Mechanisms and Machine Science

Milan Rackov
Radivoje Mitrović
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Machine and Industrial Design in Mechanical Engineering

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Mechanisms and Machine Science

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Chapter 30
MCDM Approach in Choosing the Optimal Composite Shaft Material—Application of SAW Method

Zorica Djordjevic, Sasa Jovanovic, Sonja Kostic, Amra Talic-Cikmis, and Danijela Nikolic

Abstract In this paper, the selection of materials for production of shafts is considered from the aspect of the influence of a large number of parameters (mechanical characteristics of the material, density or mass of the shaft, fiber orientation angle in composite materials, shaft bending displacement values, free frequencies, etc.). In order to include all the above criteria in the selection of materials, the approach of Multi-Criteria Decision-Making (MCDM) using the Simple Additive Weighting Method (SAW) was applied. The analysis was performed for four different shaft materials (steel, aluminum, Carbon Fiber Reinforced Polymers CFRP and Glass Fiber Reinforced Polymers GFRP). The results of the analysis showed that the best characteristics, in addition to steel shafts, have composite shafts made of CFRP and GFRP with fiber orientation 0° and that they can be their adequate replacement, especially in systems where the weight of the structure is to be as small as possible.

Keywords Composite materials · Shafts · SAW method

30.1 Introduction

Composite materials are a combination of two or more materials with different mechanical and physico-chemical properties in order to obtain materials with improved characteristics in relation to the constituent components. Some of the advantages of composite concerning to traditional metallic materials are reflected in increased tensile strength, impact resistance, vibration, fatigue, temperature changes,

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reduced weight and the like. The specificity of composite materials is that these characteristics can vary depending on the amount and type of material used, and the angle of orientation of the fibers in the composite.

Composites consist of fibers and a matrix. Fibers (carbon, glass, aramid, etc.) form the supporting part of the composite, while the matrix (metal, polymer, ceramic, etc.) serves to bond and transfer loads between the fibers, gives shape to the structure, prevents damage to the fibers, etc.

Composite shafts, in comparison with steel, are characterized by increased load capacity, reduced weight, higher fatigue endurance, extremely harmonious vibration damping, the increased value of critical speed, etc. Carbon or glass fibers in combination with epoxy or polyester resin are most often used to make shafts. Also, hybrid shafts obtained by a combination of metal (steel or aluminum) and a composite material give good results.

When choosing an adequate material for the production of shafts, a large number of material characteristics, ie criteria must be taken into account (physical and mechanical characteristics should be maximum, while the weight, price and weightiness of the production organization should be minimal). Since the problem of material selection is very complex, it is recommended to apply some of the methods of MCDM.

Not so many researchers have proposed a specific analysis model to select the right material for a particular application. In study [1], the selection of suitable natural fibers for resin reinforcement for the production of roto molded product was analyzed, using the technique of MCDM. In particular, the MOORA and TOPSIS methods were used. It was concluded that, as far as natural fibers are concerned, the best properties for this purpose were shown by coconut fibers.

Researchers in [2] dealt with the analysis of mechanical properties of polyamide-based composites in combination with carbon fibers from the aspect of engineering application. An integrated multicriteria approach in material selection was applied, using the fuzzy best–worst method and the fuzzy G-VIKOR method.

The analysis of polymer composite materials reinforced with sugar palm fibers using three different multicriteria methods (AHP, TOPSIS and ELECTRE) was performed by researchers in [3].

Researchers have shown that the application of the method of MCDM can significantly facilitate the choice of materials in the automotive industry [4]. For this purpose, they used the methods of MOORA, TOPSIS and VIKOR.

30.2 Selection of the Composite Shaft Material

The analyzed shaft has an annular cross section 1 m long, 0.05 m middle radius, and 0.005 m wall thickness. The influence of the shaft material and the angle of orientation of the composite fibers on the values of maximum displacements due to bending and free frequencies of the shaft is considered.

Table 30.1 Material property values

Material	Elastic modulus, E_1 (MPa)	Elastic modulus, E_2 (MPa)	Shear modulus, G_{12} (MPa)	Density, ρ (kg/m^3)	Max. deflection, f (mm)	Free frequencies, f_s (Hz)
Steel	210,000	210,000	83,000	7830	0.087	277.6
Aluminum	70,000	70,000	2800	2600	0.262	278.2
CFRP$(0)_4$	130,000	10,000	7000	1500	0.440	426.7
GFRP$(0)_4$	40,300	6200	3000	1900	0.984	232.4
CFRP$(90)_4$	130,000	10,000	7000	1500	1.495	139.8
GFRP$(90)_4$	40,300	6200	3000	1900	2.521	111.7
Type of criteria	Max	Max	Max	Min	Min	Max

The results were obtained numerically using the software FEMAP and NeNastran. The shaft is modeled by isoparametric quadrangular finite elements in the form of multilayer shells. Composite shafts are made as laminates consisting of 4 layers—lamina.

