ENVIRONMENTALLY FRIENDLY CAR REINFORCED PLASTICS IN AUTOMOTIVE ENGINEERING STRUCTURAL DESIGN CONSIDERATIONS

Part 2

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Summary

A review of applications of reinforced polymers and polymer composites to the construction of automotive vehicles has been presented. Particular attention has been paid to the heavily loaded parts and subassemblies. Various components of vehicle body and power transmission and suspension systems, as well as subassemblies situated in the engine compartment have been analysed. In each case, the structure of the part involved, the material type used, and the loads to be borne have been described. The parts to be analysed have been deliberately selected to show the technological progress that takes place in the application of reinforced plastics to the construction of load-bearing structures of modern vehicles. The paper has been provided with conclusions concerning the development trends and directions of further research in the field of the use of reinforced polymers for the construction of vital vehicle parts and subassemblies.

Keywords: polymer composite, vehicle body, power transmission system, composite leaf spring.

1. Introduction

The use of polymer materials for the construction of vehicles should not be considered mere replacement of metal with another substance. Such materials, especially reinforced plastics, enable the designer to freely shape the cross-section of the element to be made and, thus, to decide about the rigidity of the element. It is possible to make parts of predetermined stiffness characteristics and to design multifunctional vehicle components. By the application of reinforced plastics, in particular polymer composites, the design of a specific component may be significantly simplified without impairing its functionality.

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In comparison with steel parts, the structural elements made from reinforced plastics show higher fatigue strength and are corrosion-proof and their weight makes only a small fraction of that of their metal equivalents. An important good point of the reinforced polymer materials is the pattern of initiation and propagation of fatigue damage. Unlike steel parts, the parts made from such materials do not break suddenly, which significantly improves the safety of vehicle operation.

2. Selected applications: structural design considerations

The use of reinforced plastics to make vehicle bodies and body components well represents the current state of development of the materials of this kind. They are used as materials not only for the body parts that are not exposed to loads, such as fenders, covers, or shields, but also for load-bearing components, e.g. bumpers, roof panels, suspension system components, and, increasingly, complete monocoque bodies. This is perfectly illustrated by the designs of racing cars, where polymer composites are very widely used for the construction of car bodies and various load-bearing components. In the BMW Sauber F1, the whole load-bearing structure of the car has been made from polymer composites reinforced with carbon fibre. The rigidity of this structure is comparable with that of a corresponding steel structure while the mass is as low as one fifth of the latter. Similarly, the unitised body of the Porsche Carrera GTF has been made from a CFRP[4] composite with epoxy resin matrix. In this car, a composite engine and gearbox frame, integrated with the driver and passenger compartment to form the main load-bearing structure of the car, was introduced for the first time to series production [1]. In comparison with the corresponding steel structure, the rigidity of the car body increased while the mass dropped by about 40%. Similar effects were obtained by using polymer composites reinforced with carbon fibre and aramid fibre in the Bugatti Veyron car. This vehicle was built in cooperation with Carbo Tech Composites [2].

The BMW concern consistently strives to raise the share of polymer composites in the construction of its vehicles. It uses the composites to make both load-bearing and non-load-bearing body components. As an example, shields made from laminated composites based on glass fibre and polypropylene have been applied to protect the car underbody structure from the impact of external factors (Fig. 1) [3].

In the same model, carbon composites have been used to build the load-bearing structure of the body roof (Fig. 2). This solution has increased the body rigidity and puncture resistance of the roof, which has improved the safety of occupants when the car overturns.

In the BMW 6 models, SMC materials reinforced with glass fibre have been used to make the boot lid. In the sports version of this car, the roof panel and bumper beams have been made from a polymer composite reinforced with carbon fibre (Fig. 2).

In both cases, the composite roof sheathing is bonded to the car body. The roof manufacturing process includes dry shaping, impregnation with resin (by the RTM

[4] CFRP = Carbon fibre reinforced polymer

Fig. 1. Roof sheathing made from a carbon composite, BMW 3 [3].

