Part One

Fundamental Background

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Overview of Composite Materials and their Automotive Applications

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1.1   Introduction

This chapter presents an overview of recent automotive applications of advanced composites. A summary of available composites that could be used in automotive industries is presented. This work mainly deals with new research and studies done in order to investigate the present and potential use of composites for automotive structural components (e.g. tubes, plates, driveshafts, springs, brake discs, etc.). The important conclusions of these experimental and numerical simulation studies are shown in detail. It is important to note that most studies have an interest in enhancing the mechanical properties of automotive parts as well as providing better ecological and economical solutions. The influence of reinforcement types and architecture on the mechanical behaviour of automotive parts is investigated.

It is remarked that unidirectional composites and composite laminates are the most used composites, with a domination of glass fibres. However, carbon reinforced polymers and carbon ceramic composites along with nanocomposites could be considered as the most advanced composites currently in use for the automotive industry. Moreover, the emergence of natural fibre reinforced polymers, green composites, as a replacement of glass fibre reinforced polymers is discussed.

Recently, the use of composite materials has increased rapidly in automotive domains. As reported, according to [1], it is remarked that the total global consumption of lightweight materials used in transportation equipment will increase at a compound annual growth rate (CAGR) of 9.9% in tonnage terms and 5.7% in value terms between 2006 and 2011 (from

42.8 million tons/US$80.5 billion in 2006 to 68.5 million tons/US$106.4 billion in 2011) [2]. The use of composites consists of chassis parts, bumpers, driveshafts, brake discs, springs, fuel tanks, and so on.

From a historical point of view, it should be noticed that the first car body made from (glass fibre reinforced polymer, GFRP) composites was for the Chevrolet Corvette, which was introduced to the public at Motorama show at New York in 1953 [3]. For these days, the Corvette series still use composite materials in its design. In motor sports, the use of carbon fibre reinforced polymers has been shown in Formula 1, with the McLaren MP4 in 1981. The open wheel car benefits from lighter body, which leads to a well distributed weight in order to achieve more mechanical grip on the track which significantly increases the overall performance of the car. Nowadays, all Formula series cars and other racing touring cars use composites in huge amounts in almost all of their body parts.

Composites have many advantages over traditional materials, such as their relatively high strength and low weight, excellent corrosion resistance, thermal properties and dimensional stability and more resistance to impact, fatigue and other static and dynamic loads that car structures could be subjected. These advantages increase the performance of cars and lead to safer and lower energy consumption. It should be noticed that car performance is affected not only by the engine horsepower, but also by other important parameters such as the weight/horsepower ratio and the good distribution of the weight. Moreover, lighter vehicles lead to a reduction of fuel consumption. It has been estimated that the fuel economy improves by 7% for every 10% of weight reduction from a vehicle's total weight [1, 2]. It is reported that using carbon fibre composites instead of traditional materials in body and chassis car parts could save 50% of weight [1, 2]. In addition, it means for every kilogram of weight reduced in a vehicle, there is about 20 kg of carbon dioxide reduction [2].

The major problems still facing the large use of composites in automotive domains are: the high cost in comparison with traditional materials (steel, alloy, aluminium), the complex and expensive manufacturing process for a large number of parts, the unknown physical (mechanical, thermal) behaviour of some kind of composites. Thus, many studies and research are conducted to solve these problems in order to extend the use of composites in large mass. Ford, with a collaboration with materials experts through the Hightech NRW research project, leads the search for a solution of a cost efficient manufacturing of carbon fibre composite components [4]. As estimated by Ford, the use of carbon fibre composites in addition to other advanced materials in the manufacturing of many automotive parts will reduce the weight of their cars by 340 kg at the end of the decade [4]. Another example is the consortium, led by Umeco and partnered by Aston Martin Lagonda, Delta Motorsport Ltd, ABB Robotics and Pentangle Engineering Services Ltd, that has been created to look into the potential for using high-performance composites. The project aims to reduce the cost of composite body in white vehicle structures for the mainstream automotive sector [5].

Many types of composites exist, which give the opportunity to select the optimum material design for any structure. However, this leads to many studies that deal with the mechanical behaviour of composites. The most used composites are composite laminates which consist of several plies with unidirectional long fibres. More developed kinds of composites known as textile composites (woven, braided and knitted fabrics) has emerged recently to be adopted in automotive applications. Moreover, nanocomposites have been used in order to enhance the performance of car structures. Hybrid composites also have been adopted especially in

designing tubes and beams. Hybrids consist of several layers of composites and other types of materials, such as aluminium. The aluminium layer is reinforced by laminated or unidirectional (UD) composites composites. These kinds of lightweight materials are used to resist impact loading, as will be shown in the section below.

In this chapter, a brief general introduction of composites type is presented in the second section, while the automotive applications of advanced composites are discussed in the third section. In the fourth section, the potential of analytical and numerical analysis is presented.

1.2 Polymer Composite Materials

In general, composite materials are composed from at least two materials, where one is the reinforcing phase and the other is the matrix. Many combinations can be shown, with different kinds of materials and architectures.

There are two classification systems of composite materials. One is based on the matrix material (metal matrix composites, MMC; ceramic matrix composites, CMC; polymer matrix composites, PMC) and the second is based on the material structure: particulate (random orientation of particles; preferred orientation of particles), fibrous (short-fibre reinforced composites; long-fibre reinforced composites) and laminate composites.

The various PMC are classified as thermoplastic and thermosets and can be reinforced with various types of fibres depending upon the applications. The PMC are used in various automotive applications like crashworthiness, body panels, bumpers and so on. The CMC are used in elevated temperatures of various engine components and braking systems. The MMC use magnesium, copper and aluminium as their matrix with fibres to be used in various engine and crash absorbing components. Moreover, MMC with aluminium matrix and ceramic based composites find some automotive applications with supercar brake discs.

The PMC have heavily been used in the automotive industry. Polymers used in automotive applications are divided into thermoplastics and thermosets. Thermoplastics are high molecular weight materials that soften or melt on the application of heat. Thermoset processing requires the non-reversible conversion of a low molecular weight base resin to a polymerised structure. The resultant material cannot be re-melted or re-formed.

In automotive applications, reinforced plastics are the major composite material. For polymer composites, common fillers used include calcium carbonate ($CaCO_3$), talc, wollastonite, glass and carbon fibre. Some of the common processing techniques for polymer composites are: injection moulding, sheet moulding compound (SMC), glass-mat thermoplastic (GMT) compression moulding, resin transfer moulding (RTM) and reaction injection moulding (RIM).

Some of the factors affecting the processing and manufacture of polymer composites are fibre distribution in the matrix, compatibility between the matrix and fibres, fibre orientation and thermal stability of the fibre.

A common processing technique for the production of polymer composites is thermoforming. Thermoforming is commonly used to produce fibre-mat thermoplastic composites. The fibre and the polymer are inserted into a heated mould. The thermoplastic then flows into the fibre component. The hybrid material is then combined into a composite in a cold press. Compression moulding using thermoset polymer matrices is another major processing technique used to manufacture large parts for the automotive industry.

The main categories of polymer composites used in automotive applications are as follows [6]:

- **Non-structural composites**, composites composed of short glass fibre-reinforced plastics with the reinforcement in the range of 10–50% by weight used in pedal systems, mirror housing and so on.
- **Semi-structural composites**, composites composed of several layers of the reinforcement, which is in the form of a mat in a matrix. The mat could be a chopped strand mat, a random continuous strand mat, or a unidirectional mat. The matrix could be a thermoplastic or a thermoset. These composites are used in body panels, front end structures, seat backs and so on.
- **Structural composites**, structural thermoplastic composites (TPC), structural reaction injection moulded core parts, bumper systems and so on.

