

MATERIAL SELECTION METHOD FOR COMPOSITE SPRINGS

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ABSTRACT

In this contribution a method for an objective material selection process for composites is presented. The concept is based on a dataset with properties of different fibers and matrices. In the first step, composite properties are being calculated for each possible composite combination, including the demands determined before. In the next step, different factors are being introduced, which are rating the individual material property. The final step is the formation of a top-down-ranking with a material recommendation.

Furthermore, a software implementation is presented as an automation of the method. In order to evaluate the approach, the procedure is being tested on three spring examples. At last, a short schematic plan with operating instructions is being derived and discussed in comparison to existing material selection guides. The research is a contribution to extend the range of composite spring applications and shows aspects for future developments.

Index Terms – composite material selection method, fiber composite springs, automated material rating

1. INTRODUCTION AND MOTIVATION

Modern composite materials such as GFRP, CFRP and AFRP have long been established as an integral part of material construction. They are preferred for parts that do not depend heavily on the costs. Due to further technological improvements, engineers have diverse opportunities for their component designs and methods for manufacturing. [1]

Springs made of fiber composite materials are being investigated and used for over 50 years now [2]. Nowadays, materials and production technologies provide excellent spring characteristics combined with the advantages of corrosion resistance, mass reduction, internal damping and good fatigue behavior. In particular the design and manufacturing of composite meander and leaf springs has reached the state of automated series production and enables lightweight design with a mass reduction up to 50-75% (examples in **Figure 1**). [2][3][4]



(a) **Figure 1:** Examples for glass fiber composite springs with mass reduction of 50-75% [4]:
(a) typical leaf spring with linear spring rate
(b) special leaf spring with specific deformation behavior and progressive spring rate
(c) meander spring as replacement for metal compression springs

Local layup adaptations offer a precise adjustment of the spring rate, allow predetermined breaking points or strengthen endangered areas respectively. These adjustments can be achieved by variation of the number of layers, usage of different fiber materials and modification of the fiber orientation.

Nevertheless, the usage of composite materials for springs requires solid specialist knowledge and practical experience to prevent fundamentally wrong decisions in the product development process. A further challenge is the optimization of the material choice in fiber composite plastics not exclusively based on the loads, but much more on the demands over the whole product lifecycle (e.g. UV resistance, chemical stability or fire behavior).

In order to facilitate engineers, who have no experience with composites, this paper shows a method for an objective process of material selection and a resultant software implementation.

2. COMPOSITE MATERIAL SELECTION METHODS AND GUIDELINES

There have already been various approaches in the past to establish guidelines for the selection of fiber and matrix materials. Therefore, three important aids are described below.

2.1 NASA Reliability Guideline GD-ED-2210

The NASA Reliability Guideline GD-ED-2210 [5] provides material selection and production methods, the compliance with both technical and financial requirements as well as the fulfillment of the time schedule. The guideline essentially recommends the usage of preimpregnated fibers (PrePreg) respectively manufacturing procedures with high fiber volume content such as Resin-Transfer-Molding (RTM) or pultrusion.

Furthermore, the guideline is focused on space applications and limited in choice of materials, especially for polymer matrices. The material selection is based on Figures of Merit (FOM). The definition of a limited number of evaluation criteria (FOMs), such as the density-related strength (R_m/ρ), prevents a holistic evaluation of the materials.

This is particularly problematic regarding the fact, that the advantages and disadvantages of fiber composite plastics are frequently not assessed correctly in the case of insufficient experience. The evaluation of the material is only based on one FOM without considering other properties in detail, such as chemical resistance, in this early stage of engineering.

Companies that have already had experience with the use of fiber composite plastics decide differently from those companies that have so far only planned their use [6, p. 13]. Thus, the evaluation based on one FOM is insufficient, especially for inexperienced users of fiber composite materials [7, pp. 166, 167].

2.2 Knowledgebase of different composite handbooks

As a second composite selection guideline, the rules from different composite handbooks are mentioned (e.g. [6][7][8]). Exemplarily, the rules by *Schürmann* [8] are contemplated. Lightweight construction is clearly focused in this handbook. In addition, special attention is paid to the use of glass fibers. For stiffer structures, carbon fibers should be used and for applications where higher costs can be accepted and extreme lightweight construction is required, the use of aramid fibers is proposed.

For components with the demand of high impact strength, an (additional) reinforcement is proposed by aramid or PE fibers. In order to achieve compromises between different properties, the fibers should be mixed. For high-temperature applications, carbon (C), silicon carbide (SiC) and aluminium oxide (Al₂O₃) fibers are recommended. For the selection of the matrix, it is pointed out, that the use of already widely applied and qualified systems is recommended. For more specific questions, *Schürmann* refers to the fiber and matrix manufacturers.

Overall the general rules mentioned in composite handbooks offer a fast but superficial introduction into composites. However, a more diverse selection of materials is not possible without extensive literature studies. A more exact knowledge of the material properties requires their independent research and a manual comparison.

