Chapter 1
Introduction

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Abstract Polymer composites offer the possibility for functional integration since the material is produced simultaneously with the product. The efficiency of composite structures raises through functional integration. The specific production processes of composites offer the possibility to improve and to integrate more functions thus making the structure more valuable. Passive functions can be improved by combination of different materials from nano to macro scale, i.e. strength, toughness, bearing strength, compression after impact properties or production tolerances. Active functions can be realized by smart materials, i.e. morphing, active vibration control, active structure acoustic control or structure health monitoring. The basis is a comprehensive understanding of materials, simulation, design methods, production technologies and adaptronics. These disciplines together deliver advanced lightweight solutions for applications ranging from mechanical engineering to vehicles, airframe and space structures along the complete process chain. The book provides basics as well as inspiring ideas for engineers working in the field of adaptive, tolerant and robust composite structures.

The existence of load carrying structures has been taken for granted up to the point that their function is hardly being perceived. But with regard to the efficient use of resources load carrying structures receive a new importance since they represent masses and thus their movement requires energy. In many cases load carrying structures constitute a significant part of the total mass of a technical product. Many functions of a technical product, however, add their own masses. If the load carrying structure is called a primary structure with respective primary masses, all

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M. Wiedemann and M. Sinapius (eds.), *Adaptive, Tolerant and Efficient Composite Structures*, Research Topics in Aerospace, DOI: 10.1007/978-3-642-29190-6_1,

the parts providing the other functions are secondary masses. These parts are for example motors, sensors, brackets, housings, cables, media tubes, interior panels. Although these functions finally constitute the technical product, they are of minor importance with respect to the global load carrying function of the complete product. Especially in passenger transport a considerable number of functions is needed to ensure the required safety and to provide the requested comfort.

The traditional approach of product development is characterized by the separation of functions: in a safe, reliable and stable way and without unwanted deflections and vibrations passive primary structures carry the accelerated masses of all the other functions and the operational loads caused by the product mission. The division of technical parts into those responsible for the load carrying and the others that provide further functions is caused by the separate development processes of single technical components which are combined to more complex subcomponents and finally to the global product at a later stage in the development process. With regard to an efficient use of energy and the maximum saving of resources it must be the aim to reduce the moving technical product mass to the absolute minimum. If the structure is facing only small operational loads this might be achieved by the substitution of heavier material by lighter ones. In other areas as for example electronics, the functions can be minimized as well as the power generators or batteries making the products lighter. But in the field of transport, energy and production, i.e. whenever high loads have to be carried by large technical machineries or vehicles other measures have to be taken.

Lightweight design gained importance first in aviation whereas its theoretical foundations date back more than 100 years to Maxwell [1] and Mitchell [2]. It was the lightweight design of the airframes which made it possible to realize technically and economically relevant flight distances. But at the beginning of the 20th century lightweight design was also applied beside aviation in constructions where a shortage of material occurred. Pioneering examples of lightweight architecture were provided by Sukov [3] who was the builder of large pylons and transmission towers in Russia.

The traditional lightweight design develops its potential when loads have to be carried over a certain distance with a minimum of material application. If F is a single load or p a load per unit length or q a shear load per unit length and l the distance over which the load has to be carried, a characteristic structure parameter can be defined as follows:

$$K \equiv F/l^2 \; oder \; K \equiv p/l \; oder \; K \equiv q/l$$

The smaller this characteristic structure parameter K is, i.e. the slender the structure is, the more importance lightweight design gains. The use of the characteristic structure parameter allows the optimization of lightweight structures as shown by Wiedemann [4].

