2
3-D textile reinforced composites for the transportation industry

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2.1 Introduction

Composites with directionally oriented long-fibre reinforcement have proven their potential for realizing high-performance, low-mass structural components in the aerospace industry over the past 40 years. Starting from the German glider 'Phönix', which was designed and manufactured using glass fibre reinforced resin, right to the Airbus carbon fibre fin, the material has helped to extend the limits of the performance and efficiency of planes, helicopters and space structures further and further. The benefits are reductions in fuel consumption and emission, improved payloads and extended service lives due to higher mass-specific stiffness, strength and energy absorption, as well as better fatigue and corrosion performance than metals.

As a consequence, it is not very surprising that other fields of application outside the aerospace sector have an increasing interest in applying this kind of material, too. In the automotive industry, the need for cars with higher efficiency and no losses in terms of safety and comfort has become more and more important because of interest in improved environmental compatibility – low mass is one of the key factors in reaching this goal.

Nevertheless, there are significant differences in the requirements for manufacturing methods and structural performance which prevent an easy transfer of know-how from aerospace to automotive applications. One of the most crucial differences is that of production rates. While aerospace components are usually manufactured at a rate of no more than a few hundred, the high-volume automotive market has a need for some hundred thousand components a year. Another difference is the costs allowed for weight reductions. While the space industry spends up to some US$10,000 just to save 1 kg of mass in a satellite, the automotive market currently accepts no more than some US$10–20.

Thus, the big challenge for the next few years will be developing materials, processing methods and structural concepts which allow cost-effective, high-volume manufacturing of low-mass composite components. A very promising approach to achieving this goal is the development and application of advanced textile technologies, such as 3-D weaving, 3-D braiding, knitting or stitching, offering the potential for automated manufacturing of near net shaped fibre preforms with optimized fibre reinforcement in 3-D space according to structural requirements.

In combination with appropriate impregnation or consolidation techniques, a significant reduction of manual work can be realized compared with state-of-the-art aerospace technologies based on unidirectional fibre tapes or 2-D weavings. In this way, one of the most important requirements for cost reduction in aerospace and the introduction of composites in high-volume automotive applications can be fulfilled. Another very interesting feature is the possibility to produce a 3-D fibre reinforcement in the composite material. It has been shown that this results in significantly improved damage tolerance and structural integrity.

The focal points in this chapter are the description of benefits and drawbacks involved in composite materials with conventional and textile reinforcement compared with metals, the requirements for the material with regard to aerospace and automotive applications, and discussion of first exemplary applications demonstrating the potential of textile structural composites for improving mechanical performance and reducing manufacturing costs.

2.2 The mechanical performance of conventional and 3-D reinforced composites

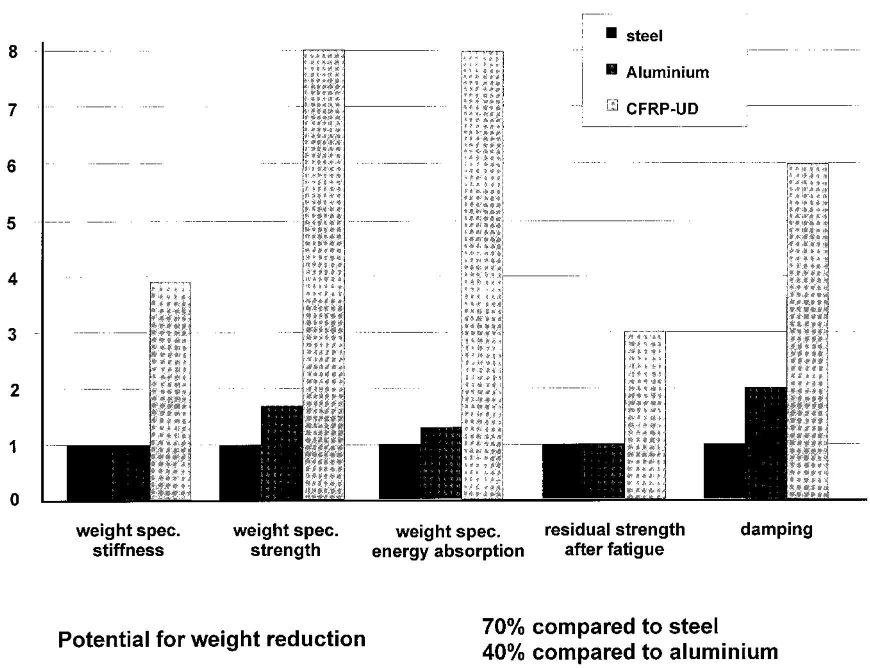
The mechanical performance of composites is mainly determined by the fibre type and the reinforcing fibre geometry. The most important fibre types are glass, carbon and aramide fibres. It has been shown that carbon fibres offer by far the best potential in terms of stiffness. Therefore, they represent the most important material for aerospace applications. They have so far not been considered as a structural material for high-volume automotive applications because prices are very high, ranging from \$20 to 500/kg. In this field, glass fibres, which are priced at approximately \$3/kg, represent the most important material.

In the near future it can be expected that much cheaper carbon fibres will be launched on the market. Nevertheless, the mechanical performance and the textile processability of this new fibre class have to be proven, because it may be necessary to use much thicker fibre bundles to reach the cost reduction goal. The second factor of influence is the reinforcing fibre geometry, whereby composites can be broken down into two classes: material with non-directional (short) fibre reinforcement (mats, injection moulding) and with directionally oriented long fibres (unidirectional tapes, fabrics).

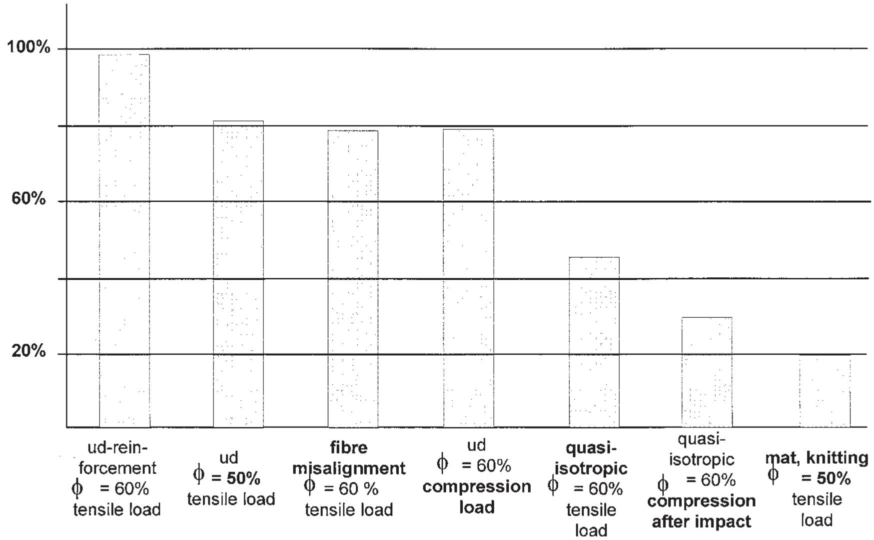
For aerospace components, only directionally oriented long fibres are used, as this configuration alone allows full utilization of the fibre properties, and an optimal anisotropic design according to the structural requirements concerned. So far, use of this material in high-volume manufacturing has been limited to easily shaped components, because the manufacturing process requires a lot of manual work.

In Fig. 2.1, the most important mechanical properties of the composites are compared with light metals and steel. It is shown that the most significant mass reductions can be achieved using carbon fibres and a non-isotropic fibre reinforcement, as required by the respective loads. When comparing quasi-isotropic composites with metals, one will find that mass savings of more than 30% compared with aluminium, and 60% compared with steel are feasible.

