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A QUALITATIVE STUDY TO IDENTIFY THE NEED AND REQUIREMENTS ON FURTHER DEVELOPMENT OF DESIGN GUIDELINES FOR FIBRE-REINFORCED COMPOSITES

Butenko, Viktoriia; Wilwer, Jürgen; Spadinger, Markus; Albers, Albert
Karlsruhe Institute of Technology (KIT), Germany

Abstract

This paper describes the methodological approach and results of a qualitative study used to identify the needs and requirements on the further development of design guidelines for fibre-reinforced polymers. To this purpose the method of the semi-structured interview was chosen. A total of 16 industry representatives from different countries, industries and departments took part in the interview study. The results have shown that the necessary information in design guidelines depends very much on the requirements placed on the product, the field of activity of participants and their experience level as well as the industry sector. Apart from this the requirements for desirable content to be found in design guidelines was much the same in North America as in Germany. Furthermore, the results have shown that the current solutions available these days to support the design engineers during the product development with fibre composite materials are no longer contemporary. There is a need to rethink the classical concept of design guidelines and to adapt these to the requirements of the industry.

Keywords: Design process, Design guidelines, Requirements, Fiber-reinforced composites, Design engineering

Contact:
Viktoriia Butenko
Karlsruhe Institute of Technology (KIT)
Institute of Product Engineering
Germany
viktoriia.butenko@kit.edu

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1 INTRODUCTION

Fibre-reinforced plastics are widely applied in automotive and aerospace industry due to their good mechanical properties, low density and high lightweight construction potential. With these properties, they offer several advantages to the conventional construction materials such as steel, aluminium etc. However, the resulting mechanical properties of a reinforced product depend on the matrix material, the type of fibre (Mayer, 2009, p. 301ff), their volume content (Mayer, 2009, p. 306; Askeland, et.al, 2010, p. 666), their orientation and distribution (Mayer, 2009, p. 306; Mathews, Rawlings, 1994, p. 168-200) as well as processing methods (Campbell, 2010, p. 489-515). Due to the anisotropic structure of reinforced plastics, which implies various properties in different directions, freedom of design is significant bigger then by conventional materials. This allows individual design solutions and maximal utilization of materials potential, but at the same time, it makes the design process more complex (Campbell, 2010, p. 489).

The creating of a product design requires technical knowledge, creativity and close co-ordination with experts from different disciplines like production, material technologies etc. In addition, quick access to relevant information is necessary, because there is too many and too specific information about matrix materials, possibilities for fibre arrangement, suitable manufacturing processes, their influence on product quality, different design principles etc. that it takes too much time to find what is needed.

During the last 40 years, many lists of design guidelines and lessons learned have been compiled to exchange knowledge and experience in this subject (Campbell, 2010, p. 503). The problem is that the usual guidelines and lessons learned provide either general data or focus on a very specific topic. In some sources the information could be found in the form of figures with comments like “wrong design” and “right design” with little details to the context (Eyerer et. al, 2008, p. 472; Michaeli and Wegener, 1990, p. 122-125). Another problem is the search for suitable information. It takes a lot of time to collect the relevant data from different sources in order to start working on design solutions. Since each product development process is individual (Albers, 2010) and the requirements are changing often, it is important to support design engineers during their creative activities by providing simple access to the necessary information and thereby save time in research and minimize the risk of product failures.

The objective of the current paper is to identify the need and requirements on the further development of design guidelines to support design engineers in different product development processes by interactive software-aided providing relevant engineering-specific information. The addressed two research questions in this paper are:

1. Witch challenges in the development of products made of fibre-reinforced plastics exist from the perspective of different disciplines and industries?
2. What kind of engineering-specific information in design guidelines should be included for efficient supporting of design process by product development with fibre-reinforced polymers?

   To this purpose, qualitative semi-structured interviews with industrial representatives from different fields and countries were conducted and needs as well as requirements on design guidelines for fibre- reinforced polymers were collected. The results of the interviews serve as input for a quantitative research to review the achieved results.