Lightweight design could demonstrate its potential first in the area of lightweight metal alloys through the increasing differentiation of structural parts and their related loading and failure mechanism. Topology optimizations have first

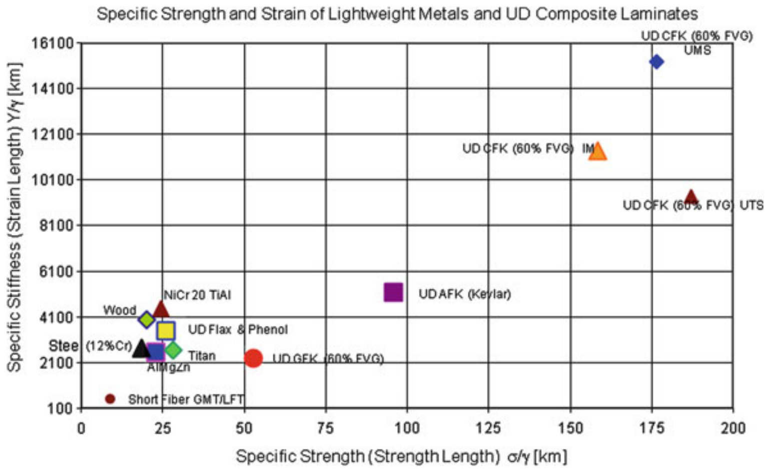

Fig. 1.1 Strength and stiffness of composite materials in comparison to metal alloys and bio materials

been applied successfully by analytical methods [5–8] in order to maximize the usage of the strength of the material.

Defined anisotropy with distinct strength or stiffness oriented in the same direction as the applied loads characterizes lightweight design solutions. Stringer stiffened plates, truss work structures with a maximum normal loading, sandwich structures with high bending stiffness in combination with low core material density are examples of the traditional lightweight design applied to many moving products today.

A further development in lightweight design took place by the introduction of composite materials which show a superior mechanical behaviour with regard to strength and stiffness compared to metal materials. Strength and stiffness are the most important mechanical properties that determine the required amount of structure material. If the yield strength is defined as σ, the Youngs modulus as Y and the material density as ρ, the specific strength R_σ and the specific stiffness R_Y can be taken for the comparison of different structure materials.

$$R_\sigma = \frac{\sigma}{\rho g}; \quad R_Y = \frac{Y}{\rho g}$$

The specific strength can be understood as the maximum length a material (e.g. a wire) can reach hanging down to the ground without a rupture caused by its own weight.

In Fig. 1.1 several composite materials, for example, are compared with lightweight metal materials. While the specific strength of the composites can be eight times higher than the one of lightweight metal alloys, the specific stiffness can reach up to four times higher values. In other words: if the structure has to sustain a certain load in strength a composite structure can be up to eight times lighter than the metal one. If the structure is sized by stiffness requirements, it can be up to four times lighter in composite materials. In practice in most of the cases this potential cannot be reached due to various other constraints, as for example the minimum skin thickness, local load introduction provisions and the possibilities for repair.

On the other hand in addition to the advantages in weight caused by the specific properties of composite materials the specific production process opens up new possibilities for the manufacturing of large complex structure components without extra joints and couplings which after all also cause additional weight.

This benefit in weight is being paid for by the price of the semi-finished products, i.e. fibers and resin, and by the consumption of time and energy and therefore costly production technologies.

Considering the increasing complexity of the material's characteristic parameters, i.e. the material anisotropy, the local complexity of load-material interaction as well as the need for the global analysis of complex structures, the analytical approaches have been replaced by numerical ones of which the finite element method (FEM) is the most popular one [9].

Today's research and the development of primary structures is aiming at achieving the maximum possible lightweight design in metal and—to an increasing extent—in polymer composite materials. Effort is being put into optimizing the structures in detail with respect to strength, stability, durability and damage tolerance by means of FEM.

The relatively high costs per part for lightweight composite structures are justified in aeronautics by the large snow ball effect in weight savings and have been accepted for a long time. But now the demand for composite material application in ground based transport systems (cars, trams, trains) is steadily increasing despite the higher costs and the smaller snow ball effects because of the growing demand to save energy in all technical fields.

The development in weight saving within primary structures, however, has been counter balanced in many cases by an increasing number of additional functions incorporated into the product with the consequence of a further weight increase. Sometimes this increase in weight is caused by more stringent safety requirements, sometimes by requested improvements in comfort. The total weight of the famous VW Golf, for example, has been increased due to safety and comfort requirements by 364 kg or 45% from 1974 to 2008 without increasing the seat capacity [10]. It shall be mentioned that this effect has partially been balanced by improving the efficiency of the motor and by reducing the fuel consumption by about 30%.

