Mechanical Properties and Dynamic Mechanical Analysis of Thermoplastic-Natural Fiber/Glass Reinforced Composites

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Summary: The mechanical properties and dynamic behavior of thermoplastic composites based on polypropylene/glass fibers and polypropylene/natural fibers (i.e. kenaf, hemp, flax) are presented. A survey is given on some aspects, crucial for the use of these composites in structural and non-structural components such as their vibration-damping response, in relation to the composite compaction level and the manufacturing procedure. In order to investigate a wide vibration frequency range, including acoustic frequencies, different testing techniques, both with forced and free vibrations, were applied. A comparison between natural fiber and glass fiber reinforced laminates is presented. Compaction levels, allowing to obtain the best compromise between mechanical performance and damping response, are investigated.

Keywords: damping properties; dynamic mechanical analysis; natural fiber composites; thermoplastic matrix; vibration testing

Introduction

The recycle of conventional composite materials poses relevant problems in many industrial fields. Natural Fiber Composites (NFC) have recently gained much attention due to their low cost, environmental benefits, easy disposal, reduction in volatile organic emissions, and their potential to compete with Glass Fiber Composites (GFC). Interest in natural fibers is not only based over ecological aspects; NFC have good mechanical performances in relation to their low specific weight and low price.[1,2] Natural fibers, such as flax, hemp and kenaf, exhibit specific mechanical properties comparable to those of synthetic fibers like glass. Moreover they are lighter, biodegradable, and less expensive. NFC have the potential to be attractive alternative to synthetic fiber composites. However, natural fibers exhibit some drawbacks, which limit their actual applications, such as larger scatter in their properties, lower thermal stability and sensitivity to moisture absorption.[3] Synthetic non-biodegradable polymers are commonly employed as matrices; some of these, such as polypropylene or some thermosets[4–6] have processing temperatures compatible with temperature limits of natural fibers and, moreover, can reduce their moisture absorption rate.

The ability to reduce noise and vibrations is a characteristic, which may extend the application range of NFC in the automotive field;[7,8] impact resistance and damage response without exposed rigid fibers, potentially dangerous, represent additional advantages. Interior panels, dashboards and under-hood covers are examples of vehicle components, which can be manufactured by NFC.[9,10] The production of house appliances is also expected to get important benefits from the employment of natural fiber based composites.

In this research, the mechanical properties of GFC and NFC, in relation to the compaction level, obtainable during processing, are compared. The possibility of

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obtaining components with a no-press, vacuum bagging, technique is explored. The vibration damping characteristics of the materials were tested by dynamic-mechanical analysis. Forced vibration dynamic mechanical tests are quite limited in the frequency range. In order to extend the measured frequency range, two additional vibration tests of NFC and GFC laminates were conducted and compared.

Experimental Part

Composites were manufactured by using random Glass Fiber Mat (GMT) and Natural Fiber Mat (NFM) with thermoplastic matrix (PP) (Glascoform and Nafcoform from Quadrant Plastics Gmbh). Kenaf, Hemp and Flax (KHF) fibers were used as the reinforced phase in NFM. The weight fraction of reinforcement in glass and natural fiber mats was, respectively, 0.4 and 0.5. The nominal specific weight of the mats was 2000 g/m^2 for NFM and 1800 g/m^2 for GMT.

Test specimens with different compaction levels and thickness of NFC and GFC were manufactured by compression molding (CM) for 5 min at 190 °C. A new vacuum bagging process (VB), which does not require the use of heavy presses and moulds, was also explored to produce laminates: with this technique, the polymer/fiber mat, sealed in a vacuum bag, is compacted in oven on a light metal mold. The relations between processing parameters such as temperature, vacuum level, mold material and laminate thickness, compaction and fiber distribution were investigated in comparison with corresponding laminates obtained by hot pressing. A vacuum of 0.85 bar allowed to compact the NFM and GMT, respectively, down to 2.5 mm and 3.5 mm thickness.

Actual matrix, fiber and void volume fractions of all fabricated specimens were measured using a density balance, according to ASTM D792. The measured density values and estimated volume fractions for all types of composites investigated are reported in Table 1. It can be observed that compression of mats down to 2 mm thickness leads to almost full compaction. Only partial compaction is achieved with vacuum bagging technique.

