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MODAL ANALYSIS OF A COMPOSITE CRANKSHAFT FOR AN INTERNAL COMBUSTION ENGINE (ICE)

ABSTRACT: Crankshafts are responsible for transforming the reciprocating motion of engine pistons into rotational motion. During their service life, due to the extremely high number of load cycles, crankshafts must exhibit high fatigue strength and durability. Furthermore, crankshafts, especially in diesel engines, operate at relatively low rotational speeds and high torque values, making them susceptible to resonant vibrations. The combination of these factors (high-cycle fatigue and resonant vibrations) can lead to a reduction in crankshaft service life. The subject of this paper is the investigation of potential improvements through the application of new materials with the lowest possible mass, while maintaining sufficient fatigue strength and dynamic stability. Using the software tools SolidWorks and Femap, both steel and composite crankshafts were modelled and numerically analysed. The research results indicate that the application of composite materials can significantly reduce the mass of the crankshaft without compromising its mechanical strength and dynamic stability.

KEYWORDS: crankshaft, composite materials, modal analysis, natural frequencies, deformations

MODALNA ANALIZA KOMPOZITNOG KOLENASTOG VRATILA MOTORA SA UNUTRAŠNJIM SAGOREVANJEM

REZIME: Kolenasta vratila imaju ulogu da naizmenično pravolinijsko kretanje klipova motora transformišu u rotaciono kretanje. Tokom radnog veka, zbog vrlo velikog broja ciklusa opterećenja, ova vratila moraju imati veliku otpornost na zamor i izdržljivost. Takođe, kolenasta vratila, pogotovo ako se radi o dizel motorima, rade pri malom broju obrtaja sa velikim vrednostima obrtnih momenata tako da su podložna rezonantnim vibracijama. Kombinacija ovih parametara (visokociklični zamor i rezonantne vibracije) dovodi do smanjenja radnog veka radilice. Predmet

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ovog rada su poboljšanja u smislu potrage za novim materijalima sa što je moguće manjom masom, ali dovoljnom zamornom izdržljivošću i dinamičkom stabilnošću. Primenom softverskih alata SolidWorks i Femap izmodelirana su i numerički analizirana kako čelično tako i kompozitna vratila. Rezultati istraživanja pokazuju da se primenom kompozitnih materijala može znatno smanjiti masa kolenastog vratila, bez narušavanja njegove mehaničke otpornosti i gubitka stabilnosti..

KLJUČNE REČI: kolenasto vratilo, kompozitni materijali, modalna analiza, sopstvene frekvencije, deformacije

INTRODUCTION

The crankshaft is one of the most heavily loaded and geometrically most complex components of an internal combustion engine (ICE); it converts the reciprocating (back-and-forth) motion of the pistons into rotational motion, which is then transmitted to the drivetrain (Hoag & Dondlinger, 2016). Due to the combined effects of bending, torsion, and axial loading that act simultaneously in the fillet zones of the main and crank pin journals, crankshafts are susceptible to failure caused by high-cycle fatigue, which remains one of the most commonly reported causes of engine failure in service (Fonte, et al. 2013).

In addition to fatigue, crankshafts are subjected to periodically varying gas and inertial forces that excite torsional, axial, and bending oscillations. If the excitation frequency approaches one of the crankshaft's natural frequencies, resonance can occur, causing a sudden increase in dynamic stress and potentially leading to premature failure (Horváth & Égert, 2015). This risk is especially pronounced in low- and medium-speed, high-torque engines such as diesel engines, which is why the dynamic (modal) behaviour of the crankshaft must already be verified at the design stage.

At the same time, the automotive industry is under constant pressure to reduce vehicle mass in order to improve fuel consumption and lower harmful emissions. Fibre-reinforced polymer composites (FRP) offer a favourable combination of low density and high specific stiffness, and are therefore increasingly being considered as a replacement for conventional steel in structural and rotating vehicle components (Đorđević, 2018). Recent numerical studies on composite drive shafts, chassis, and crankshafts confirm that replacing steel with polymers reinforced with carbon, aramid, or glass fibres can simultaneously reduce mass and shift the natural frequencies outside the normal operating range (Samuel & Tayong, 2023; Wakshume, 2025; Sarnobat, et al. 2026).