2.3 Knowledge-based systems and neural networks

A distinction from the above-mentioned guidelines is represented by the approach for material choices by computer-assisted systems. Digital databases have high potential, regarding to currentness of material data and efficient considerations of changing demands. There is the possibility of not only providing data, but also actively processing it [9].

For ceramic matrix composites, a prototype for a knowledge-based software tool was developed by *Sapuan et al.* in 2002 [10]. Caused by stringent standards on the emissions of combustion engines, a higher combustion temperature was determined. Ceramic matrix composites can meet these gaining requirements.

In continuance of his work, *Sapuan* cooperated with *Mujtaba* (University of Bradford). A computer simulation was developed, based on an artificial neural network for the determination of a suitable natural fiber polymer system. The neural network identifies a ranking of various fibers. To test their software, they simulated a shelf [11, p. 317]. Therefore, material properties of 121 different fiber types were determined or collected. In addition, the aesthetics, the cost and the availability were considered.

Due to the restriction to natural fiber reinforced plastics and / or ceramic fiber and matrix materials, and concentration on motor components, a general approach for the determination of a suitable material for lightweight construction, as necessary for springs, is not possible.

3. NEW MATERIAL SELECTION METHOD FOR COMPOSITE SPRINGS

3.1 Objective

Due to insufficient knowledge of fiber composite materials regarding their properties, their processing and their material-compatible design, engineers often avoid their use or choose a material combination which is not optimal for their application. In this way, the establishment of fiber composites in wider areas of industry is limited and potential is not utilized. In addition, there is a considerable increase in development expenditure due to lack of knowledge of the designers. [6]

At this point, this work aims at reducing the effort and finding an optimized result in the determination of a suitable material pairing. In order to achieve this goal, a system for the evaluation and recommendation of material combinations adapted to the individual needs of the user is developed. For this purpose, the user is given the possibility to determine the requirements to the system in order to obtain optimized results. A simple comparison of the individual materials is difficult since the simple addition of the individual properties does not provide sufficient accuracy [6, p. 4].

In order to counter these difficulties in the selection of materials, the individual material properties are systematically examined for their compatibility by the composite components and checked for possible calculation options. Based on the results obtained, the materials are evaluated and presented according to the requirements of the user.

3.2 General conditions and valuation criteria

In the first step of the new evaluation concept, it is necessary to define the criteria and the boundary conditions. **Figure 2** gives an overview of the ascertained properties.

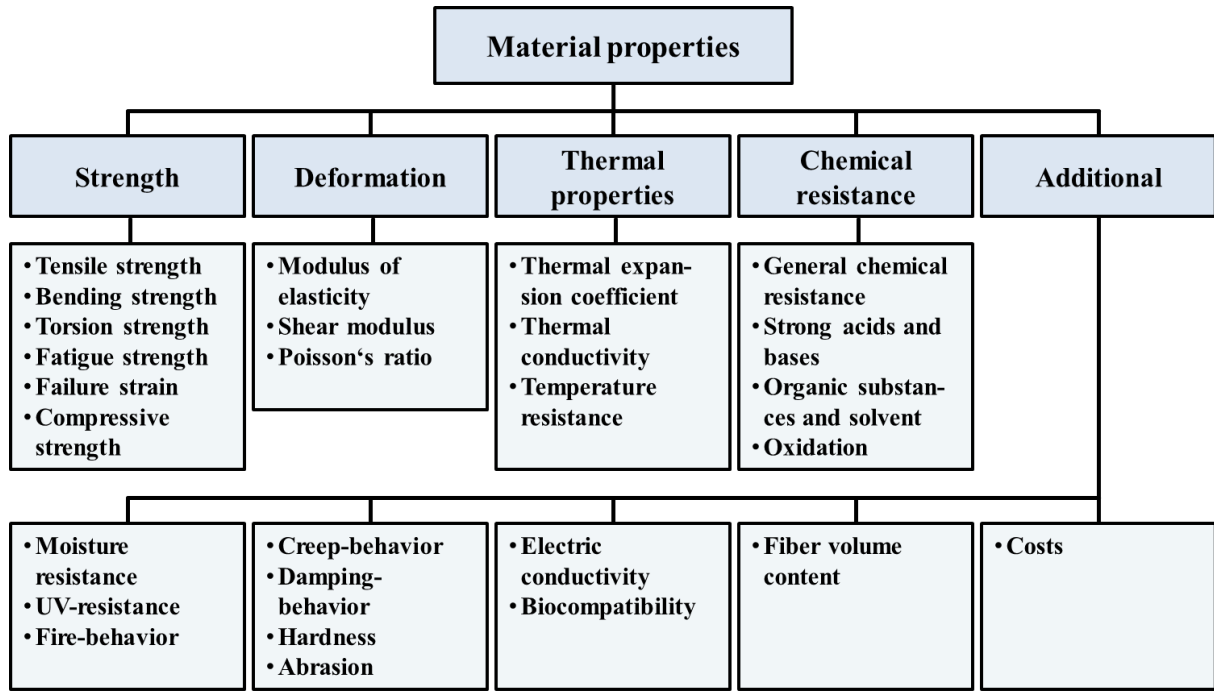


Figure 2: Classification of ascertained material properties for the material selection method for composite springs

Subsequently, possibilities for evaluation and calculation were defined for every criterion. Due to the extensive influences and necessary explanations, only three criteria are explained in more detail below (further details in [12]).

