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VIBRATION BEHAVIOR OF THERMOPLASTIC COMPOSITE WITH DIFFERENT GLASS FIBER CONTENTS UNDER LOW-TEMPERATURE CONDITIONS

[1] Hayrettin ŞEN, [2,*] Murat AKDAĞ, [3] Gökçe Mehmet GENÇER, [4] Nahit ÖZTOPRAK

[1] *Izmir Katip Celebi University, Mechatronics Engineering, Izmir, TÜRKİYE*
[2,3,4] *Dokuz Eylul University, Mechanical Engineering Department, Izmir, TÜRKİYE*
[1] hayrettin.sen@ikcu.edu.tr, [2] murat.akdag@deu.edu.tr, [3] mehmet.gencer@deu.edu.tr, [4] nahit.oztoprak@deu.edu.tr

Highlights

- Free vibration responses of the thermoplastic composite beam were investigated.
- Effect of subzero temperature on the natural frequency and damping ratio was observed.
- The relation between the change of glass fiber content and vibration characteristics was revealed.

***Corresponding Author**: Murat AKDAĞ, murat.akdag@deu.edu.tr

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ABSTRACT: Glass fiber-reinforced thermoplastic composites are continuously finding their application especially in the field of aerospace and marine due to their stiffness-to-weight advantages. Accordingly, it has gained prominence to evaluate the behavior of composites under diversified environmental conditions where vibration inputs are common. In this research, effect of various environments on the free vibration response of long glass fiber-reinforced polypropylene (PP) composites with different fiber ratios is investigated. Free vibration under an impulse response of thermoplastic composite samples is studied experimentally in a vibration test setup with fixed support. Numerical simulations are also performed through 3D FE models. The present study has revealed that the decrease in temperature increases the natural frequency of the PP composites by over 20%, exceeding 20 Hz. Moreover, whether the composites have 20 wt.% or 40 wt.% long glass fiber content, the damping factors of thermoplastic composites are highly dependent on temperature. The damping ratio distinctly decreases to below 0.008 at -70°C while it increases by over 50% at 0°C relative to the value at room temperature.

Keywords: *Free Vibration Analysis, Glass Fiber, Polypropylene Composite, Subzero Temperature*

1. INTRODUCTION

Developing technology has triggered to substitution of conventional materials with modern engineered materials that can offer a variety of required qualities altogether. Especially, to ensure the low emission goal and efficient use of natural resources due to the increasing environmental restrictions, without sacrificing any mechanical property, the importance of the utilization of polymer-based composite materials that are lighter than traditional alloys has been growing rapidly in the designed structures [1]. In this regard, thermoplastic-based composites with remarkable characteristics, such as being light and having good recyclability, low cost, high ductility, and adequate damping strength; are commonly employed in the aviation, automotive, marine, and petroleum industries [2], [3], [4], [5], [6].

Fiber-reinforced composites are mostly preferred materials among the various composites in engineering applications [7]. While the fibers, having high strength and modulus, take the bearing role, the matrix material transfers the stress between fibers, performs a barrier role against unfavorable environmental conditions, and protects the fibers from wear by wrapping them [8]. Glass fiber as a reinforcement has a usage share of approximately 90% in the industry due to its notable qualities, which include being readily available in a variety of forms, inexpensively processable using various manufacturing techniques, and inert [9]. Considering the effect of glass fiber on improving the mechanical properties of the composite, its utilization as a reinforcement in polypropylene (PP), one of the thermoplastic-based matrixes now in use, is cost-effective and quite common [2], [3], [4], [5], [6], [8], [9], [10].

According to the application fields, engineering materials should continue to exhibit the expected qualities under various and variable conditions. For instance, while modern airplanes should endure varying temperatures between -55°C and 50°C [11], spacecraft and satellites operating in low-orbit conditions should withstand changing temperatures between -170°C and 200°C. Consequently, studies

***Corresponding Author**: Murat AKDAĞ, murat.akdag@deu.edu.tr

also have been carried out in aerospace engineering to investigate and optimize the properties of the composite materials used as wing, airframe, and structural elements of cryogenic fuel tanks under extreme circumstances [12], [13].