Nevertheless, this comparison is based on 'idealized' laboratory-scale values determined under the following conditions: unidirectional reinforcement, high fibre volume fraction (60%), tensile load, no fibre undulation and no delaminations. In realistic applications several additional



2.1 Comparison between mechanical performance of metals and composite materials.



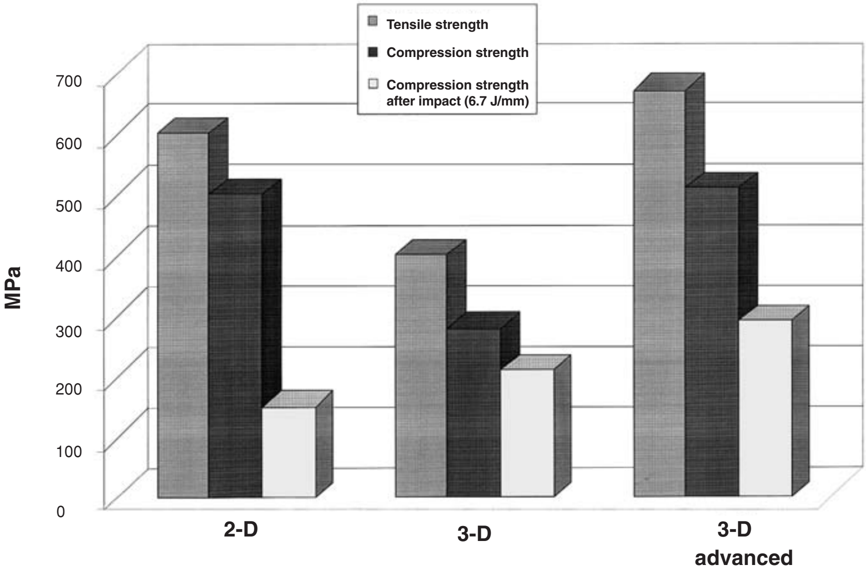
2.2 Degradation of composite performance due to manufacturing and in-service effects.

factors of influence have to be taken into consideration which can be caused by the series manufacturing process, the structural service conditions, the component geometry and the fibre reinforcement. Figure 2.2 gives an idea of the magnitude of the various factors of influence.

It is obvious that unidirectional tape-based composites offer the highest utilization of fibre properties and therefore the highest in-plane stiffness and strength, because the fibres are aligned without any curvature exactly in the loading direction and no resin-rich areas cause strain inhomogeneities within the material.

All textile structures show a more or less high degree of fibre undulation. In 2-D weavings this effect is caused by the mutual crosslinking of weft and warp fibres, and weft knittings consist more or less of a mesh system with curved fibres. Additional degradations of in-plane properties are caused principally by a 3-D reinforcement, because the z-directional fibre fraction reduces the share of load-carrying fibres and generates resin-rich areas. Optimizing these effects is very important especially for aerospace applications: despite the growing need for cost savings, low weight is still the driving force for research and development in this field of application.

In the past years, significant improvements have been realized for example in the field of 3-D weaving. In Fig. 2.3 2-D weavings, 'conventional' 3-D weavings and advanced 3-D weavings, manufactured by a process recently developed by the North Carolina State University, are compared. It is shown that, owing to reduced fibre undulation and fibre damage, the



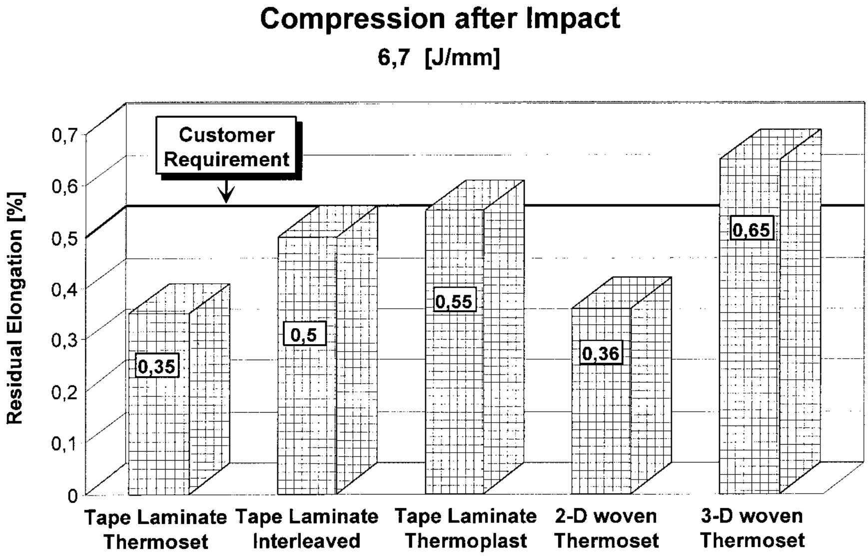
2.3 Mechanical performance of various 2-D and 3-D woven composites.

effect of the 3-D reinforcement can be compensated and the stiffness and strength of 2-D weavings can be achieved.

Naturally, no problems with fibre curvature occur in multiaxial warp knittings, because the fibre layers are placed on top of each other without crosslinking. Nevertheless, the stitching fibres, holding the single layers together, can lead to a reduction of mechanical performance owing to fibre damage or to disturbance of the reinforcing fibre alignment. The mechanical performance of weft knittings can be improved by prestretching the meshes before curing or by an additional fibre system running straight through the mesh system.

High stiffness and strength are just two criteria for the evaluation and selection of a structural material for automotive and aerospace applications. In particular, components that are susceptible to impact or crash loads have to be designed according to their mechanical performance after a first failure. This can lead to the necessity of high safety factors, reducing the weight reduction potential. Therefore, the ‘damage tolerance’ can be an important material property.

Conventional 2-D reinforced composites based on tapes or weavings tend to delaminate owing to impact loads, because the bonding between the single layers is relatively poor, which leads to poor interlaminar performance. A significant improvement is possible by a 3-D through-the-thickness fibre reinforcement, which can be realized by 3-D-weaving, 3-D-braiding or stitching.



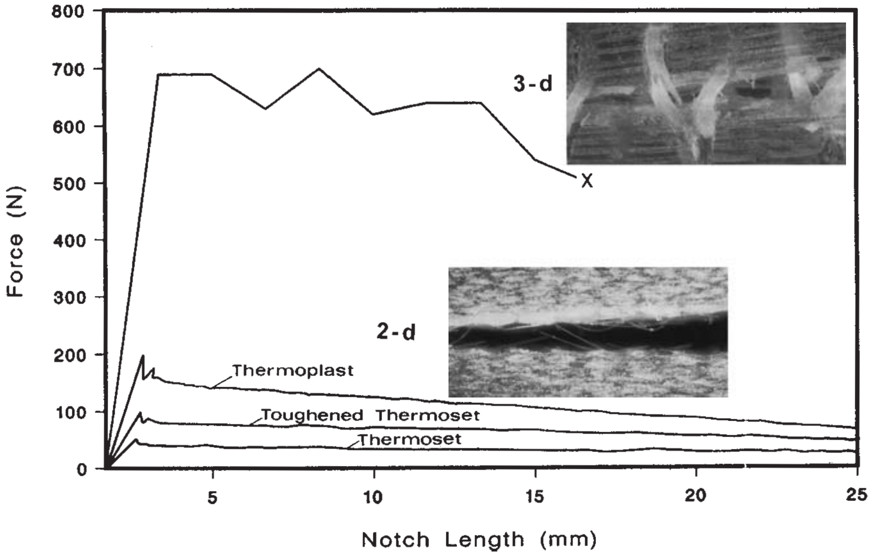
2.4 Damage tolerance of different composite materials.

