SUB-CRITICAL CRACK GROWTH IN HIGHLY STRESSED FORMULA 1 RACE CAR COMPOSITE SUSPENSION COMPONENTS

Gary Savage
Honda Racing F1 Team

ABSTRACT

One of the many advantages in the use of composite materials in engineering structures is their resistance to fatigue. Careful component design means that complex, weight-efficient components can be produced which are "intrinsically safe" in that they have an effectively infinite fatigue life. Excessive loading and manufacturing/design details may, however, invoke a process analogous to fatigue in metal components leading to ultimate failure of the component at a load below its design limit. A somewhat qualitative analysis has shown this mechanism to result primarily due to sub-critical crack growth within the resin matrix material. Although the phenomena need further investigation, it was found that the crack growth could be suppressed by using a resin matrix with a much higher toughness. A short introduction to the use of composite materials in formula 1 is given along with a discussion to illustrate how the practical application of Materials Science and Fracture Mechanics principles were used to solve a potentially serious problem.

1. COMPOSITE MATERIALS IN FORMULA 1

In Formula One, weight saving is all-important. Despite the governing body imposing a minimum weight limit, teams still spend much of their time trying to hone components to the lowest possible weight. This is because dropping below the minimum weight allows them to redistribute weight around the car in the form of ballast. Vehicle dynamics studies 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 Half a kilo taken off the rollover hoop, for example, and added to the bottom of the car in ballast lowers the centre of gravity and can be worth up to a tenth of a second. Such fractions of a second are hard fought for. Every team is constantly looking for ways to get ahead or simply keep up. It is this intense level of competition that fuels the frantic pace of development in formula one. There is therefore an incentive to use weight efficient materials; particularly fibre reinforced composites, wherever possible.

Carbon fibre composites were first used in Formula 1 in 1980, when McLaren Technical Director John Barnard designed and built the first carbon fibre chassis (1). Barnard was attracted to carbon fibre, which at the time was used almost exclusively by the aerospace industry, because of its incredibly high specific stiffness. He correctly postulated that carbon fibres could offer a huge step both in chassis stiffness and weight reduction. His composite McLaren MP4-1 (Figure 1) revolutionised the world of racing car design when it hit the track in 1981, despite his detractors initially dismissing the idea of using such brittle materials in race car construction. By 1984 however, the whole of Formula 1 had jumped on the carbon fibre bandwagon. Barnard's concept has today been accepted as the industry standard in all types of formula racing car design. In fact, so established is the practice that the FIA's current Formula 1 technical regulations are written in such a way that it would be very difficult to make a chassis out of anything else. During the design of the MP4/1, Barnard 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 1990s, Savage and Leaper from McLaren developed composite suspension members (2).

Composite suspension components are now universally used by F1 teams (Figure 2). Apart from the obvious weight savings, composite push rods and wishbones etc. have a much improved durability and so can be made far more cost effective than the steel parts which they replaced. The most recent innovation was the introduction of composite gearboxes (3). The carbon fibre reinforced epoxy structures (Figure 3) are significantly lighter (up to 25%) than traditional metal alloy boxes, significantly stiffer, can be operated at higher temperatures and are easy to modify and repair. Aside from the structural materials a number of "speciality" fibre reinforced composites are also used. These include carbon-carbon brakes and clutches, and ablatives in and around the exhaust ports.

Formula 1 is now in the vanguard of carbon composite research and development, even more so than the aerospace industry from which the technology was derived. This is because aircraft lead times are so much longer than F1 cars. A car is designed and built in a matter of months, so the latest materials can always be incorporated. An aircraft takes years to move from the design stage to full production, so the materials used in an airframe are invariably out of date by the time it reaches service. A lot of the materials that you see on an F1 car won't be used on aircraft for perhaps another 7-10 years. Similarly, many of the composite materials used on today's aircraft, such as the Eurofighter, became obsolete in F1 in the early 1990s; quite amazing considering that F1 as a whole adopted carbon fibre just thirty years ago.