1.2.1   Non-Structural Composites

The use of composite materials has been limited to automotive structural components, however recently there has been a wide use of composites in non-structural functional components. Schouwenaars *et al.* [7] studied the fracture during assembly of a radiator head produced from a nylon/33% short glass fibre composite. The study focused on finding the elastic constants and fracture stresses and on resolving some of the manufacturing problems such as distortion after moulding and deformations induced during assembly. They used a combination of in situ measurements, microscopy and reverse modelling of non-linear material properties to determine the stiffness constants and strength as a function of fibre length distribution and fibre orientation distribution. The integrated approach was used effectively to resolve the manufacturing problems presented.

Lee *et al.* [8] addressed the advantages of using composites in reducing the mass of automotive components and improving the fuel efficiency by developing a hybrid valve lifter to be used in an automotive internal combustion engine. The lifter was made from carbon fibre/phenolic composite and steel. The design and manufacture of the hybrid valve was investigated based on the functional requirements such as durability. The mass of the composite was 35% lighter than the conventional steel valve lifter and showed to be durable for the test loads.

Imihezri *et al.* [9] studied the mould flow and component design of a 30% glass fibre polyamide composite to be used as a clutch pedal. Different profile cross-sections were analysed using finite element analysis for stress and using mould flow software for flow properties.

1.2.2   Semi-Structural Composites

Sheet moulded compound (SMC) panels as exterior body panels have been increasingly used in automotive industry [10]. Among the main factors to consider in the design of the body panels are material cost and mass reduction. Mass reduction is achieved by using materials with the high strength-to-weight ratios which composite materials offer [2]. However, there are some barriers for the use of composites in the production of automotive parts, such their cost and their manufacturing.

General Motors Research Laboratories evaluated different body panel designs for a front wheel drive compact car for equal stiffness requirements [11]. The materials considered as

a substitute for steel were aluminium, glass SMC and carbon SMC. The SMC fibre content was in the range of 10–70% by weight. The glass SMC showed 27% reduction in mass, while aluminium and carbon SMC showed a mass reduction of 35 and 45%, respectively. Although the carbon SMC showed the highest mass reduction, it had a higher cost due to the higher selling price of carbon fibres. General Motors also uses continuous fibre glass epoxy composites for front and rear leaf springs in selected passenger cars and for longitudinal leaf springs in the GM mini-van. The glass/epoxy leaf spring had a mass reduction ratio of 4: 1 over the conventional steel leaf.

Feraboli *et al.* [12] studied the effect of fibre architecture on the delamination and flexural behaviour of carbon/epoxy body panels of the Lamborghini Murcielogo. They studied the use of four prepreg tapes, two fabrics and woven laminates over directional tape. The strength, durability, environmental resistance, vibration damping and surface finish of the composite body panels were investigated. The body panels were bonded to the tubular steel chassis by a methacrylate adhesive which was found to be effective than other adhesives like epoxy and polyurethane.

Feuillade *et al.* [13] studied the influence of material formulation and SMC process on the surface quality of SMC body panels. The main parameters considered were the amount of sizing on the fibres, the type of antistatic agent and its deposit method and the type of film former. Two commercially sized glass fibres were studied. The results showed that, during the impregnation process, the natures of the antistatic agent and the film former, the fibre wetting properties and the sizing influenced the surface quality of the SMC moulded panels.

Ning *et al.* [14] designed, analysed and manufactured an air conditioning cover roof door on a mass transit bus. Thermoplastic composites and thermoforming processing technology was used in the manufacture of the part. The composite was found to have weight savings of 39%, as compared to aluminium, with an enhanced rigidity of 42% reduced free-standing deflection.

1.2.3 Structural Composites

In addition to the requirements of light weight and lower cost, materials used in automotive applications should also meet the requirements of safety and the ability to absorb impact energy in what is referred to as crashworthiness. Polymer composites have been replacing metal components due to their reduced weight (which improves fuel consumption), their durability and their crashworthiness. Several studies were done on the impact energy absorption, durability and the crushing behaviour of polymer composites [15–24].

Davoodi *et al.* [25] studied the design of a fibre-reinforced epoxy composite bumper absorber. The study focused on studying the use of composites in energy absorption in a car bumper as a pedestrian energy absorber. A carbon reinforced composite was investigated. It was found that the fibre-reinforced epoxy composite absorber is sufficient for pedestrian impact and can substitute for the existing materials, such as expanded polypropylene foam.

Bisagni *et al.* [26] studied the progressive crushing behaviour of fibre-reinforced composite energy absorbers for Formula One side impact and steering column impact. Two series of tubes with different lamina were investigated. A finite element model using LS-DYNA was also developed. The composite absorbers had a high capacity of energy absorption. The numerical model accurately predicted the overall shape, magnitude of impact, deformation and failure of the composite absorbers with about 10% difference to experimental results.

Launay *et al.* [27] studied the cyclic behaviour of a 35% short glass fibre-reinforced polyamide composite to be used in an automotive application. Mechanical tests were done on two different relative humidity specimens. The creep and stress relaxation behaviour of the materials were studied to predict the fatigue life of the polymer matrix composite under different loadings and environmental conditions.

Ruggles *et al.* [28] studied the fatigue properties of carbon fibre-reinforced epoxy matrix composites. The study focused on developing experimentally based, durability-driven design guidelines for the long-term reliability of carbon reinforced composites for structural automotive components. A temperature-dependence study was also done to study the variation of the fatigue behaviour of the composite with temperature.

It is worth mentioning that composites used in automotive applications are joined in different methods. The main methods are mechanical fastening, adhesive bonding and welding. Mechanical joints such as rivets and bolts have the disadvantage of creating stress concentrations. Adhesive bonding uses a combination of polymer-based adhesive blends and provides some advantages, such as controlled mechanical properties of the adhesive, smooth surface finish between the joined materials, increased life time of the joint and good sealing. Welding, which is commonly used in metallic parts, has limited applications with composites. Welding has some advantages, such as durability and short processing time. For thermoplastic composites, the common welding techniques are: ultrasonic, induction and resistance welding.

Concerning advanced composites used or to be implemented in automotive industries, fibre reinforced polymers (FRP) with glass, aramid, carbon and graphite fibres should receive notice (Table 1.1). The polymeric matrix is in a general epoxy resin or polyester (Table 1.2). However, more recently nanocomposites have found some applications in automotive industries. Moreover, metal matrix composites (MMC) with aluminium matrix and ceramic based composites found some automotive applications with supercar brake discs. Composite architectures found in automotive applications are composite laminates, textiles, hybrids and nanocomposites. Tables 1.1, 1.2 and 1.3 show the mechanical properties of some fibre/polymeric matrices and composites. It is well remarked the advantage that composites bring in terms of high stiffness with a low density material.

Advanced composite materials with long fibres can be categorised into three major categories: laminates, hybrid composites and textiles.

Table 1.1 Mechanical properties of some fibres and metals [29].

Material	Young's modulus (Gpa)	Shear modulus (Gpa)	Axial Poisson's ratio	Ultimate strength (Mpa) tension	Strain to failure (%)	Density (Kg/m^3)
Carbon fibre HT-T300	230	23	0.23	3530	1.5	1750
Carbon fibre IM-T800	294	23	0.23	5586	1.9	1800
Carbon fibre HM	385	20	0.23	3630	0.4	2170
E-glass fibre glass	72	27.7	0.3	3450	4.7	2580
S-glass fibre	87	33.5	0.3	4710	5.6	2460
Kevlar 49 fibre	124	5	0.3	3850	2.8	1440
Steel	206	81	0.27	648	4	7800
Aluminium	69	25.6	0.35	234	3.5	2600

Table 1.2 Mechanical properties of some polymeric matrices [29, 30].