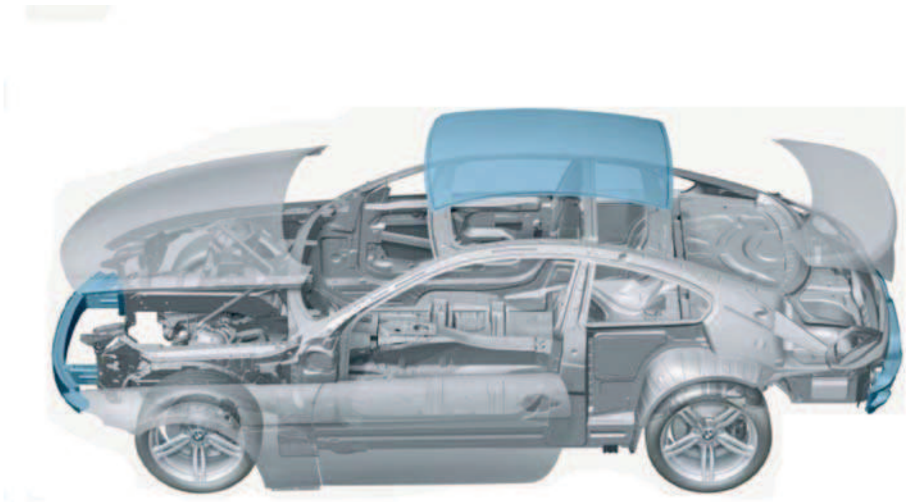

Fig. 2. Boot lid made from SMC and bumper beams and roof made from plastic reinforced with carbon fibre (blue), BMW 6 [4, 5].

method) and coating with transparent lacquer. The thin-walled bumper beams are made another way, by applying the material gradually, one layer after another, to a core, which is afterwards removed when the material has been impregnated with resin and cured [6].

According to BMW's plans, the range of applications of plastics reinforced with carbon fibres is to be extended to large load-bearing structure components, e.g. complete bodies or side wall skeletons. This will result in further reduction in vehicle mass and improvement in road safety.

Fig. 3. Concept design of the side wall skeleton of a BMW car [7].

Fig. 4. Body of a lightweight BMW concept car.
The front part (bright): aluminium alloys; the remaining body structure: carbon composite [8].

The passenger compartment and the rear part were made from a polymer composite while the front part was made from aluminium alloys. Such a design made it possible to reduce the body mass by 50% or 30% in comparison with the corresponding steel or aluminium body options, respectively [8].

The monocoque vehicle body and its components are the most heavily loaded parts. They are exposed to the loads coming from the power transmission system when the engine torque is transmitted to the road wheels, the loads related to the mass of individual vehicle assemblies, and the loads related to resistance to motion and to the impact of road on the vehicle. During vehicle motion, the body is exposed to particularly challenging torsion and bending loads. Therefore, the materials used for the construction of vehicle bodies should have high fatigue strength at a complex state of stress. To make the structures under consideration, carbon composites with fibre content of about 50%, by volume, have been used. Such materials enable the builder to control their strength characteristics by applying appropriate type and directional arrangement of the reinforcing material used. The Audi Company used an epoxy composite reinforced with carbon cloth to make the floor (Fig. 8) and roof sheathing of a monocoque car body. For the construction of the rear bulkhead, an epoxy composite reinforced with a combination of aramid and carbon fibres (ACFC) was used. These structures have been shown in Fig. 9 [10].

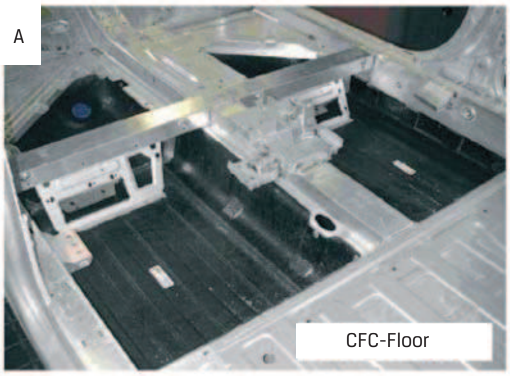

Fig. 5. Body structure of the Audi A2 [10]: A – The bottom part of the body made from carbon fibre.

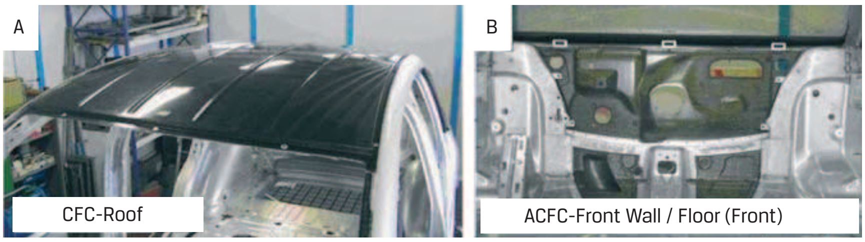

Fig. 6. Body components of the Audi A2 [10]:
A – Roof sheathing made from carbon fibre; B – Bulkhead made from aramid-carbon fibre.

