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Fatigue testing of steel profiles filled with polymer concrete for machine tool body applications

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Welded steel body components are commonly employed in special-purpose machine tools due to their high stiffness. However, this design approach typically results in low damping capacity. To enhance the dynamic performance of such structures, the use of polymer concrete as a filler material in closed profiles has been proposed. This paper presents the results of an experimental investigation on steel beams filled with polymer concrete. Three different polymer concrete mixtures were selected for testing. The study includes fatigue testing to evaluate whether long-term variable loading, representative of operational conditions, induces structural changes in the polymer concrete. The study analyzed the natural frequencies corresponding to the first three resonance modes, as well as the damping coefficients. Based on the measurement results, it was found that throughout the entire fatigue testing range, the variation in the sample's natural frequency ranged from 1.5 to 29.5 Hz. In contrast, the damping coefficient varied between 0.023 and 0.161 for the tested sample. Dynamic parameters were analyzed, and the most effective indicator for assessing structural alterations is proposed by the author.

1. Introduction

The structural components of cutting machine tools are most commonly manufactured from cast iron. These bodies exhibit favorable mechanical properties, particularly high damping capacity, making them suitable for use in mass-produced machine tools. This suitability stems from the nature of the manufacturing process, which involves the preparation of casting molds, the casting itself, and a prolonged seasoning period before the component can be integrated into the production line.

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Cast iron components are typically characterized by high weight, limited design flexibility, and elevated costs when applied to small-batch or custom production [1–3]. For specialized machine tools produced in single units according to specific customer requirements, the cost and lead time associated with cast iron components are often prohibitive. As a result, machine tool designers are exploring alternative materials for structural elements.

One such alternative involves the use of layered composite structures composed of carbon fiber, resin, and aluminum, as described in [4]. The study analyzed two hybrid configurations—surface reinforcement and composite jackets—focusing on maximum deflection under deadweight and the first natural frequency. Damping capacity was enhanced by introducing a friction layer between the composite and aluminum in the spindle holder.

Another approach, presented in [5], involves a hybrid structure combining cast iron and mineral casting for lathe components. The authors proposed a thin-walled cast iron body filled with polymer concrete, which resulted in improved static and dynamic performance. Choi and Lee [6] developed a carbon fiber-epoxy spindle that demonstrated higher natural frequency and damping compared to a steel spindle. Suh et al. [7] proposed a carbon fiber composite laminate for spindle covers. Additional applications of composites to enhance dynamic stiffness include headstocks [8].

Kim et al. [9] investigated sandwich structures composed of fiber-reinforced composites, polymer foams, and resin concrete for use in micro-EDM machine frames. The resulting prototype exhibited favorable stiffness and damping characteristics.

Cortes and Castillo [10] compared the dynamic properties of beams made from gray cast iron and polymer concrete, demonstrating that polymer concrete offers superior damping over a broader frequency range.

Another potential solution for structural components is the use of welded steel profiles. While these structures provide the necessary stiffness, they typically exhibit lower damping than cast iron components. To address this limitation, the internal cavities of welded steel profiles can be filled with polymeric materials possessing high damping capacity.

Dunaj et al. [11] presented experimental results for steel beams filled with polymer concrete, leading to the development of a computational model consistent with the observed behavior.

Dunaj et al. [12], the results of experimental and numerical studies on the application of a prototype lathe body made from steel profiles filled with polymer concrete were presented. The use of such infill enabled the development of a lightweight machine body structure with favorable stiffness and damping characteristics. Moreover, the study demonstrated that complete filling of all internal cavities with polymer concrete does not always lead to improved machining stability. The proposed manufacturing approach for machine tool body components may serve as a promising alternative to the conventional use of gray cast iron casting technology.

Research on the static stiffness of a lathe body constructed from steel profiles filled with polymer concrete was presented in [13]. It was shown that polymer concrete infill increases both stiffness and damping; however, it is not the sole factor influencing the behavior of the entire structure. The study indicated that other weak points, unrelated to the body structure itself, may exist and have a more significant impact on the overall stiffness of the machine. The authors recommend that a comprehensive evaluation should consider multiple performance characteristics rather than focusing on a single selected parameter.

Dunaj [14], the author proposed a modeling approach for heterogeneous materials such as polymer concrete, which consists of a solid aggregate phase bonded by a polymer matrix. Significant differences in the properties of individual components can influence the overall behavior of the composite. Modeling the material by distinguishing between its constituent phases improves the accuracy of simulations compared to treating the material as homogeneous.

Dunaj et al. [15], numerical simulations of steel-section body elements were compared with those filled with polymer concrete. The results confirmed that the infill generally increased the resonant frequencies of the corresponding vibration modes without introducing new modes absent in the unfilled steel structure.

Sangkeun et al. [16], the results of tests conducted on polymer concrete beams were presented. The findings indicate that the incorporation of carbon fibers into the polymer concrete mixture increases the damping ratio by approximately a factor of three, while maintaining a comparable value of the modulus of elasticity relative to conventionally produced concrete. The authors conclude that the inclusion of carbon fibers in the polymer concrete composition has a beneficial effect on the reduction of resonance vibrations. The solution proposed in the study pertains to the case where polymer concrete is used as a standalone structural material.

Qian and Stroeven [17], proposed the incorporation of additional steel fibers into the concrete mix. The research focused on their influence on the properties of the concrete mixture itself, as well as on their distribution and concentration within the mix. The proposed solution involves the development of a new type of concrete mixture with cement as the binder. The authors conclude that a small amount of fine particles should be included in the composition of hybrid concrete. Furthermore, the varying sizes of the filling elements (steel fibers) affect the mechanical properties of the tested polymer concrete to different extents. Additionally, the authors state that a mixture of fibers made from different types of materials, combined with their uniform spatial distribution within the polymer concrete, leads to an improvement in the strength properties of the tested polymer concretes.