The aim of this paper is to numerically investigate the modal behaviour of a passenger-vehicle crankshaft made of conventional steel (42CrMo4) and three composite alternatives - carbon-fibre-reinforced polymer (CFRP), aramid-fibre-reinforced polymer (AFRP), and glass-fibre-reinforced polymer (GFRP). The analysis focuses exclusively on fibre-reinforced polymers, as they represent the group of materials with the most realistic potential for structural application in crankshafts; using the finite element method (FEM), the first five natural frequencies were compared and the resulting mass reduction was determined.

LOADING AND CALCULATION OF THE CRANKSHAFT'S NATURAL FREQUENCIES

During engine operation, the crankshaft receives the force of the expanding combustion gases through the connecting rod at the crank pin (big-end) journal and converts it into torque, which is transmitted to the flywheel through the main journals. Since the load occurs intermittently and cyclically throughout the entire service life of the engine, the fillets of the main and crank pin journals, the lubrication holes, and the press-fitted joints represent critical, fatigue-sensitive locations of this component (Nikolić, 2004). These cyclic loads also cause angular, transverse, and axial oscillations of the crankshaft which, in the case of resonance, generate additional stresses that, combined with the base stresses, can lead to failure of the crankshaft.

The main cause of crankshaft vibration is its imbalance, which can lead to very large oscillation amplitudes and, as a result, damage to the crankshaft within a very short period of time. The intensity of the vibrations is influenced by many factors, such as the number and arrangement of the cylinders, the engine power, and others. For this reason, particular attention must be paid to calculating the natural frequency values and checking the possibility of resonance occurring in crankshafts.

Governing equations of modal analysis

The undamped free-vibration equation of motion of the discretised crankshaft is given by Equation (1), where K and M are the global stiffness and mass matrices assembled from the finite element model and q is the nodal displacement vector.

$$\left(\boldsymbol{K} - \omega^2 \boldsymbol{M}\right) \cdot \boldsymbol{q} = 0 \tag{1}$$

Non-trivial solutions require the determinant of the system to vanish, Equation (2); the n roots ω_i^2 of this characteristic equation are the squares of the natural circular frequencies of the crankshaft, and the associated eigenvectors are the corresponding mode shapes.

$$\left|\boldsymbol{K} - \omega^2 \boldsymbol{M}\right| = 0 \tag{2}$$

The natural frequency in Hz corresponding to each circular frequency is obtained from Equation (3).

$$f = \omega/(2\pi) \tag{3}$$

The critical rotational speed of the crankshaft can be calculated using the following expression:

$$n = 60 \cdot f/k \tag{4}$$

where:
n – critical rotational speed, min^{-1};
f – natural frequency, Hz;
k – harmonic order (for a four-cylinder engine, the fourth harmonic order is the most critical; therefore, k=4).

NUMERICAL MODEL AND METHODOLOGY

Geometry and finite element model

The crankshaft geometry (V-type engine; total length 583 mm, cylinder bore 80 mm, main and crank pin journal diameters of 60 mm and 55 mm, respectively) was created in SolidWorks according to standard recommendations for crankshaft dimensioning (Statków, 2024) and imported into Femap 2021.2. for finite element analysis. The crankshaft model was discretized using second-order tetrahedral finite elements. Figure 1 shows the model with the generated finite element mesh and the boundary conditions applied at the bearing locations, as well as on the part of the flange that connects to the flywheel. All analysed crankshaft variants had the same geometric dimensions, the same mesh, and the same boundary conditions. The only difference was the type of material used.