Exposing fiber-reinforced composite materials to low temperatures may result in the formation of internal stress-based micro-cracks between fibers and matrix due to the unequal thermal expansion coefficients. Therefore, it may be possible that the desired characteristics of a composite material may not be achieved as the ambient temperature drops or changes [2]. This becomes more critical in particular if an engineering material utilized in the aerospace/space industry is also required to resist dynamic loading or vibrations under this kind of extreme service conditions. To prevent any fracture or crack initiation, the structural component of a designed system should endure internal or external vibrations. Since the damping capability of the structure determines the stability of the system [14].

Several studies focus on the mechanical characteristics of polymer-based composites under sub-zero temperatures. However, in low temperatures, free vibration behaviors of the composites are still being investigated. To the best of authors' knowledge, there is no published study comparing the vibration performance of the long glass fiber-reinforced PP composites in room and sub-zero temperature regions. In this work, the damping and natural frequency responses of PP composites fabricated with a ratio of 20 wt.% and 40 wt.% long glass fiber reinforcement are investigated, especially at low temperatures. Thus, a significant contribution to the literature is made by determining the responses by vibrational phenomena that composites may exhibit under various temperatures during the service conditions.

2. EXPERIMENTAL STUDY

2.1. Preparation of Composites

20 wt.% and 40 wt.% long glass fiber (~12 mm) reinforced-homopolypropylene composite granules procured from Nuh Kompozit Inc. (Istanbul, Turkey) are used for the fabrication of thermoplastic composite panels in this research. The E-glass reinforced thermoplastic composites are manufactured through a Fontijne Presses - LabEcon60 Laboratory Platen Press as shown in Figure 1. Load sensitive rectangular platen having the dimension of 400 × 400 mm^2 is used to compress the granules and to fabricate the panels. The panel thickness, temperature, force, and length of processing time are 4 mm, 210 ˚C, 100 kN, and 50 min, respectively. Between the press platens, the polytetrafluoroethylene (PTFE) films are utilized for easy removal of the panels and making the whole mold levelly heat. Accordingly, final composite panels with different glass fiber ratios in desired dimensions are obtained. Some technical properties of the PP composites extracted from datasheet of the supplier are shown in Table 1 [15].

2.2. Measurement of Vibration Characteristics

A Laser displacement sensor Keyence LK-G157 is used to measure the vibrations of the composite beam. Analog output of the displacement sensor is read and recorded with 3 kHz sampling rate by using a NI DAQPad-6015 data acquisition module in LabView. Laser displacement sensor, composite beam and the other equipment which are a PC, NI DAQPad-6015 and display panel Keyence LK-G3001 are shown in Figure 2. The composite beam is placed and fixed in an isolated foam box. Two thermocouples are placed inside of the composite beam to measure the temperature. The first thermocouple is inserted very close to the end point of the composite beam. The second one is also placed into a portion of composite in the fixed support region. The temperature of the composite beam is measured in every two seconds.