Material	Young's modulus (Gpa)	Shear modulus (Gpa)	Axial Poisson's ratio	Ultimate strength (Mpa) tension	Strain to failure (%)	Density (Kg/m^3)
Epoxy	3.1	1.2	0.3	70	4.0	1200
Polyester	3.5	1.4	0.3	70	5.0	1100
Resin RTM 6	2.89	1.08	0.34	75	3.4	1140
Resin RTM 120	2.60	0.96	0.35	77	—	1200

1.2.4 Laminated Composites

Composite laminates, also known as laminated composites, are composed from different plies, where each ply is considered as a UD long fibre lamina. The mechanical behaviour of each lamina is considered to be transverse isotropic, while the behaviour of the laminated composite is orthotropic. This category represents the most used kind of composites. Several kinds of architecture could be found, such as the cross-ply [0, 90] (Figure 1.1), the bi-directional [$-\theta$, $+\theta$] ([-45, $+45$], [-30, $+30$]), in addition to the tri-axial laminates [$-\theta$, 0, $+\theta$]. Laminated composites provide good in-plane mechanical properties: high in plane Young's moduli, shear modulus and in-plane ultimate strength. However, they lack stiffness in the out of plane direction, known as the through thickness direction or Z direction. This implies adding more layers in order to strengthen the through thickness direction, which means more weight and cost and prevents the manufacturing of complex shapes. Moreover, composite laminates are prone to delamination and inetrlaminar shear.

1.2.5 Textile Composites

More advanced long fibre composites have emerged known as textile composites. Textiles are categorised into three major fabric kinds: woven, braided and knitted fabrics. They are introduced to improve the mechanical behaviour of composites and to offer more choices of composite architectures. Textiles are made from interlaced, interlocked, or knitted yarns that

Table 1.3 Mechanical properties of different kinds of composites.

| Composite	Longitudinal Young's modulus (Gpa)	Ultimate strength (Mpa) tension	Density (Kg/m^3)
Composite unidirectional graphite/epoxy	181	1500	1600
Composite unidirectional glass/epoxy	38.60	1062	1800
[0,90] graphite/epoxy	95.98	373.0	1600
[0,90] glass/epoxy	23.58	88.25	1800
Textile 2D "Taffetas" carbon/epoxy	59.4	515.05	1500
Textile 3D "interlock"	49.02	672	1400
Textile 3D "orthogonal"	57.5	770	1500
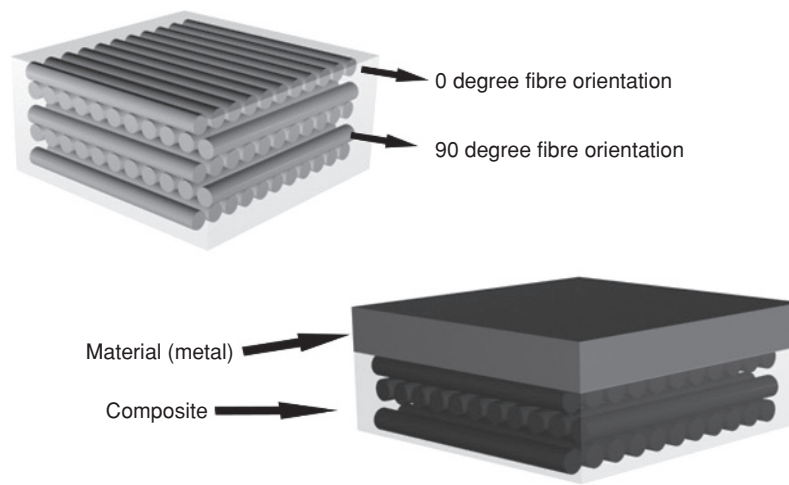
Figure 1.1 Cross-ply laminated composites and hybrid metal-composite material.

undulate above and beneath other yarns to form a complex architecture. Known textiles are composed of yarns with long fibres impregnated in polymer resin, metal, or ceramic matrices. Different 2D and 3D geometries and structures of woven, braided and knitted fabrics could be classified according to the number and shape of yarns. Thus, a large number of different architectures are introduced due to the development and demand needs of industries.

Woven composites represent the biggest category of textiles. Concerning the 2D woven fabrics, the composite is made of two sets of yarns: the warp and weft yarns. They are interlaced in a 90° "in-plane". In this kind of woven fabrics, one type of yarn (warp or weft) goes beneath only one set of the other type of yarn and they have a sinusoidal longitudinal profile. The 2D woven composites can be categorised into three major types: the plain weave, the harness satin weave and the twill weave fabrics (Figure 1.2).

The 3D woven composites introduce a yarn in the through thickness direction. The 3D woven composites are designed in order to reinforce the third direction and to avoid delamination between the layers. They are widely used in highly advanced industries, especially in the aeronautics fields, due to their stability and strength in all three axes. The weaver yarns in these composites go beneath more than one set of layers. They are divided into two types: Orthogonal weave and angle interlock weave fabrics. These two types are also divided into two kinds of fabrics: the layer-to-layer and the through-thickness weaves. 3D orthogonal woven composites are characterised by three set of orthogonal yarns: warp weaver yarns, stuffer yarns and weft yarns. However, the angle interlock fabrics can consist of two or three yarn types. In angle interlock fabrics, the warp weaver yarns have a crimp angle between 0 and 90°, while in orthogonal fabrics these yarns have a 90° angle with the (xy) plane (Figure 1.3).

Concerning the braided fabrics, they have an architecture close to those of 2D woven composites, but in this case the yarns are interlaced by a braider angle which is different from 90°. 2D braided composites are divided in general into: diamond fabrics (Figure 1.4a) and tri-axial fabrics (Figure 1.4b). Diamond fabrics consist of only two sets of braider yarns, while tri-axially braided fabrics have an additional axial yarn. The main advantage of these
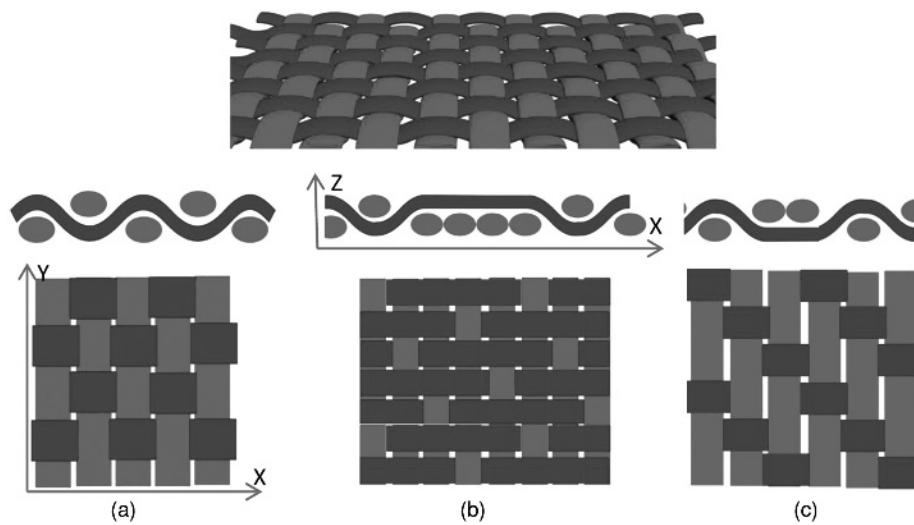
Figure 1.2 2D woven composites: (a) 2D plain weave composite, (b) Five harness satin weave composite, (c) 2D twill weave composite.
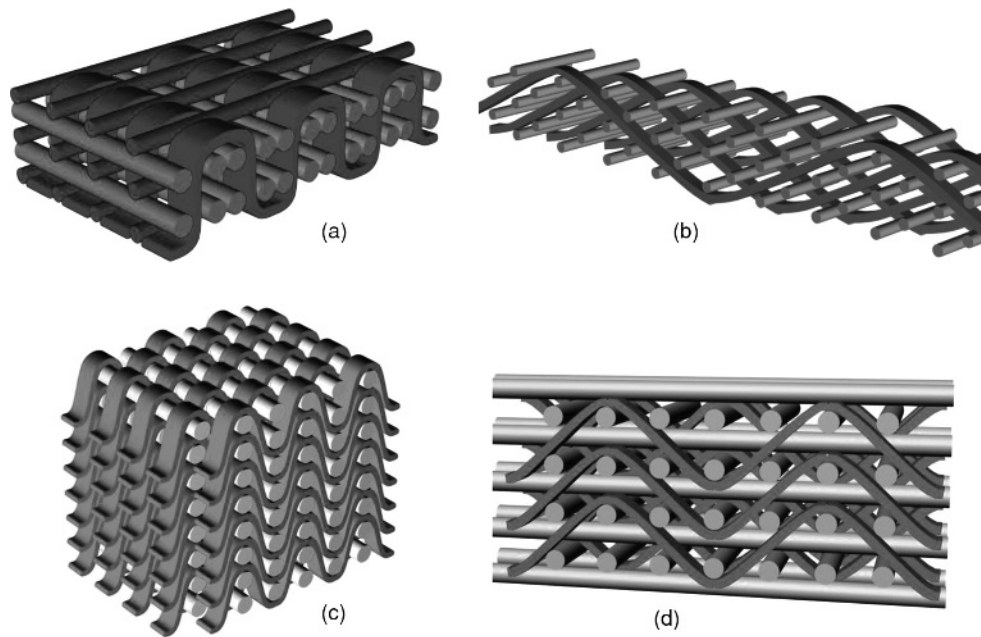

