Enhancing the exploitation and efficiency of fibre reinforced composite structures by improvement of interlaminar fracture toughness

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Abstract

Fibre reinforced composite materials are used extensively in stiffness critical, weight sensitive structures such as those found in aerospace and motor racing. They are characterized by high in-plane strength, stiffness and toughness and low density. The most widely used family of these materials is essentially two dimensional, characterized by relatively poor out of plane properties. As a consequence of low interlaminar toughness in particular, many possible applications are precluded and others severely compromised in performance per unit weight efficiency. Formula 1 racing represents the most advanced exploitation of composite materials both in terms of the percentage usage and complexity of application (1). In order to develop their products leading F1 teams work very closely with the major raw materials suppliers to expand the horizons of composites usage. The problems of interlaminar performance are discussed along with the techniques used to measure them and the fracture mechanics principles applied to improve them. A number of Formula 1 applications and developments are used to illustrate the effectiveness of the improved understanding of the interlaminar fracture behaviour of composites.

Interlaminar response of composite materials.

It is generally accepted that the interlaminar fracture mode is potentially the major life-limiting failure process in fibre reinforced composite materials subject to severe service loading (2). The test most often referred to in the literature for evaluating the interlaminar performance of composites is the "short beam shear test" (3). A shortened span is used on a three-point flexure test fixture in order to maximise the shear stress at the specimen's neutral axis. The shear testing of fibre-reinforced composites is dominated by the matrix phase. In the short beam shear test it is difficult to establish a state of pure shear. The relatively low strength of the matrix and interface renders the composite vulnerable to any extraneous local normal stress. A further complication is the existence of areas and planes of weakness, along which a specimen may fail preferentially, irrespective of the principal axes of the stress field. In multiphase (toughened) composites it is extremely likely that cracks will propagate in a non-self consistent manner i.e. they will deviate from the path of the initial crack direction. In most test configurations this will result in the measured property being notional rather than genuine.

It has been shown that the interlaminar fracture toughness test is a useful method of characterising the interlaminar failure of carbon fibre fabric reinforced composites (4). The energy per unit area required to propagate an existing flaw between the plies of the material is evaluated as a measure of the ability of the material to resist interlaminar fracture.

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 1. After the initial peak load the curve is much flatter than a plastically deforming metal tube. 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.

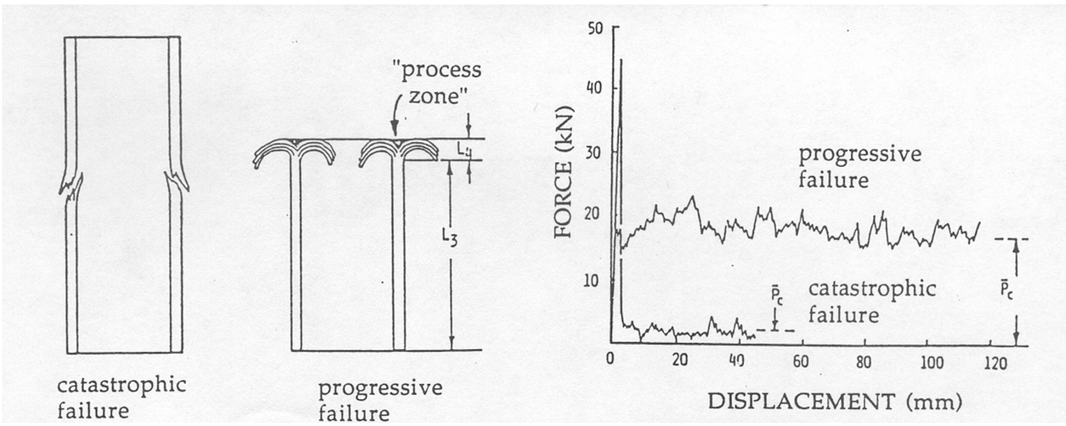


Figure 1. Axial crushing of composite tubes.

Toughening mechanisms in composites.