2 STATE OF THE ART

The mechanical properties as well as the specific processing possibilities of fibre-reinforced plastics have a considerable influence on the product development and lead to different constructive solutions compared to conventional materials (Pahl, G. et al., 2013, p.648). However, analogues to working with metallic/traditional materials rules and restrictions exist for components designed with fibre-reinforced plastic. This chapter provides essential foundations for two most commonly used methods like design guidelines and lessons learned. The main focus is to present their theoretical use and role in the design process.

Design process

In the foreground of a successful component design, a reliable function filling under various boundary conditions set by loads, environment, ergonomics, etc. is without doubt guaranteed to ensure the useful value of the component (Campbell, 2010, p. 510).

To make it clear the designing process of fibre-reinforced polymers consists of four major steps: the selection of the material (matrix and fibre), choosing a manufacturing process, deciding on the material and structural design. These steps are iterative, especially in the early stages of the design process. The selected material and the complexity of the component design affect the choice of manufacturing process and vice versa. (Campbell, 2010, p. 489-515).
Nowadays, the design process looks different than in the past. Teams with different backgrounds like engineering, tooling, manufacturing and quality assurance are involved in this process. The computerized technologies have been greatly improved and allow very good support (Campbell, 2010, p. 489).

Design guidelines

Design guidelines are defined as collections of information, aiming to support engineers at finding solutions to their constructive problems. They contain specifications, restrictions and suggestions for realizable geometries and can be available in written form and/or as visual representations. They include gained experience from previous design solutions or research approaches (VDI-2223, 2004, p. 66).

Lessons learned

Lessons learned are experiences from previous projects that describe what kind of problems occurred and how those were handled and may be avoided in the future. Lessons learned are widely used in the industry. In most cases, such experiences are summarized in a predefined form and made available within a company.

2.1 Role of design guidelines and lessons learned in product development

Achieving successful results in engineering requires a diverse quantity of knowledge. In addition to the fundamental knowledge in engineering, like mechanics and mathematics, knowledge of the following topics must be available (Albers et. al. 2012, p. 8):

- knowledge about electrical engineering and mechatronics
- knowledge about material science and production processes
- knowledge about requirements, norms and patents
- knowledge about construction documentation
- holistic thinking
- and more.

However, engineering is not all knowledge, but also skills. These can be acquired by working, exercises and training. Still, the rate of acquiring skills depends on knowledge. Given a lack of knowledge, the process of learning is slowed down. Therefore, design guidelines and lessons learned containing objective knowledge, do support engineers at their learning process.
This is, what makes them valuable for anyone, who has not yet obtained the quantity of knowledge listed above. They contain information of less apparent sources, ensure rational workflows, give recommendations and suggestions to solutions, which have not been obvious. (Roth, 2001, p.1) They not only reduce the effort on the design process, but also reduce constructional risks by referring to potential weak points (VDI-2223, 2004, p. 66ff). The use of guidelines often results in more efficient product development process. (Hubka, Eder, 1992, p. 61).

2.2 Analysis of existing lessons learned and design guidelines for fibre-reinforced polymers in the literature

In Composite Materials Handbook (2012), lessons learned are organized in six different categories for convenience. These categories are: 1) analysis and design; 2) processing; 3) fabrication and assembly; 4) quality control; 5) testing and 6) certification. Each topic contents various numbers of lessons learned. However, the design part has the most of them. An example for the structure and content is in Figure 1 below.

Lessons	Reason or consequence
Design and analysis: Carbon fibers must be isolated from aluminum or steel by using an adhesive layer and/or a thin glass fiber ply at faying surfaces	Galvanic interaction between carbon and aluminum or steel will cause corrosion of the metal.
Design and analysis: Use fiber dominated laminate wherever possible. The [0°/±45°/90°] orientation is recommended for major load carrying structures. A minimum of 10% of the fibers should be oriented in each direction.	Fibers carry the load; the resin is relatively weak. This will minimize matrix and stiffness degradation.
Fabrication and assembly: Hand drills can cause significant damage.	Feed and speed are less precise. Hole perpendicularity may be imperfect.
Quality control: Continuing process control and process monitoring are required during production	Assures that neither the process nor the material is changing
Testing: A well planned test program must include an accelerated approach for taking into account the effects of moisture, temperature, impact damage, etc.	Including moisture and elevated temperature on a real-time basis for full-scale testing is impractical for most components.