Figure 1. The original composite F1 chassis, McLaren MP4-1

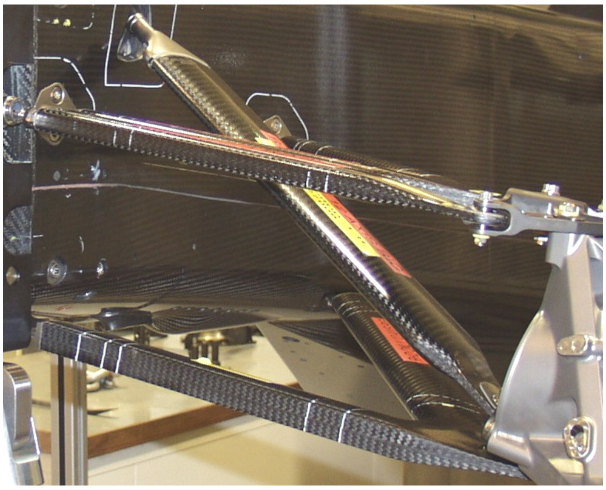


Figure 2. Composite suspension members.

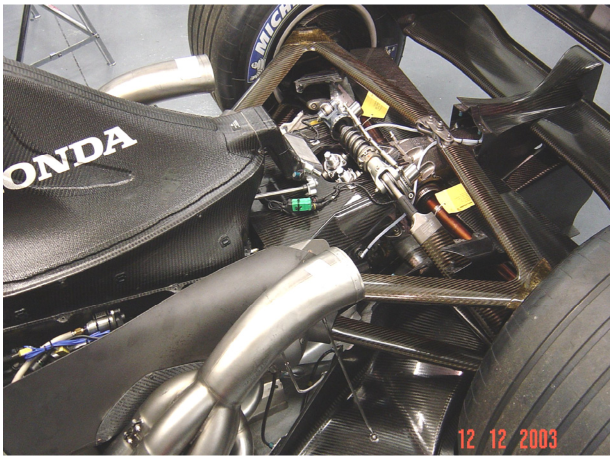


Figure 3. Composite gearbox and rear suspension

2. SUSPENSION DESIGN

A mantra often used in the Formula 1 media is "F1 cars are all about aerodynamics" In reality, the key factor in the performance of any racing car is tyres and keeping those tyres in good contact with the ground. Even in Formula 1, where the cars are able to produce up to twice their own mass in down force, this is of greater fundamental importance than aero, although of course aero plays a huge role in putting downforce through those tyres. The task of the suspension is to enable the tyres to provide optimum grip throughout the running of the car and minimise the degradation of the tyres during the process.

FIA regulations effectively restrict Formula 1 cars to double wishbone suspension (Figures 2 & 3). Suspension kinematics & compliance requirements are dictated by the team's vehicle dynamics engineering group and the tyre supplier. The suspension geometry must take into account a number of factors including; anti-squat, anti-lift, roll centre, camber change with bump and stiffness (especially toe and camber). A bespoke kinematics program is employed to generate data for LapSim (circuit simulation) and ADAMS models. Aerodynamic requirements influence the section of the various components. FIA stipulate a maximum 3.5:1 depth/chord ratio regulation which effectively limits the chord. The component's aero may be sensitive to inclination, the component may require a degree of twist and its cross section kept to a minimum (in stark contrast to mechanical requirements!) to reduce "blockage". Mechanical design must take into account attachment to chassis and uprights (wheel hubs), camber, toe and castor adjustment and the packaging of brake lines, electronics (sensor wires etc) and tethers (The high strength polymeric fibre "ropes" used to keep the wheels attached in the event of a serious accident.

All of the suspension components and their associated mountings etc are initially designed to meet a series of static load criteria. These criteria are based on a number of maximum load cases which the individual pieces are anticipated to endure. A braking load of 4.5g combined with a vertical load of 2.0g, for example, is used to simulate maximum braking with the associated loads from aerodynamics and weight transfer. The loads are resolved into the suspension geometry to calculate the corresponding forces acting on each individual component. A series of loading combinations (14 in all) are similarly applied to the suspension. Each component is then individually designed according to the maximum loads they are likely to endure, multiplied by an appropriate safety factor. Race car suspension components are essentially slender columns, the most likely failure mode therefore being buckling under compression loading. The buckled wavelength is determined by the degree of constraint applied by the gripping arrangement. In the case of a perfectly cylindrical prism there is no single preferred plane in which to buckle. The aerodynamic shapes used in the suspension members are polygonal prisms, any buckling deflections will occur in the direction transverse to the thinnest dimension, i.e. within the plane of the lowest flexural rigidity.

