Development of Penetration Resistance in the Survival Cell of a Formula 1 Racing Car

G. Savage, I. Bomphray & M. Oxley
BAR Honda Formula 1

Abstract

The success of composite materials in providing stiffness efficiencies and weight reduction in Formula 1 cars is well documented. 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 design of a sophisticated driver protection system into the vehicles' structure at minimum weight penalty. The chassis itself has evolved into a "survival cell" capable of tolerating damage from minor incidents whilst at the same time being able to protect 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. A number of safety issues have been raised by injuries caused to pilots by Foreign Object Damage. This has generally involved penetration of the survival cell by broken pieces from their own or other competitors' vehicles. 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 by a special device. A minimum load must be reached prior to full penetration, coupled with the absorption of a minimum amount of energy. The pass criteria for the test also stipulate a non-catastrophic failure mode.

The introduction of mandatory safety tests has resulted in chassis design becoming increasingly dominated by strength considerations. The fracture behaviour of the composite materials used strongly influences the ability of the structure to meet the requirements of the regulations. The penetration test tends to be periodically made more stringent (as indeed are the other safety tests) requiring greater loads and energy absorption. The various factors involved in resisting penetration of the survival cell are discussed along with a review of the appropriateness of the test to increased survivability of the driver.

Introduction

During the 1960s the rate of fatal and serious injury within Formula 1 was 1 in every 8 crashes. The 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 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. It was, however, also 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 material. 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 2006 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. Since the late 1980s the 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" (5).

During the 2000 season a number of safety issues were raised by injuries caused to drivers by Foreign Object Damage. This generally involved penetration of their survival cell by broken pieces of their own or other competitor's vehicles (Figure 1). In an attempt to combat this potentially very dangerous occurrence, a "side intrusion" test was introduced. Each team is required to submit a panel for testing which is representative of the construction of their monocoque.

Figure 1. Penetration of the survival cell by a broken wishbone, resulting in injury to the driver's leg.

The side intrusion test

The penetration resistance of the chassis is evaluated by testing flat coupons manufactured to a lay up identical to the survival cell. The operation is carried out in such a way as to simulate the conditions by which it may be loaded during a side impact in service. The coupon measures 550mm x 550mm, incorporating a rigid border of 25mm width. The test piece is fastened onto a rigid frame, with the outer surface uppermost, by means of 28 M8 bolts fastened to a torque of 20Nm. Loading is carried out within an Instron universal test frame of minimum capacity 300kN, by means of a conical "impactor" fixed via a load cell to the machine's moving crosshead (in the case of an electro-mechanical machine) or actuator if servo-hydraulic equipment is used (Figure 2). The conical device measures a minimum of 200mm in length with a 138±1mm diameter flat loading face with an edge radius of 10±1mm. This device is designed to represent the loading conditions of a Formula 1 deformable nose cone during perpendicular impact (known colloquially as "T-boning").

Figure 2. Intrusion panel test set-up.

The cone is positioned on the centre of the test panel and forced through it at a rate of 2±1mm.min^{-1}, with load/deflection data collected at 10Hz. The test is complete after a displacement of 150mm. The data are presented to include:

1. Chassis reference number
2. Thickness of test sample
3. Graphical representation of load v displacement
4. Graphical representation of energy v displacement
5. Maximum load achieved over the first 100mm of deflection
6. Energy absorbed over the first 100mm of deflection

The pass criteria are the maximum load to exceed 250kN (originally 150kN when the test was first introduced for the 2001 season) and energy absorption greater than 6kJ. A further requirement is that the specimen must fail in a "non-catastrophic" manner, with no influence of the border region on the outcome.

Results and observations

The standard construction used in F1 monocoque design consists of two thin carbon composite skins bonded to aluminium honeycomb core (Figure 3) (6). The stiffness critical nature of the structure dictated the use of primarily high modulus, unidirectional material angled at approximately 45^o to the axis of the car in order to react torsion loading from the wheels. Such a lay-up however proved next to useless in the side intrusion test (Figure 4). The penetrator was able to punch straight through the brittle panel at low load with correspondingly little absorption of energy. The new regulations forced designers to adopt some of the techniques used to resist ballistic penetration (7), employing woven fabrics based upon high strength intermediate modulus fibres (8). Figure 5 shows a load/deflection plot from a panel which has passed the test.