Figure 1.3 Different architectures of 3D woven composites: (a) 3D orthogonal woven composite, (b) 3D through-thickness angle interlock woven composite, (c) 3D layer to layer angle interlock woven composite, (d) 3D layer to layer angle interlock woven composite.
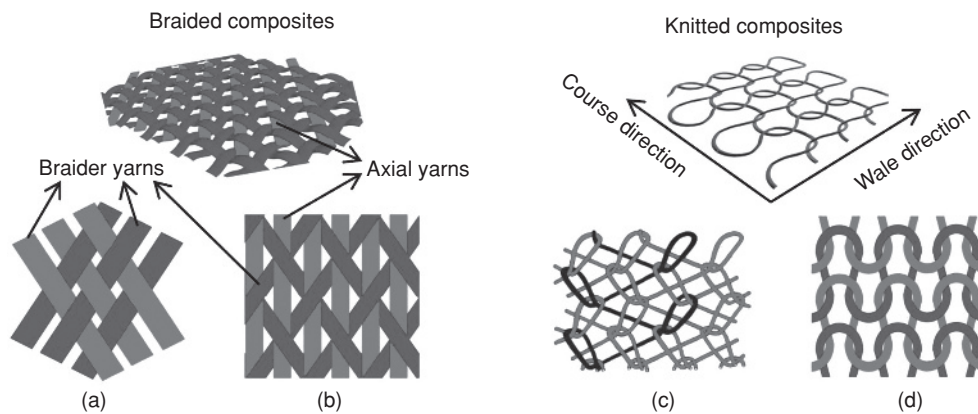
Figure 1.4   (a) 2D diamond braided composite, (b) 2D tri-axially braided composite, (c) warp knitted composite, (d) weft knitted composite.

composites is their high shear resistance. It is well noticed that weaver yarns in 2D woven composites, 3D angle interlock woven composites and 2D braided composites have a similar undulated shape; the description and modelling of this type of yarns will be discussed in the following section.

   Knitted composites are textiles made from basic construction units called loops. They are divided into two types: warp knitted (Figure 1.4c) and weft knitted (Figure 1.4d) fabrics. They are characterised by the number of loops into horizontal direction, called course (C = number of loops/unit length), and by the number of loops into vertical direction, called wale (W = number of loops/unit length).

1.2.6   *Hybrid Composites*

Hybrid composites are made from several layers of composites and other materials (Figure 1.1). In general, for automotive applications, it is well noticed that the aluminium–composite combination is used as a hybrid composite. The composite layer could be any kind of composites described previously. The composite layer is used to reinforce the aluminium structure in order to enhance its mechanical properties. It is remarked that the use of hybrid composites is increasing, especially in tubular structures subjected to impact loading.

1.3   **Application of Composite Materials in the Automotive Industry**

It is well remarked that the application of composites in the automotive industries is increasing. In which concern, the focus of this study is on new research concerning advanced composites. These new kinds of composites consist of polymeric or metallic matrices reinforced with long fibres of carbon, glass and Kevlar materials.

   The application of advanced composites will be shown in the next sections by reviewing the recent works that have been done in order to enhance the understanding of composites during impact, fatigue load and other complex loads. The review of studies dealing with
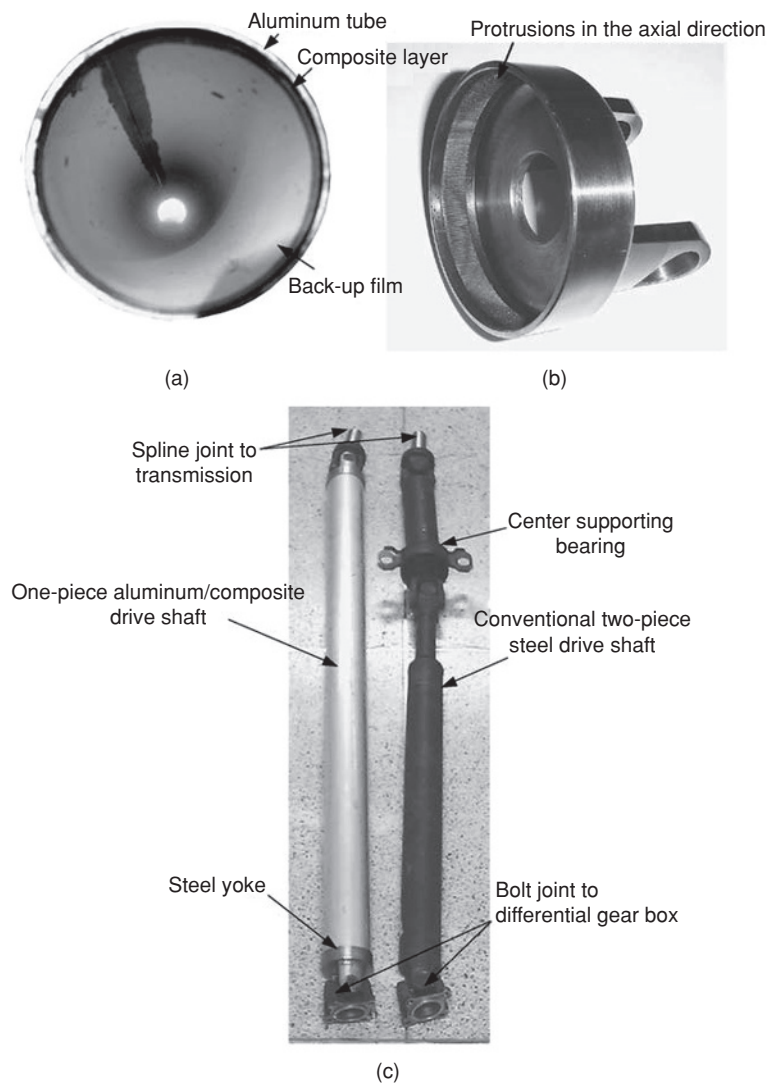
Figure 1.5   Hybrid composite driveshafts [35]. Reproduced from Ref. [35]. Copyright 2004 Elsevier.

advanced composites is divided into: crashworthiness studies, the development of automotive parts subjected to heavy static and dynamic loads, such as driveshafts (Figure 1.5), composite springs and gas turbines, and the use of natural fibre reinforced polymers as green composites replacing glass fibre reinforced polymer.

