DEVELOPMENT OF A COMPOSITE WHEEL WITH INTEGRATED HUB MOTOR

N. Schweizer[1*], A. Giessl[2], O. Schwarzhaupt[1], A. Büter[1]

[1]*Fraunhofer Institute of Structural Durability and System Reliability LBF, Bartningstr. 47, 64289 Darmstadt, Germany*
[2]*A. Kayser Automotive Systems GmbH, Hullerser Landstr. 43, 37574 Einbeck, Germany*
**nicole.schweizer@lbf.fraunhofer.de*

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Abstract
Lightweight Design is becoming increasingly important for automotive engineering. Fiber reinforced plastics have a wide range of advantages compared to metal based materials, in addition to the weight-saving aspect. In this study, a wheel of carbon fiber reinforced plastics with an integrated electric motor was developed. The main focus of the development was to achieve the optimum of lightweight potential considering structural durability. During the realization, the technical challenges of multifunctional design were considered in the whole product life cycle. Finally, an outlook regarding the validation of structural durability and system reliability of composite safety components is given, in general.

1 Introduction
1.1 Lightweight Design as a Key Technology for the Automotive Engineering
Over the last decade, lightweight design has become an important criterion for developments in automotive engineering. Fiber reinforced plastics (FRP) are getting more and more utilized in high volume of automotive production. Safety-relevant components in particular, such as chassis and wheels are potential fields of application for the various fiber reinforced plastics due to the possibilities they offer. The wide range of variants of these materials is already immense today and continues to grow. Material systems exist for almost any application, from those that are very easy to process to those that are particularly effective. It is therefore not just the mere weight saving potential that makes these materials so attractive. In contrast to metallic lightweight materials, fiber reinforced plastics also offer an additional degree of freedom, through which the material and component properties can be influenced. The type of matrices and fibers influences the properties as well as their volume ratio and the orientation of the fibers in the component. Weight-specific factors, such as durability and stiffness, and also the production costs can be ideally balanced depending on the profile of requirements.

Lightweight design means the ability to achieve a reduction in weight while retaining adequate stiffness, dynamic stability and structural durability. It demands of the developed components and structures that they reliably perform the required tasks over the course of their entire service life. The design of lightweight structures in general is based on the proof of adequate static strength since lightweight components are not only exposed to sudden and impact stresses but principally to cyclic loading during their service life. Therefore, a very light, structurally stable component or structure will be exposed during service. All critical loadings, to which the construction will be subjected to during service, are measured or calculated. Then, the corresponding strains, occurring within the structure are extrapolated over the service life with respect to the operational conditions, and finally are combined to load spectra. One may differentiate between three different types of loads, as shown in Figure 1: misuse loads, special events and operational loading. The collective loading of the working loads and of the exceptional and misapplied loads characterizes all of the loads, which will occur over the service life of the structure, and therefore relates directly to its rated service life. However, the loadings themselves and the strength of the materials used are subject to natural variations. The failure probability due to this variance can be reduced by rigorous material inspections, precise manufacturing and exact loading parameters. Still, a 100% reliability cannot be achieved [1].

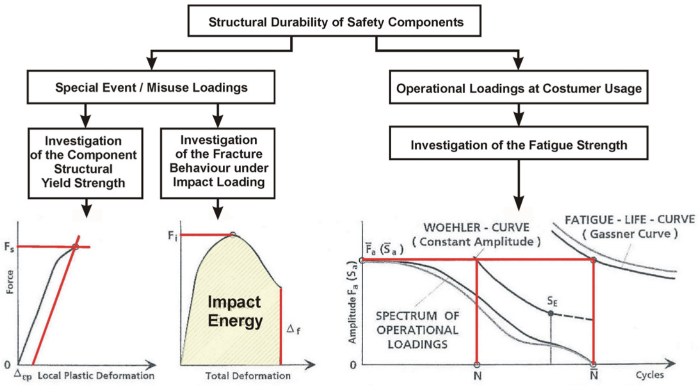

Figure 1. Affecting parameters regarding fatigue strength of components. [2]

Due to their high specific strength and stiffness the use of fiber reinforced plastics - especially carbon fiber reinforced plastics (CFRP) - offers the advantages of lightweight design, increased structural damping and improved damage tolerance. The higher specific tensile strength and the larger specific elasticity modulus enable a significant reduction of the vibrating mass of moving components. Through a lower vehicle mass, a reduced driving power is needed for achieving comparable driving performance. Hence, lower pollutant emissions are achieved. Furthermore, the heavy battery weight for hybrid and electric vehicles makes the lightweight design concept essential. The large weight saving is important in order to be able to achieve acceptable ranges in traffic. A reduction of the weight consequently results in a reduction of the weight-dependent driving resistance of the vehicle, making the lightweight design a key technology in automotive development. In addition to the excellent design freedom, other advantages of lightweight design are the driving comfort and the functional integration.