Figure 1. Lessons learned (Composite Material Handbook, 2012)

Design guidelines for fibre-reinforced polymers were analysed from more than 20 different information sources such as technical books and publications. The results have shown that information are usually provided as transitions from unfavourable to favourable constructions based on "good versus bad"-examples in the form of illustrations as shown in Figure 2.

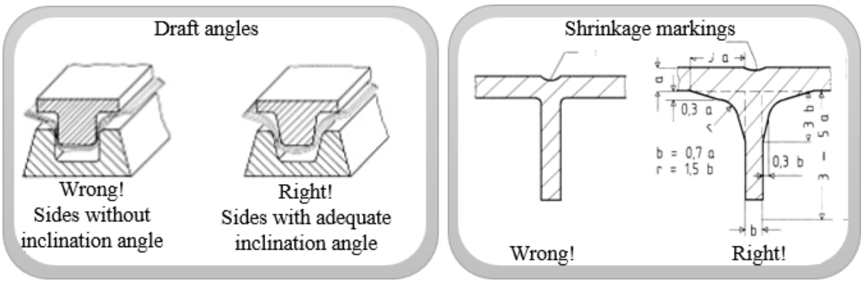

Figure 2. Guidelines for designing ribs on fibre reinforced sheets in form of illustrations (Michaeli and Wegener, 1990)

Another form of design recommendations that can be found in the literature shown in the Table 1 below.

Table 1. Design recommendations in text form (Eyerer et. al, 2008, p. 469-480)

Topic	Description / Recommendation
Ribs design in keeping up with demands on injection molding	Should be taken into account at the ribs design: Ribs location in component part - Number of ribs - Clamping conditions of ribs - Rib thickness between 0,5 up to 0,7 wall thickness - Cooling time by injection molding - Molding direction Design of draft angles is important for ribs to avoid the destruction of form because of material shrinkage in the tool area.

Both examples provide information to the same subject in a different way. The first figure on the right side shows exact information to geometric dimensions of rib. The second one gives an overview what should be considered at designing ribs to keep up with demands on injection moulding. Here, the difference between given details is very apparent. The first example focuses deeply on one specific topic, while the second one provides superficial information. The information in second example would probably be sufficient for project planning but too little for a design engineer. The last one will need

exactly information what should be considered by molding direction or cooling time and what effects could occur and how these could be avoided?
Information in design guidelines and lessons learned are spread over several books and publications so that is very laborious and time consuming to find relevant information.
As the examples above show, only a small part information necessary for the design process is available for a general circle of users. Another part of information only exists as practical knowledge and is either unprocessed or inaccessible to a wider circle of users / engineers.
Compared to classic isotropic materials, working with fibre-reinforced parts allows the designer more opportunities due to their anisotropic behaviour. Those possibilities, such as different combinations between matrix and fibre material, fibre length, fibre orientation, fibre volume fraction and the selection of a suitable production process must be considered during the design process (Campbell, 2010 p. 489-512), because each design option has direct impact on chemical and mechanical behaviour. It is essential to be aware that the finished material only emerges during the parts production. Therefore, this materials group shows an exceptional coupling between geometry, production process and material properties (AVK, 2014, p. 295).
The information found in the literature focuses mostly on the one respective, but the product must meet numerous aspects at the same time. The lack of information given makes it difficult to find the optimum design solution in due consideration of requirements on products.

3 RESEARCH QUESTIONS

The analysis of the state of the art leads to two following research questions:

1. What are the challenges in the development of products made of fibre-reinforced plastics from the perspective of different disciplines and industries?
2. What kind of engineering-specific information in design guidelines should be included for efficient supporting of design process by product development with fibre-reinforced polymers?