Strength

As one of the most important factors in lightweight design, strength has to be considered. The computational prediction of stress limit values of fiber composite components is much more complex compared to the calculation of components made of metallic or other homogeneous materials. The responsible reason is the anisotropic and often layered construction of fiber composite parts. For this reason, it is, for example, common practice in aviation to limit the design of CFRP components to static calculations. The necessary condition for this simplification is the limitation of the permissible strain to 0.45%, hence vibration fatigue failure can be excluded [13, p. 4].

The assessment of potential materials with regard to their suitability for parts subjected to vibrations is correspondingly complex, which is why only the tensile strength is used for the classification of the materials with regard to their strength. The strength of unidirectionally (UD) structured laminates can easily be estimated using the mixing rule [14, p. 78]. The failure stress σ can be calculated as follows using the tensile strength of the fiber (R_{mF}), the fiber volume content φ_F , the modulus of elasticity of the matrix material (E_M) and the modulus of elasticity of the fiber material in the fiber direction (E_{F1}) [15, p. 308]:

$$\sigma = R_{mF} \cdot \varphi_F + R_{mF} \cdot (1 - \varphi_F) \cdot \frac{E_M}{E_{F1}} \quad (1)$$

Thermal Expansion

The *Schapery* model [16] can be used to estimate the thermal expansion coefficients of long-fiber reinforced composites. $\alpha_{||}$ characterizes the thermal expansion in the axial direction and α_{\perp} describes the transverse direction. The thermal expansion coefficient of

the fiber (α_F) and the matrix (α_M) as well as the Poisson's ratio of the fiber (ν_F) and the matrix (ν_M) result in the following formulas:

$$\alpha_{||} = \frac{E_{F1} \cdot \alpha_F \cdot \varphi_F + E_M \cdot \alpha_M \cdot (1 - \varphi_F)}{E_C} \quad (2)$$

$$\text{with elasticity of the composite [14, p. 78]: } E_C = \varphi_F \cdot E_{F1} + (1 - \varphi_F) \cdot E_M \quad (3)$$

$$\alpha_{\perp} = (1 + \nu_M) \cdot \alpha_M \cdot \varphi_F + (1 + \nu_F) \cdot \alpha_F \cdot \varphi_F - \alpha_{||} \cdot (\nu_F \cdot \varphi_F + \nu_M \cdot (1 - \varphi_F)) \quad (4)$$

Biocompatibility

Components which are used in living organisms must be biocompatible. Failures may result in rejection reactions which may occur in conjunction with mild irritation and even fatal inflammation (e.g. artificial hip joints). Due to inadequate assessment possibilities, the biocompatibility will be evaluated qualitatively (criterion of exclusion).

In addition to all criteria, costs always play an important role in the development of a product and its components. This is why the designer is obliged to decide with regard to the product costs. When selecting a fiber composite, the cost aspect can be assessed by using the simple mixing price, based on the weight of each component.

3.3 Development of the valuation concept and software implementation

In general, the concept is based on the schematic *Input – Processing – Output* as shown in **Figure 3**. The software implementation was done in *Microsoft Excel*®.

The material recommendation is based on the fiber and matrix data. Through the relationships described in section 3.2, the properties of each possible composite combination can automatically be calculated from these data. The requirements have to be chosen by the user. Additionally, a weighting has to be included for balancing the requirements to the users or the company's needs.

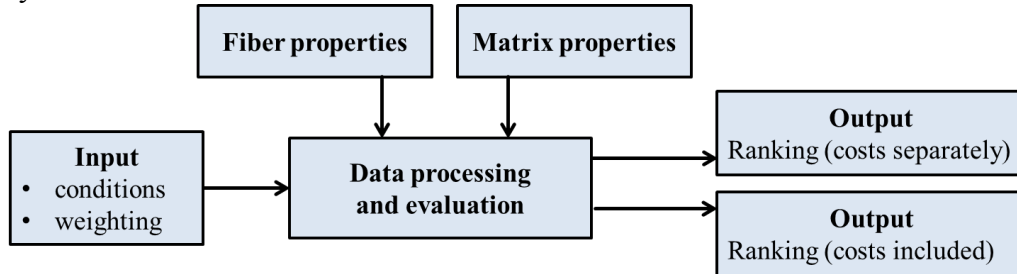


Figure 3: Schematic of the material selection method

All material combinations are evaluated and then a corresponding recommendation is issued in form of a ranking. The fiber and matrix data are taken from the literature and manufacturer's data. The corresponding sources are deposited in the appropriate place. Furthermore, the user has the possibility to change and supplement the data.

3.3.1 Input

For this purpose, various material properties and requirements are listed in the start page of the Excel-sheet. The input mask is shown in **Figure 4**. An option for weighting is assigned to each of them. The user has the possibility to adjust the weight by means of a corresponding controller or by manual entry into the intended field. In addition, in the case of the quantified material properties, it is possible to choose between the maximum or minimum values. A special position is taken by the thermal expansion, which can also assume negative values. Therefore, a distinction is made between "minimum", "maximum" and "near zero".