1.2 CFRP Lightweight Wheel with an Integrated Electric Motor

The CFRP lightweight wheel with a size of 6.5 x 15" (without CFRP housing to integrate the hub motor, without metal parts, such as sleeves for bearing and screws and without motor components) has a weight of approximately 3.5 kg. The motor housing is not directly connected to the rim, but to the inner area of the wheel axle. This prevents radial or lateral loads, especially shocks caused by rough road or curbstone crossing, from being transferred directly to the hub motor. Another advantage of the separation of the load paths is that the rim can be more flexible than if it were directly connected to the hub motor. For increasing the flexural rigidity at a constant weight, foam cores were inserted into the spokes. A smaller, commercially available hub motor was used as the electric motor. The hub motor, consisting of a ring with permanent magnets (external rotor) and a yoke ring with electromagnets (stator), has a motor capacity of 4 kW and a drive voltage of 2 x 24.5 V (Figure 2).

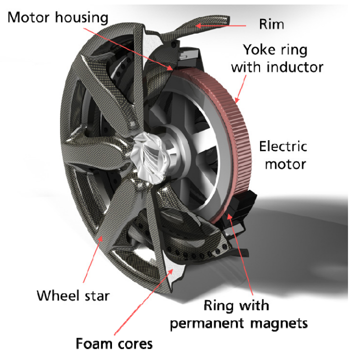

Figure 2. Section of the CFRP wheel with motor housing and integrated electric motor. [3]

2 Development Process

2.1 Technical Challenges for Multifunctional Design

The realization of multifunctional design has a great influence on a component and on every step of its product life cycle, see Figure 3. This includes the project planning from the concept phase and manufacturing, over operational use to the way of how to process the end-of-life component. Thus, the final decision for the systematic application of (active) multifunctional design can only be made, if the whole component-life-cycle is considered.

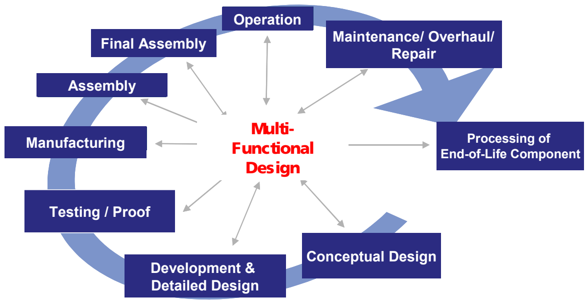

Figure 3. Product life cycle and its interaction with multifunctional design. [4]

The main focus of the presented project was to achieve a prototype composite wheel with integrated hub motor with the optimum of lightweight potential considering structural durability and system reliability. Therefore, in the case of the presented CFRP wheel the product life cycle was finished with the step “Assembly”, see Figure 3.

2.2 Design of the Wheel

As a first step in the development process, a design study based on today’s existing plastic wheels was done. Subsequently, solution variants were determined for the possible design methods to amount and attach the hub motor and for the optimal utilization of the offered material properties. From these solutions, the rough concept for the carbon fiber reinforced plastic (CFRP) wheel with integrated electric motor was developed. For the definition and the optimization of the laminate a surface model (with no thickness information yet) was designed. Additionally, the virtual model served to generate the negative and positive mold for the manufacturing process. To obtain an optimized design, which considers the material properties, soft radii and flowing transitions were used. Hence, stress peaks or stiffness changes in the part were avoided by a continuous fiber routing in line with the flow of forces.

The procedure for laminate definition, laminate optimization and finally for the derivation of the molds begins with the subdivision of the surface model into zones with different laminate

definitions (Figure 4). This step facilitates the subsequent calculation and optimization of the laminate by using the finite element method (FEM).
The laminate of the individual zones can very easily be predetermined and adjusted using a table for the specific design parameter of each zone. An FEM mesh of shell elements was produced on basis of the surface model with zone geometries. The layer structure of the respective zone is transferred to the individual elements during the crosslinking. The laminate of the individual element here is based on a coordinate system related to each zone. Simulations were carried out for occurring loads when driving on rough roads and cornering. Based on the assumption that the components are thin-walled, the calculation uses the shell theory, which only considers in-plane stress. The in-plane stresses and shear forces were evaluated for each layer in parallel and perpendicular to the fibers. The exploitation of the material could therefore be optimized by using several loops. The required wall thicknesses of the individual zones were determined with the laminate optimization (Figure 5).