3. THE FRONT PUSH ROD

The front push rod from the Honda Racing F1 RA107 (2006 season) car (Figure 4) consists of a simple thin-walled carbon fibre composite aero-tube into which titanium (Ti 6Al 4V alloy) end fittings are bonded. The lower fitting houses a bearing which enables the component to fit to the upright. The upper fitting consists of two parts. A flat lower section is bonded into the composite tube. A second upper fitting, again housing a bearing, bolts to this piece and attaches it to the rocker in the chassis which actuates the spring and damper arrangement. The length of the push rod may be altered by the addition and removal of a series of spacers between the two upper fittings and is the method by which the front ride height of the car is set and the car balanced from left to right. The composite component is laid up in two half moulds which are bolted together prior to the curing operation. Two thin strips of woven composite (oriented at ±45° to the axis of the tube), known as joining plies, are used to form a "strapped butt joint" (4) in order to bond the two halves together. The tube and joint are consolidated in a single operation by the insertion of a pressure bag (@7bar) and heat in an autoclave.

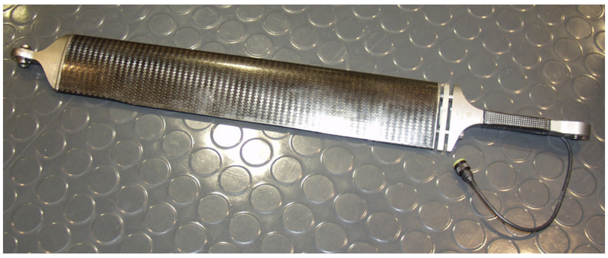


Figure 4. Honda RA106 Front push rod.

The loading in all of the suspension members is, to a first approximation, resolved into simple tension/compression and, as previously discussed, the torque due to braking largely responsible for the most critical loads. The loading in the push rods is primarily in compression, the only tensile forces being relatively trivial occurring in the sporadic instances when the wheel leaves the circuit (during "kerbing" for example). The stability of an elastic slender prismatic column under compression loading was first discussed by Euler (5). If the axial compressive load P is less than the critical elastic buckling load (P_b) the "pinned-end" column (in which the ends are free to rotate) remains straight, undergoes only elastic axial compression and is in stable equilibrium (Figure 5a). As the load increase, the equilibrium becomes unstable and any slight lateral load will produce a deflection leading to collapse through bending (Figure 5b).

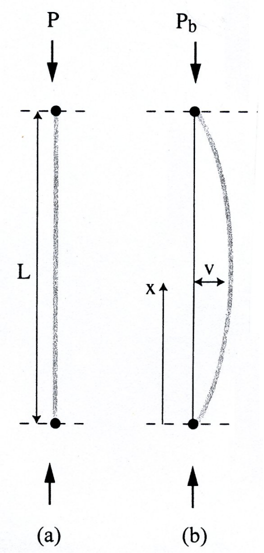


Figure 5. (a) pinned column under axial load (b) fundamental case of buckling

The critical load for column instability under compression may be determined using the differential equation of the deflection curve providing one assumes a small deflection (v) is assumed (6,7);

$$-M = E_1 I_{\min} \frac{d^2 v}{dx^2} \equiv E_1 I_{\min} v'' \qquad (1)$$

Where M is the internal bending moment, E_1 the axial elastic modulus, I_{min} is the minimum second moment of area and v'' is the curvature of the bent column.

$$P_b = \frac{\pi^2 E_1 I_{\min}}{L^2} \qquad (2)$$

where L is the length of the column.

This is of course the fundamental condition known as the "Euler Load". Real columns invariably differ from the ideal case because imperfections and non-conformity exist. In the case of our push rod, inconsistent and variable griping (due to the variability of the bearings and rotation of the component etc.) lead to eccentric loading. Inhomogeneity in manufacture and the non-symmetric nature of the global design lead to an uneven distribution of load. Any variation in from one component to another will be manifest as a scatter in the buckling loads. Nevertheless, the Euler buckling load (calculated using the maximum usable length and multiplied by a suitable safety factor) remains a good component design parameter.

Composite structures are designed to have just the right amount of fibres in the correct directions to resist the applied loads, with the minimum of matrix resin to hold the structure together (8). To achieve this precision, the composites industry produces an intermediate product known as "prepreg". Prepreg consists sheets of aligned (unidirectional) or woven fibres, surrounded by a partially polymerised resin. Components are formed by building up successive plies of prepreg in a mould followed by curing under temperature and pressure.