Tensile properties were measured following ASTM D5083 standard. The specimens were desiccated in oven for 3 hour at 105 °C before testing. At least five specimens were tested for each compaction level investigated. Tensile tests were performed with an MTS 858 testing machine. Strain measurements were performed with strain gauges mounted on the samples. The gauge length was 25 mm. The mechanical properties (e.g. secant modulus at 0.05% strain, tensile strength) of all the samples were measured. The elongation rate was 1 mm/min.

For the evaluation of the linear viscoelastic behavior, low amplitude oscillatory measurements were carried out by a Rheometrics Dynamic Analyzer RDA-II, by using rectangular-plate geometry, in a temperature range of 24–26 °C. Frequency sweep measurements were performed to

Table 1.
Density and constituent volume fractions measured in PP-KHF and PP-G composites.

Material	Thickness (technique)	Density (g/cm^3)	Volume Fraction		
			matrix	void	fiber
PP-KHF	2 mm (CM)	1.007 ± 0.017	0.55	0.07	0.38
PP-KHF	3 mm (CM)	0.561 ± 0.034	0.31	0.48	0.21
PP-KHF	3.5 mm (VB)	0.533 ± 0.017	0.29	0.51	0.20
PP-KHF	4 mm (CM)	0.461 ± 0.001	0.26	0.57	0.17
PP-G	2 mm (CM)	1.111 ± 0.054	0.73	0.09	0.18
PP-G	2.5 mm (VB)	0.972 ± 0.021	0.64	0.20	0.16
PP-G	3 mm (CM)	0.649 ± 0.021	0.43	0.47	0.10
PP-G	4 mm (CM)	0.510 ± 0.013	0.34	0.58	0.08
PP	2 mm (CM)	0.906 ± 0.001	1.00	–	–

evaluate NFC and GFC dynamic properties. The storage modulus (G′), loss modulus (G″) and loss factor ($\eta = \tan\delta$) of the composites were measured as function of frequency, ranging from 0.01 to 80 Hz. Three specimens for each test were used. NFC and GFC prepared with different techniques (compression molding, vacuum bagging) and thickness were tested.

This test method, according to ASTM E756, measures the flexural, free vibration-damping properties of a composite beam: loss factor (η) and Young's modulus (E). Accurate over a frequency range of 100 to 1000 Hz, this method is useful in testing materials that have applications in structural vibration, building acoustics, and the control of audible noise. Compared to dynamic-mechanical analysis, this method allows to investigate higher frequency range. The two different tests are complementary for isotropic material, but for 2D random materials they cannot be directly compared because measurements are made on different section areas and in different loading modes (torsion and flexure). Reliable indications of the vibration behavior are however obtained.

Figure 1 shows the experimental set-up, selected to obtain the best signal-to-noise ratio. The modal loss factor is measured as the ratio of the half-power bandwidth to the resonant frequency. Three or more modes are commonly measured starting with mode 3. Modes 1 and 2 were not measured. Modal analysis was carried out using the HKS Abaqus/Standard finite element package to check the frequency of the experimental flexural modes obtained with the transducer. Subspace iteration method was used for calculating the resonance frequencies.

To validate the measurement system, an aluminum beam (Al2024-T3) was tested as reference specimen. The specimen nominal dimensions were 40 mm width, 300 mm free length and 1.5 mm thickness. Damping ratio (as $\xi = \eta/2$, Table 2) and Young's modulus (Table 3) were consistent with expected values.[11–13] Young's modulus of the beam material was calculated from the expression:

$$E = \frac{12\rho l^4 f_n^2}{H^2 C_n^2} \qquad (1)$$

where:

E = Young's modulus of beam material [Pa],
f_n = the resonance frequency for mode n [Hz],
H = thickness of beam [m]
l = length of beam [m],
ρ = density of beam [Kg/m^3],
C_n = coefficient for mode n, of clamped-free (uniform) beam,
where:

$C_1 = 0.55959$, $C_2 = 3.5069$, $C_3 = 9.8194$, $C_n = (\pi/2)(n - 0.5)^2$ for $n > 3$.