In Fig. 2.4, the damage tolerances of various composite materials, characterized by the compression after impact test, are compared. In this test, composite plates are impacted and afterwards compression tested according to exactly defined specifications. The remaining strength and breaking elongation represents a value for the damage tolerance evaluation and the design of impact-susceptible structures.

It is shown that performance after impact can be improved significantly by the 3-D fibre reinforcement. With a fibre share of below 5%, the design goal of 0.5% after impact that is required in aerospace can be reached even with brittle resin systems. The parameters that influence performance are type, thickness and distance of *z*-fibres as well as the reinforcing geometry. Figure 2.5 illustrates the reason for higher impregnation speed. Compared with 2-D composites, the *z*-fibres lead to a significant improvement in bonding of the single layers, as demonstrated by the peel strength.

The structural integrity is of major importance, especially for automotive applications. After a crash, the structures have to maintain a minimum mechanical performance. Complete debonding of component parts has to be avoided. These criteria can be realized easily by metals owing to their plastic deformation characteristics. The more or less brittle crush behaviour of conventional, especially carbon fibre reinforced composites is much more critical in this respect.

This performance can also be improved by a 3-D fibre reinforcement.



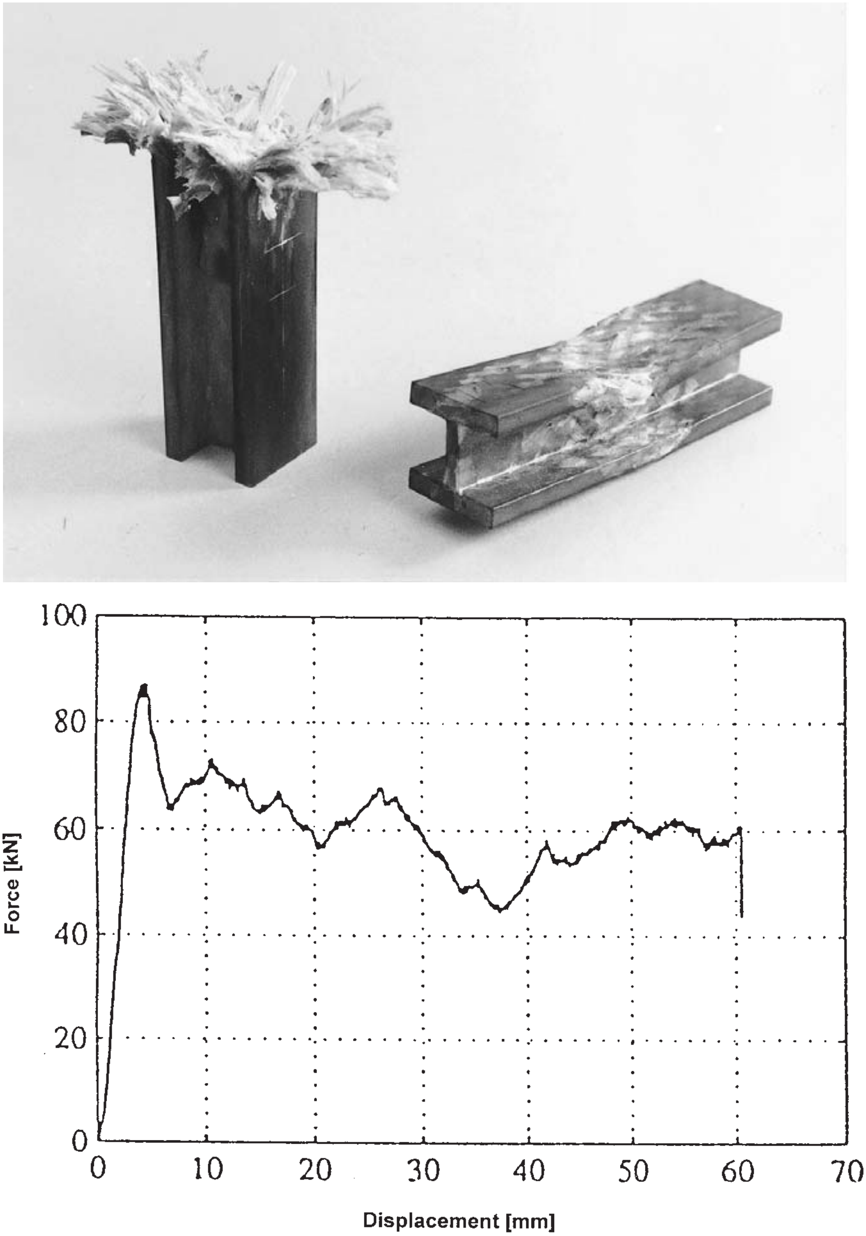
2.5 Notch growth in 2-D and 3-D reinforced composites.

Figure 2.6 shows double T-shaped beams, typical structural components in automotive and aerospace design, after longitudinal and transversal crash tests. The preforms for the composite structures are integrally 3-D braided by a new '*n*-step' braiding process in an optimum configuration according to the loads. The integral fibre reinforcement guarantees high structural integrity with locally restricted damage area and high after-crash performance. An additional feature is the high mass-specific energy absorption owing to the complex, exactly controllable failure modes in the 3-D fibre structure.

More complex preforms for composites with high structural integrity which cannot be made by one textile technology can be realized by stitching several basic preforms together. A stiffened panel is discussed in Chapter 5 as an example. It has been made by stitching the warp-knitted skin to a 3-D braided profile.

2.3 Manufacturing textile structural composites

The diverse textile processes, such as advanced weaving, braiding, knitting or stitching, allow the production of more or less complex fibre preforms. While weavings and warp knittings are predestined for flat panels, braidings allow the manufacture of profiles. The most complex preforms can be realized where warp-knitting is used. Tables 2.1 and 2.2 summarize the most important features of textile process and composites as well as the



2.6 Structural integrity of 3-D braided profiles after crash.

Table 2.1. Textile processes for composites: an overview

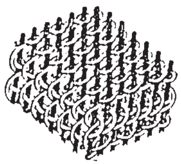
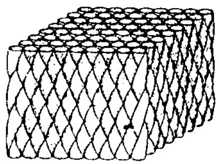
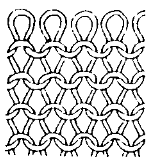
Textile process	Principle – design	Preform geometry	Fibre orientation	Productivity mounting	Development goals
3D weaving		Flat fabrics Integral stiffeners Integral sandwich-structure Simple profiles	Limited to weft and warp direction (0/90) Various *z*-fibre reinforcements	High productivity Very high mounting time	Multiaxial 3D weavings with integrated 45° fibres
3D braiding		Open and closed profiles (I, L, Z, O, U, . . .) Flat fabrics	Braiding fibres 10–80° Local integration of straight 0° fibres	Medium productivity High mounting time	Varying cross-sections Varying fibre orientation
Knitting (weft)		Very complex preforms (knot-elements, curved structures)	Fibres mainly in mesh structure	Medium productivity Short mounting time	Integration of straight fibres in the mesh structure

Table 2.1. (cont.)

