# DESIGN AND DIMENSIONING STANDARDS FOR MULTI-MATERIAL COMPONENTS FOR THE AUTOMOTIVE INDUSTRY CONSIDERING THEIR FAILURE PROBABILITY

S. Kleemann*[1], T. Vietor[1]

[1] *Institut für Konstruktionstechnik', Technische Universität Braunschweig, Lager Kamp 8, 38106 Braunschweig*
* *Corresponding Author: s.kleemann@tu-braunschweig.de*

**Keywords:** design for x, multi-material design, hybrid design, design catalogue,

**Abstract**
*Dependencies between the design strategy of fiber reinforced plastics, the manufacturing process, the material testing, the maintenance and the quality control are immense. The approach to manage these dependencies is a design catalog with design and dimensioning standards considering the design strategy for fiber reinforced plastics. This catalogue provides the dimensioning standards as well as information about the required material test, the quality control and maintenance considering the design strategy.*

## 1. Introduction

The amount of customer demands regarding vehicle comfort, safety or driving dynamics are rising continuously. In the past, these demands led to increasing vehicle weight. However, this trend was stopped by developing new vehicle concepts and by using lightweight materials (light metals, high-strength steel or fiber reinforced plastics). Thus the vehicle weight is kept at a constant or slightly decreasing level, especially in vehicles with conventional drivetrains. Nevertheless, this lightweight trend must be continued, taking into account the automotive standards in quality, ecology and economy in the future [1].
In this paper the combination of both, fiber reinforced plastics and metallic materials, is called multi-material or hybrid design. The combination of fiber reinforced plastics with steel or steel-aluminum structures is currently not available for mass production. This is due to the high cost of the fiber materials. In addition, the process time in producing fiber reinforced components is high. Thus the production of mixed structures with fiber reinforced components seems to be more suitable for mass production. The usage of multi-material design influences the vehicle concept. In addition, the production of lightweight materials requires a larger amount of energy and resources. Therefore the usage of carbon fiber reinforced plastics amortizes ecologically not until 85.000 km to 130.000 km traveled [2].
In this context, it is necessary to design innovative vehicle concepts and components in addition to new manufacturing technologies. Ecology, lightweight design and economy are conflicting development goals. Thus compromises are required and an evaluation of the ecological, economical, and lightweight properties is necessary. Moreover the use case needs to be specified to reach high lightweight design. To achieve the best possible lightweight design the exact

knowledge of load frequency and amplitude is required and the fatigue life has to be defined in order to design with thin walled sections and a minimal safety factor. With the purpose of dimensioning components it is essential to identify the set of requirements. Furthermore there are differences between the dimensioning and design of components in different industry sectors. In aircraft design for example, where fiber reinforced plastics and multi-material design is state of the art, some components are designed with a specified damage tolerance to achieve the best possible lightweight design. In order to use such statistical failure criteria, a number of constraints has to be fulfilled. Damage tolerance analysis requires a high calculation accuracy. More accurate calculations require specific statistically verified material parameters regarding their elastic behavior and strength. To ensure the components properties a high quality assurance during production is required and the maintenance interval and effort have to be specified. For any other industry sector is this approach not practical and a more robust approach, which still provides lightweight design, is required.
The approach to manage this dependencies is a design catalog with design and dimensioning standards considering the damage tolerance for fiber reinforced plastics. As future prospect the jointing technologies of multi-material components like bolting, bonding and riveting will be included. This design catalog is a knowledge store for the engineer and will provide the adequate design and dimensioning standards and a list of the required tests of materials according to the desired damage tolerance. Moreover it will illustrate how extensive the dimensioning and tests of materials become, if a lower damage tolerance is desired.

## 2. State of research

In this section lightweight design principles will be explained, in order to affiliate the issue discussed in this paper. Then the design methodological theory on design catalogues will be explained, which are used to manage the identified issue in the course of the development process.

### *2.1. Lightweight design principles*

Design standards for lightweight design in general are shown, amongst others, in Klein and Wiedemann [3, 4], special design standards for the automotive sector are summarized by Nehuis and Friedrich [5, 6]. Specific design principles for fiber reinforced plastics are shown, amongst others, in Schürmann and Flemming [7, 8]. A selection of design principles for lightweight design will be explained briefly in order to affiliate the issue discussed in this paper.

Refining of structures:
Refining of structures can decrease the weight of a structure. For example, for surface structures in particular a smaller cross-sectional area can be reinforced with ribs (see Fig. 1). Other

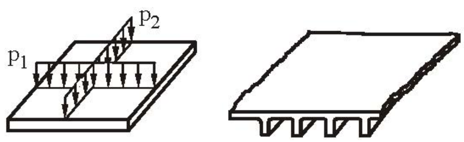



**Figure 1.** Stiffening plates by ribs[3]

examples for this design principle are tailored rolled blanks or sandwich structures. In comparison to a massive structure, refined structures achieve superior properties and reach high quality lightweight design. The refining of structures can lead to a functional separation and therefore be inconsistent with the previous design principle.