In the same manner as described above, Young's modulus and the loss factor of plain PP, PP-KHF and PP-G composites were measured and compared. Three specimens

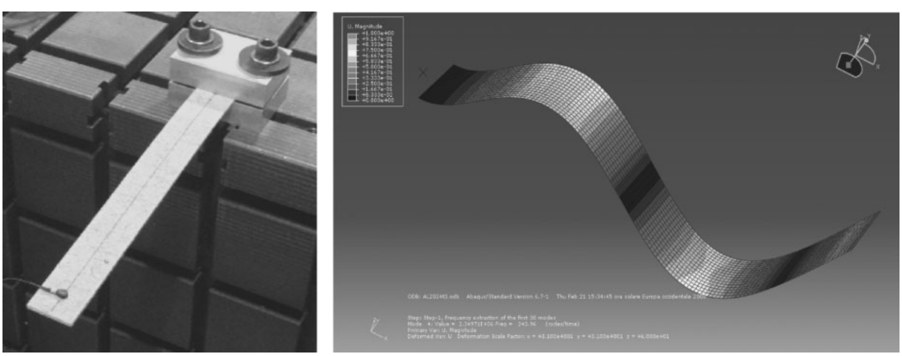

Figure 1.
Experimental set-up and FEM analysis according to standard test geometry.

Table 2.
Results of vibration-damping test on Al2024-T3.

No. Mode	Numerical resonance frequency [Hz]	Experimental resonance frequency [Hz]	Δ Experimental-Numerical frequency [%]	Experimental damping ξ
1	13.7	13.7	0.1	–
2	86.6	86.4	−0.2	–
3	244.0	243.2	−0.3	0.0009
4	480.8	479.1	−0.4	0.0007
5	798.6	795.8	−0.4	0.0005
6	1197.3	1193.5	−0.3	0.0006

for each test were used. Beam dimensions were selected, based on desired frequency range of the measurements and the characteristics of the damping material to be tested. Dimensions found to be successful were 40 mm width and 200 to 300 mm free length.

A New Vibration-Damping Test

In order to extend the measure frequency range, a new test method was investigated. This method, thanks to a free-free modal analysis, opens up to new measurement approaches. The experimental set-up is different compared to the previous method but uses the same equipment. In order to reduce the noise of the clamping set up, the clamping-sample system was suspended with elastic bands (Figure 2). Elastic bands work very well for supporting a structure without damping its vibration or adding undesirable boundary conditions.

To check the measurement system, polypropylene beams were tested as reference specimens. The isotropic behavior of PP has allowed to evaluate and compare all the different tests investigated: ASTM E756 (fixed), new test method (free) and dynamic mechanical analysis (RDA). Beam dimensions were selected according to the desired frequency range of the measurements. The beam dimensions were 40 mm width and 200 to 300 mm free length. As shown in Figure 3, the results of the three tests methods overlap, although covering different frequency ranges.

Results and Discussion

Tensile strength and modulus measurements showed that both in case of glass and natural fibers, mat processing technique introduces a non negligible anisotropic

Table 3.
Elastic modulus measured with vibration-damping test on Al2024-T3.

No. Mode	1	2	3
ρ [Kg/m^3]	2780	2780	2780
l [m]	0.3	0.3	0.3
f_n [Hz]	13.7	86.4	243.2
H [m]	0.0015	0.0015	0.0015
C_n	0.55959	3.5069	9.8194
$E_{vibration}$ [MPa]	71980	72900	73670
Δ $E_{tensile}$[a] - $E_{vibration}$ [%]	1.5	0.3	−0.8

[a] From tensile test: E = 73100 MPa.

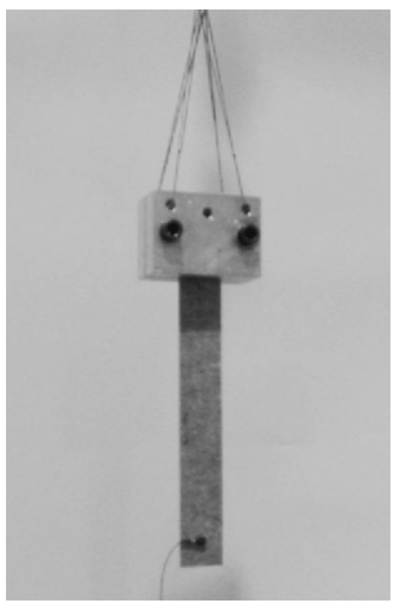

Figure 2.
Experimental set-up of the new free vibration test.

