

Chassis Rigidity

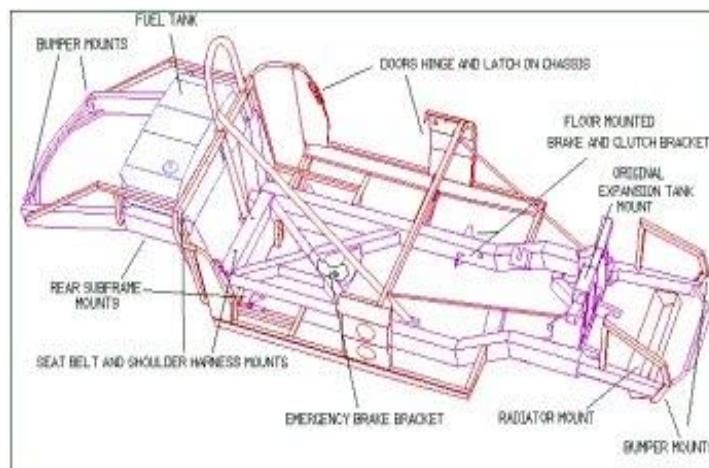
One way of improving vehicle handling is to strengthen the chassis. Since the late 80s, we saw chassis rigidity of new cars have increased significantly. Whenever a new car is launched, the manufacturer must claim its torsional rigidity has been increased by at least 20%. This is due both to the requirements for crash protection, and to improve handling.

Consider a car with a very weak chassis, which is easy to flex and twist under force. If it has stiff springs and dampers in the suspension, the shock caused by road irregularity will be transferred to the chassis directly. The weak chassis will be twisted and bent, thus the suspension geometry will be reshaped, creating non-neutral steer and other side effects, which the original suspension design was not intended to cope with. Therefore a weak chassis must ride on softer spring and dampers.

For the benefit of handling, we always want stiff spring and damper as long as ride comfort is acceptable. So we need a rigid chassis, which could cope with the stiff suspensions without flex or twist.

Different Types of Chassis

Ladder Chassis



AC Cobra's chassis.

This is the earliest type of chassis. From the earliest cars until the early 60s, nearly all cars in the world used it as standard. Today, most SUVs still employ it. Its construction, indicated by its name, looks like a ladder

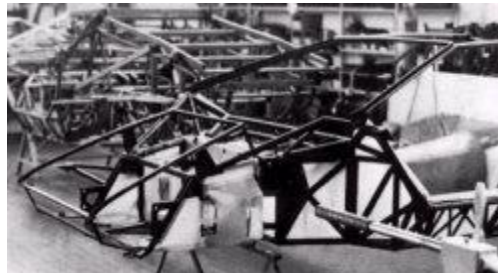
- two longitudinal rails interconnected by several lateral and cross braces. The longitudinal members are the main stress member. They deal with the load and also the longitudinal forces caused by acceleration and braking. The lateral and cross members provide resistance to lateral forces and further increase torsional rigidity.

Advantage:	It is easy and cheap for hand build.
Disadvantage:	Since it is a 2 dimensional structure, torsional rigidity is very much lower than other chassis, especially when dealing with vertical load or bumps.
Who use it ?	Most SUVs, classic cars, Lincoln Town Car, Ford Crown Victoria etc.

Tubular Space Frame



TVR Tuscan



Lamborghini Countach

Since the ladder chassis is not strong enough, motor racing engineers developed a 3 dimensional design - Tubular space frame. One of the earliest examples was the post-war Maserati Tipo 61 "Birdcage" racing car. The tubular space frame chassis employs dozens of circular-section tubes (some may use square-section tubes for easier connection to the body panels, though circular section provides the maximum strength), position in different directions to provide mechanical strength against forces from anywhere. These tubes are welded together and forms a very complex structure, as you can see in the above pictures.

For higher strength required by high performance sports cars, tubular space frame chassis usually incorporate a strong structure under both doors (see the picture of Lamborghini Countach), hence result in unusually high door sill and difficult access to the cabin.