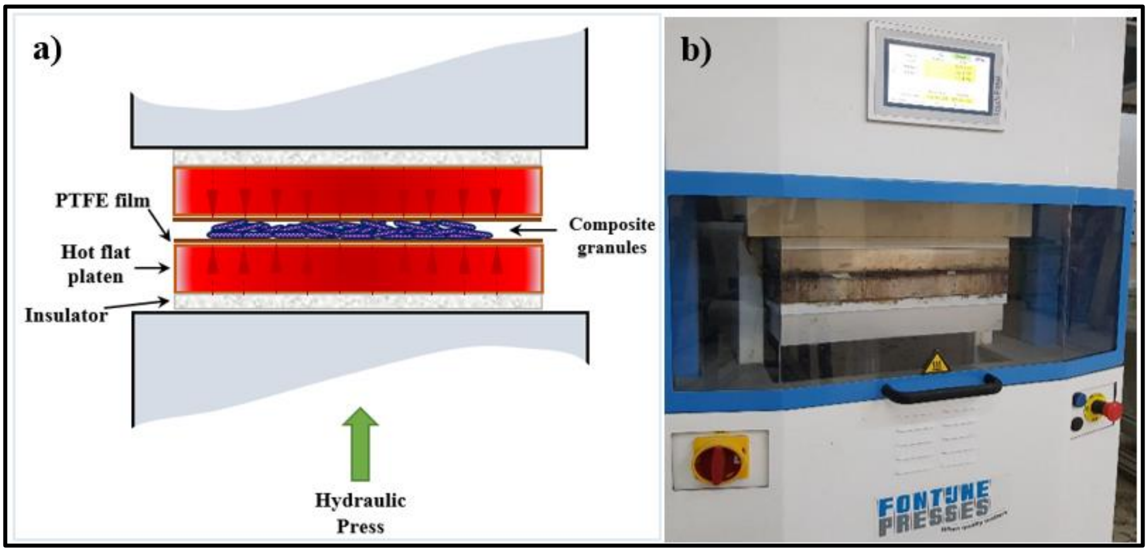

Figure 1. Hot pressing process; a) Schematic illustration, b) Hot-pressing machine

Table 1. Properties of the thermoplastic composites

Properties	**Duramax LFT PP 40**	**Duramax LFT PP 20**
Glass fiber percent (%)	40	20
Density (g/cm^3)	1.20	1.03
Tensile strength (MPa)	119	92
Flexural strength (MPa)	190	125
Izod impact, unnotched (kJ/m^2)	37.5	30

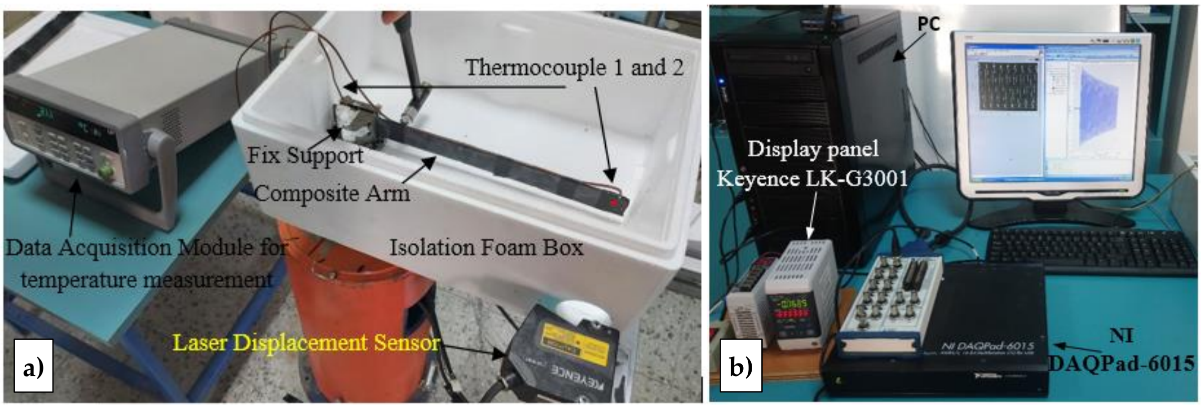

Figure 2. a) Measurement setup, b) Data logging setup of measured values

The solid CO_2 is placed inside the foam box and box lid is then closed. As shown in Figure 3-a, the composite beams are uniformly cooled to -75 °C with no regional variations. The temperatures of the thermocouple at the tip are observed. The temperature changes of the thermocouples at the tips of both 20 wt.% and 40 wt.% long glass fiber reinforced composite (GFRP) are demonstrated in Figure 3-b. The 40 wt.% GFRP has reached the lowest and highest temperatures in a shorter time than 20 wt.% GFRP as expected since the 40 wt.% GFRP has more glass fiber content. This is in line with the previous study showing that the effective thermal conductivity of polymer composite increases with the glass fiber volume fraction [16]. When the temperatures are reached up to -75°C, the lid is opened, and an impulse force is applied on the composite beam by using a hammer at the desired temperatures. Accordingly, the vibration of the composites is measured by the laser displacement sensor.