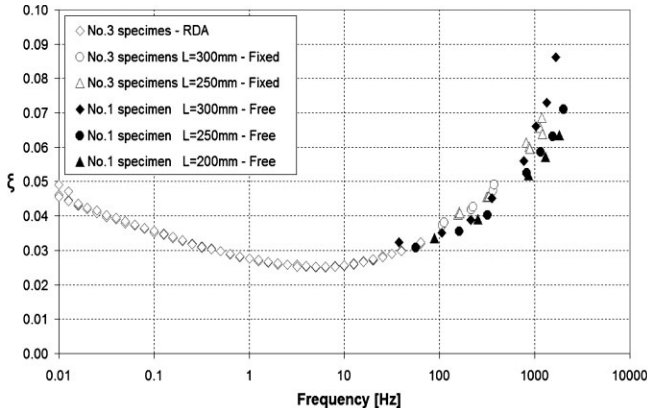

Figure 3.
Polypropylene damping ratio obtained with different tests.

behavior (Figure 4 and 5). Strength and tensile modulus of compacted NFC (e.g. 2 mm thick), in transverse direction (T) were respectively 34% and 24% higher than in roll direction (L). This occurs also for the GFC (respectively 54% and 41%). Average values and standard deviation of tensile modulus, strength and strain to failure for composites were estimated. The data show that all tested NFC (2 mm thick), in longitudinal direction, have tensile modulus higher (21%) than GMT, while, in transverse direction, have similar tensile modulus. Strength of GMT is considerably higher (35%) than for NFC material in transverse direction, while it is comparable in longitudinal direction. At lower compaction levels, strength and tensile modulus decrease their values (Table 4 and 5). Plain PP, compression molded, presented a tensile modulus of 1100 ± 45 MPa and a tensile strength of 30.8 ± 1.0 MPa.

The stress-strain curve becomes markedly nonlinear at lower compaction levels. This nonlinear behavior can be explained considering that lower compaction results in limited interaction between fibers and matrix, presence of extensive voids and poor bonding; this reduces the effect of fiber reinforcement in the composite. In

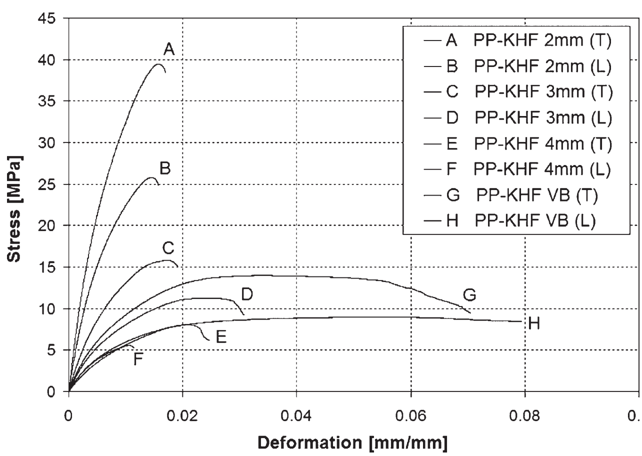

Figure 4.
PP-KHF tensile behavior.

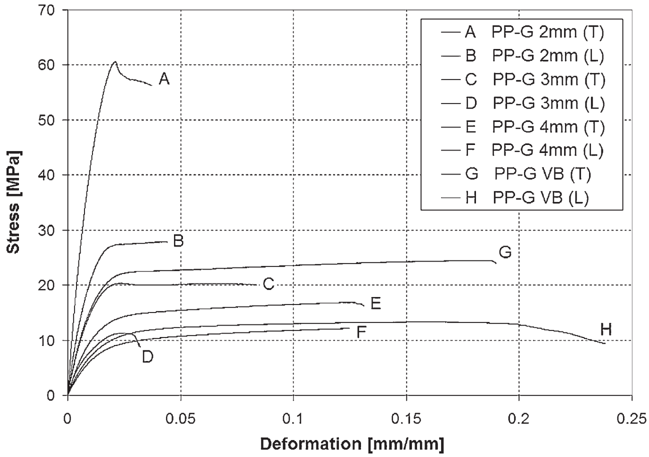

Figure 5.
PP-G tensile behavior.

Table 4.
Results of mechanical tests on PP-KHF composites.

Material	Tensile (transverse direction)		Tensile (longitudinal direction)	
	Modulus (MPa)	Strength (MPa)	Modulus (MPa)	Strength (MPa)
P-KHF 2 mm	5880 ± 1106	39.7 ± 2.5	4440 ± 179	26.1 ± 1.2
PP-KHF 3 mm	2470 ± 206	17.5 ± 1.1	1550 ± 98	11.3 ± 0.4
PP-KHF VB	1880 ± 214	14.0 ± 1.2	1265 ± 38	9.2 ± 1.0
PP-KHF 4 mm	1020 ± 48	8.2 ± 0.4	1215 ± 83	5.8 ± 0.6

fact, the force needed to break the material compacted down to 4 mm thickness is lower than the the force needed to break the same material compacted down to 2 mm thickness.