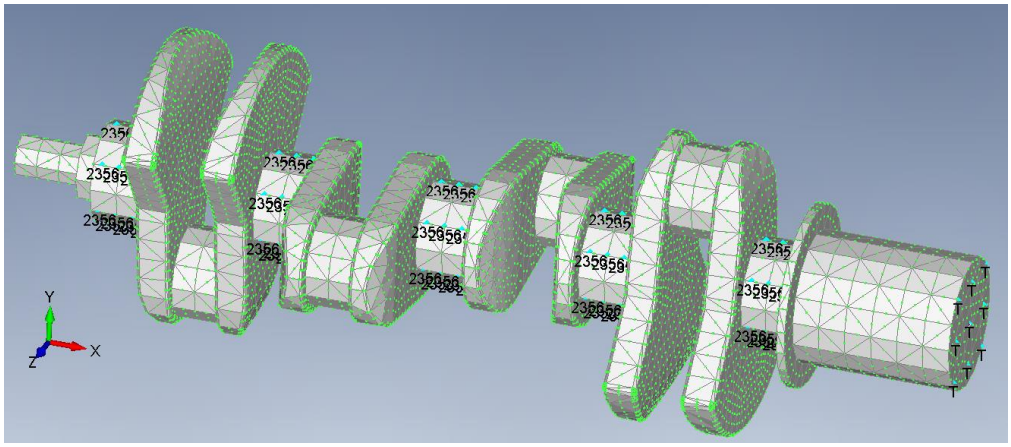


Figure 1 Crankshaft model

Material properties

A numerical modal analysis was carried out for the original steel crankshaft made of 42CrMo4 steel, as well as for composite crankshafts made of carbon-fibre-reinforced polymer (CFRP), aramid-fibre-reinforced polymer (AFRP), and glass-fibre-reinforced polymer (GFRP). Of the three composites considered, CFRP offers the highest specific stiffness and strength, along with excellent fatigue resistance, but also the highest material cost and pronounced

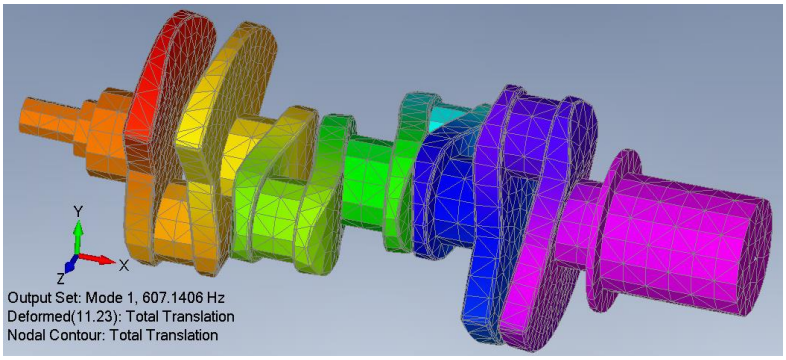
anisotropy (Đorđević, 2018). AFRP has lower stiffness than CFRP but very good impact and wear resistance. GFRP is the cheapest and easiest to process of the three materials, but has the lowest specific stiffness, which can result in lower natural frequencies compared to the steel variant for the same geometry. Comparative numerical studies of CFRP versus other fibre systems in vehicle structural components consistently show that CFRP provides the highest stiffness and natural frequencies, while glass- and aramid-fibre-reinforced variants sacrifice some dynamic stiffness in exchange for lower cost and easier manufacturing (Wakshume, 2025). The mechanical properties of the steel and the analysed composite materials are given in Table 1.

Table 1 Material properties used in the finite element model

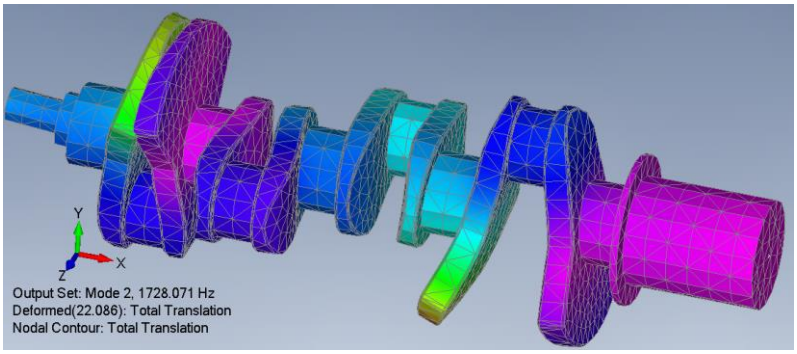
Material	Young's Modulus E, GPa	Shear Modulus G, GPa	Poisson's Ratio ν	Density ρ, kg/m³
42CrMo4 steel	210	81	0,30	7850
CFRP	126	49	0,28	1810
AFRP	72	27	0,34	1310
GFRP	39	15.6	0,25	1910