Even apart from this example it can be stated that for technical products the energy consumption has increased over the last decades despite the enormous improvements in lightweight design and the efficiency of the motors. This is mainly due to the increased number of functions incorporated into the technical products caused by the increasing safety and comfort requirements as already mentioned above.

A further step in the direction of a consequent lightweight design is the consideration of all these additional functions and their related material with the

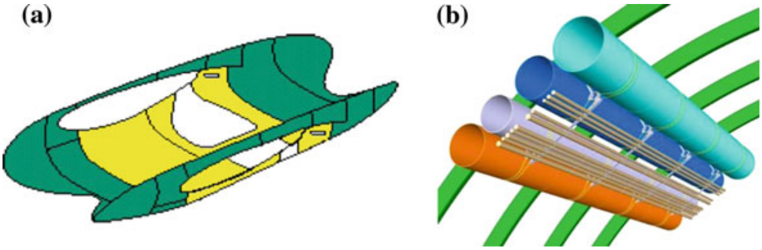

Fig. 1.2 **a** Secondary structure belly fairing A320. **b** Cabin piping

guiding idea that the more all the material which is required by further functions can be incorporated into the load carrying task of the primary structure, the more weight can be saved. Isolated product functions can be re-considered with respect to their capability of carrying a certain part of the load in order to further minimize the total weight of the product. In principle there are two approaches to be taken:

1. One can make distinct use of secondary masses to carry the product loads.
2. One can integrate as many of the additional functionalities as possible into the primary structure.

If secondary masses are used to carry the product loads, questions concerning the assembly of parts, regarding maintenance, inspectability, comfort, safety and often also certification have to be considered and answered. Secondary structures are frequently used as fairing and protective means in damage prone areas. The questions regarding their load carrying capability in case of damage have to be answered. Solutions have to be found to replace such damaged parts with reasonable effort. Secondary structures protect against surrounding conditions, for example passengers against low temperatures or pressures, against strong airflow or vibrations. The question is how many of these protective functions can be maintained, if the secondary structure is more integrated into the primary one. Load bearing joints must be designed without any tolerances and must be durable over the entire operational lifetime of the product but have to be repeatedly detachable at the same time. This requirement seems to be achievable. New assembly technologies are currently under development as for example detachable bonded joints.

Sometimes the use of secondary structures in the load carrying task of a primary structure requires the incorporation of a load-monitoring system [11] that indicates the potential loss of the load carrying capability. The design has to be made in such a way that this loss can be accepted temporarily which results in some limitations in the operational handling.

In the airplane fuselage for example a combination of the classic primary structure with the cabin lining and the design of a double shell structure could be a very efficient means to create a stiff structure against global and local bending. Large aerodynamic fairings, for example in the intersection between the fuselage and the wing, can be considered and designed so that they partially carry global loads, Fig. 1.2a. Similarly media routes possess the ability to release the primary

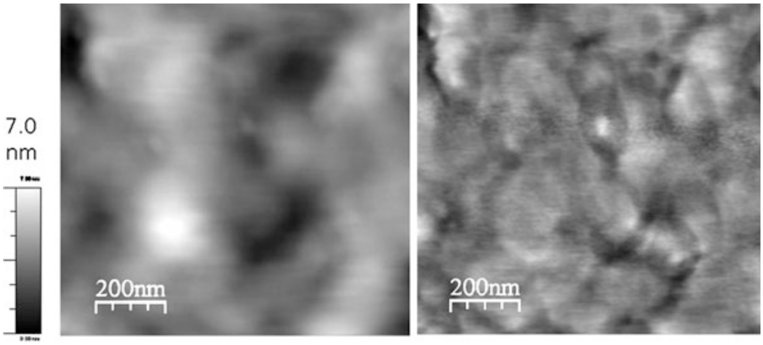

Fig. 1.3 Contrast of storage modulus of resin matrix reinforced by nanoparticles (*left* topography, *right* real part amplitude)

structure partially and therefore to contribute to the reduction of the total weight, Fig. 1.2b.

In car design the combination of primary and secondary structures is sometimes already realized, for example by the integration of the windshield front panel into the car structure.