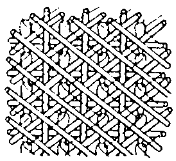
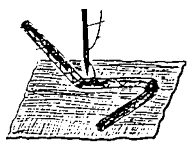
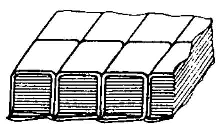
Textile process	Principle – design	Preform geometry	Fibre orientation	Productivity mounting	Development goals
Knitting (warp)		Flat fabrics Integral sandwich-structures	Multiaxial in-plane orientation 0°/90°/±45° Up to 7 layers fixed by knitting fibre	High productivity High mounting time	Integration of more layers in one production step
Embroidery		Attaching additional fibres on basic fabrics	Very complex fibre orientation, for example in main stress direction	Slow process Short mounting time	Improvement of production speed Optimization of control program for 3-D structures
Stitching		Very complex preforms by combining several textile structures	Depending on basic preforms	Very quick process Short mounting time	Optimization of control program for 3-D structures Optimization of stitch-head (damage, size)

Table 2.2. Textile structural composites: an overview

Textile structure	Mechanical properties	Composite manufacturing	Typical structural elements	Typical applications
3-D woven	High stiffness and strength only in 0° and 90° directions Very high damage tolerance	RTM Pressing (thermoplast and thermoset, film and prepreg) Limited drapeability	Slightly curved panels under biaxial load Sandwich-panels Simply shaped profiles	Cell-skin elements Fitting elements Body-in-white structures Chassis structures
3-D braided	High stiffness and strength above all in 0° direction High structural integrity of complex profiles	RTM Pressing (see weaving) Pultrusion (profiles) High deformability	Complex, open and closed profiles Flat panels with limited cross-section	Stiffening elements Chassis structures Spaceframe elements
Knitted (weft)	High stiffness and strength only in fill-fibre direction High energy absorption High structural integrity	RTM Pressing (see weavings) Very good drapeability Minimum waste	Knot-elements Complex, curved panels with limited stiffness and strength	Spaceframe elements Helmet shells Cladding element with high damage tolerance
Knitted (warp)	High stiffness and strength also under shear loading	RTM Pressing (see weaving) 45° fibres in roll direction	Flat and curved panels under biaxial load Curved sandwich-panels	Cell-skin elements Fitting elements Body-in-white structures Chassis elements
Embroidered	High stiffness and strength also under shear loads (for example, load introduction)	RTM Pressing (see weaving) No waste of embroidery fibre	Local reinforcement Load-introduction and load-transmission elements	Rotor-blade joining element Inspection-hole cover
Stitched	High damage tolerance High structural integrity Reduction of in-plane properties possible due to damage	RTM Pressing (see weaving) Complex moulds for complex structure	Stiffened panels consisting of woven or knitted flat panels with braided profiles Complex 3-D structures	Highly integrated panels for cell structures Complex fittings

development goals. A detailed description of the various textile technologies can be found in Chapter 1.

Impregnating the complex shaped 3-D fibre structures applies for suitable infiltration and consolidation techniques in order to obtain high and constant fibre volume fractions with low void content during the composite manufacturing process.

In general, the manufacturing methods used in both aerospace and non-aerospace applications are quite different. While autoclave prepreg technology is the most important technique for aerospace components, injection moulding and pressing techniques (SMC, GMT) are used for high-volume applications. The reason is that the autoclave prepreg technique results in large fibre volume fractions (typically 60%) and high performance. On the other hand, there is a penalty in the form of extremely high cycle times, typically lasting several hours. SMC, GMT and injection moulding techniques allow cycle times of less than one minute. On the other hand, fibre volume fractions are relatively poor (typically 30%).

In combination with textile preforms, the RTM process (resin transfer moulding) is of special interest. In this process, a resin is pressed under vacuum into a closed mould where the fibre preform is fixed. The achievable fibre volume fractions amount to more than 50%, while cycle times of less than 10 minutes can be realized with appropriate resin systems.

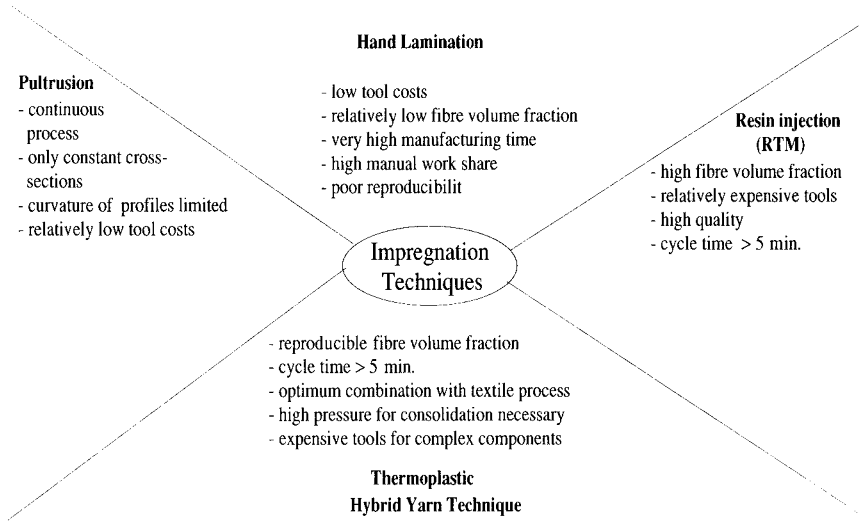
Although the density of the 3-D fibre structures can be very high, the impregnation speed is more or less higher compared with conventional 2-D structures. The reason for this effect is that the additional fibres in thickness direction form 'flow channels' which support resin transfer through the thickness.

The continuous pultrusion process is of greatest interest for the impregnation of profile-shaped fibre preforms with a constant cross-section. Interesting developments are performed, especially in combination with 3-D braiding.

The most important impregnation techniques are summarized in Fig. 2.7.

In general, thermoplastic matrix composites offer a high potential for realizing short cycle times because no chemical reaction has to take place in the mould, and quick hot-forming techniques, comparable to the pressing of metal sheets, can be applied. On the other hand, thermoplastics generally require higher temperatures and pressure, and thus more expensive tooling and higher energy consumption. This is especially true of PEEK, the only thermoplastic matrix material for aerospace structural components with a melting point of 400 °C.

The use of hybrid structures, consisting of reinforcing fibres and thermoplastic fibres, is of special interest in combination with textile technologies. According to the level of fibre mixture, the process is called commingling, or co-weaving (or co-braiding). In the commingling process, the com-



2.7 Impregnation techniques for textile structural composites.

bination of reinforcing fibres and thermoplastic 'matrix' fibres occurs at fibre level. In the co-weaving or co-braiding process the two fibre types are mixed during the textile process.

The advantage of the first approach is that the textile processing of the reinforcing fibres can be improved because the tough thermoplastics protect the brittle glass or carbon fibres. Additionally, the composite quality is better than co-weaving and co-braiding, owing to increased homogeneity.

With a view to an overall cost evaluation, tooling may play an important role in low- and medium-volume manufacturing. In general, composite tools are much cheaper than steel tools. Therefore, part costs may be lower because of the use of composites for small series production, although material costs are much higher than those of steel.

Nevertheless, the tooling technology for impregnating very complex textile preforms requires special developments to allow cost-effective component manufacturing. Promising techniques are, for example, the differential pressure RTM or the so-called 'Scrimp process', where only one tooling half is hard and the other one is formed by a vacuum foil.

Of special interest for complex hollow structures is the wax core technique. These cores can be melted in very complex geometries and act, for example, as a braiding core during the textile process and as part of the impregnation tool during composite manufacturing. After curing they can be melted out completely.

2.4 3-D composites in aerospace structures

Table 2.3 summarizes the most important requirements for a material to be used in aerospace applications. While mechanical performance, long-term behaviour and behaviour under special environmental conditions are of the greatest importance, costs for production and service have also gained in significance. The significance of the various requirements is, of course, different for military and civil aircraft.