The inherent toughness of a material is considered to be an "intrinsic" property whereas those mechanisms that are invoked in order to alleviate fracture are described as being "extrinsic". The most important intrinsic toughening mechanism present in fibre-reinforced composites is that of fibre bridging. This accounts for its in-plane toughness (5). The relatively brittle matrix and weak fibre/matrix interface on the other hand results in a poor interlaminar toughness. Tight quality control in the processing of components will reduce the number and severity of voids within a composite. This will improve the interlaminar strength of a component, but have much smaller effect on its toughness. Any flaws induced during manufacture or in service are therefore prone to propagation under load, which may ultimately lead to premature failure. Composite components are designed and manufactured in order to minimise defects and interlaminar loading. In reality though, all materials contain defects to some extent and there is always a degree of "off-axis" loading on components. A significant improvement the ability of composite structures to tolerate defects/damage and resist out of plane loading can only be achieved using an extrinsic mechanism The traditional method of toughening a composite is to induce a degree of "ductility" within the matrix phase by the addition of thermoplastic oligomers (6,7). The thermoplastic is observed to reduce stress concentration at the

crack tip and promote crack branching (Figure 2).

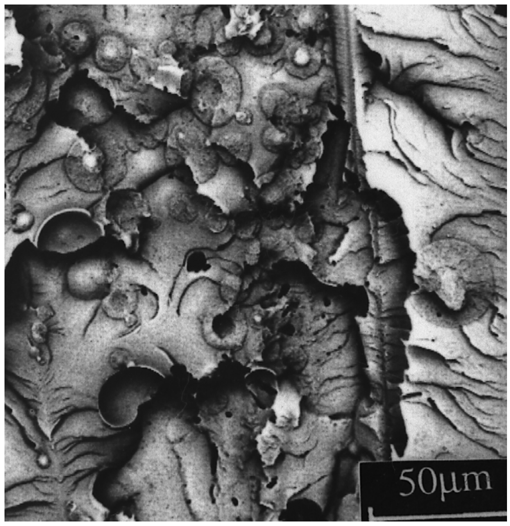


Figure 2. Thermoplastic toughened epoxy resin

Experimental Procedure.

Materials.

The composite materials used in this study were provided by Cytec Engineered Materials. The matrix resins were 2020, a commercially available toughened epoxy and 2035 an experimental "super-toughened" epoxy developed specifically for motor sport usage in conjunction with the BAR team. Fibre reinforcement was provided using Toray T800 (intermediate modulus) and M46J (high modulus) and Hercules IM9 (Intermediate modulus/ultra high strength) carbon each woven into a 200gm^{-2} twill fabric (8). Composite laminates were formed by hand lay up of the prepreg and autoclave curing at 135^{o}C and 7bar applied pressure. All mechanical testing was carried out on an Instron 5800 universal test frame. Tensile properties were evaluated using industry standard techniques (3).

Interlaminar shear strength

Interlaminar shear strength measurements were carried out using a shortened three-point flexure test with a span/depth ratio of 4/1 to maximise the shear stress at the neutral axis (Figure 3). ILS was calculated from:

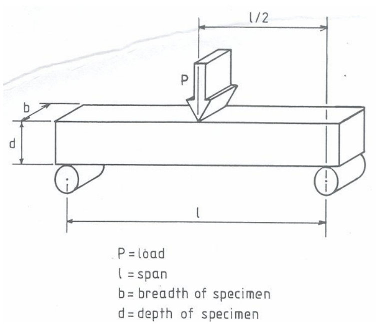


Figure 3. 3-point flexure test configuration

$$ILS = \frac{3P}{4bd} \qquad (1)$$

where P is the failure load, l the span, b specimen breadth, d is specimen depth and m the slope of the linear portion of the load/deflection curve.

Interlaminar fracture toughness

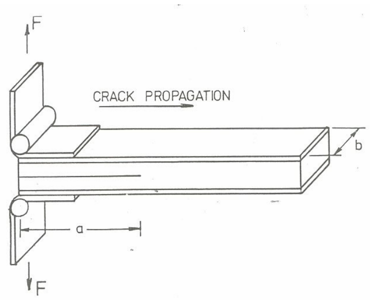


Figure 4. The DCB test geometry

Interlaminar crack growth within the composites was studied using the double cantilever beam (DCB) test. The specimen was loaded by applying symmetrical opening tensile forces at the ends of the beam as shown in Figure 4. This enabled the mode I critical strain energy release rate (toughness) G_{IC} to be ascertained. According to simple beam theory, a crack extension from {a to (a+Δa)} induces a change in compliance resulting in a loss of strain energy (dU). Assuming a stable crack growth (G_{IC} is constant) then:

$$G_{IC} = -\frac{1}{b}\frac{dU}{dA} \qquad (2)$$

where U is the total energy stored in the specimen and b its width (9, 10, 11). Figure 5 shows a typical load/displacement/crack-length curve for an interlaminar crack propagating in a composite of the type studied, where F and d are the applied load and corresponding deflection. The specimen is loaded to F_i whence the crack begins to extend. The load drops to F_{i+1} whilst the crack extends from a_i to (a_i+a_{i+1}). The energy released dU is equal to the area under the load/deflection curve dA. For a small crack growth increment the loading and unloading curves may be assumed linear such that:

$$-dU = dA = ½(F_i\,\delta_{i+1} - F_{i+1}\,\delta_i) \qquad (3)$$

A mean value of G_{IC} was determined by measuring F_i, F_{i+1}, d_i and d_{i+1} for a series of n extensions of length $(a_{i+1}-a_i)$:

$$G_{IC} = \frac{1}{2b\sum_{i=1}^{n}(a_{i+1}-a_i)}\sum_{i=1}^{n}(F_i\,\delta_{i+1} - F_{i+1}\,\delta_i) \qquad (4)$$

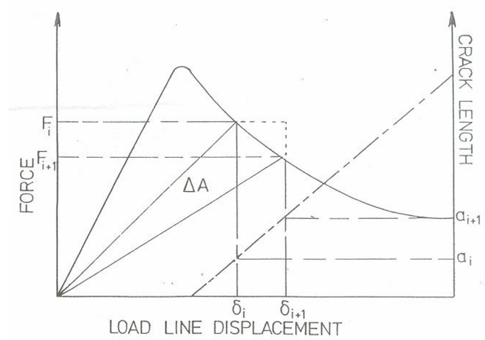


Figure 5 Typical force-displacement-crack length curve.

A crack initiator was added in the form of a 25m long, double layer of aluminium foil, liberally coated in release agent, placed between the central plies. Crack length measurement was achieved via resistive crack gauges affixed to one side of the test specimen. G_{IC} was calculated using equation (4) via an analysis package within the Instron control software. An example of the output obtained is shown in Figure 6.

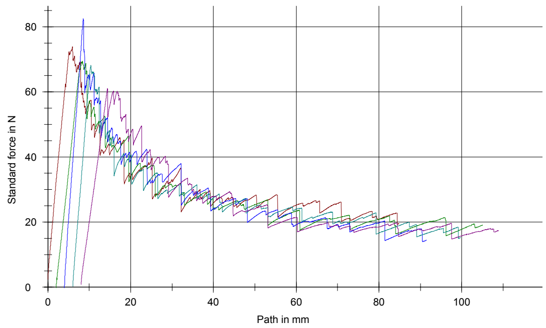


Figure 6. Data output from DCB test.

Specific energy absorption

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 7) (12).

Figure 7. Measuring the energy absorption efficiency of a composite material.

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

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

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.

Results and Discussion

Table 1. Experimental results

Composite (Fibres/Resin)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Inter laminar Shear strength (MPa)	Inter laminar Fracture Toughness, G_{IC} (Jm^{-2})	Specific Energy absorption (Jg^{-1})
M46J/2020	639	106	64	338	47
T800/2020	981	68	84	462	62
IM9/2020	1084	71	86	446	69
M46J/2035	687	108	72	431	58
T800/2035	1050	72	94	800	74
IM9/2035	1184	74	96	792	78

Note; all composites based upon 200gm-2 2x2 twill weave fabric reinforcement, and standard resin content of 42 ±2% by weight.

The primary mechanical properties of composites (tensile strength and stiffness) are dominated by the fibre reinforcement (Table 1). The matrix phase on the other hand contributes significantly to the secondary attributes such as resistance to out of plane loading and damage tolerance. Of the four modes of deformation/energy absorption available to composite materials, fibre fracture is by far the most significant. The increased work of fracture obtained from higher and higher strength fibres is shown to increase the specific energy absorption. This can only be achieved however if the tendency of the composite to delaminate under load is reduced. The toughness of the resin thus plays a significant role in optimising its ability to absorb energy. This is particularly useful when designing "dual function" components that have a structural purpose in addition to acting as an impact safety device (13).