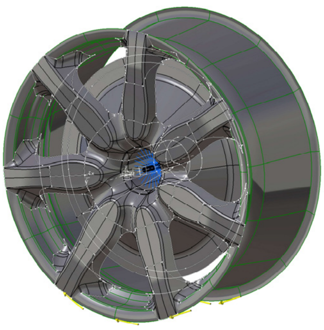

Figure 4. Subdivided surface model into zones for different laminate definitions.

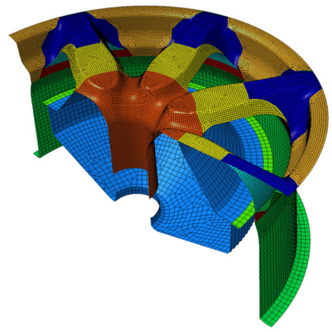

Figure 5. FE model of the wheel, thickness distribution for calculated load cases.

The calculation of this prototype CFRP wheel was made under simplified conditions because the utilized software - *LBF.WheelStrength*, developed specifically for wheel design - is based on the evaluation of isotropic materials and does not yet take into account the existing anisotropic material properties of the FRP wheel. There is still need for action here. Work is being done on this at present. In the next step a volume model was created from the surface model with the wall thickness information. The mold cores for the tool could then be derived from this volume model. The final design step was to create the shape of the cuts of the individual layers with a draping simulation.

2.3 Manufacturing

A carbon fiber prepreg system was used in order to generate the required volume content of fibers, to guarantee a uniform resin-fiber distribution and to keep the equipment costs lower than i.e. infusion processes. A standard system from the company Hexcel was selected: M49 as the epoxy resin base with a "high strength carbon fiber" as the technical fiber. A 2x2 twill weave with sufficient draping properties was selected as the weave of the fiber mat for the wheel rim and spokes. By using twill weave fabric with 50% of fibers in 0° direction and 90° direction respectively, the two main directions are covered at the same time. [4] Unidirectional (UD) fibers were selected for the rim cylinder due to their geometric simplicity. The wheel that displays a complex three-dimensional geometry is produced here in one piece. For economic reasons, a two-part mold made of closed cell rigid foam with a polyurethane base was used for the prototype manufacturing (Figure 6). The mold was sealed and wetted with release agents before the fiber mats were applied to prevent the epoxy resin matrix adhering to the mold surface.
A corresponding ply book listing the number of layers with their respective orientation and any other relevant manufacturing data was drawn up for the structure of the woven fabric

layers of the individual sections. The layer structure was a result of the simulation carried out in the design process. The layers were defined in accordance to the stresses and strains of the wheel rim, occurring in the 0°, 45°, 90° and -45° orientations. The resulting stacking sequence was then used for the manufacturing. Intermittently, vacuum was built up over the mold during the application of a defined number of layers in order to press the layers together and hereby achieving a higher quality of the component. The final vacuum built-up with the corresponding sequence of layers was cured for two hours in an autoclave at a temperature of 120°C and a pressure of 3.5 bar and tempered at a temperature of 50°C for 16 hours. The finished component was extracted, separated from both halves of the mold and then finished. The wheel, housing and wheel hub were bonded to each other after mounting the valve and fitting the tire. Finally, the electric motor components were attached and the whole system was put into operation.

Figure 6. Moulds made of closed cell rigid foam with polyurethane base for manufacturing the prototype wheel.

Figure 7. Completed composite wheel with integrated hub motor.

3 Multifunctional Design – Requirements Regarding Structural Durability and System Reliability

The development and the qualification of multifunctional safety systems for operational use have to be carried out with regard to the knowledge and methods of the structural durability and system reliability. The effects of the defects and failures of the entire system, as well as the failure type analysis are very significant for the development phase of multifunctional design since the defects and failures of any subsystem can also lead to a breakdown of the entire system. Design, which can take on various functions equally, can also fail in more than one way, see Figure 8. In order to meet all demands and to be able to specify the term "failure" in association with a function, the different functions must first of all be examined during the reliability analysis. However, for the qualitative reliability analysis performed on multifunctional design of safety components and systems, all various functions have to be considered.