Compared to the automotive industry, composites have a long history in aerospace applications. In passenger planes, their share has reached 15%, while in modern fighter aircraft more than 50% of the structural material consists of composites. Helicopters are designed almost exclusively using composites.

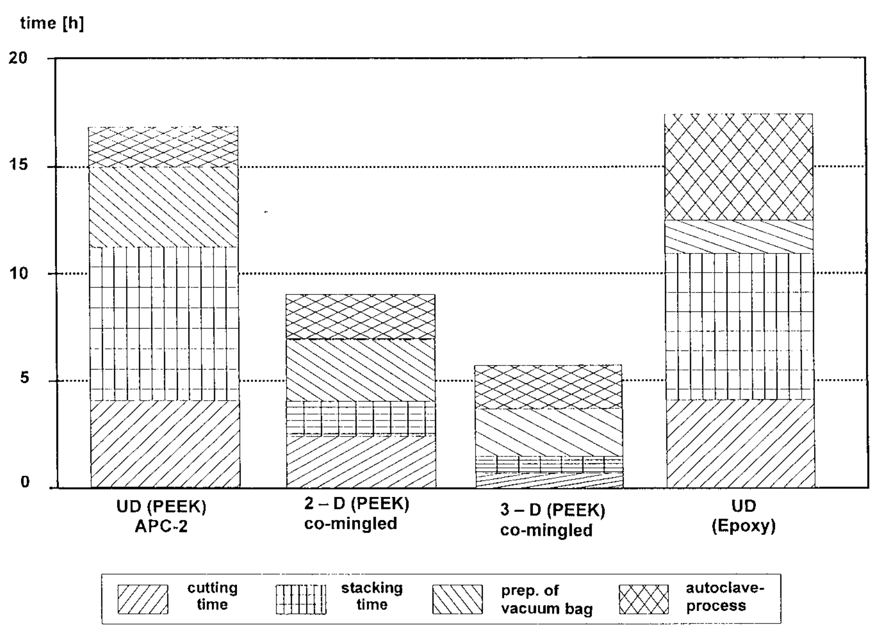
All major aerospace companies have launched technology programmes to apply composites in structural components of passenger planes other than just the fins. Fuselage structures and wing components are under investigation. The focal points are new design, material and manufacturing concepts, and textile structural composites play an important role in the research and development projects.

Table 2.3. General requirements for materials to be used in structural applications

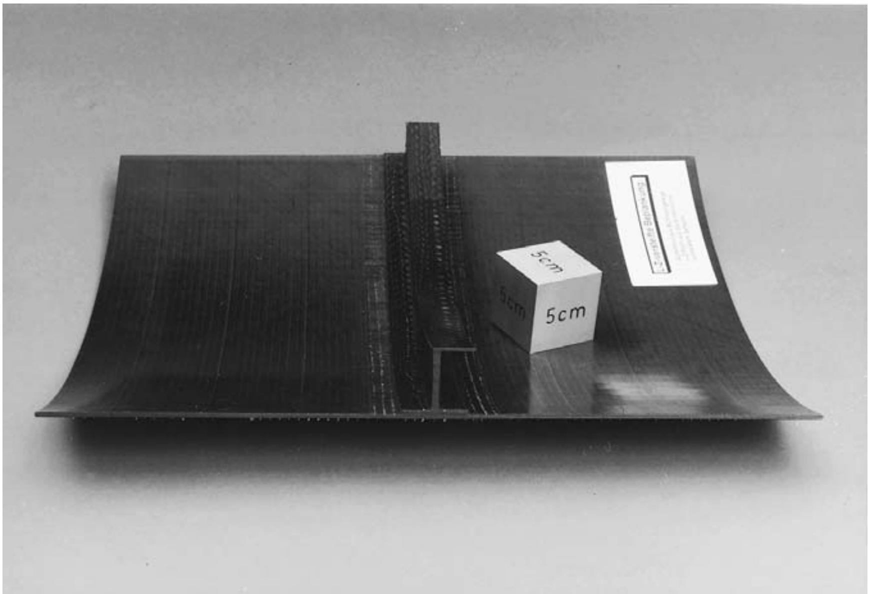
	Product improvement	Required material properties
Aerospace	Payload Range Fuel economy Direct operational costs Safety	High stiffness and strength High damage tolerance (compression after impact $\varepsilon > 0.5\%$) High reproducibility High energy absorption (helicopter) Processing cost reduction Optimization of scrap
Ground transportation	Fuel economy Payload Low noise level Emission	Low cycle times (<<5 min) Low material price (<$10/kg) Limited manual work Medium stiffness and strength ($E > 20$ GPa) High energy absorption High design freedom Potential for recycling Potential for low investments Potential for improvements due to 3-D textiles

In order to demonstrate the advantage of textile structural composites, Daimler-Benz has conducted a research programme to manufacture and test a fin-leading edge of a fighter aircraft. The component was produced using 2-D weavings and 3-D weavings with a thermoplastic and thermoset matrix. Figure 2.8 summarizes manufacturing time estimates. It shows impressively that the use of the 3-D woven textile preform may reduce manual work significantly. Furthermore, the damage tolerance of the impact-susceptible component has been improved due to the 3-D reinforcement – no delaminations occurred after impact testing. On the other hand, 3-D weavings do not allow a structural optimization of the component, because the torsional stiffness of this material is relatively poor due to the lack of ±45° fibres. A promising approach would be to apply new multiaxial 3D weavings or multiaxial warp knittings.

Another demonstrator component based on textile structural composites has been produced independently by McDonnell Douglas, Daimler-Benz and others. At Daimler-Benz stiffened panels have been manufactured with 3-D woven or warp-knitted skin and 3-D braided stiffeners stitched together to a complex preform (see Fig. 2.9). The fibre structure was subsequently impregnated in an RTM process by the DLR in Braunschweig. Table 2.4 shows a cost and weight estimate for the typical aerospace component, compared with aluminium and a tape-based structure. The textile-