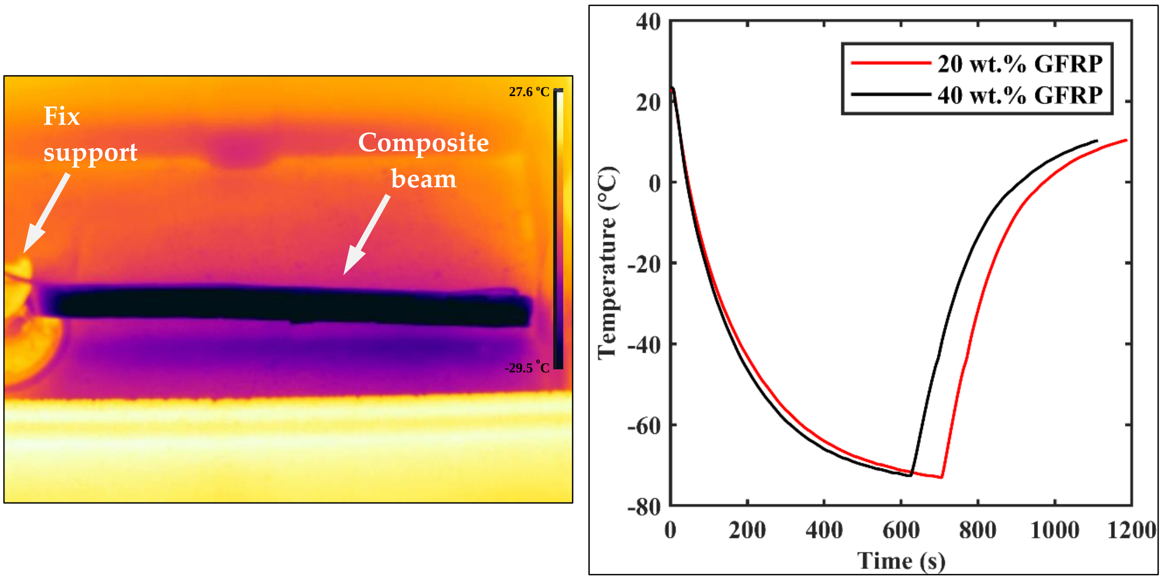

Figure 3. Details of cooling process; (a) Thermal image of the composite, (b) Temperature changes of the tip thermocouples

3. RESULTS AND DISCUSSION

The obtained natural frequencies and damping ratios for both 20 wt.% and 40 wt.% GFRP beams are given in Table 2. The vibration results for both 20 wt.% and 40 wt.% GFRP composites for different temperatures are also exhibited in Figure 4 and Figure 5, respectively. When considering the 40 wt.% GFRP, the natural frequency is higher than that of the 20 wt.% GFRP under the same temperature condition due the more glass fiber existence. This result is in line with the previous studies which emphasize that increasing the fiber fraction from 30% to 60% enhances the natural frequency (Hz) [17] and that the frequency of particle reinforced-composite changes in direct proportion to elastic modulus (E) of the composite [18]. The natural frequencies are increased for both type of GFRPs with the temperature decrease since the glass fiber and homopolypropylene become more brittle and stiffer. It is observed that the damping ratio of 20 wt.% GFRP is higher than that of the 40 wt.% GFRP under the same temperature condition since the homopolypropylene provides more damping than glass fiber. However, it is additionally discovered that the change of the damping does not show the same behavior as the variation of the natural frequency with temperature. The damping ratios of the GFRPs increase while the temperature decreases around 0°C, then the damping ratios are started to decrease exponentially as seen in Figure 6. In the report of a study conducted by NASA [19] it is seen that similar results were obtained for the damping behavior of stainless-steel. The reason for this behavior could not be explained in that report. This behavior may be attributed to the fact that the thermal expansion coefficient of homopolypropylene is higher than glass fiber. For this reason, it is thought that the matrix material shrinks more during cooling that making intermolecular energy transfer easier, and as a result, the damping rate decreases significantly. To summarize, these findings of the free vibration parameters can be associated with the modulus of elasticity of the polymeric matrix material, which changes depending on temperature.