Sezan [18], the author proposed the development of a polymer concrete mixture intended for use in the construction of machine tool bodies (technological machinery). The tested material exhibited damping properties approximately four to seven times greater than those of gray cast iron. The authors were unable to clearly identify which specific components of the polymer concrete were responsible for the enhanced damping characteristics. A key conclusion presented in the study is the potential for combining polymer concrete with a metallic load-bearing structure, which is planned to be the subject of future research. The fatigue-tested beams represent an example of such a hybrid construction, combining a steel element with polymer concrete.

Žiga [19], a strength analysis was conducted on steel tubes filled with concrete and with concrete reinforced with polypropylene fibers. The mechanical tests confirmed that filling a steel tube with concrete significantly increases the structural stiffness compared to an unfilled tube. In the assessment of tensile stresses, even after internal cracking was observed, the stiffness remained higher than that of the empty tube. The conducted strength tests of the structure composed of a thin steel shell filled with concrete demonstrated its high stiffness.

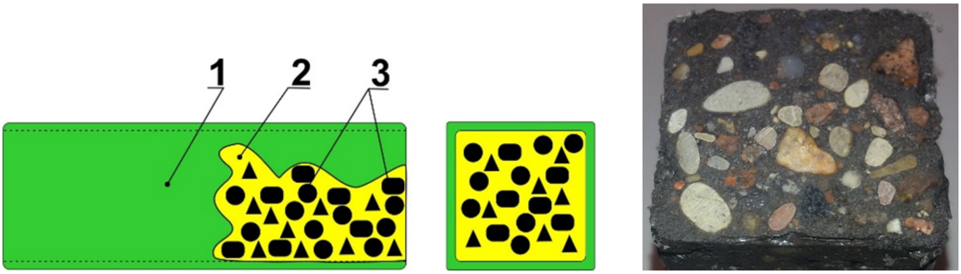
Based on these findings, it can be assumed that the increased stiffness of a steel structure filled with polymer concrete may positively influence its fatigue performance, which will be the subject of experimental investigations in the present study.

Although various methods for enhancing the damping properties of machine tool structures have been proposed, the long-term behavior of these solutions under operational conditions remains underexplored. In particular, the literature lacks studies on the effects of time-varying loads and vibrations on the properties of polymer concrete.

This paper presents the results of fatigue testing on steel beams filled with different polymer concrete mixtures. The dynamic parameters of the beams and their evolution during fatigue loading are evaluated to assess the long-term performance of the proposed solution.

2. Materials and methods

The fatigue test stand for polymer concrete mixtures consisted of a steel profile (dimensions: 70 × 70 × 1000 mm) filled with polymer concrete. A schematic of the beam filled with polymer concrete is shown in Fig. 1. Three polymer concrete mix-



(a) (b)

Fig. 1. (a) Diagram of a beam filled with polymer concrete: 1 – steel profile; 2 – resin; 3 – mineral fill fractions of different sizes; (b) cross-sectional view of the polymer concrete mixture itself, using M05 as an example

tures, selected from previously developed formulations, were subjected to fatigue testing. These mixtures were designated as M05, M07, and M11.

Table 1 presents the composition of the polymer concrete mixtures used in the experimental study. The composition is expressed as the weight percentage of each component, and the density of each mixture is also provided.

Table 1. Density and composition of mixtures for experimental studies (Percentage by mass)

Mixture	Density [kg/dm^3]	Resin [%]	Ash [%]	Fine fraction (0.5–2 mm) [%]	Medium fraction (2–8 mm) [%]	Coarse fraction (8–16 mm) [%]
M05	2.10	15	1	19	15	50
M07	1.85	26	1.7	15.7	13	43.6
M11	2.12	13.2	1.3	20	15.8	49.7

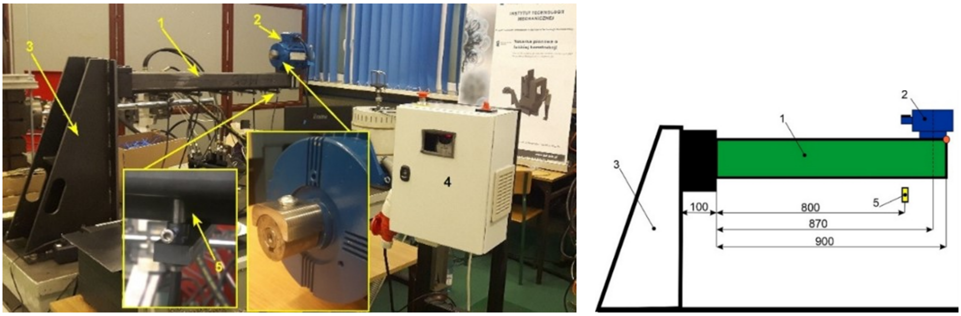
In the conducted study, a steel profile with dimensions of 70 × 70 × 1000 mm and a wall thickness of 2 mm was used. This profile corresponds to a standard hot-rolled section available on the market. One end of the profile was sealed by welding a thin steel plate, ensuring a tight closure. During the polymer concrete casting process, the profile was positioned vertically, with the sealed end at the bottom. This arrangement allowed the profile to be filled completely along its entire length.