Bedingungen		Wert [%]
Faservolumengehalt	< >	50

Anforderungen	Gewichtung [%]
Zugfestigkeit	50
Schwingfestigkeit	50
Druckfestigkeit	50
E-Modul	50
G-Modul	50
Thermische Dehnung	50
Wärmeleitfähigkeit	50
Temperaturfestigkeit bis [°C]	50
Kosten	50
<input type="checkbox"/> Oxidierende Atmosphäre	50
<input type="checkbox"/> Leichtbau	50
<input type="checkbox"/> Chemische Beständigkeit	50
<input type="checkbox"/> Resistenz gegen starke Säuren und Laugen	50
<input type="checkbox"/> Resistenz gegen organische Medien und Lösungsmittel	50
<input type="checkbox"/> Oxidationsresistenz	50
<input type="checkbox"/> Feuchtigkeitsbeständigkeit	50
<input type="checkbox"/> UV-Beständigkeit	50
<input type="checkbox"/> geringes Kriechen	50
<input type="checkbox"/> starke Dämpfung	50
<input type="checkbox"/> hohe Zähigkeit	50
<input type="checkbox"/> hohe Härte	50
<input type="checkbox"/> günstiges Brandverhalten	50
<input type="checkbox"/> günstiges Verschleißverhalten	50
<input type="checkbox"/> elektrische Leitfähigkeit	50
<input type="checkbox"/> Biokompatibilität	50

Bewerten und zu den Ergebnissen wechseln

Bewerten und zu den Ergebnissen wechseln (unter Berücksichtigung der Kosten)

Figure 4: Input mask of the software tool. At first, the user has to determine the fiber volume content in dependence of possible production methods. Next, he has to set the conditions and weightings. Finally, the evaluation starts by clicking one of the buttons below (differed in cost considerations).

The temperature resistance is not weighted, but is expressed as an actual limit. All other material properties are given the possibility to deactivate them completely by means of checkboxes. The fiber volume content, which is important for numerous material properties, is also predetermined by the user. After the user has used the given options to enter the requirements, the evaluation of the materials starts via two buttons. They divide the evaluation with or without consideration of the costs. These buttons are based on Visual Basic for Applications (VBA) macros, which sort the fiber-matrix-combination according to their suitability and switch to the corresponding sheet, which automatically displays the results.

3.3.2 Data processing

The assessment of the materials is carried out by means of a system of properties and material indices calculated from them. Each material property taken into account is thereby assessed by the respective property index (e_{ji}). Where i is the respective property and j is the material. By simply summing up the respective material properties (W_{ji}), no meaningful material index (w_j) would be calculated.

The different and partly non-existent units as well as the disproportionate magnitudes require normalization before addition. Furthermore, "best value" does not always have to be the maximum. Therefore, a simple dividing of the values of the material properties by the best value is not sufficient for the determination of the materials. The evaluation of the properties, which have a minimum as optimum, requires the range between zero and one to be used completely. In this way, the highest value can be evaluated as zero and the lowest value as one. The following operation allows this rating for the material j under m materials:

$$e_{ji} = \frac{\text{Max}(W_{1i} \text{ to } W_{mi}) - W_{ji}}{\text{Max}(W_{1i} \text{ to } W_{mi}) - \text{Min}(W_{1i} \text{ to } W_{mi})} \quad (5)$$

A similar operation is used to calculate the property indices e_{ji} of quantities that are required to have the highest possible values:

$$e_{ji} = \frac{W_{ji} - \text{Min}(W_{1i} \text{ to } W_{mi})}{\text{Max}(W_{1i} \text{ to } W_{mi}) - \text{Min}(W_{1i} \text{ to } W_{mi})} \quad (6)$$

The property indices e_{ji} can reach values between zero and one or 0% and 100%, depending on their normalization by (5) or (6). For the material index w_j follows:

$$w_j = e_{j1} + e_{j2} + \dots + e_{jn} = \sum_{i=1}^n e_{ji} \quad (7)$$

After this operation, all material properties have the same effect on the evaluation of the material. In order to enable the user to individually weight the properties, the property indices are then multiplied by the respective weighting (g), likewise in the range of 0% to 100%, before the addition to the material index. A particular position among the material properties is the temperature resistance. As an exclusion criterion, the property index of the temperature (e_{jT}), which can have the value 0 or 1, does not have to be added to the remaining property indices, but has to be finally multiplied. The calculation extends to:

$$w_j = (g_1 \cdot e_{j1} + g_2 \cdot e_{j2} + \dots + g_n \cdot e_{jn}) \cdot e_{jT} = \left(\sum_{i=1}^n g_i \cdot e_{ji} \right) \cdot e_{jT} \quad (8)$$

Furthermore, costs have to be regarded. The wide range of composite materials causes high variations in pricing. This aspect will be conveniently considered by a logarithm:

$$e_{jc} = g_c \cdot \frac{\log(\text{Max}(W_{1c} \text{ to } W_{mc})) - \log(W_{jc})}{\log(\text{Max}(W_{1c} \text{ to } W_{mc})) - \log(\text{Min}(W_{1c} \text{ to } W_{mc}))} \quad (9)$$

In conclusion, the final calculation for the material index ($w_{j,final}$) is formed as follows:

$$w_{j,final} = \frac{(\sum_{i=1}^n g_i \cdot e_{ji}) \cdot e_{jT} + e_{jc}}{\text{Max}(w_1 \text{ to } w_m)} \quad (10)$$

This material index is determined for each possible combination of fibers and matrices. Therefore, a variety of tasks runs in the background of the Excel tool. Users can add or change components in the sheet “Fibers” or “Matrices”.