1.3.1   Crashworthiness

It is remarked that great attention is given to structural component material design related to car safety from impact and shock loading at different velocities. It is well known composites

give the ability to design a lightweight structure that also can sustain much higher damage than steel and aluminium. The important parameter in crashworthiness studies of any structure to be investigated is the specific energy absorption (SEA; KJ/Kg) as well as the rate of work decay (KJ/s) to ensure a safe design that can protect the passengers [31].

Most studies are conducted to understand the behaviour of composite tubular parts. These structures are well used in the car chassis in order to enhance its crashworthiness during impact. Historically, the experimental work of Thornton and Edwards [32], in 1982, should be noticed. Different experimental tests subjected composite tubes made from glass, Kevlar and graphite fibres to impact loading. Later, other research was conducted as the work of Farley [33], in 1991, and Hamada [34], in 1996. Farley [33] studied the effects of crushing speed on the energy absorption capabilities of composite tubes. The investigated materials were graphite fibres/epoxy (Thronel 300/Fiberite 934) and Kevlar/epoxy (Kevlar fibres/Fiberite 934) composites. The main objective of that work was to determine the energy absorption capabilities as a function of crushing speed. However more recent work led by Hamada and Ramakrishna [34] concerning the optimisation of composite laminate fibre orientation for tubes subjected to impact loading was presented in 1996. The composite was a laminated carbon fibre reinforced poly-ether-ether-Kreton (PEEK) with 61% of fibre volume fraction. It was found that composite tubes with a fibre orientation of $\pm 15°$ absorbed the most specific energy (225 KJ/Kg), and this was reported as the highest ever noticed in the literature for that time [34].

More advanced composites are used for energy absorption. Textile composites and especially carbon/epoxy braided composites are promising materials to be used, as shown by Chiu *et al.* [36]. In this study, the influence of braiding angle and axial yarn content was investigated. It was shown that the average width of the splaying fronds increased with increasing braiding angle, while it decreased with increasing axial yarn content. However, the highest specific energy absorption of 88 kJ/Kg was noticed for 20° of braiding angle. However, Bouchet *et al.* [37], in 2000, investigated the crushing behaviour of hybrid composite tubes. The composite was an UD carbon fibre (THR/300 from Hexcel)/epoxy polymer DGEBA with a fibre volume fraction of 34%. The three layered carbon/epoxy UD composite was wrapped on an aluminium alloy tube with the direction of fibres perpendicular to the longitudinal axis of the tube. The influence of surface treatments on an aluminium alloy before bonding with a carbon/epoxy composite was investigated. It was shown that the surface treatments increased the specific energy absorption capacities of around 30% between the chemically etched tube and the aluminium tube without surface treatment.

More recently, the advantage of composites over traditional materials as steel and aluminium in crush structures as tubes is well shown [38]. Quasi-static and intermediate rate axial crush tests were conducted on tubular specimens of carbon/epoxy (Toray T700/G83C) and glass/polypropylene (Twintex). The highest SEA measured (86 kJ/kg) was observed for carbon/epoxy tubes at quasi-static rates with a 45° chamfer initiator. Moreover, the highest energy absorption for Twintex tubes was observed to be 57.56 kJ/kg during 45° chamfer initiated tests at 0.25 m/s. However, with steel and aluminium, SEA values of 15 and 30 kJ/kg, respectively, were observed.

The study of crashworthiness has been also investigated with other types of automotive structural parts, such as bumpers or plates. In 2003, Corum *et al.* [39] studied experimentally the susceptibility of three candidate automotive structural composites subjected to low-energy impact damage. The reinforcements of composites that had the same urethane matrix consisted

of random chopped-glass fibre and two stitch-bonded carbon-fibre mats, where one was in a cross-ply layup and the other in a quasi-isotropic layup. A pendulum device, representative of events such as tool drops, and a gas-gun projectile, representative of events such as kickups of roadway debris, were used to impact plate specimens. The glass-fibre composite was least vulnerable to damage, followed by the cross-ply carbon-fibre laminate, which had the same thickness. The quasi-isotropic carbon-fibre composite, which was thinner than the other two, sustained the most damage.

In addition, random chopped fibre reinforced composites were investigated by [40] as crash energy absorbers. According to [40], the Automotive Composite Consortium (ACC) is interested in investigating the potential use of these composites primarily because of the low costs involved in their manufacture, thus making them cost effective for automotive applications. The crashworthiness of composite plates subjected to quasi-static progressive crush tests was studied. The composite plates were made from three different kinds of materials: CCS100, HexMC and P4 composites. They were manufactured from Toray T700 chopped carbon fibre. The CCS100 composites were manufactured from chopped carbon fibre with YLA RS-35 epoxy resin using a compression moulding technique with a fibre volume fraction of 50% and a fibre length of 25.4 mm (1 inch). However, the random chopped carbon fibre epoxy resin HexMC composite plates, which had a fibre volume fraction of 57% and 50.8 mm (2 inch) fibre length, were compression moulded by Hexcel Composites LLC. The compression moulded P4 composite plates were manufactured from chopped carbon fibre having 50.8 mm (2 inch) fibre length and 36% fibre volume fraction with Hetron epoxy resin. It is remarked that all three materials have shown superior SEA as desired by the ACC, which could lead to their direct application in the automotive industries.

1.3.2   Composite Driveshaft and Spring

Composites have been recently used as structural materials of driveshafts and also springs, due to their light weight and high resistance to fatigue. In this section, some recent developments and research in this domain is investigated.

Lee *et al.* [41] investigated the torsional fatigue characteristics of a hybrid shaft of aluminium–composite co-cure joined shafts with axial compressive preload. It was observed that the fatigue strength of the hybrid shaft was much improved by the axial compressive preload, exceeding that of a pure aluminium shaft. Also, the degradation of the fatigue resistance of the hybrid shaft at sub-zero operating temperature was overcome by the axial compressive preload.

A finite element study of a composite driveshaft was done by [42]. The material consisted of hybrid carbon/glass fibre reinforced epoxy laminated composite. The layers were stacked in the following configuration [+45° glass/−45° glass/0° carbon/90° glass] which consisted of one layer of carbon/epoxy and three layers of glass/epoxy UD composites. It was shown that, with a change of carbon fibre orientation angle from 0 to 90°, the loss in the natural frequency of the shaft was 44.5%. Moreover, when shifting from the best to the worst stacking sequence, the drive shaft caused a loss of 46.07% in its buckling strength, which represented a major concern over shear strength in driveshaft design. In addition, the stacking sequence had an obvious effect on the fatigue resistance of the driveshaft.

More recently in 2011, Badie *et al.* [43] examined in their paper the effect of fibre orientation angles and stacking sequence on the torsional stiffness, natural frequency, buckling

strength, fatigue life and failure modes of composite tubes. The studied composites consisted of carbon/epoxy and glass/epoxy laminates. The important remarks to be noticed form this study is that a carbon/epoxy driveshaft showed better torsional stiffens and fatigue life in comparison with a glass/epoxy driveshaft. Moreover, the stacking sequence with fibre orientation of ±45° showed a catastrophic sudden failure mode, while the stacking 90/0° experienced progressive and gradual failure. For carbon/epoxy tubes a higher fracture strain was shown than that of glass/epoxy tubes. In addition, in hybrid tubes, the severe difference in torsional stiffness of the layers led to initially suppressed twisting. Also with these tubes, the severe difference in torsional stiffness of the layers led to containing matrix cracks at the outer plies, not extending towards the tube ends. Concerning the natural frequency, the bending natural frequency increased by decreasing the fibre orientation angle. Decreasing the angle increased the modulus in the axial direction.