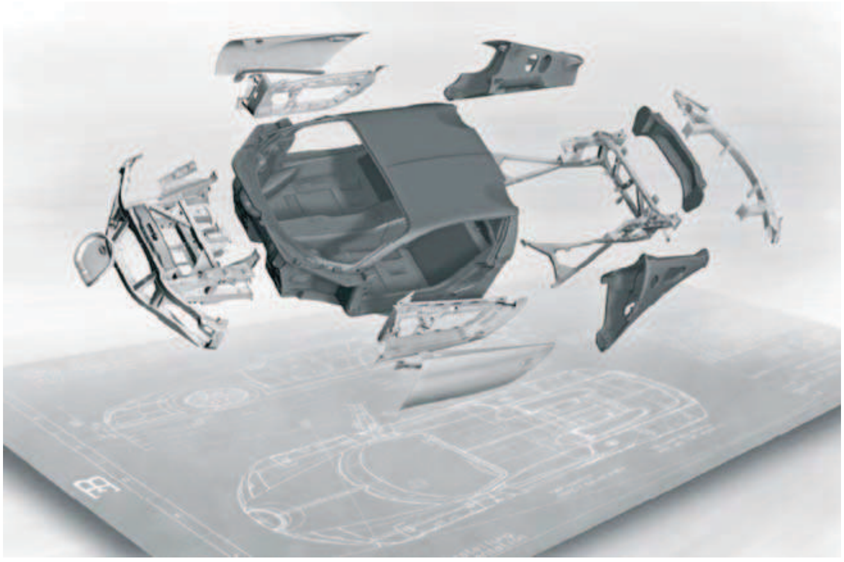

**Fig. 7. The Bugatti Veyron body structure:
cab, side panels, and rear beam made from carbon fibre (dark) [11].**

In the Bugatti Veyron car manufactured by Volkswagen [11], the main part of the monocoque body, i.e. the whole passenger compartment, has been made from a polymer composite reinforced with carbon fibre. The optimisation of this design is an effect of simulated torsion load tests. Glass fibre composites (GFK) have been used here to make the roof spoiler because the GPS housing has been located in this component because the glass fibre, in contrast with carbon fibre, does not conduct electric current. The GFK material has also been predominantly used to make the fender liners because tyre pressure sensor antennas have been placed on the side of this part not exposed to dirt impacts. The fender liner fully made from carbon composites would constitute a Faraday cage and it would suppress the signals (216 or 433 MHz). Carbon composites have been used as a material for external vehicle parts, including rear spoiler and front bumper. Only the longitudinal beams have been made from steel. In Fig. 10, the composite structures have been marked with a darker colour. The carbon composite used has very high bending strength. The acceptable bending stress and the modulus of elasticity are as high as up to 1 600 MPa and 180 MPa, respectively. Thanks to low mass density of the composites (about 1.8 kg/dm^3), a very light and rigid body has been obtained.

Car bumpers are equally often made from plastics. The use of plastics for the making of bumpers has many good points, e.g.: insusceptibility to damage at minor collisions; absence of corrosion; easy visual and structural integration of the bumper with other body parts; improved drag coefficient; easy assembly operations; high cost-effectiveness; low mass. Car bumpers must ensure adequate pedestrian safety. They must behave flexibly at minor impacts but the elastic behaviour is not recommended because of the possibility of a bouncing effect. These requirements are met by polyurethanes described before, whose viscoelastic characteristics may be pre-programmed by appropriate selection of density of the chemical components of the material. Tests with bumpers made from materials of this type were carried out at the Motor Industry Research Association[5]. It was shown during the tests that an impact with a speed of 40 km/h against a model of pedestrian's legs resulted in an acceleration of about 130 g developing at a polyurethane bumper. This acceleration value is significantly lower than the statutory limit specified as 200 g (EU Directive 2003/102/EC). The standard bumpers mass-produced at present dramatically fail to meet this requirement, with the accelerations being several times as high as this limit [11].

A bumper beam of the BMW M6 car, made from carbon composite, has been shown in Fig. 8. The beam transmits vehicle impact loads to the longitudinal beams of the car body or frame. The beam as such is exposed to high bending loads. The composite used to make this beam contains 50%, by volume, of carbon fibre, with 42% of this fibre being oriented parallel to the beam axis and the other 58% being arranged at an angle of ±45° to this axis. This structure provides the same protection of the car body as a steel beam would do, but it additionally causes a lowering of the centre of gravity of the car and a reduction in the mass of this component by about 50% and 30% in comparison with the corresponding steel structure (front bumper) and aluminium structure (rear bumper), respectively. This component is made with the use of the RTM method described previously. The composite bumper beams do not require any corrosion-proofing and are fixed to the car body without painting.