In this research, 20 matrix materials (thermosets, thermoplastics, carbon, ceramics and metals) and 21 fiber-materials (glass, aramid, carbon, silicon carbide, aluminum oxide and boron) were used and implemented with lots of properties and hints. The problem of source-dependent value-variation is solved with mean value formation from three values.

The background processes of the Excel tool are calculating the properties of each possible combination of fibers and matrices as described in chapter 3.2. All data are automatically collected in the sheet “Composite Materials” and evaluated by the formulations shown in this chapter. Finally, the ranking can be made and presented for the step “Output”.

3.3.3 Output

The system allows the user to choose between a valuation that directly includes the costs and a valuation that separates the costs like described before. For this reason, there are two different output sheets in Excel. For both variants, each line contains the obligatory data on the designation of matrix and fiber materials, as well as an overview of the notes, advantages and disadvantages listed in the “Composite Materials” sheet. Depending on the variant, the corresponding material index (standardized valuation with or without costs) is also specified.

In addition to this information, the user is provided with information on the influence of the various material properties on the evaluation, graphically in the form of a bar graph.

In the evaluation without taking into account the costs, the cost bar is provided as additional information, in order to enable the user to quickly estimate the price. A VBA macro is implemented, which scales all axes automatically when sorting and displaying the materials. In this way, the evaluated material properties of all composites can be visualized in form of a top-down-ranking. An example-ranking is shown in **Figure 5**.

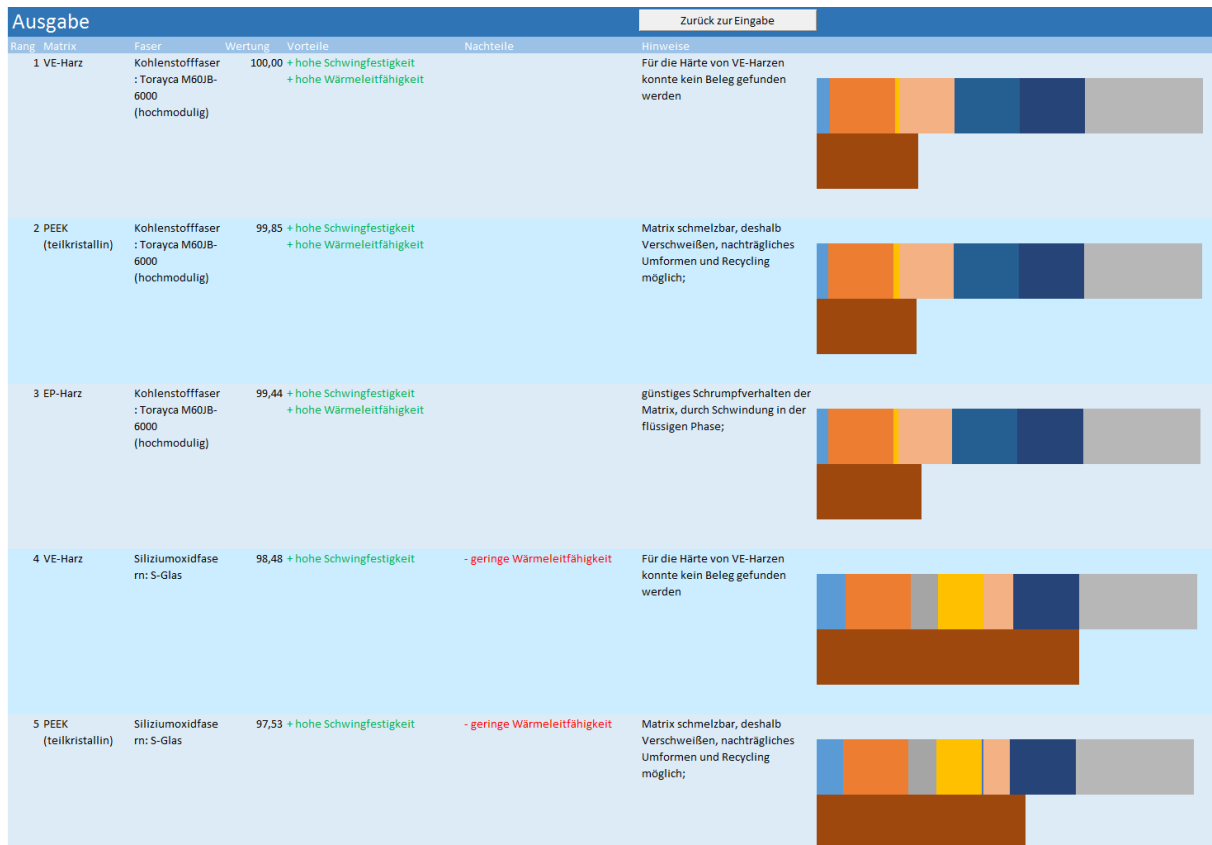


Figure 5: Output sheet for an example evaluation with separated costs (brown bars). The best five composite material combinations are shown and visualized with valuation value, advantages and disadvantages, hints and bar graphs with a color-distinguishable property representation.