Figure 3. carbon composite/honeycomb chassis construction

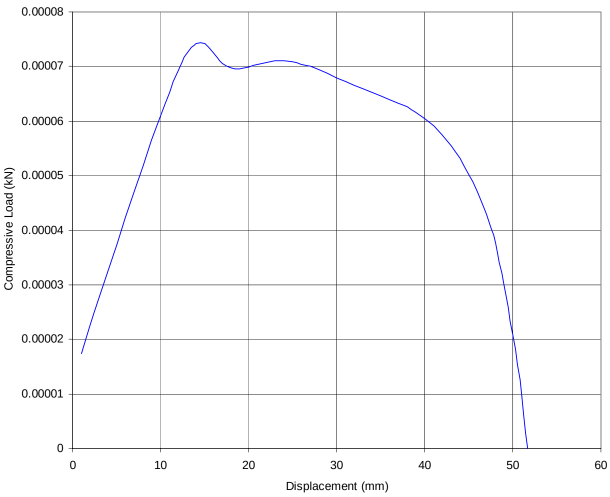

Figure 4 a UD carbon/honeycomb composite panel exhibits very poor performance in the side intrusion test

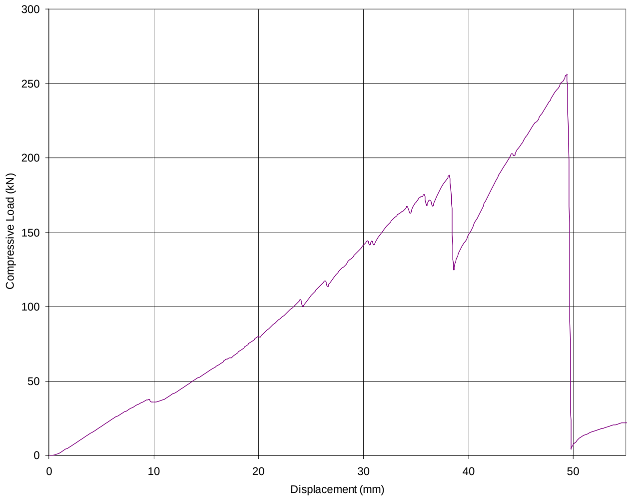

Figure 5 Load deflection response during side intrusion test on a fabric reinforced composite structure (FIA pass).

The two skins fail in a completely linear-elastic mode but the honeycomb structure as a whole exhibits a pseudo-plastic behaviour enabling the absorption of the requisite energy. Clearly the majority of the load is taken by the inner (tensile loaded) skin of the "sandwich". This has prompted the adoption of an asymmetric lay-up biased such that the inner skin is approximately twice the thickness of the outer. The fine details of the lay ups employed by the various teams are a jealously guarded secret as they seek to gain advantage over one another. Nevertheless a generic laminate based upon T1000 (9) fabric in a high toughness resin system similar to those used in the cars' energy absorbing structures is generally the preferred option (10). Subtle differences in core density and thickness, fibre architecture and choice of resin system are all employed to improve the efficiency of the penetration resistance per unit mass. As a rule of thumb, the present regulation has resulted in an increase of between 5 and 10kg in chassis weight compared to a pre-2001 season monocoque depending on how clever a particular design team are.

The requirements with respect to maximum load and energy absorption are a very straight forward output from the Instron test machine. By contrast the failure criterion is far more subjective. In common with "single hit" ballistic systems, the intrusion panel is made more efficient if the damage (and hence load) from the impactor is spread over the whole of its surface rather than being confined to the area in direct contact. Adopting such an approach runs the risk of falling foul of cracks extending into the border region. This could result in failure of the test. To illustrate this point consider Figure 6 which shows a panel which has passed the load and energy criteria, but deemed to have failed on fracture mode. The panel in Figure 7 on the other hand was judged to have passed. The difference between pass and fail can be somewhat arbitrary and often the subject of a one-sided "debate" between the team and the Technical Representative of the governing body!

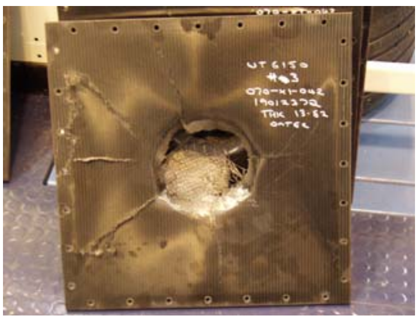

Figure 6 FIA failure

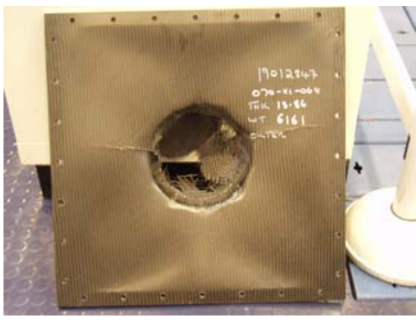

Figure 7 FIA pass!