The initial stressing of the push rod (and indeed all of the other suspension members) is as an Euler column such that the primary load bearing fibres are arranged unidirectionally along the axis of the component. Euler's equation shows that stiffness rather than strength of the composite governs the buckle load. Carbon fibres with ultra high stiffness tend to be very brittle (9) and are therefore not used in components such as this which can have a relatively "violent" service life. A compromise is struck using the "high" rather than "ultra-high" modulus type, sacrificing a little in weight efficiency to guarantee durability. The loading on the push rod is not pure compression and therefore further material, in the form of woven high strength (intermediate modulus) fibres is employed in those areas where it is required. Following the initial buckling calculation further, more detailed, structural analysis is required using finite element analysis (FEA) before the structure is finalised.

4. MATERIALS AND ANALYSIS

A major factor that has led to the expansion of carbon fibre use in F1 is the improvements being made in the materials themselves. In recent years, an increasing number of fibres have become available. By processing the fibres differently, thinner fibres with much greater tensile strength and modulus have been developed. The disadvantages are that high- and ultrahigh-modulus fibres cost more and are much more brittle than standard carbon fibres. The new ultrahigh strength varieties reduce brittleness and open up a number of applications hitherto precluded to composites, but at a cost penalty. Structural adhesives used to bond carbon components together and to add metal inserts have also improved, extending the number of parts for which it can be used. Similarly the epoxy resin matrices used to bind the fibres together have also improved. Honda's gearbox is a clear example of these advancements. It was built using an experimental high toughness resin to resist delamination due to impact that is around 90% higher in interlaminar toughness (10).

Probably the most important change in the use of carbon fibre, though, has been the improvement of detailed stress analysis. The advent of finite element analysis (FEA) coupled with vast increases in computing power, has allowed designers to asses their designs for possible weak points. There are several choices the designer can make at this point. Material can be added to areas exposed to high stresses. Alternatively, the choice of fibre, resin, weaves or orientation can be tweaked to provide a stronger component. Similarly the shape of the component can be adjusted to prevent stresses becoming concentrated. The results can then be re-subjected to FEA, which is based on data from composite suppliers and laboratory tests during the R&D phase of design, to ensure they conform to the component's requirements. The result is an iterative approach to design based, to a great extent, on designers who have a great deal of experience designing using carbon fibre. FEA provides an extra degree of confidence but all components must be rigorously tested to ensure safety.

These three factors have seen the use of carbon fibre composites increase from chasses in the early 80's, through to the point that they make up 85% of Honda's car, if the engine and wheels are excluded.

5. TESTING AND VERIFICATION FOR THE CIRCUIT

Formula One is a very low-volume application. Teams produce small quantities of small, highly complicated parts. At Honda, resin versions of the component are milled direct from CAD data. These 'masters' then have carbon fibre laid over them to create the moulds used to make the final parts. At this point, the CAD/CAM data is used to cut sheets of prepreg into the shapes that will be needed for each component. The result is much like a sewing pattern. The software also produces a booklet detailing the sequence, orientation, fibre and resin to be used for each layer of each component. Highly trained technicians then lay up each sheet according to these instructions, with a second person always double-checking the work. The laying up and checking of each layer of prepreg is recorded to ensure complete traceability. Considering that a very significant percentage of the Honda's 3617 components are made from carbon and 75% of them will have been modified between the start and the end of a racing season, these amounts to a lot of work and a long paper-trail.

Calculated loads are the maximum (highest tensile) and minimum (highest compression) loads resulting from the load case calculations, resolved into the principal axes of individual suspension components. The design load is the lowest load at which any component is permitted to fail;

$$\text{Design load} = \text{calculated load} \times \text{safety factor} \qquad (3)$$

Proof testing is the application of a load, lower than the design load but higher than the calculated load to which the component is required to be subjected prior to being deemed fit for purpose. Each component is loaded in both tension and compression along its major axes to a minimum safety factor of 1.3. In certain cases (particularly push rods) tensile test loads which are far higher than required for operational safety are applied in order to test the integrity of the adhesive bonds.