2.8 Manufacturing times for fin-leading edge.



2.9 Stiffened panel consisting of braided profiles and warp knitted skins.

Table 2.4. Cost and weight estimates for stiffened panels

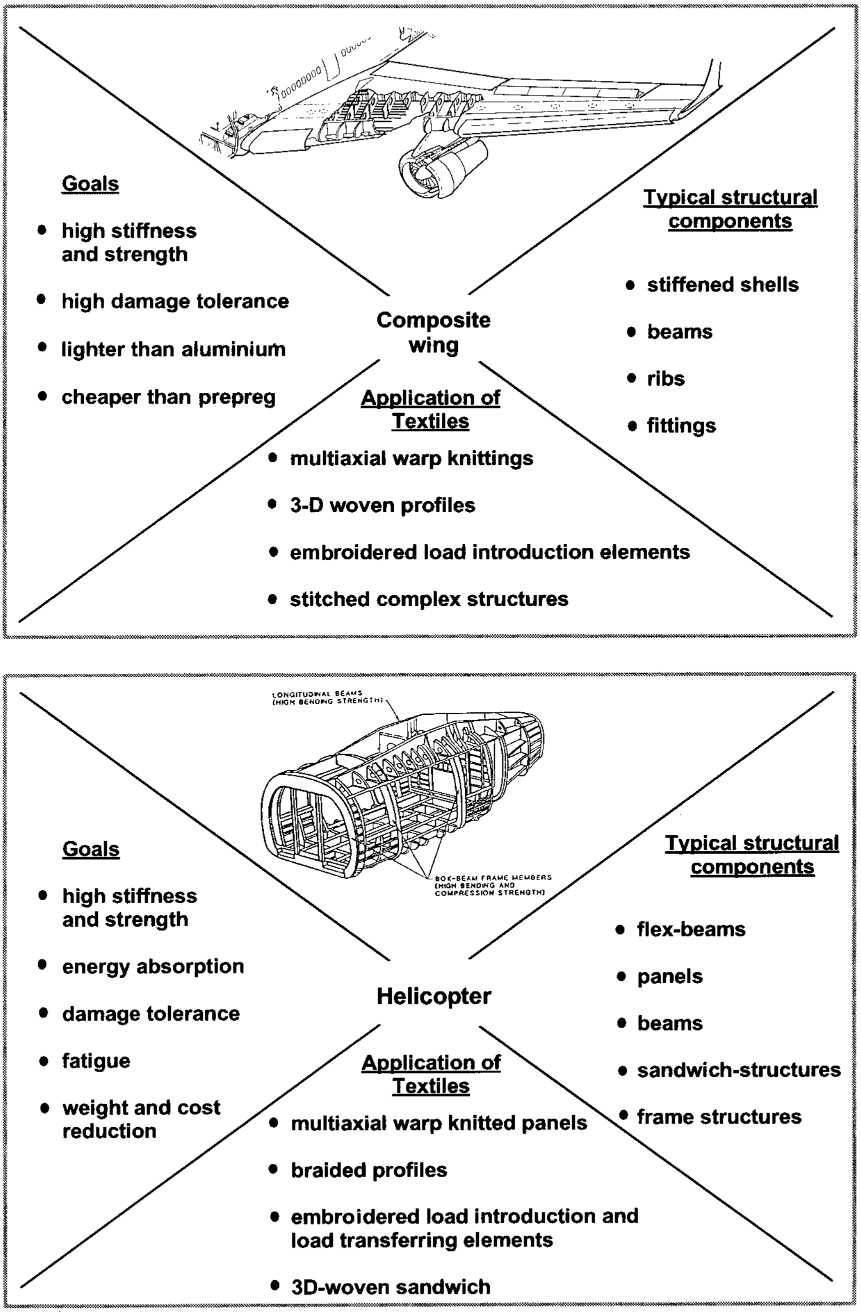
	Material (US$)	Labour (US$)	Total (US$)	Weight (%)
Aluminium (milled)	21	11	32	100
Hand-lay-up (unidirectional-prepreg)	45	120	166	70
Automated tape lay-up	29	16	46	70
Integral preform (3-D + stitched, RTM)	20	10	30	75

based part seems to represent a good compromise between costs and mechanical performance.

In Fig. 2.10 the goals, typical structural components and possible applications of textiles for aeroplanes and helicopters are summarized.

2.5 Textile structural composites in automotive structures

Table 2.3 summarizes the general requirements that materials for ground-transportation applications have to meet. The most important features are



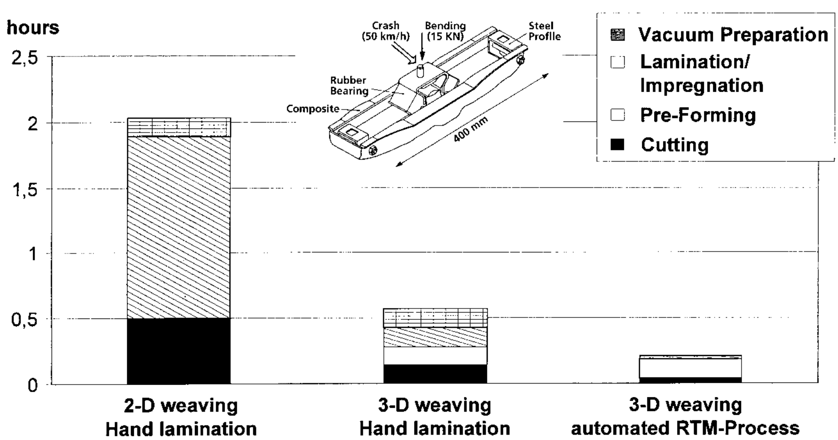
2.10 Textile structural composites in aerospace applications.

costs, manufacturability, mechanical performance, long-term behaviour, repairability and recyclability. As discussed before, composites offer some important benefits over metals, such as mechanical performance, long-term behaviour (no corrosion), high damping and low-energy expense for raw material manufacturing. On the other hand, there are currently no adequate solutions for high-volume manufacturing techniques for long-fibre reinforced composites, costs, repair and recycling. Therefore, no automotive manufacturer has so far applied this class of material for structural components in real high-volume models (50 000 to 300 000 cars per year).

Of special interest is the use of composites in chassis applications, as in this field the anisotropy of the material can be used to create all-new design concepts, allowing a significant reduction in component numbers and a very marked weight reduction compared with steel. It is, for example, possible to realize beam elements with a very high bending stiffness and low torsional stiffness, or vice versa.

In order to evaluate the applicability of textile structural composites, Daimler-Benz has manufactured and tested a 3-D reinforced engine mount at laboratory level within the framework of a research project. One component has been produced using 20 conventionally woven glass fibre layers; the other one is based on a single 3-D weaving integrating these layers in a single preform. The result is a significant decrease in manufacturing time (see Fig. 2.11), which is due to a reduction in manual work (cutting and laminating). It is expected that cycle times of less than 10 minutes are possible when applying an optimized RTM process.

Bending and fatigue tests have shown that the composite components



2.11 Manufacturing time for composite engine mounts.

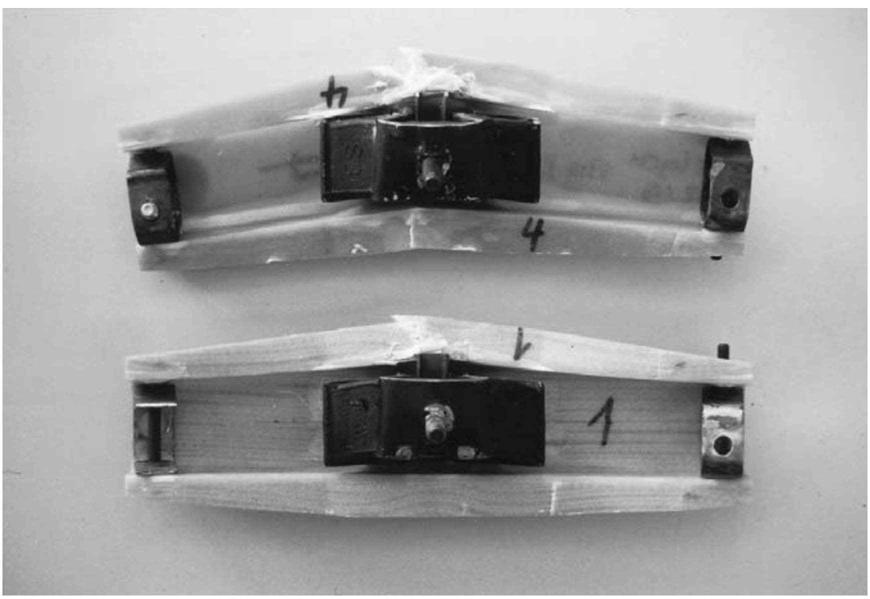
meet all requirements at a weight of less than 50% of the steel components. A special feature of the 3-D reinforced component has been demonstrated in crash tests. Energy absorption and structural integrity are higher and prevent the component from separating into two parts (see Fig. 2.12).