Discussion – the effectiveness of the test and its limitations

The side intrusion test has certainly made the survival cell of a Formula 1 car safer. There has been a distinct shift in the monocoques' design from being stiffness critical towards a strength critical structure. Since the introduction of the test in 2001 and its subsequent upgrade two years later, there have been no major injuries resulting from foreign object penetration. There are however a number of considerations which limit the effectiveness and development of the level of protection afforded. The strength of the panel is significantly higher than the peak load achieved in the FIA front impact test. As a consequence BAR Honda were able to carry out a test in which the team's homologated side intrusion panel was used as the target in a practice FIA nose crash test (4). Not only was the panel able to defeat the impact, its presence had no significant effect upon the efficiency or mechanism of the energy absorbing structure (Figure 8). When another team tried this same test into an actual chassis however, the result was a catastrophic failure. Although the intrusion panel is a representative model of the chassis' construction, it is artificially restrained. The rigidly mounted panel exhibits a uniform compliance upon impact and can thus defeat the incoming threat in exactly the same way as in the test frame. The side of the chassis is far more compliant being far less restrained particularly in the area of the cockpit opening and resulted in the structure deflecting and disintegrating under the load generated by the impact. There is a limit therefore to the load bearing capability of the panel under real life conditions.

It was postulated that the safety of the chassis could be further enhanced by increasing the failure load to 400kN, with a corresponding increase in energy absorbed. This proved to be unrealistic because of the non-linear relationship between panel weight and failure load. Indeed, the 60% increase in load could only be achieved at a 300% weight penalty. The introduction of such a regulation would leave the cars resembling a main battle tank with a huge increase in cost as carbon composites are not the cheapest of materials! Furthermore, there is no guarantee that the cars would perform any better under impact conditions as the compliance of the overall structure would not be greatly enhanced.

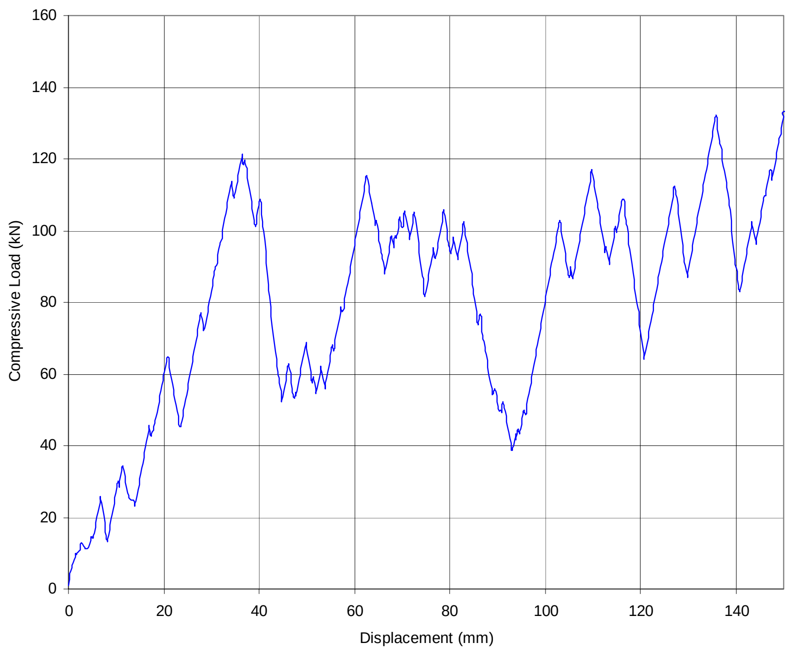

Figure 8. Load/deflection data from FIA nose impact into side intrusion panel

A further test was carried out in which a rear impact structure (10) was used to load the panel. This structure is designed to defeat approximately the same impact energy as the nose, but is far more slender. It was able to cut through the panel at a much lower load than the standard impactor (Figure 9). This occurs because the force is concentrated over a much smaller area, greatly increasing the stress, and the impactor is more rigid with much reduced (negligible) deformation during the event. This is the same phenomena which resulted in the obsolescence of chain mail and its replacement with plate armour during the middle ages (11). As metallurgy improved, swords changed from being slashing to stabbing weapons and were able to open up the mail during an attack. Indeed it is this same principle that resulted in the UD composites being useless in the side intrusion test!