The approach which the scientific articles of this book refer to is the second possible one, that is to integrate as many of the traditional non load carrying functions as possible into the primary structure itself and thus to use as much of the material as possible to carry the operational loads directly.

But the direct integration of further product functions into the primary structure causes a distortion in the concerned load paths. In many cases the integration of the function is possible through the combination of different materials that each have their specific properties and create a load carrying structure together. Already the composite structure is such a combination of materials. Composites integrate the high modulus and high strength fibers with the low strength and far less stiff resin system in order to finally stabilize the shape of the parts and keep the fibers in contour. Further materials can incorporate additional functions into the composite structure at different scales. On the smallest scale nano particles for example can improve the FST-properties (fire, smoke, toxicity) significantly as well as the compressive strength or fracture toughness of composites. An example of nano-technology research is given in Fig. 1.3 taken from Chap. 3 of this book. By scanning the surface of a nano particle reinforced specimen with an electron microscope the picture visualises the contrast of the complex storage modulus of integrated and functionalized nano particles made of Böhmite material. The stiffer areas are the brighter ones whereas in the surrounding area the grayer regions of the matrix material show a less stiff behaviour.

On the next scale level energy transforming functional materials like for example piezoelectric ceramics can bring sensory and actuator capabilities into the composite structure. But in many cases such combinations of functions cause local discontinuities in primary structural parameters as for example in density or in stiffness and strength.

A certain challenge in the design of composites with integrated functions is to ensure conformity between the material partners which are brought together in the primary structure and to minimize any detrimental effect with respect to the load carrying capability.

In the nineties of the last century the terms of active functional design, of function integration and the science of adaptronics were established [12–16]. In adaptronics the behaviour of load carrying structures is being influenced or adapted by means of energy transforming materials, often also called smart materials. Janocha [14] defines adaptronics as follows: Adaptronic structures are based upon a technology paradigm: the integration of actuators, sensors, and controls with a material or structural component.

Before the foundation of adaptronics many individual observations of special materials took place, sometimes more than four decades ago, like for example the piezoelectric behaviour of some ceramic materials [17] or the memory effect of some metal alloys [18]. In the eighties this collection of individual phenomena was more systematically analysed in the military laboratories of the US and the materials under consideration got the collective designation “smart materials” [19].

Piezoelectric ceramics for example can transform electric energy into mechanical energy and vice versa at a very high frequency, i.e. very fast. The effect is caused by the local polarization of the ceramic lattice structure, which is linked with a geometric asymmetry. The rhombohedral or tetragonal lattice structure can be oriented along an applied electric field with the effect of mechanical lengthening. Vice versa a mechanical deformation causes an electric voltage displacement that can be used to create a (small) flow of current.

Smart materials and the functions that can be realized with them are preferably integrated in composite structures which do not only possess superior mechanical properties in lightweight design but are manufactured in a specific production process. The combination of fibers and resin with the following curing process in a mould offers the advantage to integrate smart materials in the same shot. This has a great advantage over using metal lightweight structures, where the integration of either active or passive additional functions often requires an additional assembly step and extra mechanical fastening or bonding.

If piezoelectric ceramics can be brought into suitable conditions for integration, for example as piezoelectric patches, they can be perfectly integrated into a composite structure. These piezoelectric patches allow the integration of an active function into the composite primary structure. Figure 1.4 shows several possibilities how to integrate such patches and the effect of the various solutions to the mechanical parameters of strength, stiffness and yield strain.

The mechanical properties of the integration of the patch with the partial interruption of fibers (2nd to the left in the diagrams) but with a minimum of additional eccentricity are close to the properties of a later bonding of the patches to the undisturbed structure.