The distribution of the polymer concrete within the profile was governed by gravitational forces, while the open upper end facilitated the free escape of air during pouring. To further reduce the risk of air entrapment and ensure the continuity of the polymer concrete structure, the profile was gently tapped several times along its length using a rubber mallet. This procedure was intended to promote uniform filling and minimize the presence of voids.

The beams were cast under normal gravitational conditions, without the use of any specialized procedures. Prior to casting, the interior of the steel profile was cleaned to remove loose contaminants and then thoroughly dried. The composition of the polymer concrete used in the study is original and was developed by the author.

The fatigue tests were conducted to determine whether the stiffness and damping properties of the polymer concrete would degrade under long-term cyclic loading. The tests aimed to verify whether delamination within the polymer concrete structure or at the interface between the polymer concrete and the steel profile walls would occur due to induced vibrations – in other words, whether structural changes would take place.

The beam filled with polymer concrete was mounted in a fatigue test stand, as illustrated in Fig. 2. The stand consisted of a fixed support (3), to which one end of the beam (1) was rigidly attached. A dynamic excitation system was connected to the opposite end of the beam. This system used an electric motor with an



(a) (b)

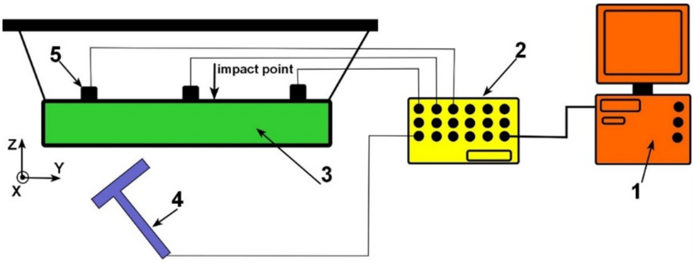
Fig. 2. (a) View of the test stand during the implementation of experimental tests 1 – tested beam, 2 – eccentric motor, 3 – beam mounting, 4 – motor speed control system, 5 – displacement sensor; (b) dimensional diagram of the fatigue test stand

eccentrically mounted mass (2) on its shaft. The motor control unit (4) allowed for precise speed adjustment. A displacement sensor (5) was used to monitor the maximum displacement amplitude during testing.

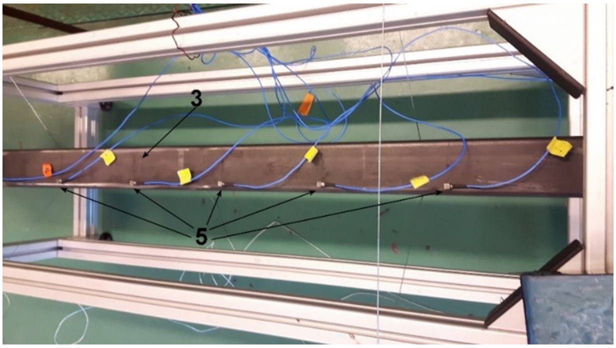
During fatigue testing, the maximum vibration amplitude at the sensor location (5) was set to 0.6 mm. This displacement is significantly greater than the typical vibration amplitudes experienced by machine tool body components during operation. The selected amplitude allowed for the evaluation of polymer concrete behavior under extreme conditions. The eccentric mass and motor speed were adjusted to achieve the target displacement for each polymer concrete mixture. For mixture M05, the required frequency was 22.5 Hz; for M07, 22.4 Hz; and for M11, 22.6 Hz.

Prior to fatigue testing, baseline measurements (denoted as 0.0 M cycles) were taken for each mixture (M05, M07, M11) before mounting the beam in the test stand. Fatigue testing was conducted up to three million load cycles, divided into seven stages. After each stage, the beam was removed from the stand and subjected to dynamic testing (modal analysis). It was then remounted in the same configuration for the next stage. The fatigue cycle intervals were: 0.6, 1.0, 1.4, 1.8, 2.2, 2.6, and 3.0 million cycles.

Fig. 3 shows a schematic and photograph of the modal test setup. The test beam (3) was freely suspended using steel cables. Acceleration sensors (5) were attached at designated measurement points. The excitation point was located near the beam's center, but offset from the node of the second vibration mode (see Fig. 6b). A preliminary frequency analysis of the beams was carried out using the finite element method (FEM). The results of this analysis made it possible to determine the mode shapes as well as the antinodes and nodes for the first three vibration modes. Knowledge of these parameters allowed for the excitation point to be selected during experimental testing in such a way that it did not coincide with a vibration node. Excitation was applied using a modal hammer (4). Measurement



(a)



(b)

Fig. 3. (a) Schematic of the stand for the implementation of the modal test: 1 – measurement computer, 2 – measurement signal acquisition system, 3 – tested beam; 4 – modal hammer; 5 – acceleration sensors; (b) view of the beam on the stand during the implementation of the modal test

signals were processed via an analog-to-digital converter (2) and recorded on a data acquisition computer (1), where further analysis was performed.

The recorded data exhibited slight variability in the results. This variability may stem from several sources. One is systematic variability due to structural changes caused by long-term cyclic loading, which is the focus of this study. Additionally, variability may arise from differences between nominally identical specimens, such as slight variations in the distribution of aggregate within the polymer concrete or minor differences in beam length. Random variability introduced by the multi-stage testing process also contributes to the observed differences.

To account for variability due to randomness and specimen differences, additional beams made with the M05 mixture were prepared. These were used to estimate the expected variation in the measured parameters and to determine whether changes observed during fatigue testing were due to actual structural changes in the polymer concrete.

Four reference beams with the M05 mixture were cast. One was used for fatigue testing, while the remaining three were used for comparative analysis. Based on the results, the expected values and confidence intervals for the dynamic parameters were determined.