RESULTS AND DISCUSSION

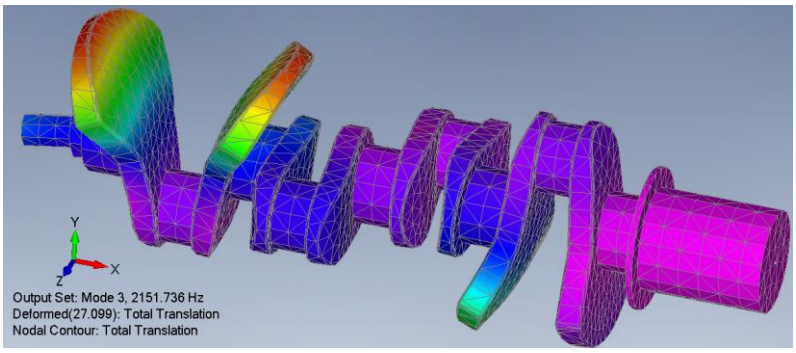
The results of the modal analysis of the steel crankshaft, for the first three oscillation modes, are shown in Figure 2.



a)



b)



c)

Figure 2 View of the crankshaft model for material 42CrMo4 at different modes: a) mode 1, b) mode 2, c) mode 3

The same analysis procedure was applied to the other crankshaft materials. The natural frequency values for the first five oscillation modes, for all four analysed crankshaft materials, are given in Table 2.

Table 2 First five natural frequencies of the crankshaft, Hz

Mode	42CrMo4	AFRP	CFRP	GFRP
1	607,1	868,7	980,3	532,3
2	1728,1	2476,2	2783,3	1512,1
3	2151,7	3085,6	3459,6	1880,2
4	2759,6	3949,4	4446,3	2415,8
5	2842,6	4089,3	4541,0	2471,2

As can be seen from Table 2, higher oscillation modes have significantly higher natural frequency values, but their oscillation amplitudes are smaller, so they represent a lower risk of failure during crankshaft operation. Based on the natural frequency values obtained for the first oscillation mode, the critical rotational speeds of the analysed crankshafts can be determined using equation (4). The resulting critical rotational speed values, for all analysed crankshaft materials, are shown graphically in Figure 3.

Looking at the obtained results, it can be concluded that the CFRP composite provides the crankshaft with the highest natural frequency values, i.e., the highest critical rotational speed, which almost completely eliminates the possibility of resonance occurring. AFRP follows immediately after it, also showing better characteristics compared to steel, while only the GFRP composite performs worse than steel. The main advantage of composites over steel is their high specific stiffness (the ratio of stiffness to mass), which directly affects the natural frequency values. This is precisely what leads to the observed behaviour of the different crankshaft materials.

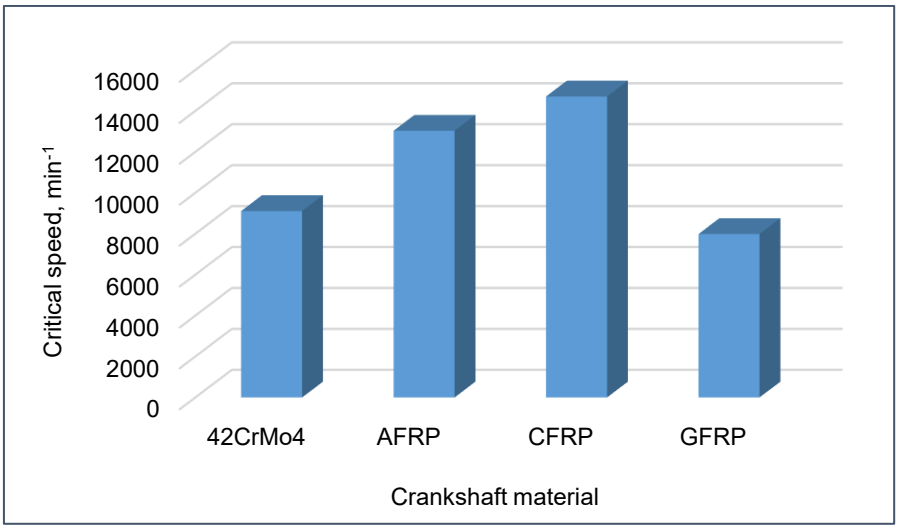


Figure 3 Graphical representation of the critical rotational speeds for the analysed crankshaft materials