It must be assumed that all engineering components in service contain defects to some degree or another. One may minimise the extent, size and effect of induced flaws by careful design manufacture and condition monitoring, but there will always be a risk. In the case of composite materials used in a harsh environment such as Formula 1, delamination represents the most likely mode of failure. The interlaminar shear strength of a composite is a good measure of its ability to resist out of plane loading. It cannot account however for the presence of defects induced during service or manufacture. The material thus requires the ability to resist the propagation of such flaws under load. Improvement of interlaminar fracture toughness is thus paramount in order to improve reliability and reduce the requirement for over conservative design. Higher G_{IC} will furthermore open up more and more design opportunities otherwise precluded to composite materials.

Design applications using improved interlaminar properties

The design procedure used in Formula 1 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 and any anticipated extraneous scenarios. Tests are then carried out on prototype representative components to check the validity of the model and to provide more accurate input data. The final design is an iterative process of mathematical modeling and laboratory testing which aims to produce a chassis capable of meeting the operational requirements at minimum weight within the available timescale.

Off-axis loading

The roll hoop on a Formula 1 car is designed to protect the driver in the event of a major accident. It also acts as the air intake for the engine and as such must be designed to comply with the aerodynamics of the car. In order to be homologated for grand prix usage the roll hoop must be capable of supporting a load of 120kN applied at a compound angle designed to simulate the most probable crash scenario, as dictated by the sport's technical regulations (12). The use of a composite based on the 2035 resin system has enabled the BAR team to make a weight reduction of the order of 15% on its 2004 car compared to that of the previous season (Figure 8) whilst still passing the test. This is particularly advantageous as the roll hoop sits at the highest point of the car, thus reducing centre of gravity height.

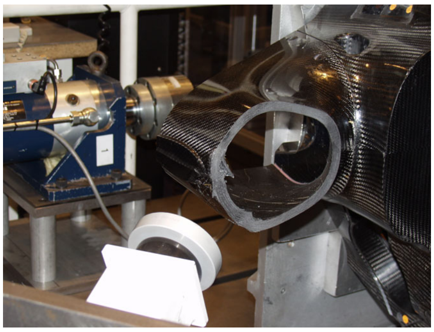
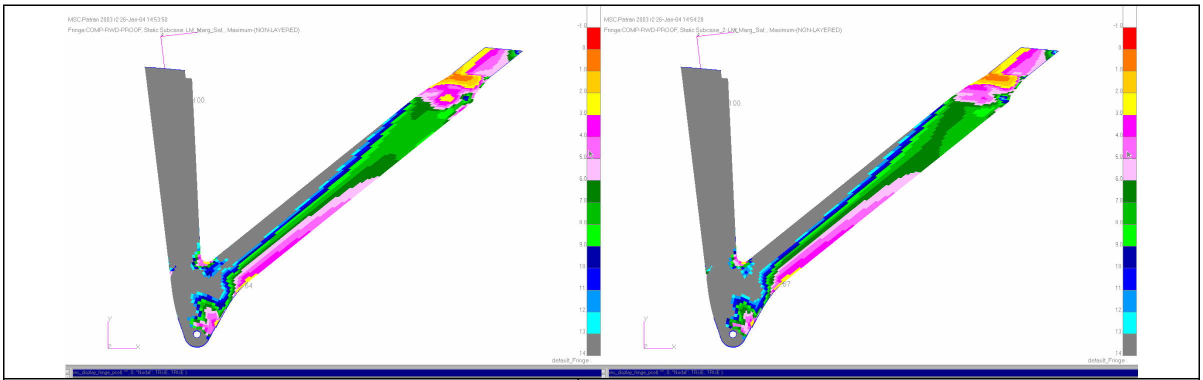


Figure 8. Ultimate strength of the roll hoop is dependent on interlaminar properties

"Flexure blades" (Figure 9) are routinely used in F1 suspension members in order to replace conventional spherical bearings. This is done in order to reduce (un-sprung) mass and to improve handling. The flexing of the blade under driving loads induces severe off-axis loading into the composite material. Enhanced interlaminar toughness greatly increases their longevity and reliability.



2020	2035

Figure 9. Improving the strength of composite flexure blades by use of higher G_{IC} material.