The investigation of these questions is carried out within the framework of the project "Integrated engineering of continuous-discontinuous long-fibre-reinforced polymer structures" funded by the German Research Foundation (DGF). The project that started in 2015 is scheduled to end in 2024 and it´s goal is to develop concepts for the production, modelling and dimensioning of hybrid continuous-discontinuous fibre composite structures. The most important concern is the combination of continuous (CoFRP) and discontinuous (DiCoFRP) fibre-reinforced polymers in single components with respect to the handling and positioning of the reinforcing substructures. 14 doctoral students from different disciplines like material characterization, simulation, technology and design are working on this project. The generated knowledge will be subsequently transferred into the design guidelines and will be made available to the industry.
In order to ensure benefits and applications of new design guidelines in the industry, it is important to raise the requirements on them from the future potential users, who are in this case, industrial representatives. The next chapter presents the methodology and approach for obtaining those requirements.

4 METHODOLOGY

The empirical methods of social research were used to ascertain the requirements.
To determine if there would be any need on further development of design guidelines and to get to know the actual situation the method of the semi-structured interview was chosen. This method offers the chance to design surveys freely and to bring new ideas or to vary in the depth during the interviews as a result what the interviewee says. This kind of the interview allows not only to delve deeply into a topic but also to understand thoroughly the answers provided (Harrell and Bradley, 2009, p. 27).
The essential steps of the research process are presented in Figure 3 below.

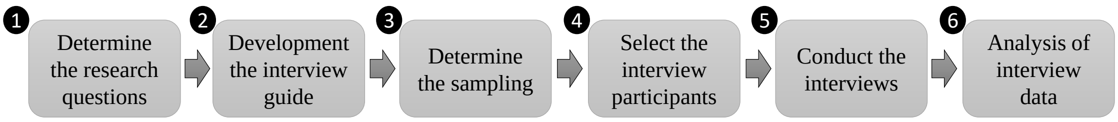

Figure 3. Procedure of the interview study

First, a research problem and related questions were formulated. After that an interview guide was developed. The interview guide is a written list of questions and topics that need to be covered. Building and following the interview guide is important to get reliable comparable qualitative data (Bernard, 1988, p. 212). A total of 7 topics were investigated to which about 30 questions were formulated. Figure 4 below presents the concept of the interview guide. The topics are shown on the left and exemplary questions are on the right side.