Reinforcement of structures in main stress direction:
The purposeful usage of ortho- or anisotropic materials can increase the stiffness of a component in a certain preferred direction. It is possible to use either a so-called constructive anisotropy or a material mechanical anisotropy. A constructive anisotropy could be a bead for increasing the buckling resistance, a material mechanical anisotropy could be the usage of the direction of rolling or unidirectional lamina of fiber reinforced plastics. Matched stiffeners can also be created by using different sheet thicknesses (e.g tailored blanks).

Total utilization of the structure:
High quality lightweight design can only be realized if excessive security concepts are questioned. The prerequisites for designing with minimal safety factors are:

- Detailed knowledge of the forces (magnitude, direction),
- Usage of high quality materials with guaranteed specifications,
- Using precise calculation methods (FEM),
- Optimized geometry (grooves, holes) and, where appropriate,
- Component testing to validate design details.

Lightweight components usually typical contain weaknesses (nicks, tears), which lead to stress concentrations. With dynamic load in the majority of cases these spots limit the safe operation of a structure with the consequence of critical failure. Onto the basis of theoretical or experimental durability predictions the predetermined service life has to ensured. In general, a long service life requirement demands a reduction of the stress, the choice of a suitable material and an optimized geometry and structure of the component.
As already mentioned, some of those design principles are inconsistent, because one can not apply every design principle on the same design task. One needs to decide from case to case which design principles are the most efficient.

### *2.2. Design Catalogues*

The knowledge of individual development engineers on, for example, physical effects or possible manufacturing processes for components is significantly conducive to the successful completion of a construction task. However, designers have often only limited and, to some extent, highly-specialized knowledge. To complete a design task, therefore, additional knowledge must be acquired. The acquisition is often very difficult and time consuming. A means of improve the subsequent results of the design process using the knowledge and experience of individual persons, it is appropriate to collect information and known (partial-) solutions and provide this targeted information. Design catalogues are simple-to-use knowledge management system that are intended to provide knowledge to the designer by providing solutions for recurring subtasks and by encouraging the further search of possible solutions. Nowadays, the originally paper-based design catalogues [9] are replaced by flexible catalogues that allow user specific access from all over the world, e.g. [10]. Besides information about recurring sub-tasks, design catalogues have also been used for providing design rules [5]. To facilitate the use, design catalogues have a uniform structure. They consist of a classification part, a main part and an access part and possibly additional notes. The schematic structure is shown in Fig. 2. The clas-

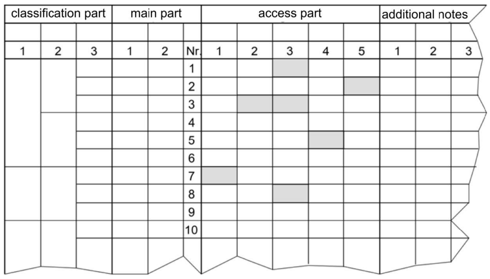



**Figure 2.** Schematic structure of a design catalogue divided into the four parts classification part, main part, access part and additional notes

sification part of the design catalogue guarantees the systematic arrangement of the contents and the shell of the catalogue. This part provides a framework for theoretically possible, but currently not yet known solutions (the so-called white fields in the main part that can serve as starting points for finding new solutions). The classification part comprises only the classification attributes. These classification attributes are preferably quantifiable or logical/structural attributes that divide the solutions of the main part into content that is clear, nearly complete and consistent. The main part is the part of a design catalogue that contains the contents of the catalogue. The contents can be objects, solutions or operations. These are displayed as clearly as possible in the form of words, phrases, symbols, formulas, sketches, drawings, etc. In the access part, the assignment of the access attributes will be organized according to the catalogue solutions. This part is adaptable to the needs of different users and can be extended. The listed access attributes in addition to the classification attributes help the designer to find a targeted solution in the catalogue.

## 3. Dimensioning regarding damage tolerance

The damage behavior of metallic materials used in structural components has been studied for several decades. Corresponding to this material behavior service and maintenance intervals are defined in order to detect either the occurrence or the progress of damage. Fiber reinforced plastics show a different behavior than the metallic materials. Because of the differences of the stiffness and strength between fiber material and matrix material, local stress and strain peaks occur in the more elastic matrix material. The homogeneity of fiber reinforced plastics is determined by the production and manufacturing process. Errors during manufacturing can cause, for example, pores and blowholes, which are, in fact, a first damage of the structure. Due to this the production and manufacturing quality is an important influence on the overall damage tolerance of fiber reinforced plastics.