In the early 50s, Mercedes-Benz created a racing car 300SLR using tubular space frame. This also brought the world the first tubular space frame road car, 300SL Gullwing. Due to the reduced accessibility of the

cabin, Mercedes had to extend the doors to the roof so that created the "Gullwings".

Since the mid 60s, many high-end sports cars also adopted tubular space frame to enhance the rigidity / weight ratio. However, many of them actually used space frames for the front and rear structure, with the cabin made as a monocoque to reduce manufacture cost.

Advantage:	Very strong in any direction. (compare with ladder chassis and monocoque chassis of the same weight)
Disadvantage:	Very complex, costly and time consuming to be built. Impossible for robotised production. It engages a lot of space, raise the door sill and result in difficult access to the cabin.
Who use it ?	All Ferrari before the 360M, Lamborghini Diablo, Jaguar XJ220, Caterham, TVR etc.



Monocoque

Today, 99% cars produced are made of steel monocoque chassis, thanks to its low production cost and suitability for automated production.

Monocoque is a one-piece structure, which defines the overall shape of the car. While ladder, tubular space frame and backbone chassis provides only the stress members and need to build the body around them, a monocoque chassis is already incorporated with the body in a single piece, as you can see in the above picture showing a Volvo V70.

In fact, the "one-piece" chassis is actually made by welding several pieces together. The floorpan, which is the largest component and all the other components are manufactured by sheet metal forming. They are spot welded together by robot arms (some even use laser welding) in a production line. The whole process just takes minutes. Monocoque chassis also benefit crash protection. Because it uses a lot of metal, crumple zone can be built into the structure.

Another advantage is space efficiency. The whole structure is actually an outer shell, unlike other types of chassis. There is no large transmission

tunnel, high door sills, large roll over bar etc. Obviously, this is very attractive to mass production cars.

There are many disadvantages as well. It's very heavy, due to the amount of metal used. As the shell is shaped to benefit space efficiency rather than strength, and the pressed sheet metal is not as strong as metal tubes or extruded metal, the rigidity-to-weight ratio is also the lowest among all kinds of chassis except the ladder chassis. Moreover, as the whole monocoque is made of steel, unlike some other chassis which combine steel chassis and a body made of aluminium or glass-fiber, monocoque is heavier than others.

Although monocoque is suitable for mass production by robots, it is nearly impossible for small-scale production. The setup cost for the tooling is too expensive. I believe Porsche is the only sports car specialist has the production volume to use a monocoque.

Advantage:	Cheap for mass production. Inherently good crash protection. Space efficient.
Disadvantage:	Heavy. Impossible for small-volume production.
Who use it ?	Nearly all mass production cars, all current Porsche.

ULSAB Monocoque



In the 90s, as tougher safety regulations demand more rigid chassis, the traditional steel monocoque becomes heavier. As a result, car makers turned to alternative materials to replace steel, most notably aluminium.

Although there is still no mass production car other than Audi with the A8 and A2, to completely eliminate steel in chassis construction, more and more cars use aluminium in body panels like the bonnet and boot lid, suspension arms and mounting sub-frames.

An association of world steel manufacturers hired Porsche Engineering Services to develop a new type of steel monocoque technology called the Ultra Light Steel Auto Body (ULSAB). As shown in the picture, basically it has the same structure as a conventional monocoque. It differs in minor details (the use of Hydroformed parts, sandwich steel and laser beam welding).