Typical structural components in transportation engineering are knot elements for spaceframe-like structures. Because of the complex geometry and loading of these parts, cost-effective manufacturing based on conventional 2-D composites is not possible. Metal casting is state-of-the-art or, if the loads are low, injection moulding.

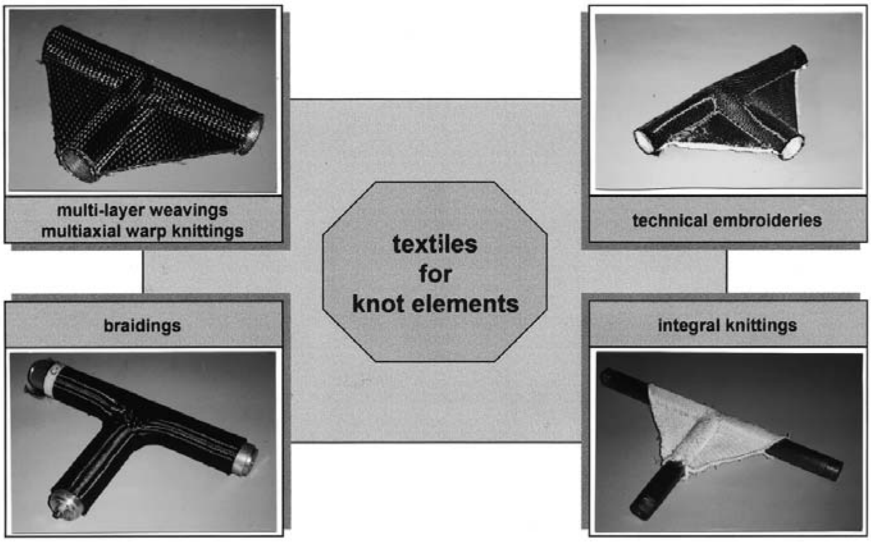
High-performance structural parts with a high weight-saving potential can be realized using new braiding or knitting technologies. Figure 2.13 illustrates the principle. The braiding process, developed by Muratec in Japan, allows positioning of fibres around a complex mandrel consisting of foam or a replaceable material such as wax.

Completely different is the preform manufacturing concept based on the knitting technology developed for example by Stoll in Germany. It allows direct transfer of a CAD file of a structure into a knitted net shaped fibre system. In highly loaded component areas additional straight fibres can be integrated in order to improve mechanical performance.

Another interesting application field is that of exterior components. An important requirement for such parts is high stiffness. A sandwich design



2.12 Crash behaviour of 2-D (top) and 3-D reinforced engine mounts.



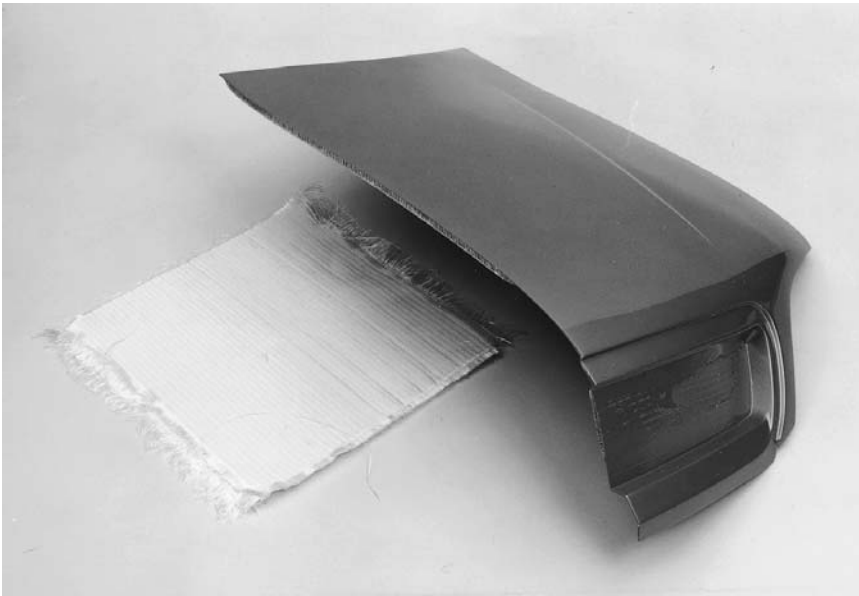
2.13 Braided, knitted and stitched knot elements for spaceframe structures.

would therefore be very effective. Nevertheless, the manufacturing of conventional sandwich structures based on foam or honeycomb cores is time consuming and expensive. Additionally, the poor damage tolerance prevents these structures from being used intensively in transportation applications.

An interesting new design and manufacturing concept is feasible by using integrally woven sandwich structures. The integral structure combining the two skins and the 'core' during the textile process offers a high potential for automated, cost-effective manufacturing of sandwich structures with a high damage tolerance because of the 3-D fibre reinforcement.

An exemplary demonstrator component is shown in Fig. 2.14. A hood for a passenger car has been made by using a glass fibre weaving in one shot. After impregnation in an epoxy resin bath and pressing to adjust the resin content, the wet preform was placed in a negative mould and pressed in the area of the structure borders by a frame. Owing to the sandwich design, the 3-D fibre reinforcement and the ability to realize very effective load introductions, the weight-saving potential of this structure is very high. Even compared with an aluminium sheet hood a weight reduction of nearly 50% is possible. Nevertheless, an important development goal for exterior applications is to improve the surface quality of textile-based composite materials.

The goals, typical structural components and possible applications of textiles are summarized in Fig. 2.15.



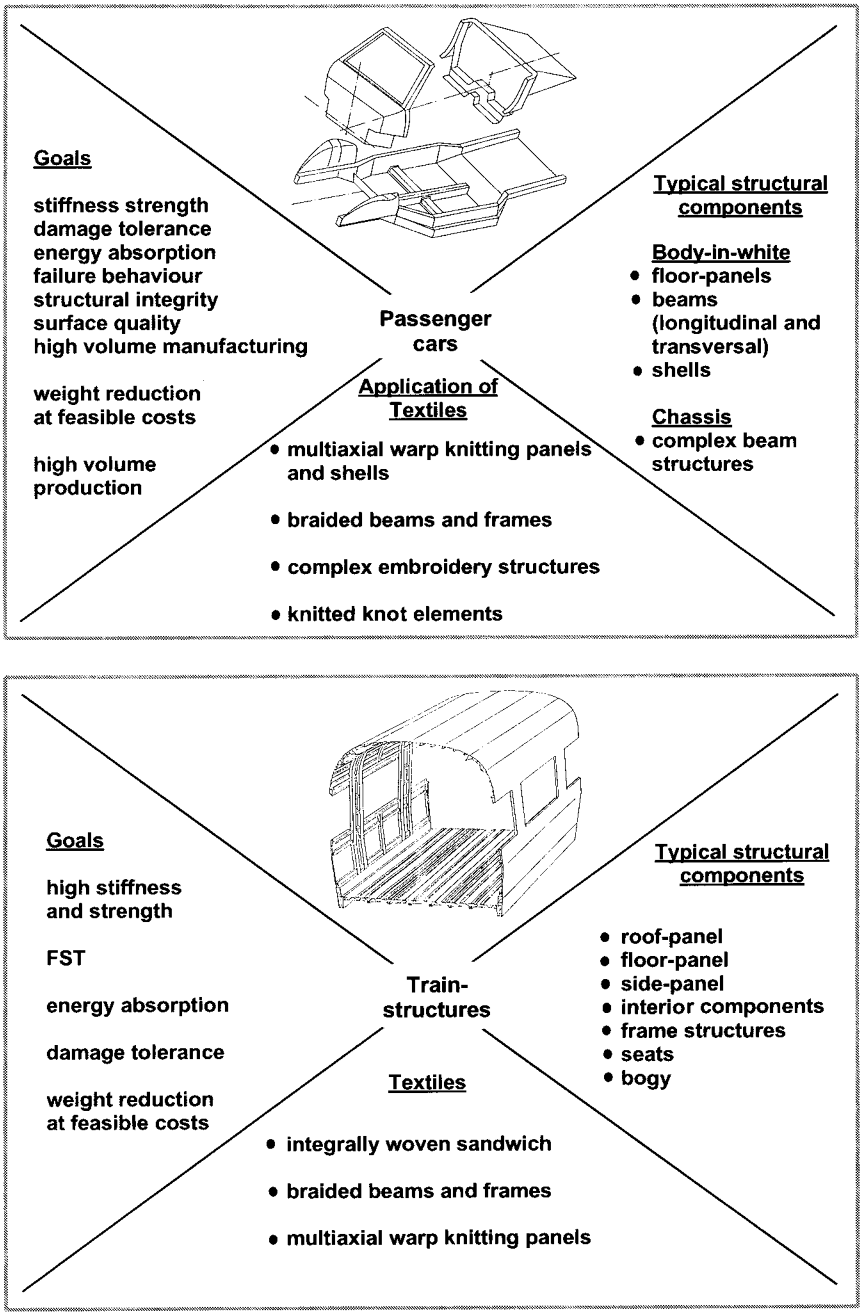
2.14 Prototype of a sandwich hood based on an integrally woven sandwich.