Table 2. Obtained natural frequencies and damping ratios under various temperatures

	20 wt.% glass fiber reinforced		40 wt.% glass fiber reinforced	
Temperature (°C)	**Natural Freq. (Hz)**	**Damping Ratio**	**Natural Freq. (Hz)**	**Damping Ratio**
20	17.25	0.0126	18.26	0.0111
10	18.13	0.0185	18.94	0.0148
0	19.32	0.0197	19.87	0.0168
-10	20.27	0.0170	20.69	0.0136
-20	20.88	0.0131	21.22	0.0118
-30	21.37	0.0109	21.57	0.0099
-40	21.6	0.0099	21.87	0.0087
-50	21.95	0.0091	22.14	0.0078
-60	22.18	0.0079	22.34	0.0073
-70	22.28	0.0077	22.53	0.0056

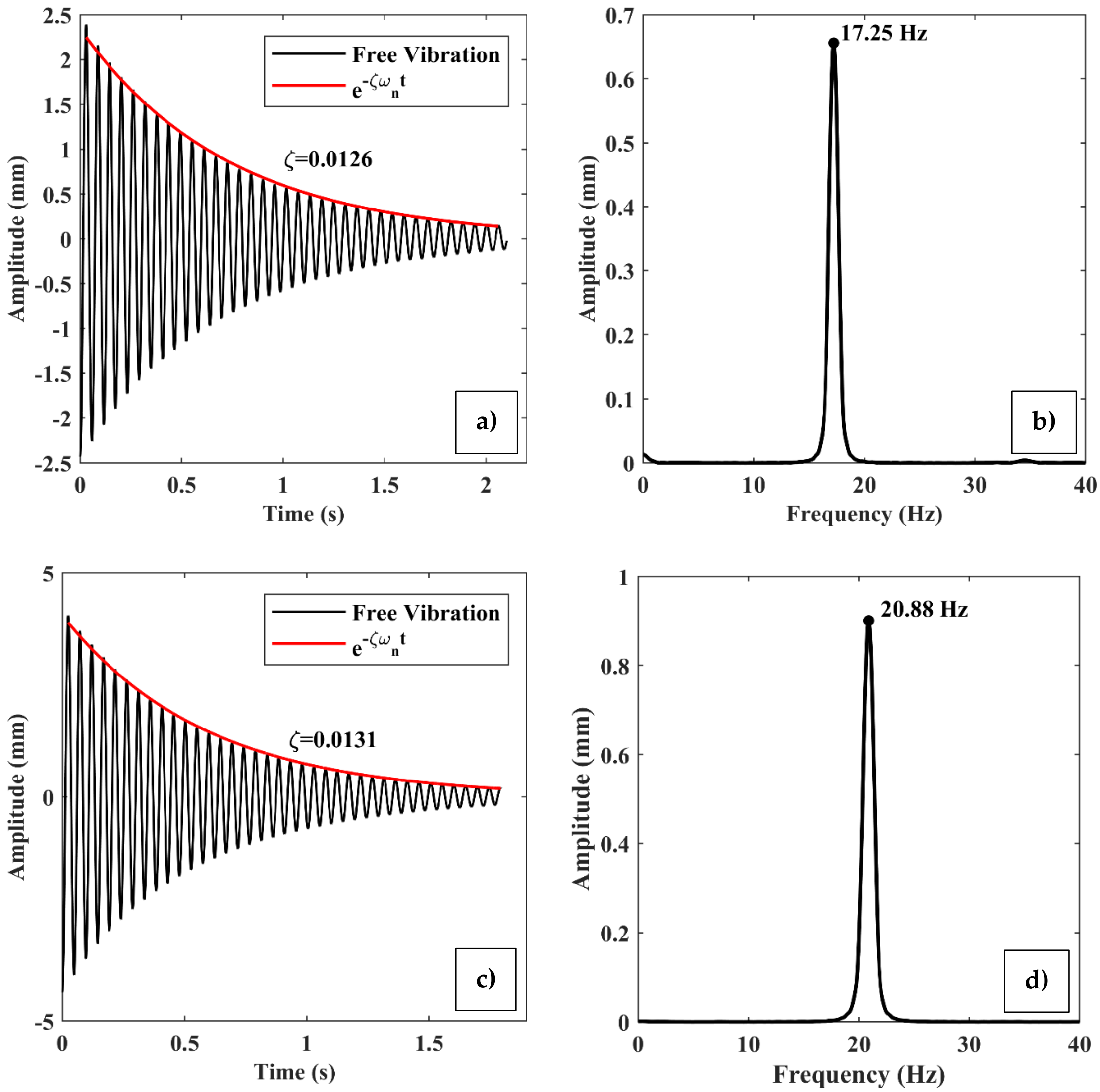

Figure 4. Vibration results of 20 wt.% GFRP; (a) and (b) @ 20°C, (c) and (d) @ -20°C