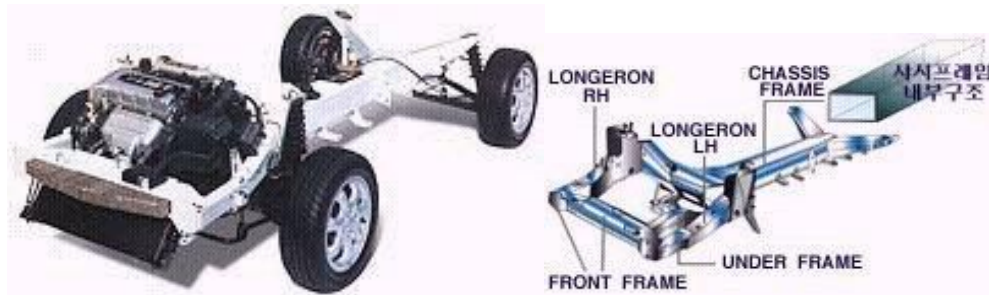
Hydroforming is a new alternative to pressing for shaping metal to desired shape,. Conventional pressing uses a heavy-weight machine to press a sheet metal into a die, this inevitably creates inhomogenous thickness (the edges and corners are always thinner than surfaces). To maintain a minimum thickness for the benefit of stiffness, car designers have to choose thicker sheet metal than originally needed. Hydroforming is very different, it forms thin steel tubes. The steel tube is placed in a die which defines the desired shape, then fluid of very high pressure will be pumped into the tube and then expands the latter to the inner surface of the die. Since the pressure of fluid is uniformal, thickness of the steel made is also uniformal. As a result, designers can use the minimum thickness steel to reduce weight.

Sandwich steel is made from a thermoplastic (polypropylene) core in between two very thin steel skins. This combination is up to 50 percent lighter compared with a piece of homogenous steel without a penalty in performance. Because it shows excellent rigidity, it is applied in areas that require high bending stiffness. However, it cannot be used in everywhere because it needs adhesive bonding or riveting instead of welding.

Compare with conventional monocoque, Porsche Engineering claim that the ULSAB it is 36% lighter yet over 50% stiffer. Although ULSAB was just annouced in early 1998, the new Opel Astra and BMW 3-Series have already used it in some parts. It will eventually replace conventional monocoque.

Advantage:	Stronger and lighter then conventional monocoque without increasing production cost.
Disadvantage:	Still not strong or light enough for the best sports cars.
Who use it ?	Opel Astra, BMW 3-series

Backbone Chassis



Kia's version Lotus Elan Mk II

Colin Chapman, the founder of Lotus, invented backbone chassis in his original Elan roadster. After failure in his experiment for a glass-fibre monocoque, Chapman discovered a strong yet cheap chassis.

The Backbone chassis is very simple: a strong tubular backbone (usually in rectangular section) connects the front and rear axle and provides nearly all the mechanical strength. Inside which there is space for the drive shaft in the case of a front-engined, rear-wheel drive layout like the Elan. The whole drivetrain, engine and suspensions are connected to both ends of the backbone. The body is built on the backbone, usually made of glass-fibre. It's strong enough for smaller sports cars but not up to the job for high-end ones.

TVR's chassis is adapted from this design - instead of a rigid backbone, it uses a lattice backbone made of tubular space frames. That's lighter and stronger (mainly because the transmission tunnel is wider and higher).

Advantage:	Strong enough for smaller sports cars. Easy to be made by hand thus cheap for low-volume production. Simple structure benefit cost. The most space-saving other than monocoque chassis.
Disadvantage:	Not strong enough for high-end sports cars. The backbone does not provide protection against side impact or off-set crash. Therefore it need other compensation means in the body. Not cost effective for mass production.
Who use it ?	Lotus Esprit, Elan Mk II, TVR, Marcos.

Glass-Fibre body



To many sports cars specialists, glass-fibre is a perfect material. It is lighter than steel and aluminium, easy to be shaped and rust-proof. Moreover, the most important is that it is cheap to be produced in small quantity - it needs only simple tooling and a pair of hands. There are a few drawbacks, though: 1) Higher tolerance in dimensions leads to bigger assembly gaps can be seen. This is usually perceived as lower visual quality compare with steel monocoque. 2) Image problem. Many people don't like "plastic cars".

Glass-fiber has become a must for British sports car specialists because it is the only way to make small quantity of cars economically. In 1957, Lotus pioneered Glass-Fiber Monocoque chassis in the Elite (see picture). The whole mechanical stressed structure was made of glass-fiber, which had the advantage of lightweight and rigidity like today's carbon-fibre monocoque. Engine, transmission and suspensions were bolted onto the glass-fibre body. As a result, the whole car weighed as light as 660 kg.

