of the structure in this configuration in terms of a load/deflection plot. The same rig is used to dynamically load the RIMP by applying the calculated load sinusoidally for 100,00cycles in order to prove it to be intrinsically safe.

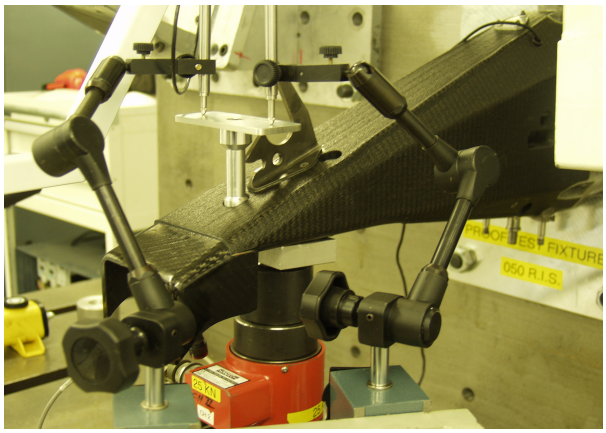


Fig.16. RIMP proof and fatigue test configuration

4.3 Condition Monitoring

Condition monitoring is the periodic re-testing and inspection of components throughout their service life in order to highlight any time-dependent structural degradation before it becomes a problem, or to verify the integrity of a repair. In the case of the RIMP this involves a repeat of the proof test and a thorough ultrasonic examination following every 1500km of circuit running (approximately 2 tests or three races). A component is said to have failed the test if it breaks under load, its stiffness has reduced by more than 5% from the original measurement or if there are any non-linearities or other irregularities in its load/deflection curve. Failure of the test can, but not necessarily, result in the part being scrapped. Furthermore, it initiates an investigation that may require repair, modification or redesign of itself and all similar items. A component that passes the test is simply returned into service.

5. CONCLUSION

The use of carbon fibre composites in Formula 1 racing car crash structures has been a major contribution to the improved safety record of the sport. An F1 car consists of around 3500 different components, the majority of which must be designed and built from scratch in the period from September to March each year. The demands of lightweight and efficient multipurpose parts, combined with the very short time available, has dictated a heuristic, semi-quantitative approach to their design. Experience and laboratory testing play important roles along with structural analysis in producing outstandingly successful

components which have saved a number of lives over the years. It must be remembered however, that without the basic impact physics of the composite materials, none of this would be possible.

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