The experimental analysis focused on the frequency response functions (FRFs) recorded at selected measurement points. The resonant frequencies of the first three vibration modes and the damping coefficients were used to evaluate changes in the dynamic properties of the tested beams.

The damping ratio is defined as the ratio of the frequency bandwidth corresponding to a 3 dB decrease in amplitude to the resonant frequency [20, 21]. This relationship is expressed by the following formula:

$$\zeta = \left(\frac{1}{2} \cdot \frac{\Delta f_{3\,\mathrm{dB}}}{f_0}\right) \cdot 100\%, \tag{1}$$

where: ζ – damping ratio, f_0 – resonance frequency.

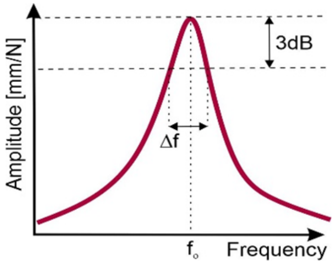


Fig. 4. Definition of the damping ratio [20, 21]

3. Results

During the fatigue testing of the beams, a series of frequency response functions (FRFs) were obtained. For all three tested polymer concrete mixtures, the FRFs

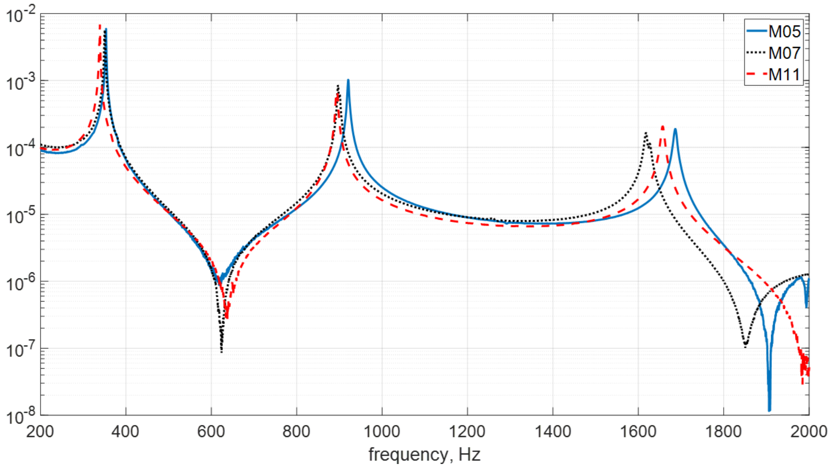


Fig. 5. Example plot of the frequency response function (FRF) recorded during experimental testing

exhibited similar shapes. Fig. 5 shows an example of a recorded response function at the measurement point located at the edge of the beam.

After double integration of the measurement signal, the frequency response function was expressed in units of dynamic compliance [mm/N]. Within the analyzed frequency range, three distinct vibration modes of the beam were identified. For each mixture (M05, M07, M11), the first vibration mode exhibited the highest amplitude, while the subsequent modes showed progressively lower amplitudes. Fig. 6 illustrates the extreme frames of the animation corresponding to the first three vibration modes of the tested beams.

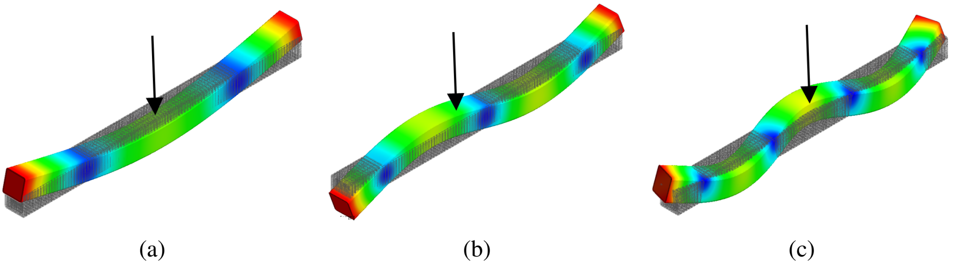


Fig. 6. Animation of the form of vibration of the beam: (a) first resonance, (b) second resonance, (c) third resonance (The excitation point used during the experimental tests is indicated by an arrow)

Fig. 7 presents the resonant frequencies recorded during fatigue testing of the beam filled with the M05 polymer concrete mixture. Across all fatigue stages, the resonant frequencies remained relatively stable, indicating no significant changes in the dynamic behavior of the beam.

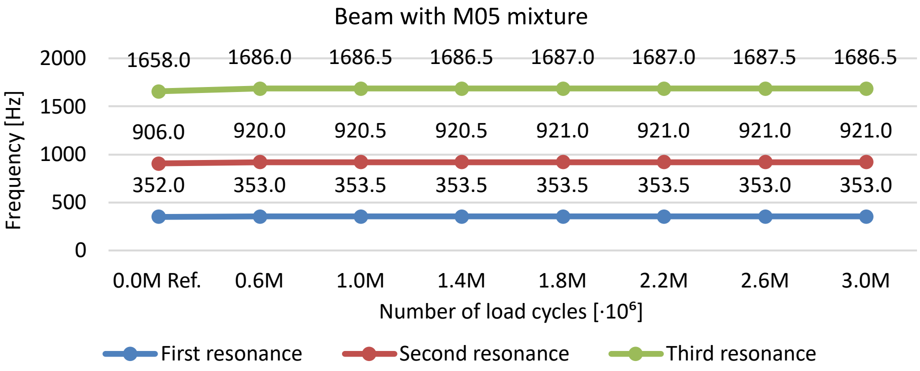


Fig. 7. Resonance frequencies of the first three resonances in fatigue tests for the M05 polymer concrete mixture

Similarly, Fig. 8 shows the resonant frequencies for the M07 mixture. As with the M05 mixture, no substantial changes in resonant frequency were observed throughout the fatigue testing up to three million load cycles.