4. VALIDATION OF THE METHOD

In order to validate the evaluation concept, three different composite springs were investigated. Therefore, already existing solutions from conventional materials (e.g. steel) should be substituted by fiber composites. Particular attention is paid to the aspect of mass. Composite-calculations are made with ANSYS Workbench[®] and the additional Composite PrepPost module. Further details in modeling and calculations are included in [12].

4.1 Suspension spring of a VW Caddy (2K)

For the first example, the suspension springs of the rear axle of a current Volkswagen Caddy are being analyzed. Advantageous are the publicly accessible documentation and the leaf spring layout, which can be easily substituted by composite materials. Therefore the comparability with respect to the mass is given.

In the first step of the material selection, the conditions for the input sheet have to be established. Suspension springs on passenger cars must withstand high loads and, like all components of vehicles, must be designed to keep fuel consumption as low as possible. Furthermore, they have to improve the driving behavior and increase the comfort. Since the

springs are frequently loaded, the material has to meet high demands on the vibration fatigue resistance. Added to this are demands on ductility, corrosion resistance and creep resistance. For the purpose of assisting the dampers in reducing vibrations, a certain degree of damping is also beneficial. In order to be able to realize the spring deflection, the high occurring stresses and the resulting large cross-sections, a very low elastic modulus is required to keep the stiffness of the spring low. Since the leaf spring is mainly subjected to bending, the shear modulus has to be of little importance. In addition to these technical requirements for the materials, their assessment must also take account of the aspect of the costs.

On the basis of these inputs, a matrix of epoxy resin with E-glass fibers as a reinforcing phase is determined as the most appropriate material, taking directly into account the costs. The output without direct consideration of the costs also shows that the epoxy / E-glass combination determined is well suited and thus represents a favorable ratio of technical and economical suitability. An even more favorable combination of strength and modulus of elasticity is offered by S-glass fibers, which entail significantly higher costs. A vinylester resin matrix also has a more favorable ratio of modulus of elasticity and strength and is priced in the same region. Due to missing data on the shear modulus, the material was rated lower. The calculations were carried out with the proposed material combination.

The conventional metal leaf spring weighs 8 kg. As a result of comparative calculations, the new epoxy / E-glass leaf spring weighs 6 kg including aluminum mounting parts (not shown in the picture). This represents a mass reduction of 25%. The suitability of glassfibers with a thermoset matrix as a material for leaf springs is confirmed by the efforts of *Muhr und Bender KG (Figure 1)* and various applications through researches at *TU Darmstadt* for example ([1][2][3][4]).

4.2 Anti-roll bar for a Formula Student race car

As a second example, an anti-roll bar for the *Formula Student* race car was examined. Modeling and calculation data were thankfully provided by *Team Starcraft e.V.*

The requirements for the anti-roll bar are similar to the requirements for the car suspension springs in chapter 4.1. Lightweight construction is also required at this point, for example in order to optimize the center of gravity. Anti-roll bars are also frequently stressed, but not permanently, which is why creep is not important. The cost aspect is not highly valued in this case because it is not a large series. Since the *Team Starcraft e.V.* is dependent on sponsoring, they are still included in the evaluation. Although the anti-roll bar is subjected to torsion, the fibers are subjected to tensile stress ($\pm 45^\circ$ orientation). Hence, the elasticity module is weighted more heavily.

As a result of these inputs, as long as the costs are included in the evaluation, the material combination S-glass fiber with epoxy resin matrix is determined as the best solution. Even without their consideration, this combination of materials is classified as very high. From a technical point of view, only an S-glass fiber / PEEK matrix system is to be preferred, which however is much more expensive.

While maintaining the geometrical dimensions, the calculations do not lead to any weight advantages due to the use of the suggested composite and necessary adapter parts. This example shows that the proposed material is not optimal. The cause of the result can be attributed to unfavorably selected input variables when using the evaluation method. Thus, the conditions were misjudged and a low modulus of elasticity was required. The demand for a high modulus of elasticity would be more useful. In conclusion, a guided input or an iterative determination of the material based on new knowledge would be meaningful.