The analysis was performed for the following materials: steel, aluminum, CFRP and GFRP. Composite shafts were considered with a fiber orientation angle of 0º (CFRP$(0)_4$ and GFRP$(0)_4$) and 90º (CFRP$(90)_4$ and GFRP$(90)_4$).

The mechanical characteristics of the analyzed materials as well as the obtained values of maximum displacements and free frequencies of the shaft, are given in Table 30.1.

30.2.1 Application of MCDM Methods in the Selection of Optimal Material

The decision-making process is used in management theory as part of the process of solving a certain problem. Many authors of management theory consider decision-making to be one of the most important tasks, both at the strategic and operational levels. Multi-criteria decision-making (MCDM) is a relatively new discipline, which through its development, should provide support to decision makers who face numerous and very often conflicting influencing factors. This method aims to maximize the quality of the decision following the selected criteria.

Methods of multi-criteria decision-making in the conceptual sense are not particularly complex and are easier to understand than classical single-criteria optimization. The most common division of MCDM procedures presupposes the existence of two basic groups of these methods [5–8], namely the Multiple Attribute Decision Making method (MADM) and the Multiple Objective Decision Making method (MODM). As the choice of one (best) of alternatives (materials) from a limited number of alternatives (materials) is sought within the set problem analyzed in this paper, we opted for the SAW method, which belongs to the group of MADM methods. The SAW (Simple Additive Weighting Method) method is a relatively simple method of multi-criteria decision-making, which takes into account the weight of the selected criteria. For each possible alternative solution, the so-called summary characteristic (A_i)—the value obtained by summing the products of relative weighting factors (W_j') and normalized performance values according to all selected criteria (r_{ij}). The alternative that corresponds to the highest calculated value of the summary characteristic (A^*) is the optimal solution:

$$A^* = \left\{ A_i \middle| \max_i \sum_{j=1}^{n} W'_j r_{ij} \right\} \quad (30.1)$$

30.2.2 Multicriteria Analysis of Material Characteristics

The paper analyzes a total of six different materials (alternatives, solutions) for six different characteristics (criteria), in fact for four materials, two of which have different fiber orientations. In the Table 30.2, the values of the selected characteristics for the considered materials are presented. At the same time, the types of criteria-characteristics are indicated and classified into those of maximization (max, the higher the value, the better the material characteristic) and minimization (min, the smaller the value, the better the material characteristic). Table 30.2 shows the values of normalized factors r_{ij}, obtained by one of the pre-ordered methods of data normalization.

The values of weight coefficients were determined using the Seaty procedure (Tables 30.3, 30.4 and 30.5). In order to examine the stability of the solution—the

Table 30.2 of normalized values of material characteristics (r_{ij})

material	Elastic modulus, E_1 (MPa)	Elastic modulus, E_2 (MPa)	Shear modulus, G_{12} (MPa)	Density, ρ (kg/m^3)	Max. deflection, f (mm)	Free frequencies, f_s (Hz)
Steel	1	1	1	0	1	0.53
Aluminum	0.18	0.31	0	0.83	0.93	0.53
CFRP(0)$_4$	0.53	0.02	0.05	1	0.85	1
GFRP(0)$_4$	0	0	0	0.94	0.63	0.38
CFRP(90)$_4$	0.53	0.02	0.05	1	0.42	0.09
GFRP(90)$_4$	0	0	0	0.94	0	0
Type of criteria	1	1	1	0	1	0.53

Table 30.3 Values of weighting coefficients (Seaty scale-procedure), variant 1

	Variant 1 (W_{i1}')							
	k_1	k_2	k_3	k_4	k_5	k_6	$\sum$	W_{i1}'
k_1	1	3	3	1	0	1	9	0.15
k_2	0	1	1	0	0	0	2	0.033333
k_3	0	1	1	0	0	0	2	0.033333
k_4	1	3	3	1	0	1	9	0.15
k_5	5	7	7	5	1	5	30	0.5
k_6	1	3	3	1	0	1	8	0.133333
$\sum$							60	1

Table 30.4 Values of weighting coefficients (Seaty scale-procedure), variant 2

	Variant 2 (W_{i2}')							
	k_1	k_2	k_3	k_4	k_5	k_6	$\sum$	W_{i2}'
k_1	1	1	1	1	1	1	6	0.166667
k_2	1	1	1	1	1	1	6	0.166667
k_3	1	1	1	1	1	1	6	0.166667
k_4	1	1	1	1	1	1	6	0.166667
k_5	1	1	1	1	1	1	6	0.166667
k_6	1	1	1	1	1	1	6	0.166667
$\sum$							36	1

Table 30.5 Values of weighting coefficients (Seaty scale-procedure), variant 3

	Variant 3 (W_{i3}')							
	k_1	k_2	k_3	k_4	k_5	k_6	$\sum$	W_{i3}'
k_1	1	3	3	0	0	0	7	0.090909
k_2	0	1	1	0	0	0	2	0.025974
k_3	0	1	1	0	0	0	2	0.025974
k_4	5	7	7	1	1	1	22	0.285714
k_5	5	7	7	1	1	1	22	0.285714
k_6	5	7	7	1	1	1	22	0.285714
$\sum$							77	1

choice of the optimal material, an analysis was performed for three different variants of weight coefficients, depending on the preference of certain characteristics.