However, this radical attempt caused too many problems to Colin Chapman. Since the connecting points between the glass-fiber body and suspensions / engine required very small tolerances, which were difficult to achieve in glass-fibre, Lotus actually scrapped many out-of-specification body. Others had to be corrected at a significant cost. As a result, every Elite was built at a loss.

Today, no matter Lotus, TVR, Marcos, GM's Corvette / Camaro / Firebird, Venturi and more, employ glass-fiber in non-stressed upper body. In other words, they just act as an asthetic enclosure and provide aerodynamic efficiency. The stressed chassis are usually backbone, tubular space-frame, aluminium space-frame or even monocoque.

Advantage:	Lightweight. Cheap to be produced in small quantity. Rust-proof.
Disadvantage:	Lower visual quality. Unable to act as stressed member.
Who use it ?	Lotus, TVR, Marcos, Corvette, Camaro, Firebird ...

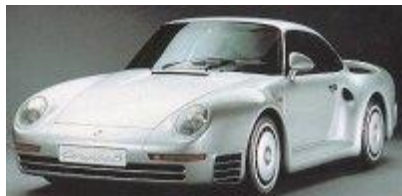
Carbon-Fiber Monocoque

Carbon Fiber is the most sophisticated material used for aerospace and motorsport applications because of its superior rigidity-to-weight ratio. In the early 80s, FIA established Group B racing category, which allowed the use of virtually any technology available as long as a minimum of 200 road cars are made. As a result, road cars featuring Carbon-Fiber body panels started to appear, such as Ferrari 288GTO and Porsche 959.

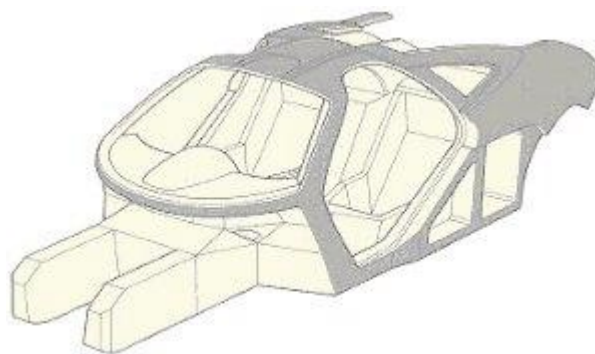
There are several Carbon-fibers commonly used in the motorsport industry. Kelvar, which was developed by Du Pont, offers the highest rigidity-to-weight ratio among them. Because of this, US army's helmets are made of Kelvar. Kelvar can also be found in the body panels of many exotic cars, although most of them simultaneously use other types of carbon-fiber in even larger amount.

Carbon-fiber panels are made by weaving carbon-fiber sheets (like a textile) on either side of an aluminium foil. The foil, which defines the shape of the panel, is stacked with several layers of carbon fiber sheets, impregnated with resin, it is then cured in an oven for 3 hours at 120°C and 90 psi pressure.

Carbon-Fiber Panels VS Carbon-Fiber Monocoque Chassis



Porsche 959, employed carbon-fiber in body panels only, is obviously



.... inferior to McLaren F1's carbon-fiber monocoque. This structure not only supports the engine / drivetrain and suspensions, it also serves as a very rigid survival cell.

Exotic car makers like to tell you their cars employ carbon-fiber in construction. This sounds very advanced, but you must ask one more question - where is the carbon-fiber used ? Body panels or Chassis ?