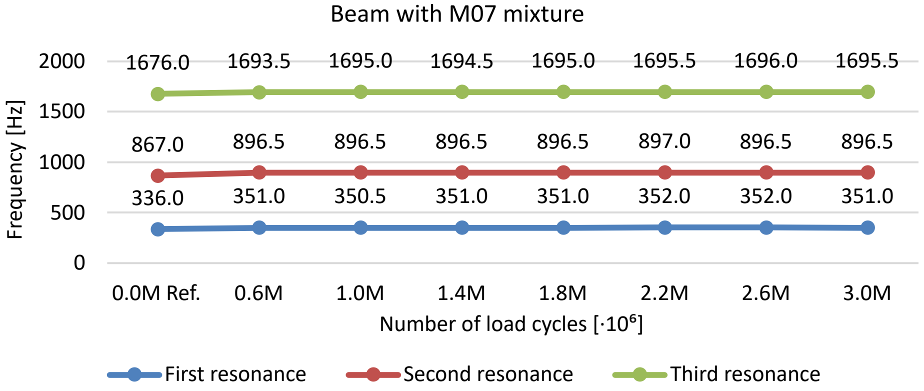


Fig. 8. Resonance frequencies of the first three resonances in fatigue tests for the M07 polymer concrete mixture

Fig. 9 displays the resonant frequencies for the M11 mixture. Again, no significant variations were detected during the fatigue testing process.

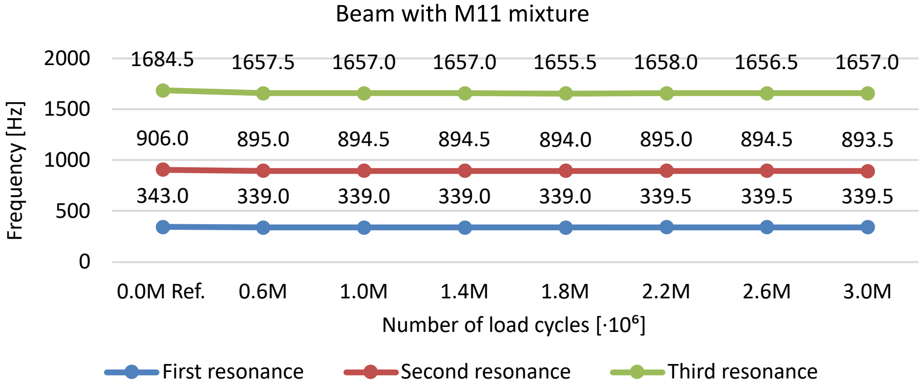


Fig. 9. Resonance frequencies of the first three resonances in fatigue tests for M11 polymer concrete mixture

Based on the analysis of the presented graphs, it can be concluded that fatigue testing up to three million cycles did not result in notable changes in resonant frequencies for any of the tested polymer concrete mixtures.

Fig. 10 presents the damping coefficients for the M05 mixture. The data indicate minor fluctuations in the damping values during fatigue testing. These variations are small and do not exhibit a consistent trend (either increasing or decreasing). It can be inferred that the damping coefficient values fluctuate around a stable mean. Furthermore, the damping coefficients for the first three vibration modes are similar, suggesting consistent damping behavior across the analyzed frequency range for the M05 mixture.

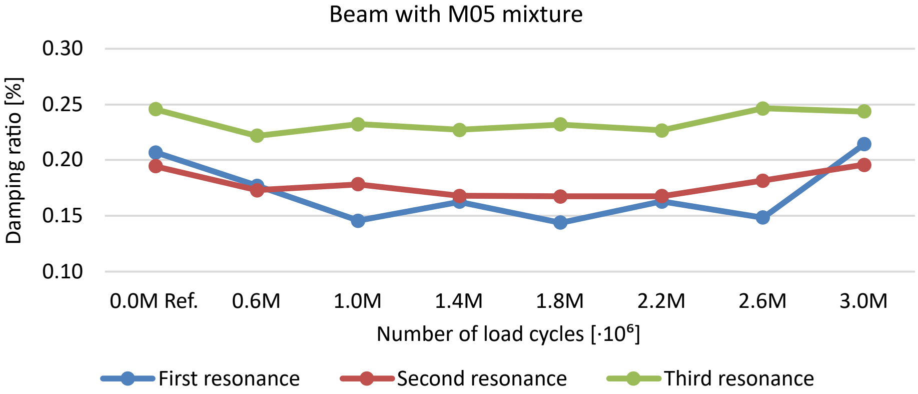


Fig. 10. Damping ratio of the first three resonances in fatigue tests for M05 polymer concrete mixture

Fig. 11 shows the damping coefficients for the M07 mixture. The results are generally consistent with those observed for the M05 mixture. However, a notable increase in the damping coefficient was recorded for the first resonance after 2.6 million load cycles. This anomaly was not sustained in the subsequent stage, where the damping value returned to its previous level. This isolated increase may be attributed to a random error during testing.