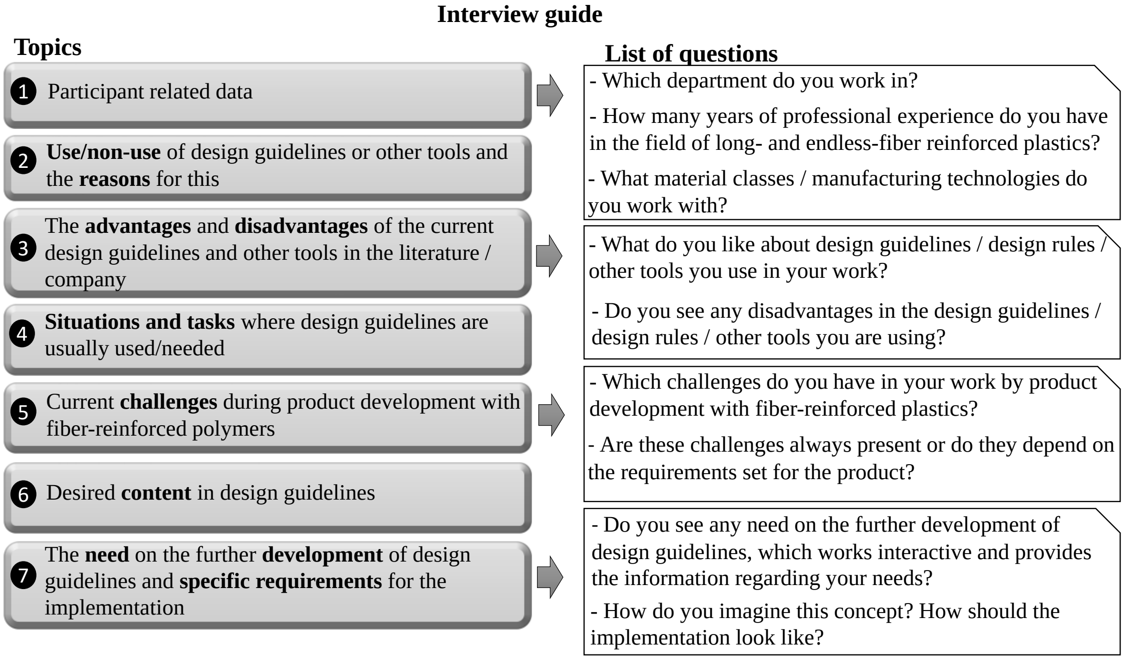

Figure 4. Interview guide

An important part of any research effort is to determine the sampling (Harrell and Bradley, 2009, p. 31). For this study, the judgement sampling was selected. This is the form of non-probability sampling that allows to specify the specific criteria for the selection of participants to obtain a representative part of the target group (Böltken, 1976, p. 24). In order to obtain diverse information, participants from different countries, industries, field of activities, and level of experience with fibre-reinforced plastics were selected. Depending on the department and the area of responsibility of the interview participants, different aspects could be discussed in depth.

The semi-structured interviews were conducted by phone and in person. The interviews itself took between 45-60 minutes each and were recording with the permission of the interviewees.

For the analysis of the interview data, the interview protocols were transcribed and worked through by using a category system. The category system is a so-called search grid that allows to filter all data given to find out the relevant information to answer the research questions (Gläser and Lauder, 2009, p. 199-204). The combination of the deductive and inductive methods for category building were applied. According approach by deductive methods the categories were created and defined before the analysis of the data material (Mayring, 2010, p. 65). In addition to the categories created, a rest category was formed for those informations which could not be assigned to one of the deductively generated categories. By reducing the data from the rest category to the central meaningful statements, new categories were formed inductively.

5 RESULTS OF THE INTERVIEW STUDY

In this chapter, the most important results of the interview study are presented.

Background of participants

16 industry representatives took part in the interview study. To gather the requirements from different perspectives, the participants were selected from different departments such as research and development, design, production, simulation etc. 6 of the participants were from North America and the remaining part from Germany.

Most of the participants came from the automotive industry. The others were from the plant engineering, wind power plant, aerospace and consulting industries. Figure 5 shows the industry as well as the department of the participants.

		Thereof active in the …					
Industry	**Number**	Design	Simulation	Production	Project management	Research and Development	Holistic product development
Automotive industry	8	4	1	1	1	1	-
Plant engineering	1	-	-	1	-	-	-
Wind power plant	1	1	-	-	-	-	-
Aerospace industry	5	1	1	1	1	1	-
Engineering consulting	1	-	-	-	-	-	1
Total	16	6	2	3	2	2	1

Figure 5. Participants

Use/non-use of design guidelines or other tools and the reasons for this

Half of the participants indicated that they use design guidelines during their work. These were in all cases company-internal and available in the form of PDF documents.

"At our company the design guidelines look like this: in the beginning, there is a text that tells you what it is all about. Then there are some pictures of how such a component could look like. The part for the construction is actually only "naked numbers," that is, mathematical relationships, for example, the choice of a suitable rib thickness as a function of the plate thickness".

The other half of the participants abandoned the use of design guidelines. Reasons for this were that the required information 1) is not available, 2) … is not based on the state of the art, 3) … is good for basics but rather not for the application, 4) or any design guidelines are needed due to the activities of the participants (in the case of research field).

Here are some statements to design guidelines and other tools in the literature:

"…Nobody wants to read a multi-page document"
"…searching for a load case is often without success"
"…design guidelines are not application oriented"

However, in-house guidelines or lessons learned also had certain disadvantages from the perspective of the participants: 1) not detailed enough, 2) confusing, 3) the search for suitable information takes too long.

Current challenges by product development - Research question 1

One question discussed throughout the interviews was what current challenges with fibre-reinforced polymers in different departments like product development, design, production, simulation etc. where seen. After assembling all information, the results were assigned to the 4 following categories: challenges with material, simulation, design and technology. Figure 6 below presents the mentioned 17 main challenges.