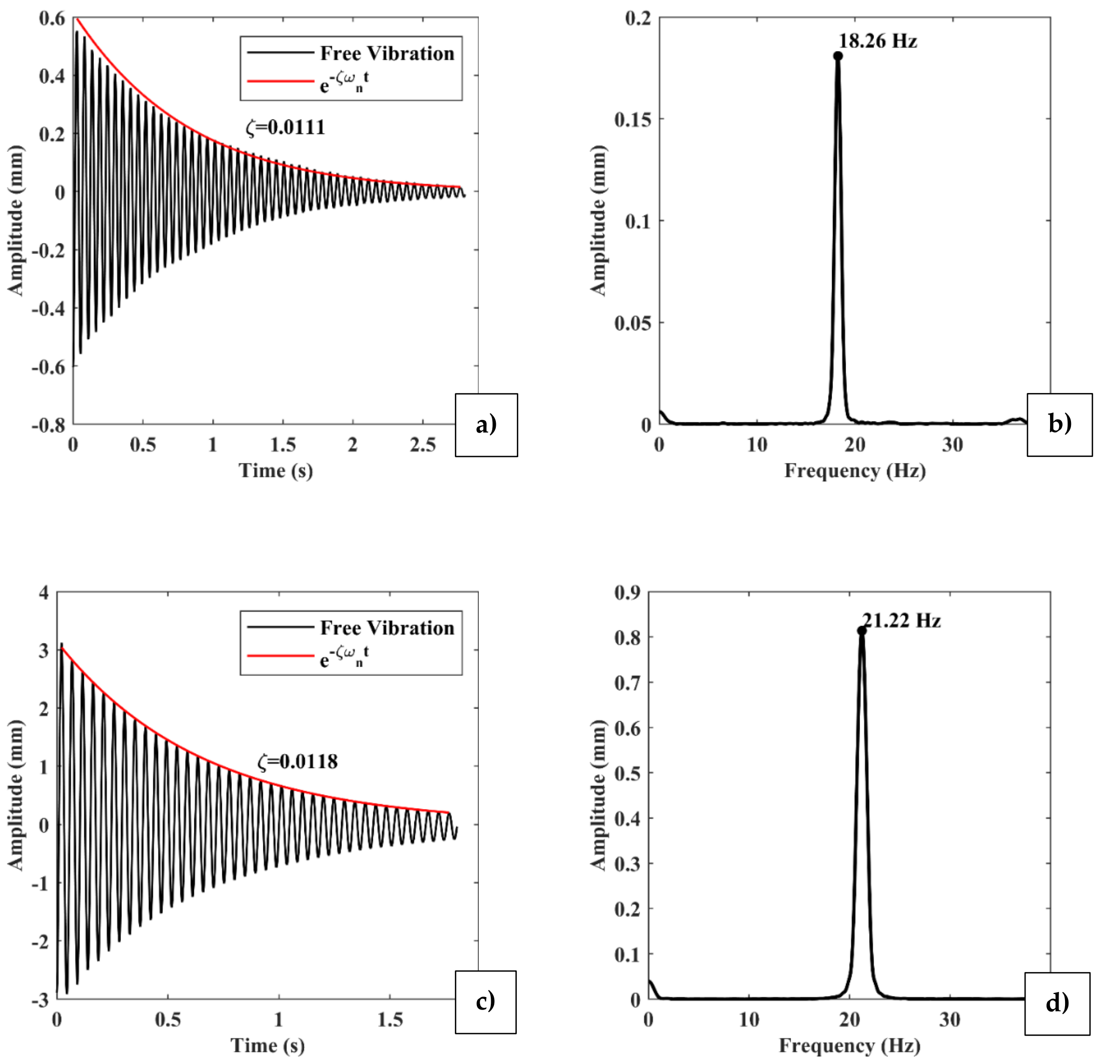

Figure 5. Vibration results of 40 wt.% GFRP; (a) and (b) @ 20°C, (c) and (d) @ -20°C