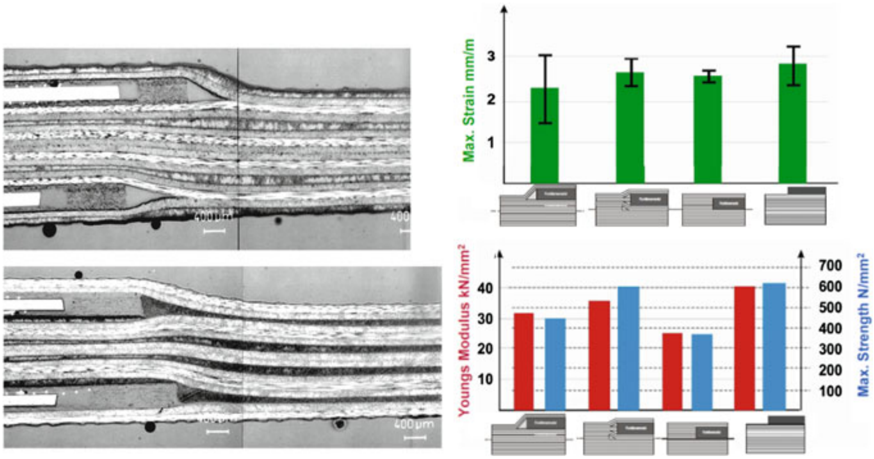

Fig. 1.4 Different types of the integration of piezoelectric foil into composite laminates and related mechanical properties

The potential of saving weight by the integration of additional functions into the primary structure works out considerably better in composite materials than into metal ones because of the integration process of the components fiber and resin.

As a consequence the disadvantage of the consumption of time and energy in the production process of composites can be turned into an advantage when it is used for the integration of a function at the same time. Functions or their carriers can now be integrated directly into the composite structure whereas they had to be applied to metal structures up to now within extra assembly steps and with brackets and fasteners which again add extra weight to the product.

The avoidance of extra production steps and assembly effort, the minimization of single parts and of the required time for assembly furthermore saves costs. In the ideal case this compensates for the extra costs caused by the pre-fabrics fiber and resin and the production of the composite structure.

The integration of functions into primary structures is often already realized, if passive functions are considered. Beside its mechanical properties each material owns further ones that are used implicitly or explicitly to ensure additional functions. Metals serve as a conductor for electrical grounding or for electromagnetic shielding whereas composites with a relatively low thermal conductivity of the resin part can serve for thermal isolation and the high chemical resistivity helps to deal with liquid media. A well-known additional function of primary structures is the capability to absorb crash energy, which can be designed in both metal and composite parts.

Often passive functions can be integrated into the composite structures much better than in metal ones. The integration of media routes is possible as well as the integration of lighting or thermal functions, for example for local heating. Information routes can be incorporated to replace extra wiring and the possibilities of improvement which can be achieved by nano particles dispersed in the resin component have already been mentioned.

Protective layers can be incorporated and material properties varying in thickness direction can be realized in composites. A proper tolerance management can be used to ensure a required surface quality which is better than the one of metal structures due to the high ability to integrate parts and due to the higher stiffness leading to less deformation when being loaded. These features help to ensure a natural laminar flow which is much easier to realize and lighter than the alternative active flow control.

Further possibilities are offered by the integration of active functions into the composite primary structure as it can be done with smart materials. Active functions usually are those that help the structure to adapt itself to changing environmental conditions. Examples of such structures which are designed to adapt to changing operational conditions are the high lift devices on the wings of an airplane. These devices are used to adapt the lift and drag coefficients of the wing to the changing air speed and angle of attack during start, cruise and landing phases of the aircraft. Today the high lift devices are a combination of more or less rigid structural parts that are actuated by discrete mechanisms, e.g. links, drive shafts and hydraulic or electric motors. If the high lift devices can change their shape with the help of a structure integrated actuation—this capability is often called morphing—the discrete mechanism can at least partially be saved and thus some of the weight associated with them [20–22]. Wear and tear of the mechanical actuation systems might be reduced and—what is much more important—gapless surfaces can be realized that minimize the effect of stall and therefore minimize the acoustic emission and the loss of aerodynamic performance.

The contradiction between the need to create a strong and stiff structure with respect to the external load to be carried and the required flexibility for actuation can be overcome. An example of such a gapless, strong but also flexible structure that can be actuated actively, e.g. a morphing structure, will be given in Chap. 31 in this book.

To reduce the vibration of rotating structures or those excited by their surroundings in a large frequency range and to decouple them from the rest of the primary structure passive damper-spring combinations or active hydraulic dampers are used today. Also their additional masses and weight can be reduced partially if it can be achieved to integrate active vibration control and means for the reduction of vibrations directly into the primary structure as it has been shown for example by Schütze et al. [23]. Another example of the capabilities of structure integrated active vibration control is given in Chap. 33 within this book.