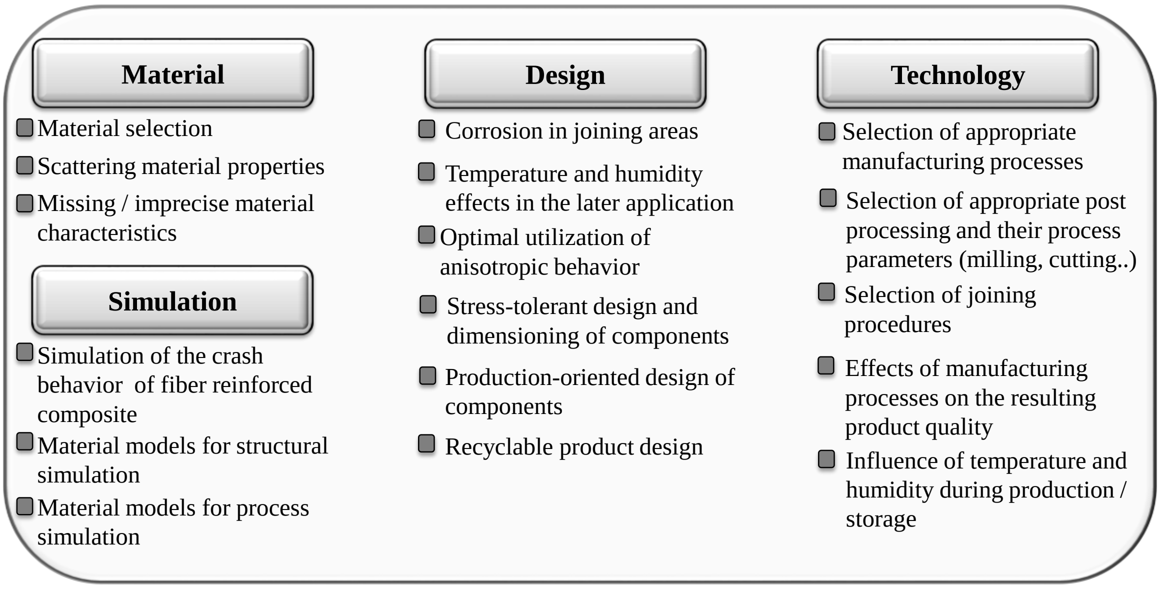

Figure 6. Challenges in the industry

Desired content in design guidelines according to determined challenges - Research question 2

In the following, the desired contents are given for identified challenges in material, simulation, design and technology categories:

Support by material selection regarding the requirements on the product this was mentioned as an important topic in design guidelines. Especially the visual side of a component is seen as an important criterion for the selection of a suitable material. Particularly in the automotive sector, the question arises for each component whether and how this will be perceived by the customer. Components with the visible areas have the highest demands on the achievable surface quality, the paint ability and, in some cases, the haptics.

The disordered microstructure in long-fibre-reinforced polymers leads to local scattering in the material properties. In order to calculate and consider these in the design of components, **information about approaches for predicting the expected scattering in material properties** and thus prediction of the component behaviour is necessary.

The consequences of inaccurate results of flow simulation is imprecise warping predictions which result from manufacturing process, but also imprecise thermal expansions and residual stresses in the later application. Here, the information about:

- **approaches** for defining the **draping strategy**,
- **approaches** to determine the **injection position** during the mould filling process
- **approaches** to determine the **demoulding strategy** after production or other **measures** to avoid / minimize **warpage** and
- **approaches** to take **process-dependent fibre-orientations** directly in the simulations into account are needed to be considered in design guidelines.

The use of computer aided methods becomes increasingly important because of a higher complexity in designing structural parts made of fibre-reinforced plastics. In addition to design guidelines, **new processes to gain initial design proposals** need to be developed. These processes need to include the local mechanical properties caused by the manufacturing process into the simulation and optimisation procedures.