Durability testing is the application of dynamic loads to a component or subassembly in order to evaluate any potential lifing problems. The load may be applied in the form of a fixed sinusoid oscillating between the maximum and minimum loads, a block sequence programme built up from the estimated stressing regime or the application of service data. Proof testing and simple uniaxial durability testing may be carried out within the confines of a universal test frame (Figure 6). Service load simulation exercises on major assemblies on the other hand require expensive bespoke multi-axis test rigs. For multi-axis testing purposes, forces or motion parameters such as acceleration, velocity and displacement can be measured. Loads etc., recorded using transducers on the car, may be manipulated using appropriate software such that they may be replayed to control the servo hydraulic actuators. Using this technology it is possible to test a component or subassembly under similar conditions to those it would experience on the race circuit. Thousands of kilometres of any track may then be completed without the parts having to leave the factory! Furthermore, the digital operation of the equipment allows the programming of safety factors with relative ease and the huge relative increase in the "virtual" speed of the laboratory test compared with that on the circuit enables a significantly accelerated programme. The 12 axis test rig (11) that Honda use for this purpose may achieve speeds equivalent to the car operating at 6000kmh^{-1} (figure 7).

The primary suspension components (wishbones, push rods and track rods) are initially tested on a universal test frame to verify them "fit for purpose. Once the parts have been manufactured, they are proof tested statically followed by dynamic testing of a full car set of components. This can be carried out by applying the maximum load cases, which generally occur under braking, in the form of sinusoids applied at the heave resonance frequency of the car (approximately 5Hz). Tests carried out in this way tend to be excessively harsh on the suspension since they are constantly applying load scenarios which the parts endure only infrequently. It is preferable therefore to use service data as it is provides a much more accurate estimate of the components' "life expectancies". Honda's qualification system applies 100,000 load cycles of uniaxial testing to prove individual components and a multi-axis test to set the service limit of complete assemblies. Once components have finished the prerequisite mileage on the rigs parts of the same type may run at the circuit without fear of failure allowing the track engineers to concentrate on set up etc.

It is worth remembering that carbon fibre is not considered expensive by F1 standards. Although the manufacture of parts is a skilled and laborious process, the costs of production are dwarfed by the costs of design, development, testing and quality control. At Honda we operate a total quality management (TQM) process, "lifing" (monitoring and documenting) major components through every aspect of their service life from conception to obsolescence. The history of each component is extensively recorded. Designs are tested both destructively and non-destructively, with individual components and sub-assemblies being subjected to simulated loads of an entire season's racing using, typically, safety factors 1.3 times higher than the largest calculated load they should ever encounter, to ensure safety and reliability. Components are also "condition monitored" (mechanically and non-destructively tested) every 2500km in order to highlight any time-dependent structural degradation before it becomes a problem or to verify the integrity of repairs. They are considered to have failed if they have broken under load, have lost more than 5% of their original stiffness or exhibit ant irregularities during NDT examination.

Figure 6. Uniaxial suspension test

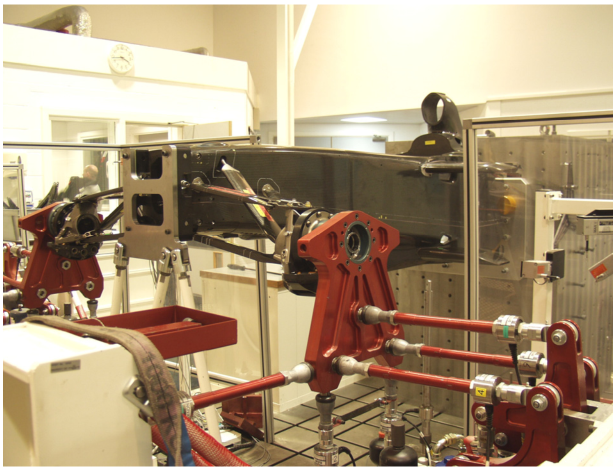


Figure 7. Multi-axis suspension testing.

There is a price to be paid for conformance. Investment is required in time, capital and personnel to operate and maintain a TQM process, which must be constantly upgraded in parallel with evolving technology. The price of conformance is however far lower than the price of non-conformance; a team whose cars consistently fail cannot hope to compete at the highest level. Honda racing F1 team have invested millions of pounds in a state of the art test lab and its attendant TQM system. During the 2006 season the team uniquely experienced zero chassis failures during the racing season QED!

6. EXCESSIVE LOADS AND BUCKLING EVALUATION

One advantage of composite suspension members is that it possible for them to exceed its buckle load and return to their original form. This is not the case with thin-walled metallic parts which undergo local plastic deformation and are thus rendered permanently deformed and unserviceable. A test was devised in order to evaluate the "robustness" of the front push rod in conditions which may arise from unexpected loads due to kerbing and pot holes for example. The standard compressive proof load was increased to induce recoverable buckling and the dynamic compressive load by 30%. The test consisted of the buckle load applied three times followed by 10,000 durability load cycles. This process was to be repeated until failure, or the completion of 100,000 cycles, whichever came first.