In order to design damage tolerant composite materials all influencing parameters must be considered. The term ”damage tolerance” is not used consistently. In general the requirements regarding damage tolerance are component and use-case specific and can not be generalized. The differences in requirements regarding damage tolerance occur as well on vehicles and such different areas can be identified. Small cracks are allowed in compliance with these limits. In this context it is important to consider briefly the design strategy:

- Safe-life:
  Safe-life means that during the entire service life no significant damage is allowed. This inevitably results in a lower design limit.
- Fail-safe:
  Fail-safe allows damage when another structural elements can ensure the damaged components function.
- Damage-tolerance:
  The structure has to endure damage without functional loss. For this kind of structure it is expected, that it endures two inspection intervals without use limitation, even if it is damaged by a flaw just detectable with conventional inspection methods.

Considering the lightweight design rule ”Total utilization of the structure”, the design strategy ”Damage-tolerance” should always be prefered in order to achieve minimal weight and a maximum utilization. Unfortunately, the selection of a construction strategy affects the overall component design severely. Therefore, several dependencies on the design strategy need to be considered.

## 4. Dependencies between dimensioning, material testing and quality control

As already mentioned, some components in aircraft design are designed with a ”damage tolerance” design strategy considering statistical effects in material parameters in order to achieve airworthiness. In order to use such statistical failure criteria, a number of constraints has to be fulfilled. Damage tolerance analysis requires a high calculation accuracy. More accurate calculations require specific statistically verified material parameters regarding their elastic behavior and strength. To ensure the components’ properties a high quality control during production is

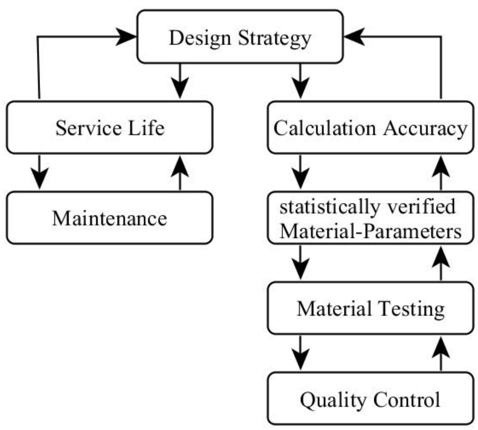



**Figure 3.** Dependencies between dimensioning

required and the maintenance interval and effort have to be specified. These mentioned dependencies are illustrated qualitatively in Fig. 3. It is indispensable to consider these dependencies already during the conceptual design of multi-material components. The decision which design strategy to use for the fiber reinforced plastic influences the production, maintenance and quality control strongly.

## 5. Design methodological approach to multi-material design

In this section the design methodological approach to multi-material design is explained. In order to provide the knowledge about the design of fiber reinforced plastics a catalogue of design rules was developed. Moreover a design catalogue for dimensioning standards was developed for managing the explained dependencies in designing fiber reinforced plastics. These dimensioning standards consider the design strategy as well as the damage tolerance.

### *5.1. Design rules*

Design rules were developed to provide the knowledge about the design of fiber reinforced plastics for multi-material design. These rules for multi-material design base on the design rules developed by the Institut für Konstruktionstechnik during the HIPAT project [5]. All rules are available in digital form and are structured by subject matter. The design rules of HIPAT already include the subjects lightweight design and functional integration and have been extended by the subject of fiber reinforced plastics.

**Design rules for multi-material design**

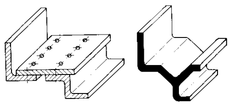
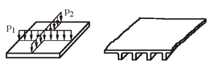
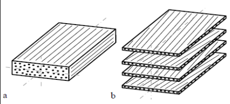
| No. | Subject | Rule | Figure | Reference | Release |
|---|---|---|---|---|---|
| **2** | Functional Integration | Reduction of component partition |  one-piece instead of joining | IK | Klein, "Leichtbaukonstruktion" |
| **15** | Lightweight Design | Refining of structures |  | [6] | Klein, "Leichtbaukonstruktion" |
| **42** | FRP | Dividing of thick unidirectional layers into several thin balanced ply layer |  | [10] | Schürmann, "Konstruieren mit Faser-Kunststoff-Verbunden" |

**Figure 4.** Design rules for multi-material design

Each design rule is formulated with a clear statement, for example ”Preference of symmetric Laminates”, and added to a corresponding image as well as references. The accurately and simply formulated instructions allow quick access to the knowledge. A detail of the design rules is shown in Fig. 4.
The figures of the design rules also allow inexperienced designers to understand complex situations quickly. This helps to avoid unnecessary iterations reducing development costs and time. The rules on lightweight design and functional integration were adapted to early stages of the design process, when there is still little knowledge on the part design. Here, the presented approach differs significantly from other lightweight construction approaches, which often focus

on optimizing already predefined geometries with respect to their dimensions [3]. Lightweight potentials that result from different solution principles get lost in such an optimization. The here presented approach helps finding the best solution principle first.