Energy absorption

The rear impact structure (RIMP) attaches to the back of the gearbox. Its purpose is to support the loads from the rear wing and to protect the driver in the event of a rear end crash. Selection of a composite based on the highly toughened resin system and ultra-high strength fibres has greatly improved the specific energy absorption of the component. Furthermore, the increased resistance to delamination has enabled an optimisation of the lay up reducing the peak load from the impact, thus protecting the gearbox. Application of this new material he enabled a reduction of 28% in weight 17.5% in peak load for the 2004 BAR RIMP (Figure 10).

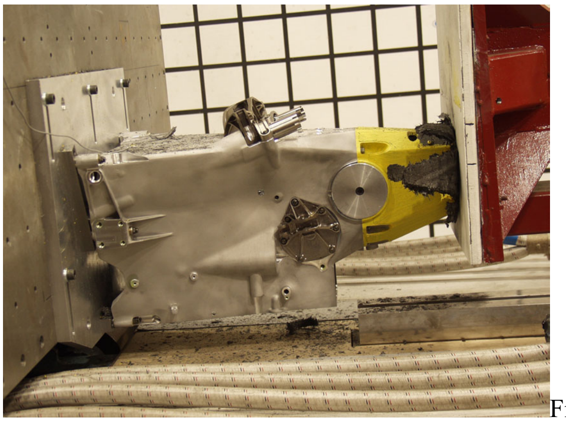
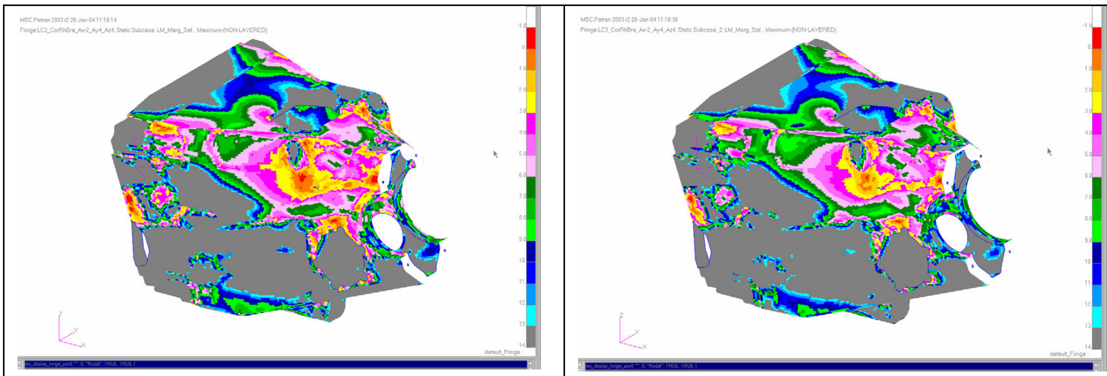


Figure 10. FIA rear impact test

New design concepts

A Formula 1 gearbox is required to transmit in excess of 900-horse power in addition to being a stiff but lightweight structural element in the primary chassis of the car (1). It must also be capable of surviving the peak load transmitted during the FIA rear crash test. A composite of high modulus fibres and 2035 resin has been used as the basis of the BAR team’s “jewel in the crown” for 2004, a carbon fibre gearbox (Figure 11). Whilst this could, and indeed has in the past, been done using a commercial product, the development of this new material has made a far more weight efficient and damage tolerant structure.



LC3, Braking and Cornering. **2020** | LC3, Braking and Cornering. **2035**

Figure 11. Gearbox laminate Margin of Safety (MoS). Scale shows the MoS to first ply failure, anything greater than zero is good. Areas in red show that a ply in this laminate is failing the maximum stress criteria. The 2020 to 2035 results show a significant increase in the MoS.

Conclusion

In terms of materials technology, fibre reinforced composites have had the greatest influence upon the design of Formula 1 racing cars (14). All of the cars that make up the grid are totally dependent upon composites in their construction. Not only have these materials provided levels of safety and performance that would otherwise be unattainable, they have facilitated advances in other areas such as aerodynamics. Despite their many advantages however, composite materials are seriously limited by relatively poor interlaminar properties. This precludes many potential applications and in others requires an overcautious, less weight efficient design solutions. Continued advances in toughened matrix materials have clearly demonstrated the importance of G_{IC}. The development of 2035 resin system has produced a potential 90% increase in the interlaminar toughness of the corresponding composites. It is not possible to calculate exactly how this translates into subsequent component designs, but the circumstantial evidence is overwhelming. In short, interlaminar fracture toughness is the key element in further exploitation of composite structures**.**

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