2.6 Conclusions

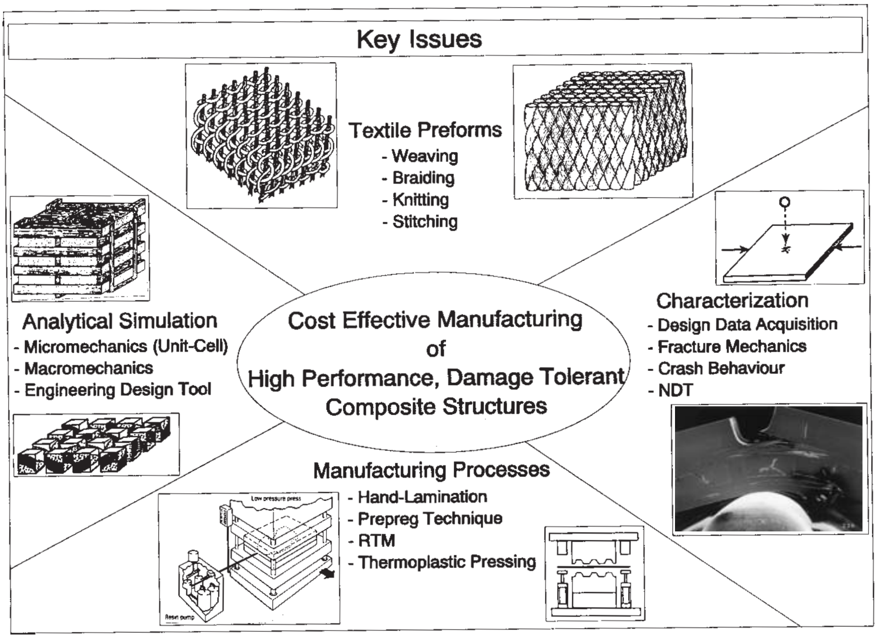
High stiffness and strength at low density, high mass-specific energy-absorption behaviour and good fatigue performance are the main features that have led to the successful application of composite materials in the aerospace industry over the past decades. Two typical examples are weight savings of approximately 25% in the Airbus fin as compared with aluminium, and an extension of the service lives of helicopter rotor blades by a factor of more than 40.

Textile structural composites with 3-D fibre reinforcement may facilitate utilizing the unique material performance in other structural components as well, e.g. the fuselage or wing components of new generations of passenger planes, such as the ultra-high-capacity aeroplanes planned by Boeing and Airbus. The main material improvements include enhanced damage tolerance due to 3-D reinforcement, and reduced manufacturing costs resulting from the application of highly productive textile technologies in the manufacture of fibre preforms. This fact may also be a key aspect when applying high-performance composites in high-volume automotive productions, trucks or trains.

Nevertheless, the research and development work on textile structural composites involves several technological fields (see Fig. 2.16). There is still



2.15 Textile structural composites in ground transportation.



2.16 Research and development tasks for textile structural composites.

a lot of work to do, starting with improving the productivity of the textile processes and optimizing the stiffness and strength of 3-D composites, and ending with fast impregnation processes and suitable simulation tools describing the mechanical behaviour. But there is no doubt that 3-D textiles will be a key factor for future developments and for the successful application of composites in aerospace and ground transportation engineering.

2.7 References

Composite materials in general

M. Krämer and P.-J. Winkler, *Möglichkeiten und Grenzen einer Synergie zum Leichtbau zwischen Automobil- und Luftfahrtindustrie*, VDI-Berichte, 1993.

H. Kellerer, 'Stand und Perspektiven moderner Verbundwerkstoffe', paper presented at BMFT-Symposium 'Materialforschung', Dresden, 1991.

H. Kellerer, J. Brandt, R. Meistring and R. Rauh, *Limits to Today's Composites: Changes for Tomorrow's Developments*. ECCM, Bordeaux, 1989.

F.J. Arendts and K. Drechsler, 'Composites with knitted fibre reinforcement', paper presented at 3rd International Symposium on Advanced Composites, Patras, 1990.

F.J. Arendts, J. Brandt and K. Drechsler, 'Integrally woven sandwich structures', paper presented at ECCM 3, Bordeaux, 1989.

J. Brandt and K. Drechsler, 'The potential of advanced textile structural composites for automotive and aerospace applications', paper presented at 4th Japan International SAMPE Conference, Tokyo, 1996.

J. Brandt and K. Drechsler, 'Application of composites in the transportation industry', paper presented at Texcomp 3, Aachen, 1996.

Automotive applications

O. Altmann, *Karosserie- und Automobilkonzepte mit Polymerwerkstoffen*, VDI-Berichte N°c.968, 1992.

E. Roth, H. Sigolotto, H. Keller and P. Kümmerlen, *Fahrerhaus in CFK-Technology, Chance oder Utopie?*, VDI-Tagung, 1995.

H.G. Haldenwanger, *Einsatz von FVK im Automobilbau- Übersicht und neue Ansätze*, VDI-Verlag, 1993.

K. Johnson, 'Resin transfer molding of complex automotive structures', paper presented at 41st Annual Conference of the Society of Plastics Industries, 1986.

K. Johnson, 'Automotive applications for textile-based composite structures', paper presented at Texcomp 3, Aachen, 1996.

Aerospace applications

W. Hartmann and H. Kellerer, *Criteria for the Material Selection for Aircraft Structures*, MRS Europe, 1985.

J. Brandt and K. Drechsler, 'The application of 3-D fibre preforms for aerospace composite structures', paper presented at ESA/ESTEC-Conference, Noordwijk, 1990.

J. Koshorst, Verbundwerkstoffe in der Luftfahrttechnik, Entwicklung und Perspektiven, paper presented at Verbundwerk 88, Frankfurt, 1988.

H. Rieckhof, Einsatz von Faserverbundwerkstoffen im Airbus-Programm, DGLR-Jahretagung 1986.

G. Behrendt, *Neue Technologien in der allgemeinen Luftfahrt*, DGLR-Bericht 87-01, 1987.