Hence, another evaluation was done with high requirements on elasticity modulus and shear modulus, but the same weighting. After the adjusted input, a combination of carbon fibers and

a PEEK matrix is proposed. By using this material, the dimensions can be reduced. The leaf spring is both narrower and thinner, resulting in a reduction of the mass to 0.078 kg including adapter, which corresponds to a reduction of 35% compared to the mass of the steel spring (0.12 kg). The spring itself weighs only 0.01 kg. For the torsion bar, a reduction of the diameter and the wall thickness could be achieved. This geometry results in a mass of 0.308 kg which corresponds to a reduction of 27% compared to the steel version (0.420 kg).

4.3 Cardan shaft for a ship drive

As a third example for validating the evaluation method, a cardan shaft for a ship drive was considered as a torsion spring (metal tube). Therefore, the company *Gelenkwellenwerk Stadtilm GmbH* thankfully provided data for a cardan shaft for small boats [17].

Since the shaft is used to transmit high torque, a high strength is an important parameter for the assessment of the material. Furthermore, a high modulus of elasticity is required, in order to avoid a strong deflection. As the ship manufacturing industry is subject to high economic pressure, the costs are heavily weighted as a criterion of valuation. The maximum operating temperature is limited to 90 °C. Due to surrounding by water and salt water, adequate resistance to moisture and corrosion must be required.

Both the assessment of the cost-relevant and the cost-neutral evaluation result in a combination of intermediate modulus carbon fibers in conjunction with a PEEK matrix.

The analysis of the steel tube is carried out under the same modeling conditions as the analysis of the fiber composite shaft. The safety factor of both versions is about 5. At a length of 1500 mm, the composite material shaft weighs 5.3 kg, while the steel shaft weighs 10.8 kg. If additional bearing positions can be saved through the mass-reduction, the costs can be reduced, so that the carbon composite shaft is more economical than the conventional steel shaft. These significant advantages represent the potential of composite materials.

5. DISCUSSION AND CONCLUSIONS

As in the examples considered, a weight reduction could be achieved by utilizing fiber composite materials. The different results depend, on the one hand, on the geometries. Beneficial for the optimization is a geometry that is suitable for fiber composite construction. On the other hand, the weightings have a decisive influence on the successful use of the evaluation table. If the user does not have sufficient experience with the considered component, an iterative use of the method can be useful, as the example of the anti-roll bar has shown. For this reason, the evaluation system (**Figure 3**) must be supplemented by a review of the results (**Figure 6**).

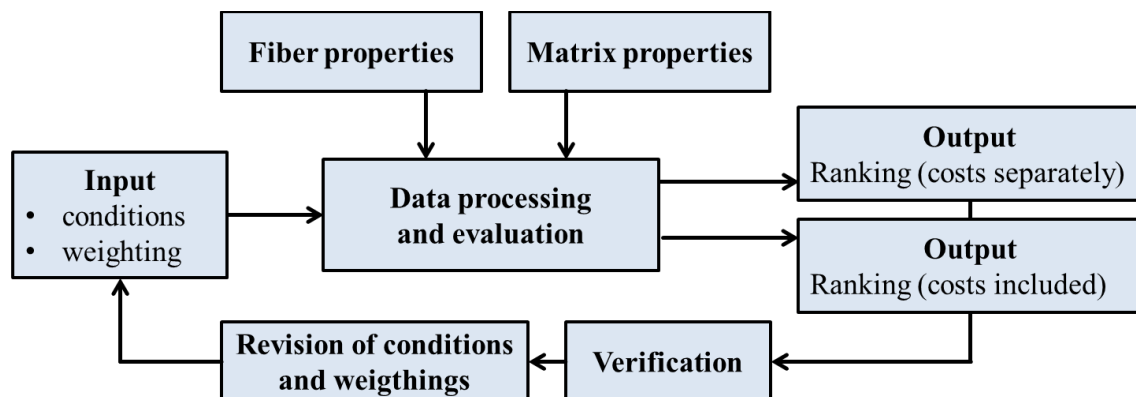


Figure 6: Schematic of the material selection method supplemented by a verification path, that is useful if the user does not have sufficient experience with the component

Ascending from the perceptions in this research, the following general rules could be derived. The first task should be the choice of the fiber material, depending on the requirements:

- Low stiffness → glass fibers
- High stiffness → carbon fibers
- High stiffness + mostly tensile loads → aramid fibers
- High stiffness + dynamic loads → carbon fibers
- High temperatures + high stiffness / very high strength → SiC-fibers (very expensive)
- High temperatures + low/medium stiffness + high strength → Al₂O₃-fibers (expensive)
- High temperatures with exclusion of oxygen → carbon fibers

The conclusions are summarized in the scheme shown in **Figure 7** representing a fiber selection methodology. A pre-selection has to be made on the basis of the temperature resistance, in order to enter into material-specific features, and finally to give a recommendation on the basis of the aspects of stiffness and strength.