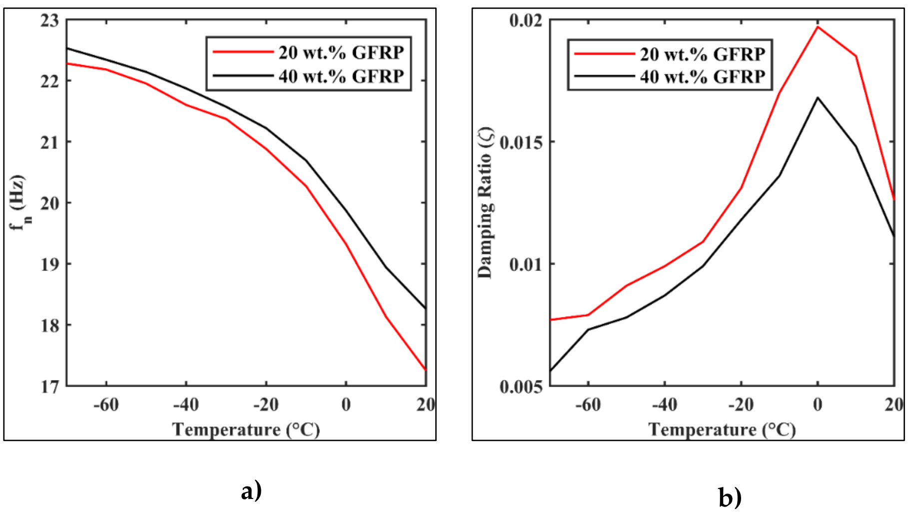

Figure 6. a) The variation of natural frequency with temperature b) The change of damping ratio according to temperature

The data obtained from the tensile tests of the thermoplastic composites used, both at room temperature and the test condition of ~ -40 ^{o}C, are given in Table 3. The results obtained are used to show a trend regarding the behavior of the material. As seen in Table 3, the elastic modulus of both materials increases as the material is cooled. The results of the frequency analysis performed by Solidworks using the values acquired from the tensile tests are also given in Table 3. Figure 7 also exhibits the results of numerical frequency analysis. It can be seen that the results derived from the analysis are compatible with the experimental results given in Table 2.

Table 3. Elastic modulus values obtained from tensile tests of thermoplastic composites at different temperatures and numerical frequency analysis results

	Room temperature		~ -40 ^{o}C	
	Elasticity modulus (GPa)	First natural frequency (Hz)	Elasticity modulus (GPa)	First natural frequency (Hz)
20 wt.% GFRP	2.235	15.473	3.595	19.623
40 wt.% GFRP	2.920	17.685	4.350	21.586