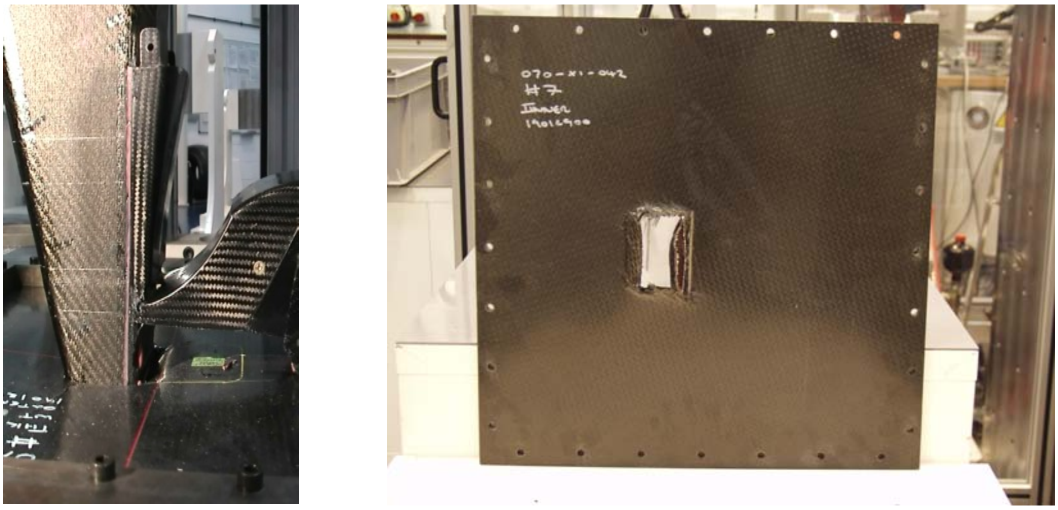

Figure 9. an impactor with a more slender aspect ratio is easily able to defeat the side penetration panel.

Although penetration protection has clearly improved driver survivability, a further concern arises from the tendency of the authority to periodically increase the performance of the impact absorbing structures on the car. The packaging of devices such as the nose box and rear impact structure is such that their size and geometry are somewhat limited. Their ability to absorb energy can only be realistically increased by making them stronger. A stronger nose box, for example, could be considered to afford better protection to the driver of the crashing vehicle. (This is not entirely true as the resultant acceleration passed on to the occupant could be considerably higher and therefore more detrimental to health for the same impact energy). By the same token however that same nose box could become an armour piercing projectile to any other car it might happen to hit.

Conclusion

Advances in technology and stringent safety rules have combined to significantly reduce the risk of death and injury resulting from crashes in Formula 1 races and tests. The governing body and the various participants are working to progressively improve driver survivability. Whilst this is an admirable course of action, it must be with a degree of realism. The nature of motor racing is such that there will always be a finite probability of injury to the driver. We may take steps to minimise this probability but it cannot be eliminated, there will always be a degree of risk. Simply making the cars stronger and stronger does not necessarily make them safer. There comes a point beyond which things cannot be improved because some other mechanism dominates survivability. Indeed badly thought out and executed technology and regulations can have a detrimental affect upon safety. It is all too easy, as in many aspects of transport, to approach race car safety with a blinkered, almost evangelical, zeal. Regulations which influence safety and survivability should only be introduced following thorough research and development, when they have been proven to meet the primary aim of protecting the driver.

References

(1) Rendall, I. "The power and the glory (a century of motor racing)" BBC Books, (1991)
(2) Wright, P., RaceCar Engineering, 9, 9, 13 (1999).
(3) Savage, GM., Met. Mater. 7, 10, 617 (1991).
(4) Savage, GM, Proc. Anales De Mecanica de la Fractura, 18, 274, Baiona (Vigo), Spain, (Mar. 2001).
(5) Savage, GM. Proc. "Materials Science, Its Nucleation and Growth", Imperial College London (2001).
(6) Savage, GM. J. STA, 140, 18 (2000).
(7) Savage, GM., Met. Mater. 5, 5, 285 (1989
(8) Savage, GM., "Carbon-carbon composites", Chapman and Hall (1992).
(9) Savage, GM. Proc. Anales De Mecanica de la Fractura, 18, 274 Baiona (Vigo), Spain (Mar 2001).
(10) Savage, GM., Bomphray, I and Oxley, M. Proc. Anales De Mecanica de la Fractura, 20, 512 Benecasim (Valencia), Spain (Apr. 2003).
(11) Burgess, M. Antiquaries Journal, 33, 48 (1953)