The low mass of the composite crankshafts, and consequently their lower moment of inertia, also directly contributes to the increase in natural frequency values, i.e., critical rotational speeds. A graphical representation of the mass of the analysed crankshaft materials can be seen in Figure 4. It can be observed that the mass of the composite crankshafts is several times lower than that of the steel crankshaft.

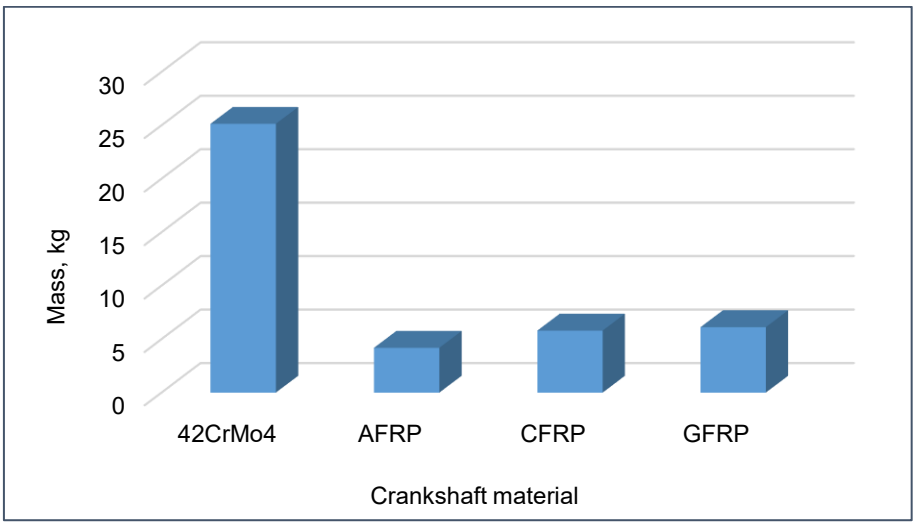


Figure 4 Graphical representation of the mass for the analysed crankshaft materials

The total modal displacements for the first oscillation mode, for the selected crankshaft materials, are shown graphically in Figure 5.

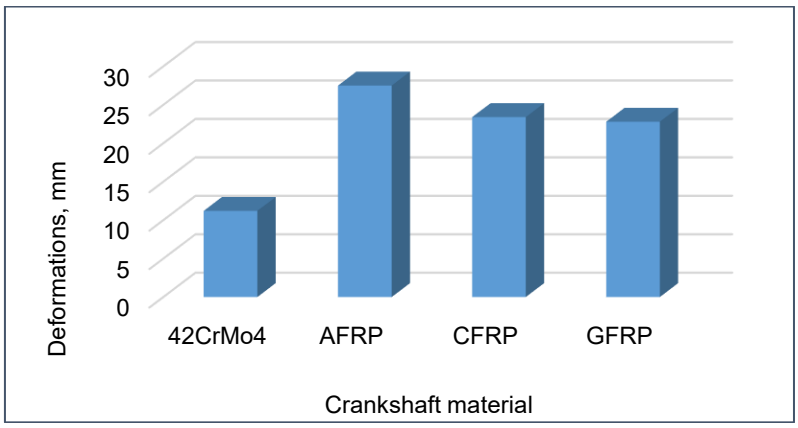


Figure 5 Graphical representation of the total displacements for the analysed crankshaft materials

The modal displacement values of the composite crankshafts are considerably higher than those of the steel crankshaft; however, the properties of the analysed composite materials are such that they can withstand the mentioned modal deformations.

MULTICRITERIA SELECTION OF CRANKSHAFT MATERIAL USING THE SAW METHOD

Methodology

The Simple Additive Weighting (SAW) method was applied to select the optimal crankshaft material. Four alternatives were evaluated using four criteria derived from the dynamic characteristics of the shaft: natural frequency (k1), critical rotational speed (k2), mass (k3), and total modal displacement (k4). The first two criteria are of the maximization type, whereas mass and modal displacement are minimized.