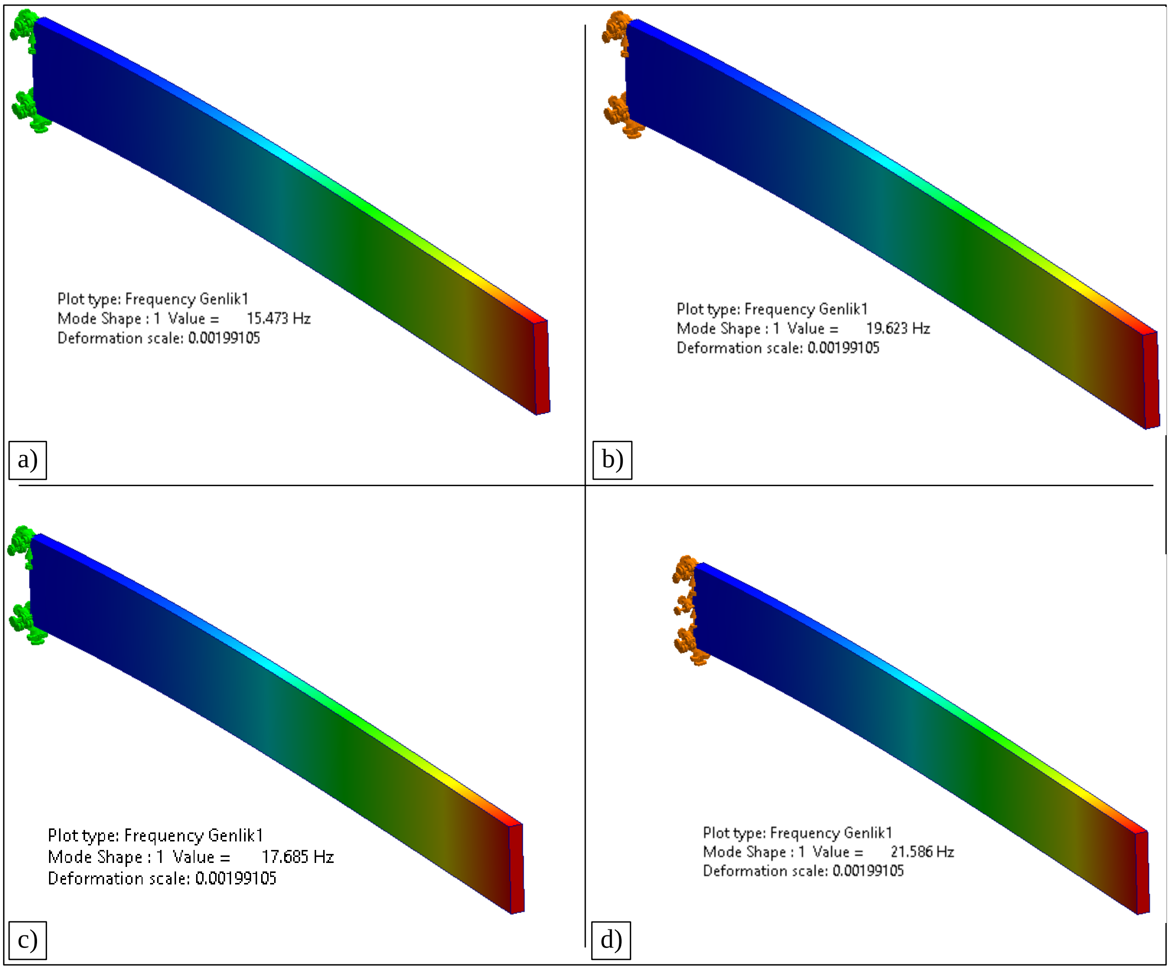

Figure 7. Numerical frequency analysis results; (a) PP20 at room temperature, (b) PP20 at ~ -40 ^{o}C, (c) PP40 at room temperature, (d) PP40 at ~ -40 ^{o}C

4. CONCLUSIONS

The goal of this research is to evaluate the vibration characteristics such as natural frequency and damping factor of the thermoplastic composites under a room temperature and low-temperature environments, and try to broaden a kind of service condition selection in composites. The main conclusions are drawn as follows:

♦ It is noticed that the natural frequencies of free vibration of thermoplastic composites are improved with the increase in glass fiber content under all temperatures examined. GFRP with 40 wt.% glass fiber at -70˚C gives the higher vibration result in terms of the natural frequency. While the increase rate in 40 wt.% GFRP composite is 23.38%, it is calculated as 29.16% for the composite with lower fiber ratio.

♦ The experimental modal analysis concludes an increasing trend in the natural frequency of the composites with the decrease in temperature. Thus, thermoplastic composites can be a promising alternative for parts subject to shock cooling since the natural frequency of the samples is improved, which leads to minimizing vibrations.

♦ Unlike the natural frequencies, damping factors of thermoplastic composites are declined with the increase in glass fiber content under all temperatures. While the damping ratio for both composites increase from a room temperature to 0˚C, it tends to decrease at sub-zero temperatures. While this decrease in damping ratio is 38.89% for 20 wt.% GFRP, it is 49.55% for 40 wt.% GFRP.

♦ The created FE model and analysis results show a tight agreement with the experimentally determined natural frequency responses for both composites.

In this study, vibration performance of the thermoplastic composites with different glass fiber ratios under sub-zero temperatures demonstrates its potential from the point of natural frequency as an outstanding candidate for low-temperature applications. In future, vibration damping behavior of alternative engineering materials and polymer-metal hybrids can be explored under cryogenic temperature environments.

Declaration of Ethical Standards

Authors declare to comply with all ethical guidelines, including authorship, citation, data reporting and original research publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data will be made available on request.

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