### *5.2. Design catalogue for dimensioning standards*

The approach to manage these dependencies is a design catalog with design and dimensioning standards considering the design strategy as well as the damage tolerance for fiber reinforced plastics (see Fig. 5). Therefore a special design catalogue summarizes information about the calculation, the required material-parameters and the material-testing. This design catalog is a

**Dimensioning standards for multi-material design**

| | | | Safe-Life | | | Fail-Safe | | | Damage Tolerance | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Component | Criteria | Nr. | Formula | Parameters | Material Testing | Formula | Parameters | Material Testing | Formula | Parameters | Material Testing |
| FRP | Fiber Failure | 1 | | | | | | | | | |
| | Inter Fiber Failure | 2 | | | | | | | | | |
| | Delamination | 3 | | | | | | | | | |

**Figure 5.** Design catalogue with dimensioning standards

knowledge store for the designing engineer and provides the adequate design and dimensioning standards for different. Moreover it will illustrate how extensive the dimensioning and tests of materials become, if a lighter design is required and therefore the design strategy has to be changed.

## 6. Conclusion and outlook

Due to the strict EU legislation lightweight design is essential for future vehicles. Conventional approaches to lightweight design such as material substitution or lightweight construction types are reaching their limits, therefore, lightweight materials like fiber reinforced plastics are considered for mass production. Due to the immense costs of fiber reinforced plastics it is desired to achieve lightweight design with a purposeful and minimal usage of such materials and to combine it with metallic materials to create hybrid design.

The specific properties of fiber reinforced plastics cause dependencies between design, dimensioning, production, material testing, maintenance and quality control. One approach to manage these dependencies is a design catalogue with different dimensioning standard considering the design strategy and the damage tolerance of fibre reinforced plastics and another design catalogue with design rules, which allows quick access to the specific knowledge required to design with multi-material design. As future prospect both design catalogues will be extended by the information about the joining technologies of multi-material components like bolting, bonding and riveting.

## Acknowledgements

The results explained in this paper have been developed in course of the Project MultiMaK, Development of design and dimensioning tools for use case specific ecologically optimised multi-material vehicle components. Therefore authors gratefully thank the Federal Ministry of Education and Research (BMBF) for financing MultiMaK in course of the Forschungscampus Open Hybrid LabFactory. The project is managed by the project executing organization Jülich (PTJ).

## References

[1] Frank Nehuis, Jafet Sánchez Ruelas, and Stechert, Carsten, Vietor, Thomas. Robust Conception of Vehicles Considering Region-Specific Requirements. *Proceedings of the 19th International Conference on Engineering Design (ICED'13 Seoul)*, 2013.

[2] J.R. Duflou, J. De Moor, I. Verpoest, and W. Dewulf. Environmental impact analysis of composite use in car manufacturing. *5CIRP6 Annals - Manufacturing Technology*, 58(1):9–12, 2009.

[3] Bernd Klein. *Leichtbau-Konstruktion: Berechnungsgrundlagen und Gestaltung*. Vieweg + Teubner Verlag, 2014.

[4] Johannes Wiedemann. *Leichtbau*. Springer-Verlag Berlin Heidelberg, [New York], 2007.

[5] Frank Nehuis, Jan Robert Ziebart, Carsten Stechert, and Thomas Vietor. Use of design methodology to accelerate the development and market introduction of new lightweight steel profiles. *DS 68-10: Proceedings of the 18th International Conference on Engineering Design (ICED 11), Impacting Society through Engineering Design, Vol. 10: Design Methods and Tools pt. 2, Lyngby/Copenhagen, Denmark, 15.-19.08.2011*, 2011.

[6] Horst E. Friedrich, editor. *Leichtbau in der Fahrzeugtechnik*. Imprint: Springer Vieweg, Wiesbaden, 2013.

[7] Helmut Schürmann. *Konstruieren mit Faser-Kunststoff-Verbunden*. Springer, Berlin and Heidelberg and New York and NY, 2., bearb. und erw. Aufl edition, 2007.

[8] Manfred Flemming. *Faserverbundbauweisen Eigenschaften: Mechanische, konstruktive, thermische, elektrische, ökologische, wirtschaftliche Aspekte*. Springer, [S.l.], 2013.

[9] Karlheinz Roth. *Kataloge*, volume 2. Springer, Berlin [u.a.], 3. Aufl., mit wesentl. Erg edition, 2001.

[10] Löffler S. Franke H.-J. Increasing the efficiency of design catalogues by using modern data processing technologies. *DS 32: Proceedings of DESIGN 2004, the 8th International Design Conference, Dubrovnik, Croatia*, 2004.