On Figs. 30.1 and 30.2 the summary characteristics (A_i) for all three variants of weight coefficients for all six potential shaft materials are given. By analyzing both diagrams, it can be seen that steel has the best cumulative characteristic, in two

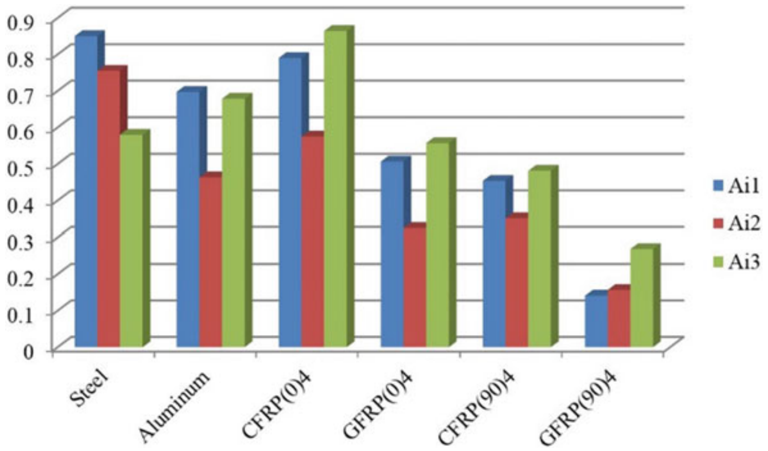

Fig. 30.1 Diagram representation of summary characteristics for three variants of performance weights—criteria for six shaft materials

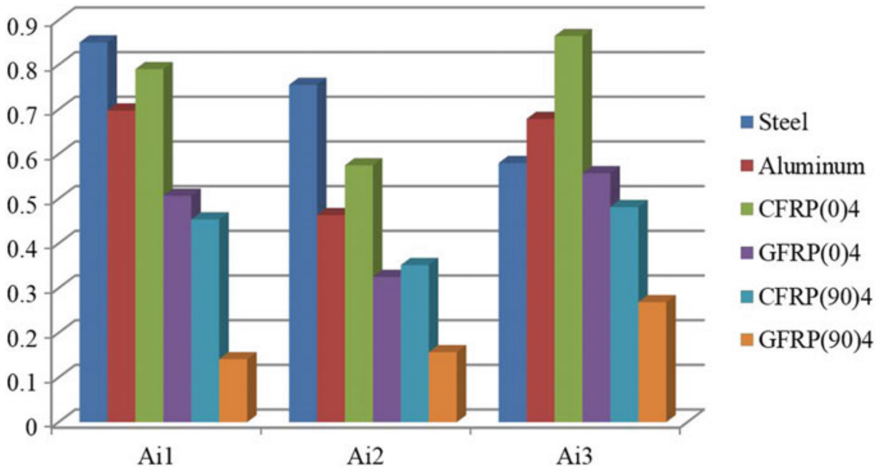

Fig. 30.2 Diagram representation of summary characteristics for three variants of performance weights—criteria

of the three cases, but that the average value is very close to the material made of polymer-reinforced carbon fibers (CFRP$(0)_4$).

30.3 Conclusion

The process of selecting the optimal material represents a significant and sensitive phase in the product design process. Within this phase, the constructor must, in accordance with the available material characteristics and the requirements of the potential construction, make an appropriate decision using an adequate method. Solving this type of design problem is most often done through the application of some of the methods of multi-criteria decision-making (MCDM). The paper specifically applies the method of additive weight factors known as the SAW method. Six selected materials (two "classic", steel and aluminum and four composite) presented with six different characteristics were analyzed. The characteristics of the material were treated as criteria, which, depending on the assessment and affinity of the constructor, were assigned different weight coefficients in the three presented variants. Based on a comparative analysis of the distribution of weight coefficients, it was concluded that of the six materials considered, the best characteristics (observing all three variants with different weight coefficients), during bending, showed shafts made of steel and composite of carbon fibers reinforced with polymers (CFRP$(0)_4$). In each of the three variants of weight coefficients these two materials showed better characteristics than the others.

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