For max criteria:

$$r_{ij} = \left(x_{ij} - x_j^{\min}\right) / \left(x_j^{\max} - x_j^{\min}\right) \tag{5}$$

For min criteria:

$$r_{ij} = \left(x_j^{\max} - x_{ij}\right) / \left(x_j^{\max} - x_j^{\min}\right) \tag{6}$$

The values of the considered criteria for the selected materials (xij) are shown in Table 3.

Table 3 Values of the considered criteria for selected materials (xij)

Material	Natural frequency fs, Hz	Critical speed n_{cr}, min^{-1}	Mass m, kg	Total modal displacement, mm
42CrMo4 steel	607,1	9106,5	25,14	11,2
AFRP	868,7	13030,5	4,19	27,5
CFRP	980,3	14704,5	5,80	23,4
GFRP	532,3	7984,5	6,12	22,8
type of criteria	**max**	**max**	**min**	**min**

The values in Table 3 form the decision matrix. After normalization, the dimensionless values shown in Table 4 were obtained.

Table 4 Normalized values of the considered criteria (rij)

Material	k1	k2	k3	k4
42CrMo4 steel	0,167	0,167	0,000	1,000
AFRP	0,751	0,751	1,000	0,000
CFRP	1,000	1,000	0,923	0,252
GFRP	0,000	0,000	0,908	0,288

Weight coefficients are considered in two variants. In Variant I, greater importance was assigned to dynamic stability and low mass (w = 0.30; 0.30; 0.25; 0.15). In Variant II, all criteria were assigned equal importance (w = 0.25).

The values of the relative weighting coefficients are shown in the diagram in Figure 6.

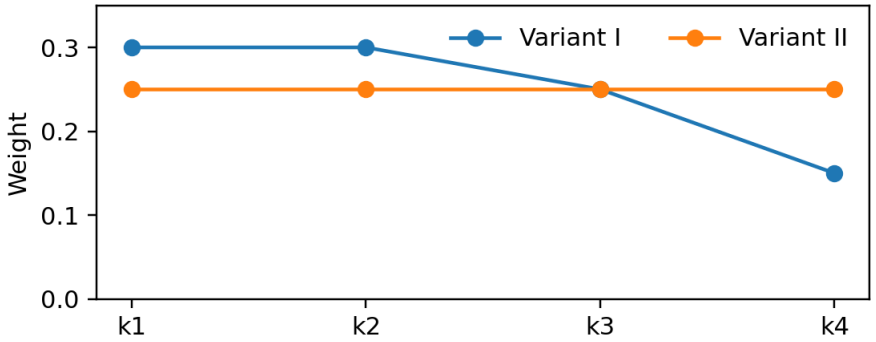


Figure 6 Relative weighting coefficients in the two variants

SAW results and discussion

The aggregate score for each alternative was calculated as Ai = Σ wj rij. The resulting scores and ranking are presented in Table 5.

Table 5 Aggregate SAW scores and ranking

Material	Variant I	Variant II	Rank
CFRP	**0,869**	**0,794**	**1**
AFRP	0,701	0,626	2
GFRP	0,270	0,299	3
42CrMo4 steel	0,250	0,334	4

The summary SAW results for the crankshaft materials considered are shown in Figure 7.