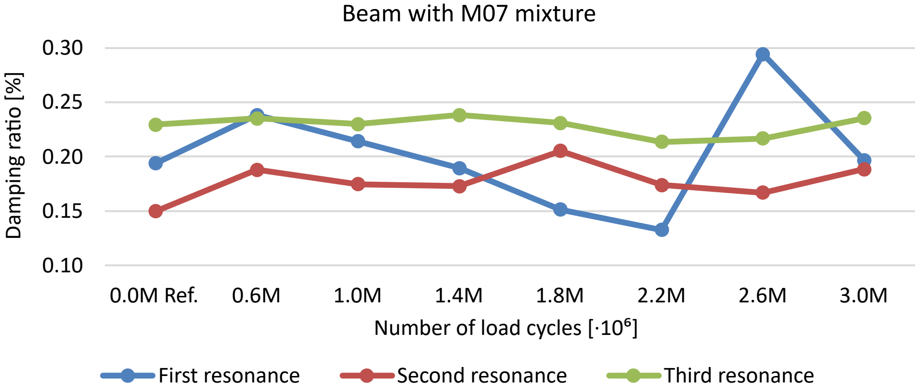


Fig. 11. Damping coefficient of the first three resonances in fatigue tests for M07 polymer concrete mixture

Fig. 12 presents the damping coefficients for the M11 mixture. In this case, the lowest damping values were consistently observed for the first vibration mode across all fatigue stages. The second and third modes exhibited slightly higher but comparable damping coefficients.

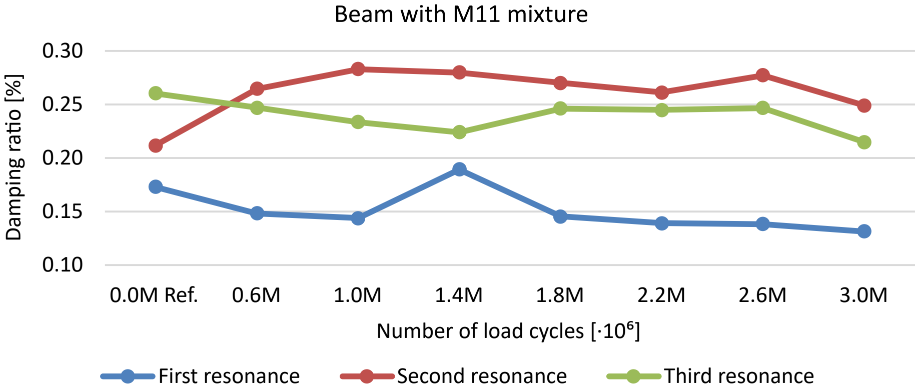


Fig. 12. Damping factor of the first three resonances in fatigue tests for M11 polymer concrete mixture

3.1. Determining of the significance of the estimated coefficients

The fatigue test results obtained for the polymer concrete mixtures M05, M07, and M11 exhibit minimal variability throughout the testing process. The observed data do not indicate any clear upward or downward trends that would suggest the development of structural changes within the polymer concrete mixtures.

To assess whether the recorded variations in parameter values are statistically significant – particularly for the M05 mixture – three additional beams were fabricated and subjected to dynamic testing without exposure to cyclic loading. Based on the results from these four beams, which were cast under similar conditions and tested using the same methodology, the expected value and confidence interval for the analyzed parameters were estimated.

The mean value was calculated using the following formula:

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i\,, \tag{2}$$

where: x – estimated parameter, n – number of samples ($n = 4$).

The standard deviation was estimated using the range method:

$$\hat{\sigma} = \frac{R}{d_2}\,, \tag{3}$$

where R is the range

$$R = x_{\max} - x_{\min}\,, \tag{4}$$

d_2 is value from the tables [22] depending on the sample size; for $n = 4$, $d_2 = 2.059$.

The confidence interval was then determined as:

$$P_i = \overline{x} \mp 2\hat{\sigma}. \tag{5}$$

Table 2 presents sample values of the resonance frequency and damping ratio for the M05 mixture at its first resonance frequency. The table includes both measured data and parameters estimated using equations (2) through (5). Similar calculations were performed for the remaining resonance frequencies and for the other tested mixtures. Figs. 13 through 18 show the estimated parameters plotted for each individual resonance.

Table 2. Table with measurement data and estimated parameters for the first resonance frequency of the M05 mixture

	Frequency [Hz]	Damping ratio ζ [%]
Measurement data		
Sample 1	340.00	0.183
Sample 2	354.50	0.147
Sample 3	349.00	0.139
Reference sample	352.00	0.207
Estimated parameters		
Minimum	340.00	0.139
Maximum	354.50	0.207
Range	14.50	0.067
Mean value	348.88	0.169
Standard deviation	7.04	0.033
Probability interval $+2 \cdot \sigma$	362.96	0.235
Probability interval $-2 \cdot \sigma$	334.79	0.103

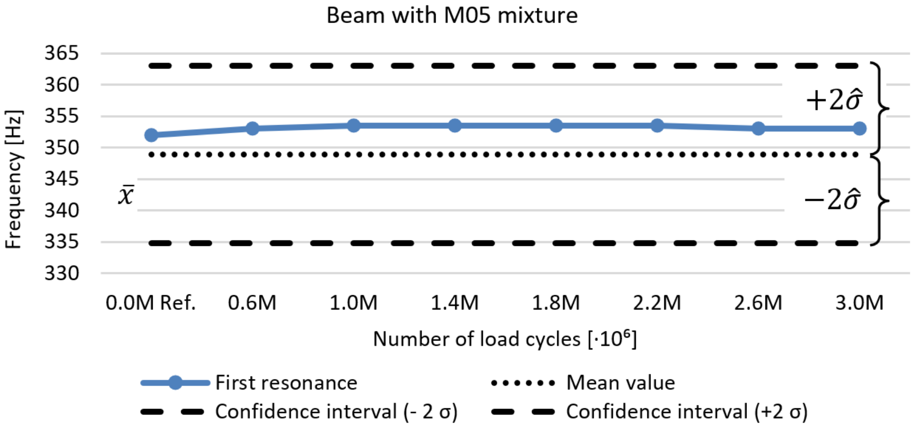


Fig. 13. Resonance frequencies for the first resonance of the M05 polymer concrete mixture, shown with the expected value and confidence interval

As shown in Figs. 13, 14, and 15, the values obtained at each stage of the fatigue tests lie close to the mean value and remain within the calculated confidence interval. A slight increase in the resonant frequency was observed after the first fatigue stage, but no further significant deviations were noted.