Recently, the use of elliptical springs made from E-glass/epoxy composite was studied [44]. A finite element model was used to investigate them, based on spring rate, log life and shear stress parameters. As a conclusion of this study, composite elliptic springs can be used for light and heavy trucks with a substantial weight reduction. Moreover the optimisation study of geometrical parameters of the cross-sectional area of the spring shows that a ratio of $a/b =$ 2 yields the best mechanical properties.

1.3.3   Other Applications

The use of composites has also been observed with many other automotive parts, high-pressure full composite cylindrical vessels [45], brake discs [46], automotive door skins [47], car bumpers [48] and automotive radiator heads made from a nylon –glass fibre composite [49]. In the automotive industry, some applications of MMC can be found, such as brake rotors, pistons, connecting rods and integrally cast MMC engine blocks. The application of carbon ceramic brakes in automotive domains (beside motors sports) was started 10 years ago with the Enzo Ferrari F60 [50]. However nowadays, due to their high cost, the application of these advanced brake discs is still limited to supercars (e.g. Corvette ZR1, Ferrari 458 Italia, Ferrari California, Nissan GTR, Audi R8, Lamborghini Gallardo, Lexus LFA) and motor racing cars [50].

More advanced composites are used in manufacturing a Japanese 100 kW gas turbine for automotive applications (Figure 1.6). In order to achieve some requirements such as higher thermal efficiency over 40% at a turbine inlet temperature of 1350 °C, lower exhaust emissions to meet Japanese regulations and multi-fuel capabilities, the application of ceramic matrix composite was investigated by Kaya [51]. Parts made from different carbon fibre reinforced ceramic matrix showed higher mechanical properties, reliability against thermal shock, particle impact damage and creep resistance.

Other kinds of composites could also have a promising future in automotive applications as polymeric nanocomposites [52]. As reported; nanocomposites could afford a weight saving of about 80% in comparison with steel [52]. They could be produced by incorporating nanometre-size clay particles in polymeric matrices such as polypropylene (PP), polyethylene (PE), polyesters, or epoxies. Different methods could be used to produce nanoncomposites, as one of these methods is the in situ intercalation polymerisation method, pioneered by the Toyota
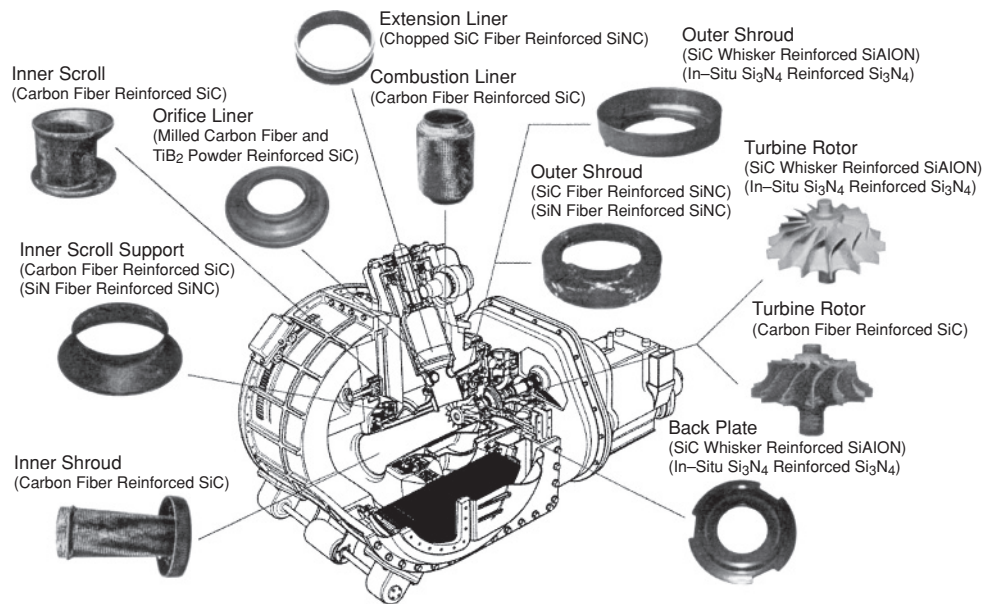
Figure 1.6 Carbon ceramic 100 Kw gas turbine [51]. Reproduced from Ref. [51]. Copyright 1999 Elsevier.

Motor Company [53]. This method was used to create a nylon 6–clay hybrid (NCH), used to make a timing-belt cover, which could be considered as the first practical example of polymeric nanocomposites for automotive applications [54].

1.4 Green Composites for Automotive Applications

Due to the demanding needs for environmentally friendly composites, the automotive industry is seeking environmentally friendly biodegradable renewable composite materials and products. Over the last few years, a number of researchers have been involved in investigating the potential use of natural fibres as load bearing components in composite materials [55–58]. The use of such materials in composites has increased due to their relatively low cost, their ability to be recycled and their high strength to weight ratios.

Natural fibres show a potential as a replacement for inorganic fibres such as glass or aramid fibres in automotive components such as trim parts in dashboards, door panels, parcel shelves, seat cushions and cabin linings [59–61]. Mercedes-Benz used an epoxy matrix with the addition of jute in the door panels in its E-class vehicles [62].

Wambua *et al.* [63] studied the possibility of replacing glass fibres by natural fibres. They investigated the mechanical properties of sisal, hemp, coir, kenaf and jute reinforced polypropylene composites. The tensile strength and modulus increased with increasing fibre volume fraction. The mechanical properties of the natural fibre composites tested were found to compare favourably with the corresponding properties of glass mat polypropylene

Table 1.4 Mechanical properties of most used natural fibres compared to E-glass fibres [68, 69].

Mechanical properties	E-glass	Flax	Hemp	Jute	Ramie	Sisal
Density (g/cm^3)	2.55	1.4	1.48	1.46	1.5	1.33
Young's modulus (Gpa)	73	60–80	70	10–30	44	38
Tensile strength (Mpa)	2400	800–1500	550–900	400–800	500	600–700
Elongation at failure (%)	3.0	1.2–1.6	1.6	1.8	2.0	2.0–3.0

composites. The specific properties of the natural fibre composites were in some cases better than those of glass. This suggested that natural fibre composites have a potential to replace glass in many applications that do not require very high load bearing capabilities.

Davoodi *et al.* [64] investigated the hybridisation of natural fibres with glass fibres for improving the mechanical properties over the natural fibres alone. A hybrid kenaf/glass fibre composite was investigated for a car bumper beam as a structural automotive component. They found that some mechanical properties such as tensile strength, Young's modulus and flexural modulus of the hybrid composite were similar to those of a typical glass mat thermoplastic bumper beam. However, the impact strength was lower, which showed the potential for the utilisation of the hybrid natural fibres by optimising some structural design parameters.

Recently the use of natural fibres in automotive domains has expended. It is reported that the growth of bio-fibres in automotive components is expected to increase by 54% per year [65]. Some kinds of strong, lightweight and low cost bio-fibres are introduced to replace glass fibre reinforced polymers in many interior applications. Fibres such as jute, kenaf, hemp, flax, banana, sisal and also wood fibre are making their way into the components of cars (Table 1.4). The bio-fibre reinforced polymers are used for door panels, seat backs, headliners, package trays, dashboards and trunk liners. Many review papers [60, 66, 67] have discussed the use of these fibres as reinforcement of a polymeric matrix, known as green composites. These papers reviewed the mechanical properties of fibres, matrices and composites. As well, they discussed the potential replacement of glass fibre reinforced polymer by the green composites, taking into account their ecological and economical influence.

Ashouri [61] presented in 2008 a review paper that discussed the use of wood plastic composite in the automotive industries. The main advantages shown by wood fibres compared to other kinds of natural fibres are to reinforce plastics due to their relative high strength and stiffness, low cost, low density, low CO_2 emission, biodegradability and being annually renewable. In the same prospect, in 2010, Alves *et al.* [70] pointed out the advantages of applying other kinds of natural fibre composites, jute fibre composites, in buggy enclosures. The study aimed at presenting the ability to replace glass fibre composites by jute fibre composites, by showing that the use of natural fibres will improve the overall environmental performance of the vehicles.