Figure 8. Compression failure of front push rod

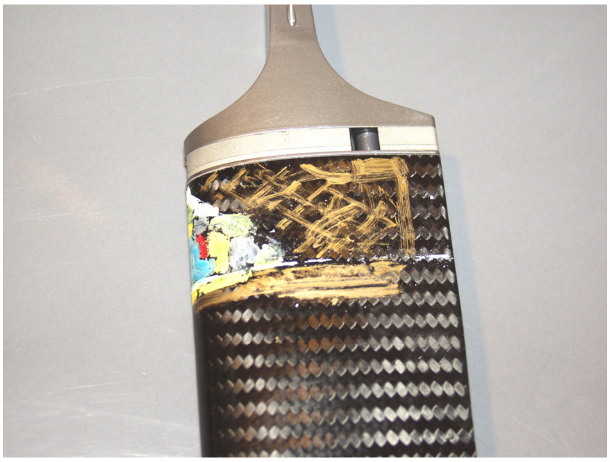
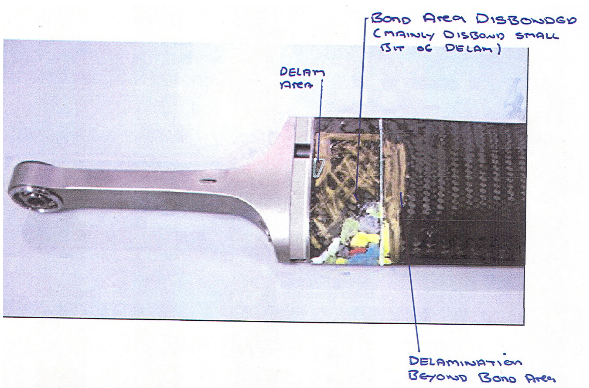


Figure 9. "disbond" revealed by UT examination

The test stopped after 37,000 cycles. A compressive failure was observed at the upper end of the composite tube, just below the metal end fitting (Figure 8). A subsequent ultra-sonic examination revealed a significant "disbonded" area in the region of the metal insert (Figure 9). It was assumed that there had been a peel failure of the adhesive bond leading to a premature buckling failure of the tube. It was further assumed that this bond failure was progressive rather than instantaneous. The test was repeated with a second, identical, component in order to investigate the nature of the bond failure. Rather than test to destruction, the test was halted periodically to enable the growth of the defected area to be mapped (Figure 10) using ultrasonics. Furthermore, the desire was to examine the defected area microscopically without any of the damage that would result from a catastrophic failure.

Optical microscopy showed that the failure was due to a crack propagating through the matrix of the composite material (Figure 11). Crack initiation was difficult to discern, but appeared to occur in the region of the tube's joining plies (Figure 12). The main crack here was approximately 650µm from the inner surface, with multi-delamination cracks which may well have then grown during later stages. The main crack then moved nearer to the surface on meeting the metal insert, usually at between 100µm and 400µm from the composite/adhesive interface. There were very few crack excursions to said interface thus proving the original assumption wrong – the bond had more than adequate strength (Figure 13). Failure appeared to be initiated at a design/manufacturing detail, and the "fatigue life" dependant upon the toughness of the resin matrix.



Colour	Number of cycles
Blue	1400
Red	2000
Yellow	3000
Silver	4000
Green	5000
White	6000
No change	7000
Gold*	10,000