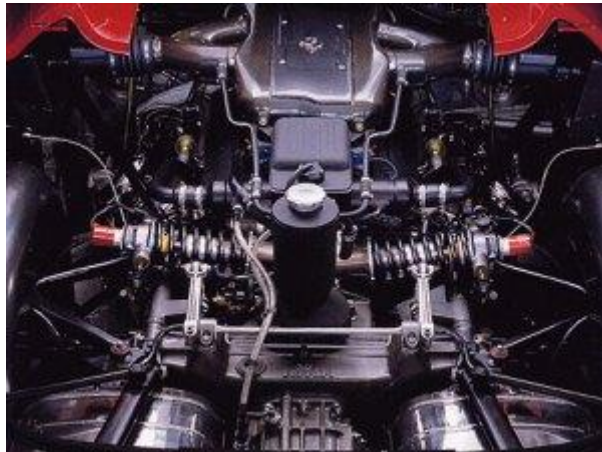
Most so-called "supercars" use carbon-fiber in body panels only, such as Porsche 959, Ferrari 288GTO, Ferrari F40 and more recently, the Porsche 911 GT1. Since body panels do nothing to provide mechanical strength, the use of carbon fiber over aluminium can barely save weight. The chassis remains to be the stress member, which is usually a heavier and weaker steel tubular frame.

The carbon-fiber monocoque chassis, has only ever appeared in McLaren F1, Bugatti EB110SS and Ferrari F50. It provides superior rigidity yet optimise weight. No other chassis could be better.

Carbon Fiber Monocoque made its debut in 1981 with McLaren's MP4/1 Formula One racing car, designed by John Barnard. No wonder McLaren F1 is the first road car to feature it.

Car	Body	Chassis
Ferrari 288GTO (1985)	carbon fiber panels	steel tubular space frame
Porsche 959 (1987)	carbon fiber panels	steel monocoque
Ferrari F40 (1988)	carbon fiber panels + doors	steel tubular space frame
McLaren F1 (1993)	carbon fiber panels	carbon fiber monocoque
Ferrari F50 (1996)	carbon fiber panels + doors	carbon fiber monocoque
Lamborghini Diablo SV (1998)	mostly aluminium panels, with carbon fiber bonnet + engine lid	steel tubular space frame
Lamborghini Diablo GT (1999)	mostly carbon fiber panels + aluminium doors	steel tubular space frame

Engine act as stressed member - Ferrari F50



Unlike McLaren F1, Ferrari F50's rear suspensions are directly bonded to the engine / gearbox assembly. This means the engine becomes the stressed member which supports the load from rear axle. Then, the whole engine / gearbox / rear suspensions structure is bonded into the carbon fiber chassis through light alloy. This is a first for a road car.

Advantage: lighter still.

Disadvantage: engine's vibration directly transfers to the body and cockpit.

In 1963, a revolutionary chassis structure appeared in Formula One, that is, the championship-winning Lotus 25. Once again, that was innovated by Colin Chapman. Chapman used the engine / gearbox as mounting points for rear suspensions in order to reduce the width of his car as well as to reduce weight. In particular, reduced width led to lower aerodynamic drag. Of course, the engine / chassis must be made stiffer to cope with the additional stressed from rear axle. Today, F1 cars still use this basic structure.

Characteristics of carbon-fiber monocoque:

Advantage: The lightest and stiffest chassis.

Disadvantage: By far the most expensive.

Who use it ? McLaren F1, Bugatti EB110SS, Ferrari F50.

Aluminium Space Frame



Audi ASF

The Audi A8 is the first mass production car featuring Aluminium Space Frame chassis. Developed in conjunction with US aluminium maker Alcoa, the ASF is intended to replace conventional steel monocoque mainly for the benefit of lightness. Audi claimed that the A8's ASF is 40% lighter yet 40% stiffer than contemporary steel monocoque. This enable the 4WD-equipped A8 to be lighter than BMW 740i.

The ASF consists of extruded aluminum sections, vacuum die cast components and aluminum sheets of different thicknesses. They all are made of high-strength aluminium alloy. At the highly stressed corners and joints, extruded sections are connected by complex aluminum die casting (nodes). New fastening methods were developed to join the body parts together. It's quite complex and production cost is far higher than steel monocoque.

The Audi A2 employed the second generation of ASF technology, which involves larger but fewer frames, hence fewer nodes requiring less welding. Laser welding is also extensively used in the assembly. All these helped reducing the production cost to the extent that the A2 is an affordable car.

Advantage: Lighter than steel monocoque. As space efficient as it.