The term "load bearing function" (see Figure 8) summarizes the mechanical requirements of the entire system (here: the wheel as safety component). The structure comprised of various materials must withstand all inner and outer loads and environmental conditions while remaining safe to operate. The requirements placed on the electric components of the active system are summarized under the term "activating function" (here: motor driving the wheel (motor characteristic)). This means that the use of the active structure, which depends upon the activation of the hub motor, must be ensured during the service time of the complete structure.

The term "interacting function" summarizes the requirements on the active system under special consideration of the interaction [5] between the mechanical and electrical components of the structure (here: operating point of the motor). These interactions include, for example, the fixed air gap of the hub motor when the electric wheel is moved or the influences of the mechanical structure on the requirements of the system's electric components.

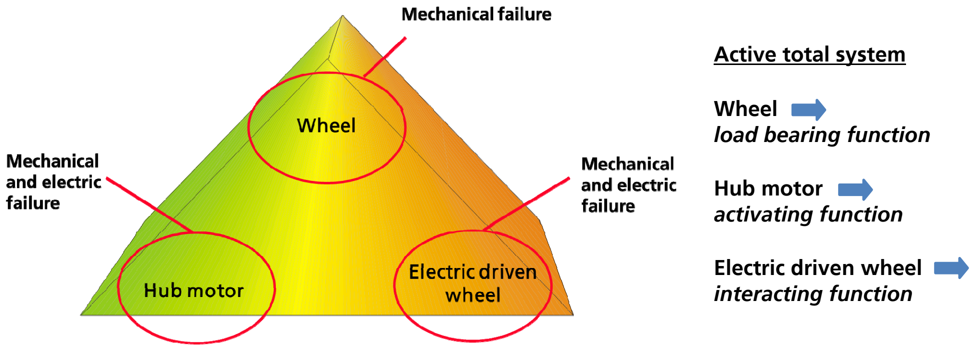

Figure 8. Multifunctional design - Functional failure.

For a quantitative system reliability analysis, the failure characteristics of individual system components or subsystems are used. In Figure 9, the special features of the failure characteristics known also as the "bathtub curve" are displayed. The key figures of the failure characteristics of each system component include the availability at a specific failure rate. The loads specific to the operation are derived from the availability or time in operation. With the help of the failure rate the actual system reliability analysis can be carried out.

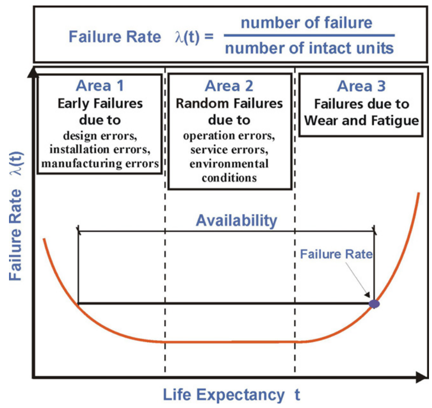

Figure 9. Failure rate diagram. [6]

Random failures are indicated by a constant, low failure rate, which can be seen as a noticeable plateau in area 2. This means, that so-called wear-out defects are excluded. Consequently, for a system that is intact, the probability for its "survival" of the next time interval is equally high at any given time. This assumption excludes failures that are caused by aging, which again are time-dependent. Aging can only be excluded if the wearing parts of a system are replaced early enough. Furthermore, this assumption requires constant operational and environmental conditions.

For validating the structural durability and system reliability of safety components made of fiber reinforced plastics, the material characteristics with their very different failure mechanisms compared to metals, manufacturing properties and component performance must be considered. Table 1 shows the significance of operational loads on structural durability. Using simplified testing methods, all these types of loading with all their respective damage relevant consequences must be taken into account.

Type of Loading	Damage Relevant Consequences
Intermittent Loading, Special Events, Peak Loads (e.g. curb stone driving, …)	Local Damage, Stiffness Decrease, Changed Load Path, Changed Fracture Behavior, Changed Functionality
Alternating Amplitudes and High Number of Cycles	Fatigue, Mechanical Aging, Changed Load Path, Friction Corrosion (slip joint, screwed/threated joint)
Variable Amplitude Loading	Fatigue behavior can be influenced by the load time history
Static Loading, High Centrifugal Forces, Humidity or Changes in Temperature	Mean Stresses, Changed Internal Stresses, Creeping/Relaxation, Varied Condition of Fit, Additional Loads
Multi-Axial Loading	Multi-Axial Stress Conditions with Varied Durability Behavior
Type of Loading (Bending, Tension, Pressure, Torsion)	Changed Fatigue Behavior and Life Expectancy
Environmental Conditions	Chemical Aging

Table 1. Significance of operational loads for structural durability.