*test stopped due to perceived bond failure

Figure 10. Mapping of defect propagation

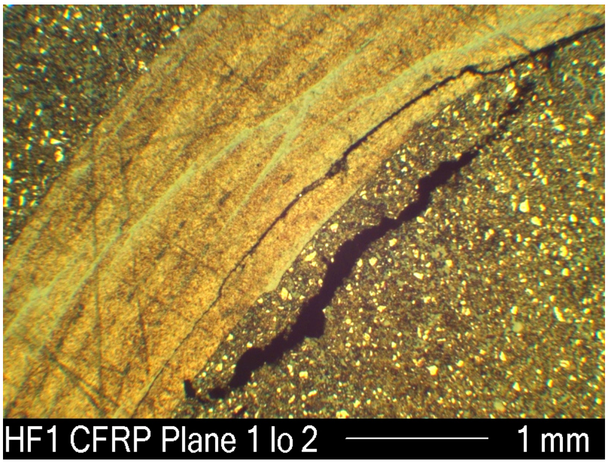


Figure 11. Crack propagating through resin matrix

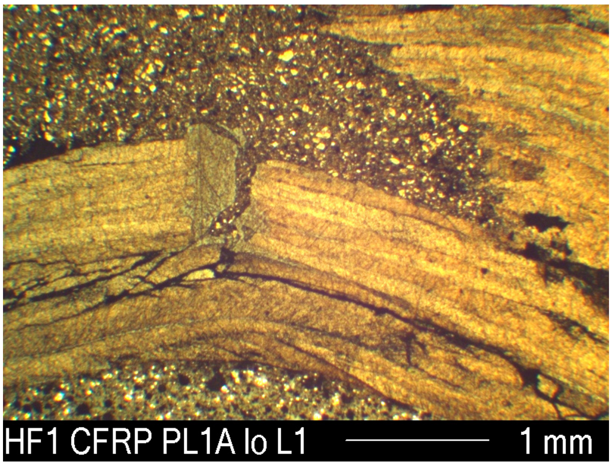


Figure 12. Crack appears to originate from the edge of the joining plies (lighter material)

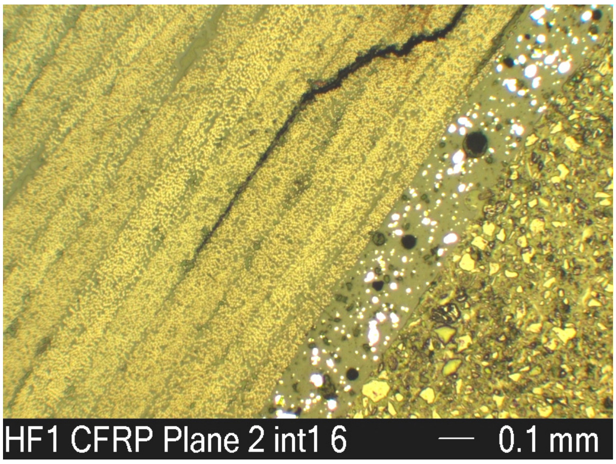


Figure 13. The adhesive bond remains intact throughout the failure process.

7. CONCLUSION

Failure of the composite resulted from compression once the defect had grown to a critical size and the structure could no longer support the load. The defect arose from sub-critical crack growth within the resin matrix in a manner that appears similar to fatigue in metals and alloys. The initiation of the crack is difficult to discern, but appears to emanate from the laminated strip which joins the two halves of the component. That is to say it appears due to an extraneous design/production detail rather than being intrinsic to the composite material. It would have been interesting to have investigated the process further and develop, perhaps, a numerical understanding of the process. Formula 1 however deals with the here and now so a very quick solution was introduced. The 2020 epoxy resin matrix was replaced with the tougher 2035 system (10). This resin exhibits a 90% higher interlaminar toughness (G_{IC}) and was used in an effort to reduce the rate of crack growth. Repeating the test with a 2035 based composite enabled an otherwise identical component to complete 100,000 cycles without failure, and no apparent defects when investigated with ultrasonics. Using this information, the team has produced a new, lighter, design for the 2007 car in which one of the metal fittings has been replaced with composite (Figure 14).

Figure 14. Honda F1 2007 front push rod

8. REFERENCES

[1] Savage, GM., Metals and Materials, 7, 10, 617 (1991).

[2] Savage, GM., Race Tech., 1, 1 (1995).

[3] Armstrong-Wilson, C., Racecar Engineering, 14, 9, 32 (2004).

[4] Savage, GM., Engineering Failure Analysis, 14, 321 (2007).

[5] Euler, L., Histoire de l'Academie, Berlin 13, 252 (1757).

[6] Gere, JM., & Timoshenko, "Mechanics of Materials", 3rd Ed., PWS-Kent, Boston, USA. (1990).

[7] Gere, JM., & Timoshenko, "Theory of Elastic Stability", 2nd Ed., McGraw-Hill Book Co., New York, USA. (1961).

[8] Savage, GM., J. STA., 140, 18 (2000).

[9] Savage, GM. "Carbon-Carbon Composites", Chapman & Hall, London (1993).

[10] Savage, GM. Engineering Failure Analysis, 13, 198 (2006).

[11] Savage, GM. Proc. "Transfac 06" San-Sebastian, Spain (Oct 2006).