Disadvantage: Still expensive for mass production

Who use it ? Audi

Lotus Elise



Elise's revolutionary chassis is made of extruded aluminium sections joined by glue and rivets. New technology can make the extruded parts curvy, as seen in the side members. This allows large part to be made in single piece, thus save bonding and weight.

To Lotus and other low-volume sports car makers, Audi's ASF technology is actually unfeasible because it requires a large press. But there is an alternative: extruding. Extrusion dies are very cheap, yet they can make extruded aluminium in any thickness. The question is: how to bond the extruded parts together to form a rigid chassis ?

The Renault Sport Spider bonds them by spot welding, while Lotus Elise uses glue and rivet to do so. Comparing their specification and you will know how superior the Elise is:

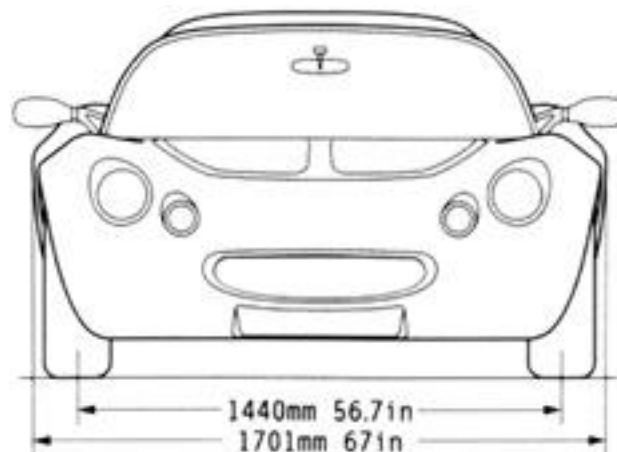
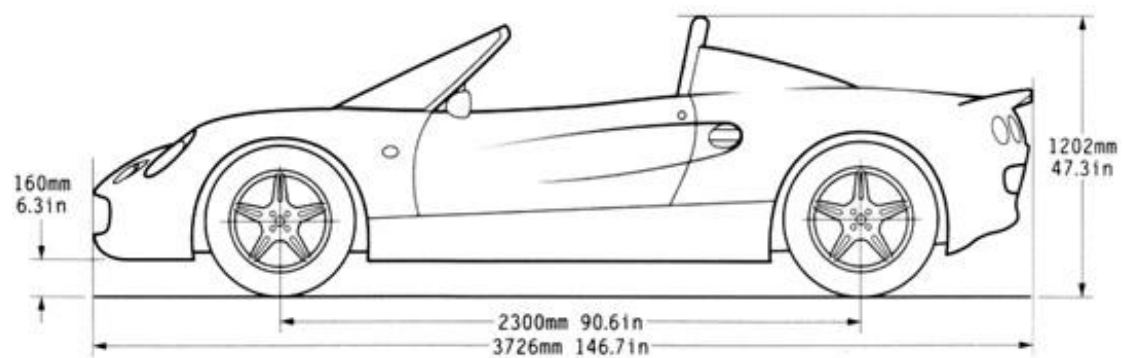
	Renault Sport Spider	Lotus Elise
Weight of chassis	80 kg	65 kg
Torsional stiffness	10,000 Nm/degree	11,000 Nm/degree
Thickness of extrusion	3 mm	1.5 mm

Lotus's technology was originated by its supplier, Hydro Aluminium of Denmark. Hydro discovered that aluminium extrusion can be bonded by epoxy resin (glue) if it is adequately prepared by a special chemical in the bonding surface. Surprisingly, glue can bond the sections together strongly and reliably. Most importantly, the aluminium extruded sections can be made much thinner than traditional welding technique. Why ? because welded joints are weak, so the thickness of material should be increased throughout a member just to make a joint strong enough. Therefore Elise's chassis could be lighter yet stiffer.



Glue can be clearly seen during production.

Unquestionably, the Lotus Elise's aluminium chassis is a revolution. It is expected that more British specialty cars will take advantage of this technology. The overall dimensions of the Elise are shown below.



This sketch shows the engine and frontal impact box.



Here is a sketch of the Elise showing the attachment of the rear steel impact section.