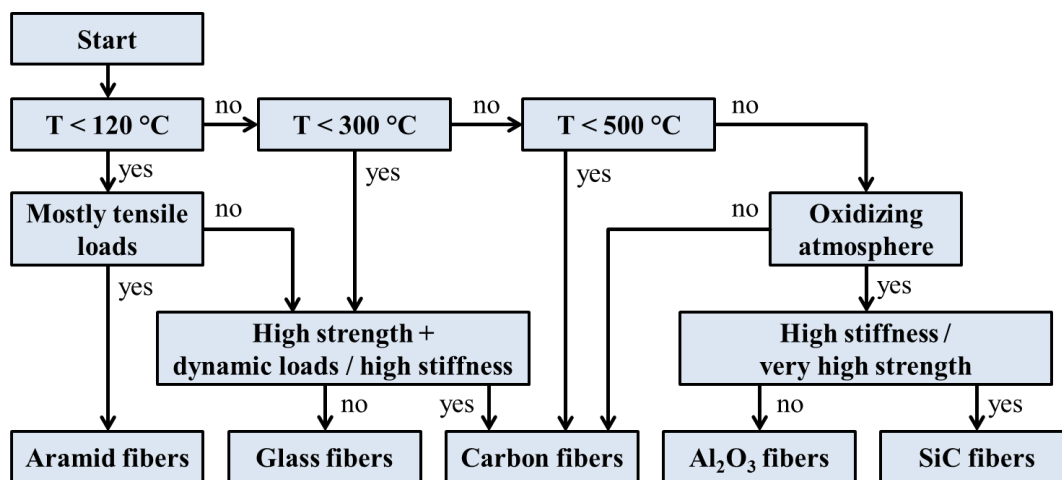


Figure 7: Schematic for fiber selection

The choice of the matrix should first be selected according to the aspects of temperature resistance and interfering media. Subsequently, a material selection adapted to the individual possibilities and oriented on the selected fiber is recommended. The diagram shown in **Figure 8** serves as a guideline for the selection of a suitable matrix material.

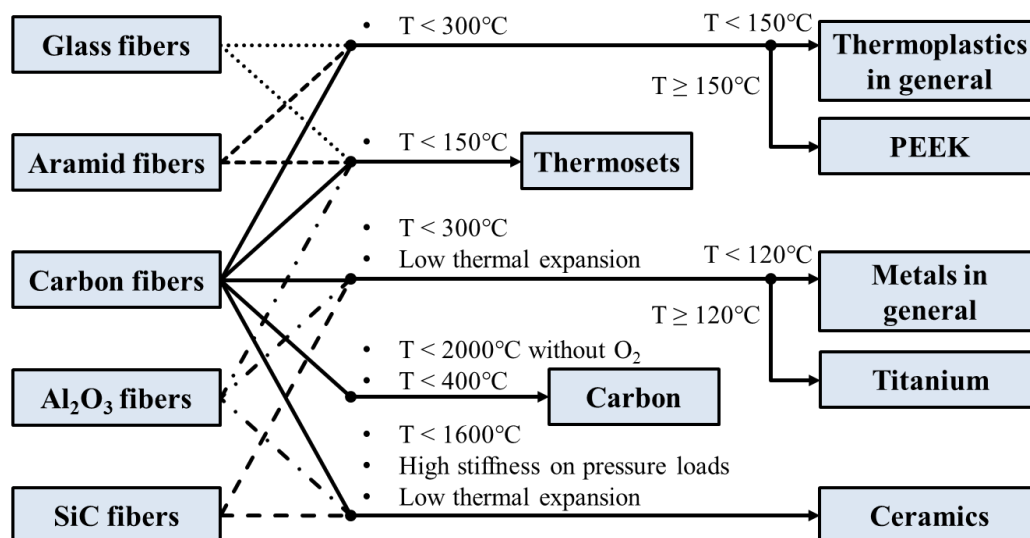


Figure 8: Schematic for matrix selection

The results obtained in the diagrams of **Figure 7** and **Figure 8** are mostly equal to rules and guidelines mentioned in Chapter 2. This confirms the correctness of the method. Furthermore, the expanded bandwidth of the considered materials reveals a more comprehensive view in the material selection process, which has not been shown so far. Especially with regard to the composite-inexperienced engineers, the method and the software tool offer the possibility to quickly make a choice in the pre-development of new components without extensive enquiries. With this contribution, an important progress was made in the computer-assisted selection of composite materials.

6. SUMMARY AND OUTLOOK

In this work, extensive information about various fiber and matrix materials was compiled. This applies in particular to the mechanical properties, the impact of environmental influences as well as the technological and the economic aspects. These data have been implemented into a calculation table in Microsoft Excel. This system offers the user the possibility to weigh all material properties to different degrees. In order to determine these, the resulting material properties are initially calculated for all combinable fiber-matrix pairings. These standardized material properties are used to evaluate each material combination.

Furthermore, a top-down-ranking is generated and presented with detailed information about the composites. Three examples of composite springs have shown the validation of the method. On the basis of the knowledge from this research, general rules could be concluded and formatted as graphical workflows for fiber and matrix selection. Additionally, these guidelines are valid beyond composite spring applications.

An outlook on further research could be the implementation of more materials, e.g. organic fibers, to enlarge the database. Other enhancements could be steps for geometry and manufacturing details, before the material requirements are being set. This would lead to more optimized recommendations. In addition, for special components, like leaf springs, a whole design feature could be created, that combines the layout (e.g. dimensions, loads, deflections) with the material selection process.

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