Fig. 8. Composite bumper beams of the BMW M6 car [11].

[5] MIRA, Nuneaton, Warwickshire, the UK.

The engineering solutions where reinforced plastics are employed are also gradually taking over very responsible engine fastening and stabilising functions. In 2006, polyamide reinforced with glass fibre (PA66 GF50) was employed for the construction of engine fastening components in the Opel Vectra and Saab 9-3 cars[12]. This subassembly not only transmits the engine weight to the car body but also is responsible for the development of a moment of reaction to the engine torque. The support components are loaded with compression and tension forces and a bending moment. Vibrations and dynamic loads are significantly dampened by rubber components or oil cushions; therefore, fatigue loads do not predominate. The replacement of aluminium alloy with reinforced plastic has resulted in a reduction in the mass of this subassembly by about 35% and in better dampening of engine vibrations. The solution under consideration has been presented in Fig. 9. Rubber bushes are fixed in a composite housing. The subassembly has been developed and manufactured by ContiTech. The manufacturer is planning to reduce the mass of this product even more by optimising the plastic reinforcing methods. Thus, the mass of this subassembly compared with that of the option made from an aluminium alloy may be reduced by about 50%.

An engine mounting cross-member made from reinforced polyamide 66 is installed as standard in the BMW 5 Gran Turismo 550i series cars [13] (Fig. 10). The employment of a long load-bearing beam has made it possible to optimise the design of this component in respect of more effective dampening of engine vibrations. The composite beam ensures the required strength and resistance to elevated temperatures. Thanks to this change of material, the mass of this component has been reduced by about 30% in comparison with that of the metal part.

Plastics reinforced with fibres find also application in the power transmission system, which is exposed to heavy loads. Drive shafts made from polymer composite reinforced with glass fibre have been mass-produced since 1980s. Originally, they were chiefly employed in vehicles with mutiaxial drive systems or, apart from this, wherever this was required for passive safety reasons. At present, vehicle manufacturers again manifest interest in such designs, seeking reduction in the mass of vehicle power transmission systems. Such a vehicle part made from carbon composite has been shown in Fig. 11.

The drive shaft is chiefly loaded with a torque directly resulting from the vehicle engine torque. This load generates tangential stress. Therefore, the fibres in the composite material must be oriented in accordance with the direction of the tangential stress for the required shear strength of the composite material to be obtained. The shafts are also exposed to breakage in result of reaching the so-called critical speed, which chiefly depends on shaft mass, out-of-balance masses, shaft length, and modulus of elasticity of the shaft material. For this reason, steel shafts often have to be supported in their central part or the particularly long shafts have to be divided into two separate shorter shafts. Thanks to the replacement of steel with carbon composite, the necessity to divide the shaft may be avoided and the shaft mass may be reduced by 15 to 40%, depending on the reinforcement type used. Not only the reduction of mass of a composite shaft reinforced with carbon fibre will be possible; a shaft made from this material may also be longer because its critical speeds will significantly exceed that of the corresponding steel unit. However, the employment of this material is considerably constrained by its high price. Nevertheless,