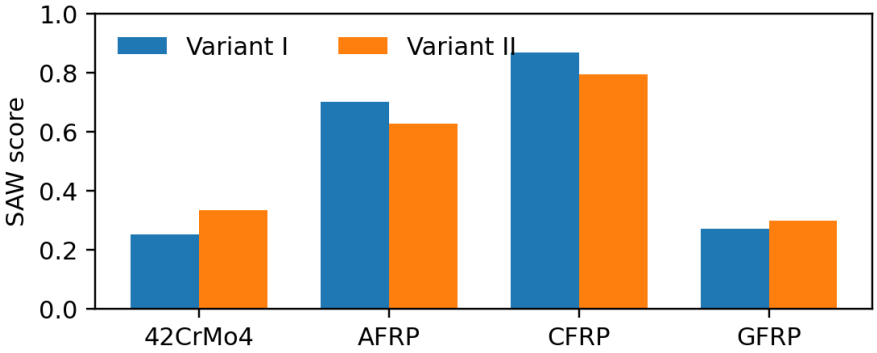


Figure 7 Aggregate SAW scores for the considered materials

Discussion

CFRP achieves the highest aggregate score in both variants. It combines the highest natural frequency and critical rotational speed with a relatively low mass, which makes it the most favourable alternative from the standpoint of the adopted criteria. AFRP ranks second, mainly because of its minimum mass and high dynamic performance. GFRP benefits from low mass but has the lowest natural frequency and critical speed. The 42CrMo4 steel exhibits the smallest modal displacement, but its substantially higher mass and lower dynamic indicators reduce its overall SAW score.

CONCLUSIONS

Based on the numerical modal and SAW analysis performed for both the conventional steel crankshaft and crankshafts made of composite materials (AFRP, CFRP, and GFRP), and on the results obtained, the following conclusions can be drawn:

1. By using composite materials, the natural frequencies of the crankshaft reach very high values, so that the critical rotational speeds are significantly higher than the maximum rotational speed the engine can reach, thereby eliminating the possibility of resonance;
2. Compared to steel, composite materials have a greater capacity to damp vibrations, meaning that the vibration amplitudes are considerably smaller, which reduces the risk of crankshaft failure;
3. By using composite materials, the mass of the crankshaft can be significantly reduced without compromising its mechanical strength.
4. The SAW analysis provides a clear ranking of the candidate crankshaft materials. CFRP is the optimal alternative in both weighting scenarios, followed by AFRP. The unchanged first and second positions indicate that the result is robust with respect to the two adopted weighting schemes.

Therefore, the use of composite crankshafts can contribute to reduced fuel consumption, improved vehicle dynamics, increased reliability and service life, as well as increased overall engine efficiency and a reduced negative impact on the environment.

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REFERENCES

Đorđević, Z. (2018). *Kompozitne konstrukcije* [Composite structures]. Faculty of Engineering, University of Kragujevac.

Fonte, M., Li, B., Reis, L., & Freitas, M. (2013). Crankshaft failure analysis of a motor vehicle. *Engineering Failure Analysis*, 35, 147–152. https://doi.org/10.1016/j.engfailanal.2012.11.014

Hoag, K., & Dondlinger, B. (2016). Cranktrain (Crankshafts, connecting rods, and flywheel). In Vehicular engine design (2nd ed., pp. 321–360). Springer.

Horváth, P., & Égert, J. (2015). Stress analysis and weight reduction of a one-cylinder engine crankshaft. *Acta Technica Jaurinensis*, 8(3), 201–217. https://doi.org/10.14513/actatechjaur.v8.n3.377

Raushan, R., Dhande, K. K., Jamadar, N. I., & Malwe, P. D. (2022). Material characterization, design and analysis of CF/PA66 drive shaft with high strength carbon steel. *Materials Today: Proceedings*, 64(1), 51-58. https://doi.org/10.1016/j.matpr.2022.03.512

Nikolić, V. (2004). *Mašinski elementi – teorija, proračun, primeri* [Machine elements – theory, calculation, examples]. Faculty of Mechanical Engineering, Kragujevac.

Samuel, M., & Tayong, R. B. (2023). 3D numerical analysis of the structural behaviour of a carbon fibre reinforced polymer drive shaft. *Results in Engineering*, 18, 101120. https://doi.org/10.1016/j.rineng.2023.101120

Sarnobat, S. S., Shiyekar, S. M., & Choudhary, K. (2026). Low-weight, high-durability crankshaft development using glass fiber composites: Numerical and experimental investigations. *Journal of Polymer & Composites*, 14(4). https://doi.org/10.37591/JOPC.vi.249342

Statków, P. R. (2024). *Calculations for I.C. engine crankshafts* (Publication 8/P). Lloyd's Register.

Wakshume, E. (2025). Lightweight composite optimization of URAL-4320 chassis using CFRP and BFRP: Structural and modal finite element analysis. *Results in Engineering*, 28, 108134. https://doi.org/10.1016/j.rineng.2025.108134