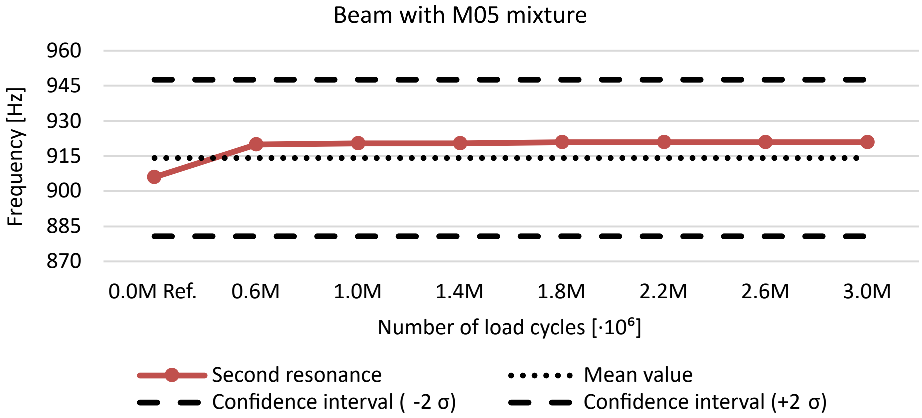


Fig. 14. Resonance frequencies for the second resonance of the M05 polymer concrete mixture, shown with the expected value and confidence interval

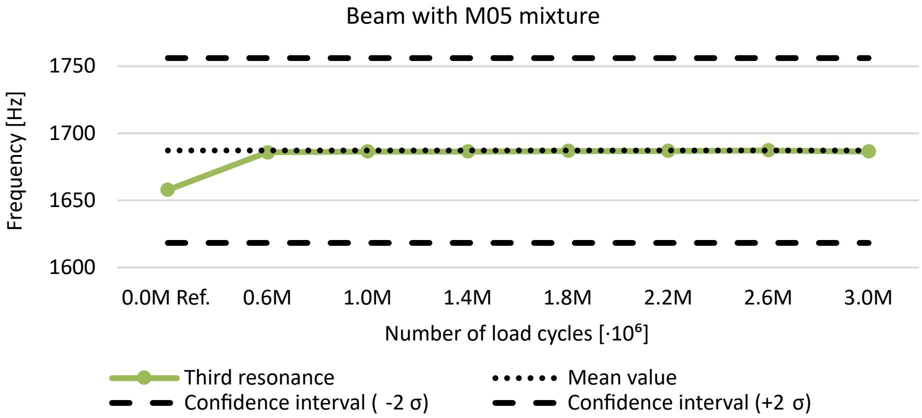


Fig. 15. Resonance frequencies for the third resonance of the M05 polymer concrete mixture, shown with the expected value and confidence interval

Figs. 16, 17, and 18 present the damping ratio values for all analyzed resonances during fatigue testing of the M05 mixture. The obtained damping ratios fall within the established confidence interval. Depending on the fatigue stage, the damping ratio values exhibit minor increases or decreases, oscillating around the expected value without indicating a consistent trend.

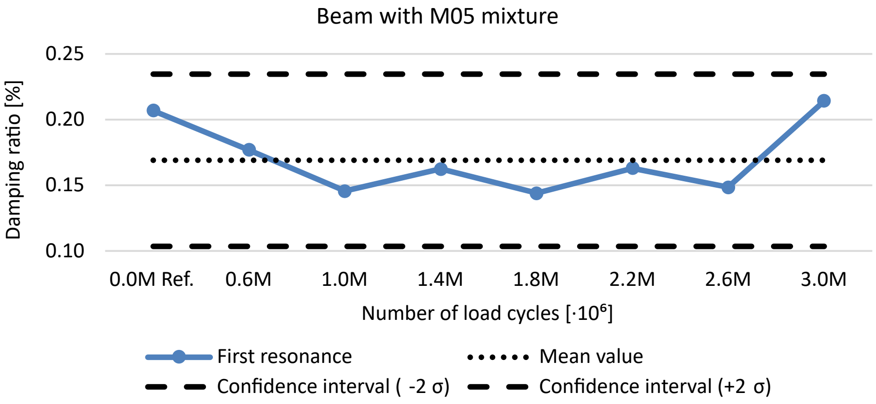


Fig. 16. Damping ratio for the first resonance of the M05 polymer concrete mixture, shown with the expected value and confidence interval