Structure vibrations in the higher frequency range cause sound emissions, which depending on their intensity lead to comfort, safety or even health problems for passengers in an aircraft or another vehicle. The protection against sound emission today is in almost all cases done by passive means with a remarkable additional weight, e.g. by damping materials.

If the structure can be built in such a way, that incorporated active functions suppress the sound emissions effectively, a lot of additional weight can be saved,

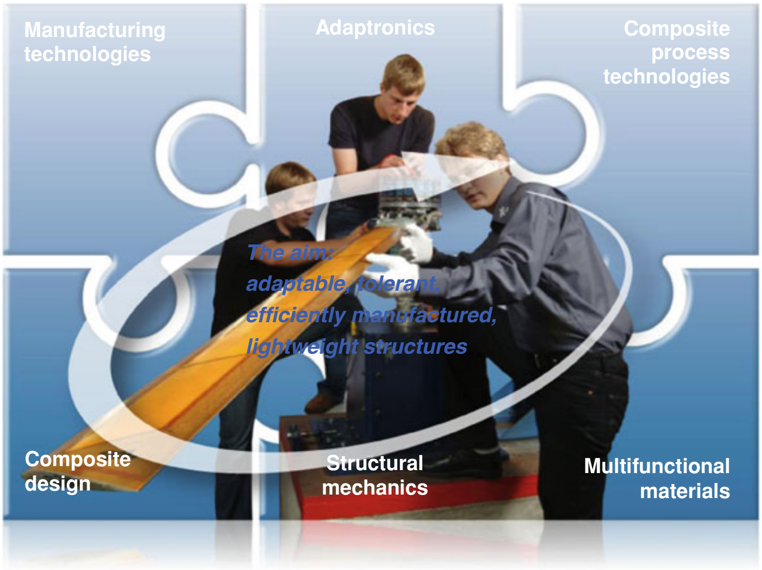

Fig. 1.5 Competencies required to realize adaptive, efficient and tolerant composite structures. *Example* adaptive composite rotor blade

as for example Weyer et al. [24] have demonstrated with a vehicle structure. Some more examples can be found in Chaps. 34 and 35.

In all of these examples the integration of functions aims to adapt the primary structure actively to the operational conditions the product is working in, i.e. to create adaptive composite structures.

An efficient integration of functions must deal with special challenges. The advantages of today's separation of functions and the combination of individual single components in one common product are the exchangeability and the possibility to replace single parts in case of malfunction. Individual components and functions have their individual failure probability and their individual reliability and operational lifetime. An efficient integration of functions is possible, if all the integrated functions possess the same reliability including the load carrying one to which they are exposed. To ensure a proper prediction of reliability and to develop the design of the primary structure with integrated functions a detailed knowledge of all the properties of the contributing constituents and their interactions is mandatory.

For the development of adaptive, efficient and tolerant composite structures a series of competencies have to be considered as being linked closely together, forming a multidisciplinary process chain. This process chain is elaborated on in detail within this book.

Figure 1.5 shows the competencies that are required to realize adaptive, efficient and tolerant composite structures and gives an example of the application of the smart materials mentioned above. A down scaled helicopter rotor blade is shown, which is actively twisted by applied piezoelectric patches in the upper and lower blade surface. More details about the active twist rotor are given in Chap. 32.

In the research field of **multifunctional materials** the basic properties of the composite constituents, e.g. fibers, resin systems and additives are investigated and their interactions are characterized in detail. In addition smart materials are explored and their potential is being analyzed with regard to the maximum efficient deployment in composite structures. The question raised repeatedly is how material properties found in the nano scale can be brought into a technically relevant macro scale and with what kind of treatment or technical process their capabilities can be used for the integration of functions. **Nano-Micro–Macro** is therefore the title of the initial chapter of the first part of this book which comprises chapters with exemplary results from research in the field of composite semi-finished components and smart materials.