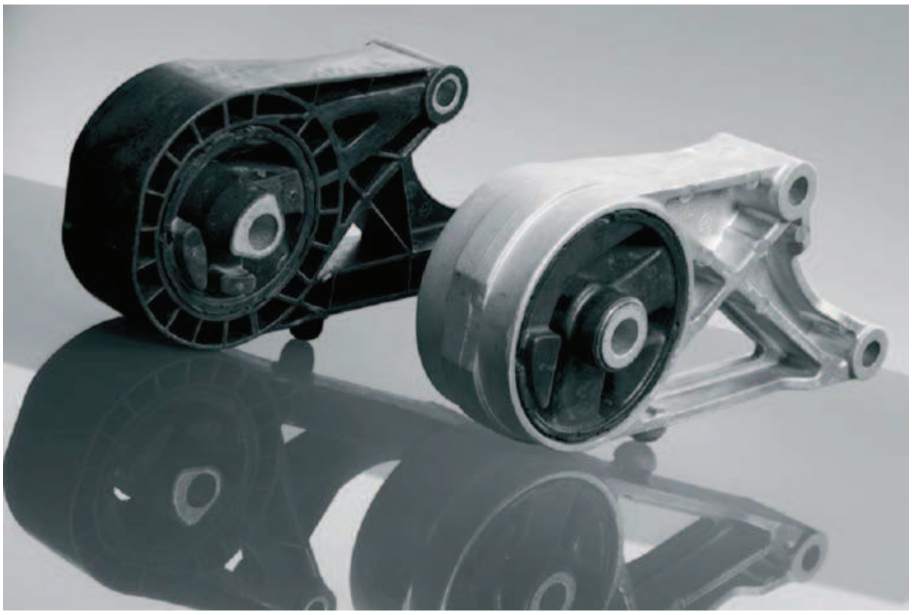

Fig. 9. Engine torque taking-over support made from an aluminium alloy and from reinforced polyamide [22].

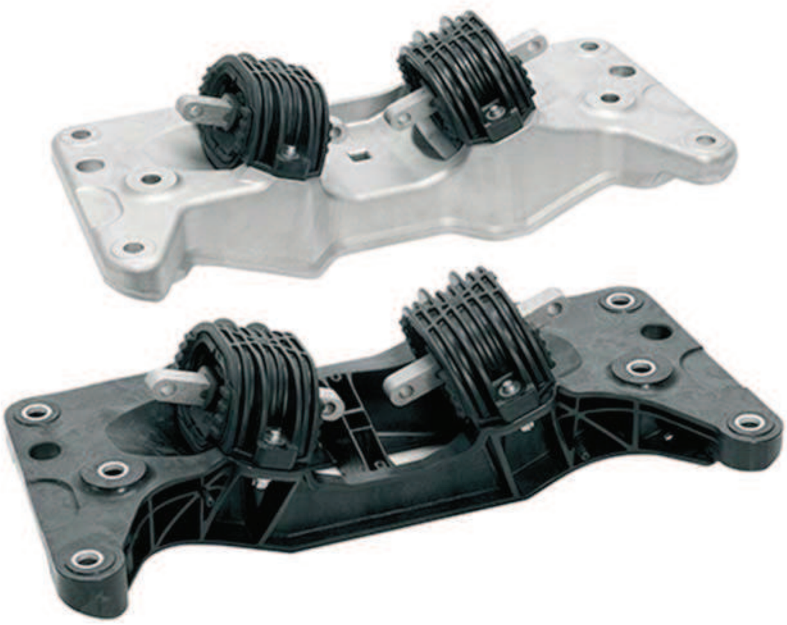

Fig. 10. Cross-member made from PA66 + glass fibre. Dark: A composite structure [24].

Fig. 11. Conventional drive shaft (top) and prototype composite drive shaft (bottom) [14].

the replacement of a multi-sectional steel shaft with a composite one-piece unit may help to reduce the cost of the system as a whole.

Advanced structures made from reinforced plastics may also be found in other systems of automotive vehicles. Clutch and accelerator pedals made from PA6 GF30 have been presented in Fig. 12. Such a solution has made it possible to reduce the mass of this subassembly by 50÷70% and to cut down the manufacturing cost [15].

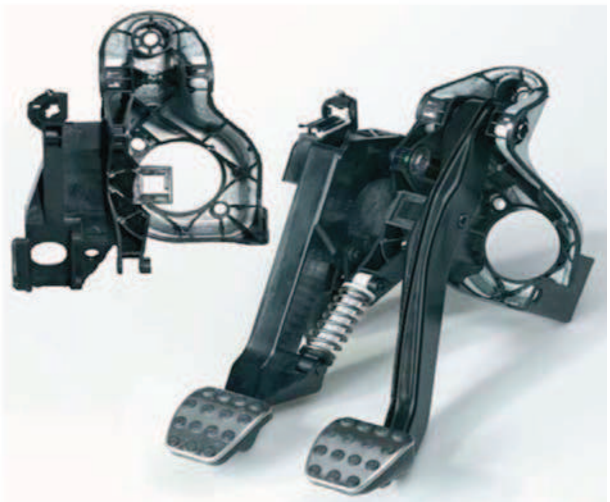

Fig. 12. Clutch and accelerator pedals made from PA6 GF30 [15].