More recently, an important review study of the green composites properties was done by Koronis *et al.* [60]. The potential use of these kinds of composites for automotive application was discussed. It was shown that bio-fibres, also known as natural fibres, could have good mechanical properties in comparison with glass fibres. Databases were presented for the important mechanical properties of some natural fibres, polymeric matrices, as well as their composites.

1.5   Modelling the Mechanical Behaviour of Composite Materials

The modelling of the mechanical behaviour of composite materials has taken a major interest in recent years. Two main methods are used to determine the mechanical behaviour of composites: analytical models and numerical models (based on finite element analysis). Numerical models have taken most attention, due to the development in computation tools and software. It is noticed that these models are more trusted and widely used by industries. However, their implementation consumes a lot of time, beside the need to use super computers. In contrast, analytical models offer straightforward solutions and are more flexible and easier tools in terms of geometrical modelling and homogenisation methods. Moreover, they need less computation time without the necessity of super computers, and there is the ability of simple integration of analytical models in optimisation tools.

The modelling of the mechanical behaviour of composites must pass at first by the prediction of the stiffness matrix of the composite as a homogenised material. In contrast with metals, which have isotropic behaviour, composites with long fibres are treated as orthotropic materials. In addition, it should be noticed that some fibres, like carbon and graphite fibres, have anisotropic behaviour, in general considered transversely isotropic, while others, like glass fibres, are considered to have isotropic behaviour. Thus, the estimation of elastic properties and ultimate strengths presents a major challenge for researchers.

Analytical or numerical modelling of the mechanical behaviour of composites aids the optimisation of any structural component made of it. However, the variety of composites imposes a real challenge and intensive work in order to determine all the required mechanical properties. The detailed discussion of methods used to determine elastic properties, ultimate strengths, fatigue and impact behaviour, is considered to be out of the scope of this chapter. However a brief review of available analytical and numerical models used as homogenisation methods is presented.

1.5.1   Modelling the Elastic Properties of Unidirectional Composites

The prediction of the elastic properties of unidirectional composites using micro-mechanical models or FE methods is considered to be a basic stage in order to determine the mechanical properties of laminates or textile composites. The effective stiffness and compliance matrices of a transversely isotropic material are defined in the elastic regime by five independent engineering constants: longitudinal and transversal Young's moduli, longitudinal (also known as axial) and transversal shear moduli and major Poisson's ratio. Analytical models used to predict these engineering constants are known as micro-mechanical models. They can be categorised into four categories: phenomenological models, elasticity approach models, semi-empirical models and homogenisation models:

- Phenomenological models: rule of mixture (ROM); Reuss [71] model.
- Semi-empirical models: modified rule of mixture (MROM); Halpin–Tsai model [72]; Chamis model [73].
- Elasticity approach models: composite cylinder assemblage (CCA) model of Hashin and Rosen [74]; Christensen generalised self-consistent model [75].
- Homogenisation models: Mori–Tanaka (M-T) model [76]; self-consistent (S-C) model [77]; bridging model [78].
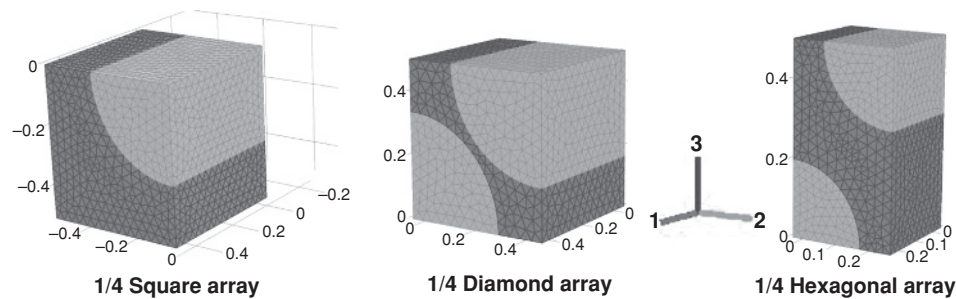
Figure 1.7   Meshing of square, diamond and hexagonal array unit cells.

Numerical FE modelling is widely used in predicting the mechanical properties of composites. Numerical modelling is a reliable tool, but the time consumed on the geometrical dimensions definition and the corresponding calculation time represent a major disadvantage against analytical models. Moreover there are many discussions and studies that deal with the appropriate boundary, symmetric and periodic conditions required to evaluate the elastic properties of UD composites. In this domain, a major work was done by Li [79]. It should be noticed that numerical FE modelling requires geometrical modelling or representation of the unit cell. For UD composites, there are three types of idealised fibre arrangements: square array, diamond array and hexagonal array (Figure 1.7).

1.5.2   Modelling of Laminated and Textile Composites

1.5.2.1   Analytical Modelling

Analytical models used for laminated and textile composites rely on two major factors for determining the stiffness of laminates and textiles: geometrical modelling and the homogenisation method. Geometrical modelling yields the required components for the homogenisation method, such as the volumes of the representative elementary volume (REV), layers, yarns and yarn sub-volumes. Furthermore, geometrical modelling gives the fibre volume fractions in the REV and in yarns as well as the orientations of yarns and yarn sub-volumes.

It should be noticed that the general scheme of homogenisation methods adopted for almost all analytical models are mainly based on a two-step homogenisation procedure: micro and macro levels. At micro level, the sub-volumes of subdivided REV are considered as unidirectional lamina with long fibres. Homogenisation at micro level is achieved, to predict the stiffness matrix of sub-volumes in a local coordinate system (123) where 1 is along the fibres. At this level, micro-mechanical models are employed.

At macro level, the transformation matrices are used to estimate the stiffness matrix of sub-volumes in a global coordinate system (*XYZ*) related to the REV. Then, a homogenisation method for the macro level is used.

For laminated composites, the famous classical lamination theory (CLT) method is the most reliable and used homogenisation method. However, for textiles, various homogenisation methods and approaches are used to assemble different sub-volumes, yarns and layers in order to predict the global stiffness matrix of the REV. These methods are based on: iso-strain assumptions, iso-stress assumption, mixed iso-strain/iso-stress assumptions, or inclusion

methods (Mori–Tanaka or self-consistent methods). A brief review of recent works concerning the modelling of elastic properties of textiles will be presented, while detailed review of these methods can be found in [80–84].

Historically, Ichikawa and Chou [84–88] were the first who tried to find analytical models in order to predict the elastic properties of 2D woven composites. They proposed three basic analytical models: the mosaic model [84], the fibre undulation model [84] and the bridging model [85]. Later, many models were proposed as extensions of these models [89–91].

Recently, most works have been conducted towards the modelling of textiles with complex geometries such as 3D n-directional braided composites and 3D woven.

The iso-strain model was used by Li *et al.* [92] for modelling the elastic behaviour of 3D five-directional braided composites. The predicted results showed good agreement with experimental results for axial Young's modulus and tensile strength with an error not exceeding 10%. In addition, a 3D iso-strain model was presented by Shokrieh and Mazloomi [93]. The model was used to evaluate the stiffness of tri-axially braided composite. They compared their results to those experimental data presented by Quek *et al.* [94]. Results showed good predictions of the transverse Young's modulus E_y and the in-plane shear modulus G_{xy}.