The **structural mechanics** is the field of research that provides sizing methods for new composite structure design concepts and production technologies. In this domain also all simulation methods for the production processes are developed and the impact of manufacturing conditions on the final structure is evaluated, for example the so called spring-in effect, which is caused by the shrinkage of the resin during the curing process and the resulting induced stresses. The load carrying capability of the structure is assessed in structural mechanics. With the help of a detailed test pyramid and the associated validation-verification strategy the agreement of analytical and numerical prediction methods with the true structure behaviour is secured. Reliable design methods are mandatory, but the challenge is to ensure reliability—or robustness—when adding additional functions into the structure. There is the need to bring all of the elements of such a structure onto the same level of reliability. **Validation Approach for Robust Primary Structures** is therefore the title of the first chapter of the second part in which the following chapters will give a survey about sizing methods for composites as well as further examples for new methods developed for better simulation and testing. This part will also give some consideration to a closed process chain for simulation in the field of composite structures.

A central role within the whole development process of adaptive, efficient and tolerant composite structures is given to the research field of **composite design**. Here design solutions have to be developed that on the one hand satisfy the requirements of the load carrying primary structure but that on the other hand allow the aimed integration of functions. The answers must comply with the specific composite production constraints and ensure the required quality of the parts. The opportunities of composite structures in design and the boundary conditions to be observed for the successful integration of functions are described in the third part entitled **Compliant aggregation of functionalities**. The first chapter gives an overview of the questions to be answered and the challenges which the design is exposed when realizing adaptive and efficient composite structures.

Without a complete knowledge of the production technologies and the capability to control and steer the related processes, the efficient integration of functions into composite structures will not be successful. The domain of **composite**

technologies therefore is the one that deals with the comprehensive research in all aspects of the interaction of production process parameters with the quality of parts. At the same time a minimum of energy and time consumption in production is a must to ensure the competitiveness with metal structures. A maximum of process automation is aimed at in order to minimize the drawback of the high amount of manual work that is still common in the production of composite structures. A large variety of technologies exists and their specific process parameters are being explored with respect to their impact on the composite parts. Sensing measures are under development to monitor the processes on line. The concept behind is the development of self-controlled and furthermore self-correcting processes. This is why the first chapter of the fourth part is entitled **Self Controlled Composite Processing**. The chapters published in this part give examples of research results derived in the field of composite technologies in order to improve the control and the steering of the production process of efficient and tolerant composite structures.

Especially the integration of active functions into the composite structures is the research field of **adaptronics**. Here the concepts and the technologies are developed for the integration of active functions such as morphing, active vibration control (AVC), active acoustic structural control (ASAC) and structural health monitoring (SHM). The basics are investigated for the efficient realization of such functions with the help of smart materials. Steering means and control algorithms are being developed here as well as the adaptability to different operational conditions of the final product. The integration of active functions still requires an external power supply that makes the adaptive composite structures difficult to handle and requires a certain effort in joining the parts and the assembly of the primary structure. Some smart material cannot only transform electric into mechanical energy, but also harvest electric energy from mechanical deflections. With this capability structures can be built collecting the energy for their active functions directly from their mechanical loading. This is the idea behind the development of a new type of smart composite structures and therefore the title **Autonomous CFRP Structures** has been chosen for the first chapter of the fifth part. In the chapters collected in this part research results are being presented that give an inside view to various aspects of the integration of active functions into the composite structures.

This book is supposed to elucidate and to illustrate some results of research that demonstrate the conditions and the potentials of adaptive, efficient and tolerant composite structures. The large variety of possible applications and the numerous questions that need to be answered to their realization only allow a selection of research data, methods and results. This collection of chapters is meant to underline how the close cooperation and interaction between the technical disciplines of material development, structure mechanics, composite design, composite technologies and adaptronics can generate a new class of lighter primary structures which can be characterized as being adaptive and efficient by the maximum integration of active and passive functions.

These new composite structures with integrated additional functions are lighter than traditional primary structures with a comparable scope of functions. The relatively high costs of their semi-finished materials can be compensated by the high degree of integration of single parts and the reduced effort in assembly.

It is our conviction that the interdisciplinary research as outlined in this book is the chance to move on towards a resource efficient mobility using adaptive, efficient and tolerant composite structures.

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