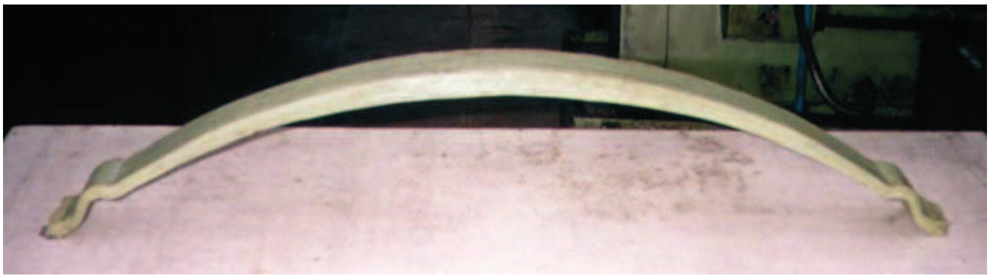

Fig. 13. Composite leaf spring without the fastening parts.

Numerous parts made from polymer composites may also be found in the suspension systems of modern vehicles. In 1980s, a series of prototype composite leaf springs like those shown in Fig. 13 were made from epoxy composite at the Higher School of Engineering in Zielona Góra. These springs passed long-lasting service (fatigue) tests and field test at the testing ground of the Higher Officers' School in Piła [16, 17]. Although our springs successfully met all the requirements laid down for automotive vehicle leaf springs, nobody has manifested any interest in the practical implementation of this design.

3. Development trends: prospects and constraints

An analysis of selected designs of vehicle components made from reinforced polymers or polymer composites has clearly shown a trend to combine many various functions in one part or assembly. Composite materials enable the obtaining of desired strength properties of the materials, thanks to which such efforts are realistic. The integration of additional structural elements in one component will further develop and this will result in simplifications that will reduce the vehicle production costs.

In the future, plastics reinforced with various continuous fibres will play a far more important role. They will be used for the making of load-bearing vehicle structures. This process can already be seen at present at the construction of racing cars. The technologies available will make it possible for the vehicle components to withstand the same loads at far less mass. Easy shaping of part cross-sections with a possibility of smooth profile changes will enable the obtaining of required stiffness values and crumple zones of vehicle body structures, which will help to improve the passive safety. Solutions making it possible to use reinforced polymer structures for the manufacturing of vehicle sheathing components based on intermediate products will develop as well, thanks to which the production process methods will be further optimised.

Modified structural materials based on plastics with additives having features formed to designers' order will be launched. Such materials may include e.g. a polymer material particularly suitable for elevated temperature applications or a highly deformable material usable at conditions of significant mechanical loads, especially of dynamic nature. The development work will definitely have to be aimed at the improvement of quality of external surfaces, in order to eliminate expensive vehicle surface refining and finishing work. In consideration of high costs of such technologies, further research and development work in the field of designing the moulding tools and the manufacturing processes will be indispensable.

In the field of designing, trends can be seen to apply lightweight structures, to hybridise parts, including plastic/plastic hybrid structures, and to develop module making and assembling technologies. An important element in the development of plastics applications in automotive engineering will undoubtedly be the wider use of reinforced materials for the making of load-bearing structures, i.e. vehicle parts and assemblies exposed to heavy loads, for example components of power transmission or suspension systems. Polymer/carbon composites will play a special role due to their high ultimate and fatigue strength. In this case, the forecasts are particularly favourable. Composite structures based on carbon fibre will have to be so developed that they could be used as module systems in large-lot production.

The development trends observed in the field of the use of reinforced plastics are not only related to designs, materials, and technologies. Further development of computerised calculation methods, covering the complete chain from material samples and determination of input data, through simulation, to validation of both vehicle components and the vehicle as a whole, is expected.

In view of the anticipated development of the application of plastics to the construction of automotive vehicles, the repair technologies must also be developed, which should include training of technical personnel.

4. Recapitulation

This paper has been intended to present the reader the progress that is now taking place in the field of designing the load-bearing vehicle structures. Conventional materials, i.e. steels and aluminium alloys, are being replaced with polymer plastics, including plastics reinforced in various ways. The design changes being introduced are not only related to the vehicle body. New materials are also used to build power transmission and suspension systems. This process requires the involvement of huge research and development potential. The research work carried out must cover the process of production of plastic components and reinforcements, the methods and processes of manufacturing specific parts and subassemblies, and the strength testing of the parts manufactured. It should be stressed that the use of polymer plastics, especially as materials for vital vehicle subassemblies, is connected with a change in the designing "philosophy." Apart from the performing of typical design work, the designer will be forced to design the strength properties of the material as such and to take into account many characteristics that exclude each other, e.g. the isotropic features of fibre-reinforced polymer composites.

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