Concerning 3D woven composites, Yanjun *et al.* [95] and El-Hage *et al.* [96] used the iso-strain model to predict the effective elastic properties of 3D angle interlock woven ceramic composite and orthogonal and angle interlock woven composites. Also, mixed iso-strain/iso-stress models have been introduced in order to improve the prediction of elastic properties of such complex composites. Pochiraju and Chou [97, 98] proposed a model for the prediction of anisotropic elastic stiffness of 3D textiles. The stiffness of the REV, decomposed into small subdivisions, is evaluated using an effective response comparison (ERC) technique. Concerning the angle interlock composites, the model yields good results in comparison to experimental data. Later, Tan *et al.* [99–102] developed two analytical models, the *ZXY* and *ZYX* models, to determine the mechanical properties and the thermal expansion coefficients of 3D orthogonal and angle interlock woven fabrics. The idealised REV is decomposed into sub-blocks which are assembled, under iso-strain and iso-stress conditions, using three models: the *X* model, *Y* model and *Z* model along the x, y and z directions, respectively. The comparison with experimental results has shown that the models predict well the effective elastic properties of 3D orthogonal woven composites while less agreement is obtained in estimating the longitudinal Young's modulus E_x of through-the-thickness 3D angle interlock woven composite [99]. However, Hallal *et al.* [103, 104] proposed analytical models in order to enhance the prediction of E_x of 3D angle interlock woven composite, especially for composites with a high content of undulated yarns. The models are also based on an assembling scheme of REV subdivisions in parallel, under the iso-strain condition, and in series, under the iso-stress condition. In [104], it is noticed that the iso-strain model have significant problems in predicting Young's modulus along a direction where the volume fraction, in the REV, of undulated yarns is high (x direction). However, the improved three-stage homogenisation method (3SHM) model has shown very good agreement with both experimental and numerical finite element (FE) results, especially for E_x.

1.5.2.2   Numerical FE Modelling

The prediction of the elastic properties and the stress –strain fields of laminated and textile composites have taken major interest with numerical FE modelling. The major problems

remain in the time consumption and the meshing of complex geometries, as well as defining the contact between yarns and matrix.

A brief review of modelling composites with FE methods is presented. Cox *et al.* [105] and Xu *et al.* [106] developed a FE model, the binary model, to predict the mechanical properties of 3D interlock composites. Nie *et al.* [107] introduced the problem that represented the angle-interlock fabric in a more concise and efficient way, which is a major problem for the computer-aided design (CAD) of multi-layered angle-interlock woven fabric, as referred by Ko [108]. In the approach of Barbero *et al.* [109], a FE model of plain weave fabrics based on geometrical measurements from photographs was developed to determine the damage evolution using a meso-mechanical continuous damage formulation under tensile loading. Also a multi scale 3D mosaic model was applied for woven composites by Bogdanovich [110] where the stress and failure of 3D woven composites were studied. Moreover, Nehme *et al.* [111] used different meshing techniques, with tetrahedral mesh for the isotropic matrix and mapped hexaedral mesh for the transversely isotropic yarns, in order to achieve the FE discretisation.

1.6   Discussion

From the above sections, it is clearly shown from recent applications of composites in automotive industries that most attention is on using composites for crashworthiness applications in order to enhance car safety and to reduce the effect of impacts. In addition, there is an increasing consideration of a potential use of green composites in large masses by replacing glass fibre reinforced composites. Moreover, composites have been also used for other structural components, such as driveshaft, springs, brake discs, gas turbine and so on. However, the emergence of new types of composites has led to further development of new enhanced manufacturing processes for a large number of structures made from composites such as resin transfer moulding (RTM), performing and the liquid compression moulding manufacturing process.

Concerning the crashworthiness applications, the use of composites as the main structural component or as part of the hybrid material in tubular structures has taken the most consideration and most research. It is important to notice that these studies started more than 30 years ago. The important physical factors studied were the specific energy absorption and the work rate decay necessary to keep deceleration below a certain value during impact ($<20\,g$). However, many parameters have been investigated in order to observe their effects on these factors, including the material kind, type of composite, stacking sequence of laminated composites and fibre orientation. Also, the review study reveals that for architecture, laminated composites are the most used; however, more recently braided composites started to receive more attention with their high shear strength. Moreover, glass fibres and carbon fibres are the most studied reinforcement with polymeric matrices. It is also clear the mechanical advantage that graphite and carbon fibres brought over glass fibre reinforced polymers and traditional materials. Concerning hybrids, the influence on the energy absorption of a surface treatment between the aluminium layer and carbon fibre reinforced polymer is studied. In addition, carbon short fibre reinforced polymers show great potential, with relatively low manufacturing cost and good mechanical properties concerning an impact crash.

Recent research also revealed that new directions in materials design tend to adopt composites as the first choice material for automotive structural parts that are subjected to severe

static and dynamic loads. In these cases, the ultimate strength as well as the fatigue resistance of the material is crucial. One of these applications is the composite drive shaft. Finite element simulations have been conducted in order to find an optimised material that has high buckling strength, can resist the torsional fatigue loading and can increase the fundamental natural bending frequency. Hybridisation of studied driveshafts is done with carbon-epoxy UD/aluminium or carbon fibre-epoxy/glass fibre-epoxy laminates. All of the studied composites are made from long fibres, where the fibre orientation and the stacking sequence of laminate layers, as well as the material type (carbon fibre or glass fibre) are well investigated. It is well found these parameters have a good influence on the mechanical properties of driveshafts.

Moreover, other new applications of composites in automotive domains are shown, with E-glass/epoxy springs that could be used for heavy trucks and could save much weight, high performance gas turbine, advanced carbon ceramic brake discs and so on.

As recently observed, new natural fibres have emerged to substitute glass fibres for mostly interior automotive parts. Naturel fibre reinforced polymers are known as green composites due to their ecological and economic effects. Natural fibres such as woods, jute, Kenaf and flax have lower densities than most used glass fibres. It is found that these composites could have a promising future especially with automotive applications, while until now the dominant natural fibres are wood fibres. Much of the research observed recently just focused on some of the mechanical properties of these composites in comparison with glass fibre reinforced polymers, with more focus on their ecological and economical influences.

In general, it is remarked how composites gives many opportunities to offer solutions for many automotive applications. However, the large variety of fibres, matrices and architectures to form a composite material, led to much research work involving the optimisation and material design of automotive structures. In addition, it is noticed that unidirectional long-fibre laminated composites well dominate the research and world market concerning automotive applications. While some attention is found related with more advanced types of composites, such as braided composites and nanocomposites, there is almost an absence of 3D woven and knitted composites.

1.7   Conclusion

This chapter has presented an overview of recent applications of composites in automotive domains. The use of composites is investigated for saving weight and enhancing stiffness and strength against fatigue or crash, which leads to the design of safer vehicles. It is shown that the advantage of composites, especially by saving weight or the use of natural fibres has enormous ecological and economic effects.

It is found that most attention has been conducted to use composites for structural components to enhance crashworthiness. In addition, the use of composites will lead to saving much weight, when replacing traditional materials such as steel. Most of the composites used for tubular parts or plates consist of laminates. The influence of fibre types and laminate stacking sequence are the most investigated. However, the use of tri-axial braided composites as a more advanced composite has also been noticed in recent works. It is found that carbon and graphite fibres possess higher mechanical properties, while their manufacturing cost still presents a great disadvantage.

Other automotive parts could benefit from composites, such as driveshafts, springs, gas turbine and brake discs. Composite laminates made from carbon fibre or glass fibre reinforced polymers are the most used for driveshafts and springs. From numerical finite element simulations, it is found that composites enhance the fatigue life as well as the stiffness of these components subjected to heavy dynamic load. For gas turbine and brake discs, advanced carbon ceramic composites have been used in order to sustain both thermal stresses and mechanical loads. Due to their high cost, the use of carbon ceramic brake discs is still limited to racing cars and modern supercars.

It is also significant to notice the attention green composites have taken recently. These composites, formed from natural fibre reinforced polymers, have been used to replace glass fibre reinforced polymers for many automotive parts. The ecological and economic benefits that green composites could afford lead to them being considered as a promising material.

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