As part of the wheel suspension, vehicle wheels in use are subjected to cyclic loads caused by driving on bad road conditions, on straight roads, in curves, during braking and acceleration. The resulting loading at a reference point of a wheel is additionally caused by internal stresses that result from the manufacture, mounting, temperature and tire pressure.
In general, the wheel stresses are multiaxial. Therefore, considering the external loading these multiaxial cyclic stresses are fundamentally composed of two parts, that is, a stress under static wheel loading that varies periodically with the revolution of the wheel as it moves along an ideal smooth road surface, and superimposed additional stresses effected by the alternating of radial and lateral forces on the wheel, generated by operational use. Figure 10 shows design load spectra (approx. 300.000 kilometers) and the damage equivalent test spectra (approx. 10.000 kilometers) for a car wheel. Further important influences are the effective wheel forces, force transfer from tire wheel to rim (principally determined by tire design) and the stiffness of the attached parts.

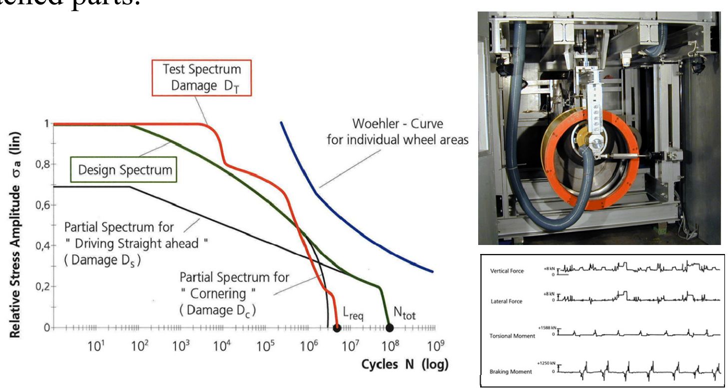

Figure 10. Damage equivalent synthetic test spectra compared to design spectra. [7]

The different ways in which forces can be transferred is the reason why tire design is key to wheel rim loading. A further important factor is the stiffness and tension of the attached parts, consisting of brakes, connections and bearings. The stiffness of the wheel also has a non-negligible effect on the wheel hub. Therefore the most important criterion for a reliable verification of structural durability is that wheel deformation must be simulated correctly, something that cannot be achieved with simplified methods and sweeping assumptions.

Hence, for simulating loads, which correspond to the wheel operational loads, the biaxial wheel testing facility (Zweiaxiale Radprüfeinrichtung, or ZWARP) is used in the Fraunhofer LBF to make a quick and economically justified inspection of structural durability, a facility also used by numerous wheel and vehicle manufactures in Europe and the USA. [7]
The evaluation of metallic wheels by means of this specific testing facility is already state of the art, while the evaluation of FRP wheels is still to be developed, due to the different material behavior.
Fiber reinforced wheels have great potential for lightweight design and they are highly damage tolerant, why they can ideally be used for car wheels. Considering safety, for fiber reinforced plastic wheels and conventional metal wheels the same level must be proven. Beside special event and misuse loads, for FRP wheels environmental effects, such as temperature, humidity and aging have to be taken into account. Environmental effects depend on the respective operational place.
Plastics have very different failure mechanisms compared to metallic materials. This results in a very individual failure behavior, depending on the laminate structure (number of layers, fiber orientation and fiber volume content) and the fiber/matrix material, which defines the anisotropic behaviour in stiffness and strength. Therefore, in general, the fatigue strength distribution of components in fiber reinforced plastics is determined by the manufacturing quality and design (fiber lay-up). Furthermore, the resulting damage mechanisms can lead to quite different failure mechanisms. However, the damage-tolerant behavior of FRP, which is already proven for tested composite wheels, can be applied to a variety of applications.

4 Summary and Outlook

In this project a prototype composite wheel with integrated hub motor was developed. The objective to achieve an optimized lightweight design was reached successfully. The special material properties were used to develop a multifunctional component with reduced weight, increased structural damping and improved damage tolerance. For composite wheels, the same safety level as metallic wheels has to be verified. In this connection, the same operating conditions must be considered. At present there are no definitive test guidelines for the approval of fiber reinforced wheels on German roads but work on this is currently in progress. Another challenge is the manufacturing in high number of pieces. To cost-efficiently produce a high number of carbon wheels, the usage of other procedures, e.g. pressing method, is needed. However, with a shorter fiber length the possible weight reduction is not fully exploited. Therefore, the aim is to find an acceptable compromise between weight reduction and manufacturing costs.

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