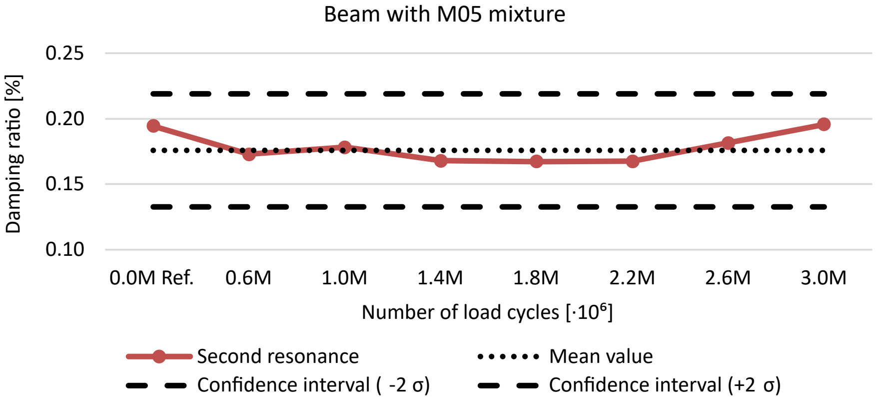


Fig. 17. Damping ratio for the second resonance of the M05 polymer concrete mixture, shown with the expected value and confidence interval

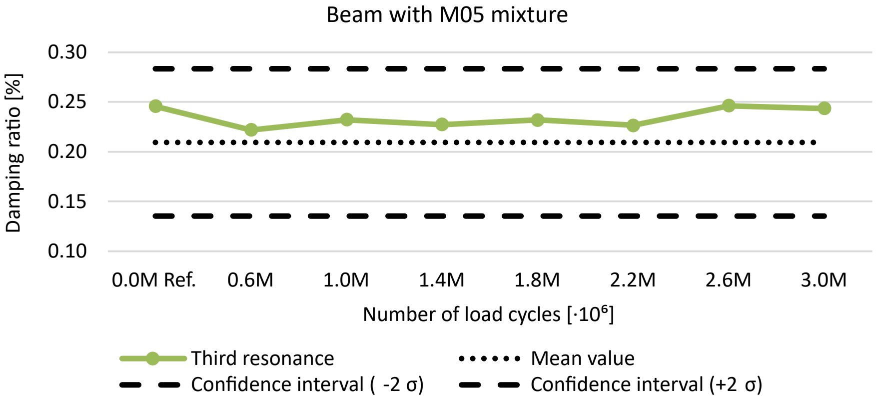


Fig. 18. Damping coefficients for the third resonance of the M05 polymer concrete mixture, shown with the expected value and confidence interval

4. Conclusions

Most studies concerning polymer concretes focus primarily on the properties of the material itself, rather than its integration with steel profiles, which limits the possibility of direct comparison with the present work. Based on the literature review presented in the introduction, it can be generally stated that the use of polymer concrete enhances damping properties compared to conventional concrete mixtures. It has been observed that various additives used in polymer concrete formulations tend to improve damping performance, while having only a minor influence on mechanical strength parameters.

Numerous authors have concluded that it is extremely challenging to quantitatively determine the influence of a specific additive on changes in dynamic properties. Such an assessment would require long-term experimental studies involving mixtures that differ incrementally in the amount of the investigated component.

A key conclusion drawn from the literature analysis, which also motivates further development of hybrid structures combining thin-walled steel profiles with polymer concrete, is the significant increase in mechanical strength compared to steel-only constructions. This allows for the design of structural components with identical geometric and spatial characteristics, but with substantially improved mechanical performance.

The fatigue tests conducted in this study demonstrated that the steel–polymer concrete composite performs well under prolonged dynamic loading conditions typical of industrial applications. It is anticipated that, over extended periods of normal operation, no deterioration in the dynamic properties of such structures will occur.

As a result of fatigue testing of beams filled with polymer concrete mixtures M05, M07, and M11 up to 3.0 million load cycles, no significant changes in the values of the dynamic parameters were observed. Based on these findings, it can be concluded that time-varying loading did not induce structural changes in the tested beams. This indicates that no delamination or discontinuities developed at the interface between the polymer concrete and the steel profile, nor within the polymer concrete itself at the filler–resin boundaries.

Consequently, it can be inferred that all three developed polymer concrete mixtures are suitable for use in the construction of machine tool body components subjected to typical operational loads arising from machining processes.

For the M05 mixture, a shift in resonant frequencies toward higher values was observed across all vibration modes when compared to the M07 and M11 mixtures. Based on this observation, the M05 mixture is recommended for use in machine tool body structures.

In industrial practice, machine tool structural components with higher resonance frequencies are generally preferred due to their superior dynamic performance. The damping coefficient for all three tested polymer concrete mixtures was found to be at a comparable level. None of the tested beams exhibited a significantly higher damping value relative to the others.

Fatigue testing revealed that, within the analyzed load range and number of fatigue cycles, no significant changes in dynamic parameters were observed in any of the tested beams that would indicate fatigue-induced damage. Based on these findings, it can be concluded that all three polymer concrete mixtures are suitable for use in machine tool structural components with respect to their fatigue performance. However, the M05 mixture is recommended for further application, as it demonstrated the highest resonance frequencies among all tested mixtures.

In this study, the dynamic properties of the tested beams were evaluated using two estimators: resonant frequency and damping ratio. Among these, the resonant frequency is considered a more reliable indicator, as it is directly derived from the measured data. In contrast, the damping ratio is calculated through secondary processing of the measurement signals.

The estimation of resonant frequency is less susceptible to errors than that of the damping ratio. Potential sources of error in damping ratio estimation include the resolution of frequency response function (FRF) measurement points, the selected sampling frequency, and the parameters of the exponential window applied to prevent spectral leakage from the acceleration sensor signals during experimental testing.

Furthermore, when two vibration modes are closely spaced in frequency, the 3 dB bandwidth used to estimate the damping ratio may encompass both modes. This overlap can distort the calculated damping value, leading to inaccurate results.

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