The **production-oriented design** of components, depending on a chosen manufacturing process, is - and should be the essential part of a design guideline. They must ensure that every **production process** is listed as far as possible **on the state of the art**. The important information for the design engineers are about **realizable geometries** and **restrictions in the production process** due to structural stiffeners. However, not only the aspect of manufacturing should be treated. The design engineers also have to be supported in the **design of load-bearing structures**. This includes the **inclusion of failure criteria** such as the buckling and kinking of components. It is important to be able to define a design space or constraints in order to limit the maximum height of ribs or beads. Furthermore, the selection of the **joining technique** has an influence on the selection of the material and the manufacturing process. For a design engineer, it is important to know which **advantages and disadvantages** a joining process entails and which **design measures** may be the outcome. The other desired contents were:

- **approaches** for stiffening components in **visible areas** (choice of stiffening, measures to avoid the insertion of ribs)
- recommendations for the **detection of potential sources of damage**
- recommendations for **damage progress calculation and**
- approaches for **recyclable product design.**

The **influence of the manufacturing processes** on the component is also an important topic for design guidelines. The **draping properties** of the semi-finished products directly determines possible component geometries and the possibilities of force transmission. It influences flow distance, mould filling behaviour and material behaviour in the edge area which are important for components produced in injection or flow processes, since these affect the resulting component quality and thus the load capacity of the components. Therefore, information to following topics are needed:

- typical **manufacturing effects** and their causes
- influences of manufacturing effects on the **component properties**
- suitable methods for **quality assurance**

Post processing of fibre-reinforced components is a relevant topic, given to its complexity. In addition to joining, cutting is a processing step that is frequently encountered in fibre-reinforced plastics. Semi-finished products must be cut to size and components must be provided with holes and sections. That is why it is important to keep the damage of cutting edges of the material as low as possible. For this purpose, **appropriate procedures** as well as **their process parameters** must be specified in a design guideline. In addition, the following contents in design guidelines are needed:

- **advantages and disadvantages** of different post processing processes
- approaches against **delamination** for different procedures
- information on **surface pre-treatment** during coating (cleaning, influence of release agents)
- information on **heat removal** during machining

To summarize, the industry representatives from different disciplines have partly overlapping and partly different demands regarding working with fibre-reinforced polymers. The necessary information in design guidelines depends very much on the requirements placed on the product, the field of activity of participants and their experience level as well as the industry sector. But apart from this the requirements for desirable content to be found in design guidelines was much the same in North America as in Germany.

Need on the further development of design guidelines

Most of the participants have seen the need on the further development of design guidelines. The statement was made by both: those who already have design guidelines offered by their company as well as by others who do not have them in their own company and do not want to look them up in the literature.

"… lack of design guidelines is something that has been discussed for years, and many attempts have been made to come up with ones (within companies/internal, and within industry groups/organizations). Over the last 3-4 decades there has been some progress, but little and not really a measurable one ".

6 INTERMEDIATE CONCLUSION AND OUTLOOK

The investigations have shown that the current solutions available these days in the literature are not suitable to support the design engineers during the product development with fibre composite materials. There is a need to rethink the classical concept of design guidelines and to adapt these to the requirements of the industry. Since a design process in earlier phases of the product development consists of iterative steps, and the material selection, the design and the production process have a strong influence on each other, it is no more sufficient to represent only a part of the necessary information in the design guidelines.

The requirements concerning a product have a decisive influence on product design. Since each product development process is individual and the requirements are changing often, it is important to support design engineers. Therefore, there is a need for the further development of design guidelines, which correspond to the industrial demands and provides relevant information according to the requirements placed on the product. By interviews with industrial representatives 17 main challenges with fibre-reinforced polymers in different departments like product development, design, production, simulation etc. where identified. To meet these challenges, design guidelines should include information on these issues. Furthermore, a new concept for the provision of design guidelines is required. To avoid confusion and long search time as well as to enable a simple updating of the information, design guidelines should be provided by a software-based solution.
In addition to guidelines, new and holistic approaches to gain initial design proposals need to be developed. These would be useful both, during the processes of material selection and structural design on the one hand and could also add basic information to design guidelines on the other hand.
The next step is to apply quantitative research methods in order to review the results from the interview study and to provide recommendations for the development of design guidelines. When the result is confirmed that the requirements in North America and Germany on design guidelines agreed on many points between, then the developed approach can be applied in both countries.

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