Samples produced with vacuum bagging technique allow to obtain strain higher then those produced with compression molding with similar thickness. Convective heat transfer induces better melting both of surface layer and internal part of mat, improving the bond between the matrix and the fibers.

Composite damping ratio measured by dynamic-mechanical tests is presented in Figure 6. It is observed that the addition of fibers reduces the damping response at high compaction levels (low thickness), both in case of Glass and Natural Fiber; however, although NFC have a higher fiber content, higher damping was measured compared to GFC.

At lower compaction levels, the material is largely composed of voids and the fibers are only partially bonded to the surround-

Table 5.
Results of mechanical tests on PP-G composites.

Material	Tensile (transverse direction)		Tensile (longitudinal direction)	
	Modulus (MPa)	Strength (MPa)	Modulus (MPa)	Strength (MPa)
PP-G 2 mm	5960 ± 292	61.0 ± 1.2	3510 ± 101	28.1 ± 2.0
PP-G VB	2680 ± 580	24.3 ± 2.6	1210 ± 40	13.3 ± 0.2
PP-G 3 mm	2510 ± 158	21.8 ± 2.0	1520 ± 43	11.3 ± 0.4
PP-G 4 mm	1620 ± 217	17.8 ± 1.2	1060 ± 233	12.3 ± 0.7

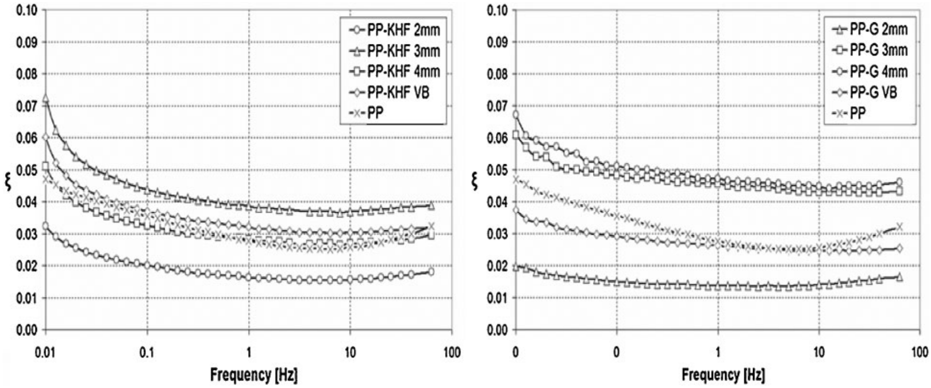

Figure 6.
PP-KHF and PP-G damping properties.

ing matrix. In such situation damping increases at values even higher than plain polypropylene. A leveling or reduction of damping was observed at the lowest compaction level.

Flexural free vibration tests allow to compare the measured elastic modulus with that obtained by tensile tests. A numerical-experimental correlation was performed (Table 6), using the results of experimental tensile and density tests. In the numerical analysis, the composite was treated as a linear elastic, isotropic and homogeneous material. The hypothesis of linear behavior was verified during the experimental tests. In Table 7, Young's modulus calculated from the expression (1) was presented. The agreement between tensile and vibration modulus was satisfactory from the 3rd mode.

Table 6.
Numerical-experimental correlation on 2 mm thick PP-KHF.

No. Mode	Numerical resonance frequency [Hz]	Experimental resonance frequency [Hz]	Δ (Experimental-Numerical) frequency [%]
1	7.3	6.7	−8.7
2	46.6	46.1	−1.0
3	131.7	132.2	0.3
4	260.1	261.8	0.6
5	432.6	431.9	−0.2
6	649.1	651.0	0.3
7	908.9	914.4	0.6
8	1211.4	1219.1	0.6

Table 7.
Elastic modulus measured with free vibration-damping test on 2 mm thick PP-KHF.

No. Mode	1	2	3	4	5
ρ [Kg/m3]	1007	1007	1007	1007	1007
l [m]	0.3	0.3	0.3	0.3	0.3
fn [Hz]	6.7	46.1	132.2	261.8	431.9
H [m]	0.002	0.002	0.002	0.002	0.002
Cn	0.55959	3.5069	9.8194	19.242	31.809
$E_{vibration}$ [MPa]	3521.9	4231.6	4432.7	4529.8	4511.3
Δ $E_{tensile}$[a] - $E_{vibration}$ [%]	20.7	4.7	0.2	−2.0	−1.5

[a]Tensile Test - Material: PP-KHF, thickness: 2 mm, direction: longitudinal.

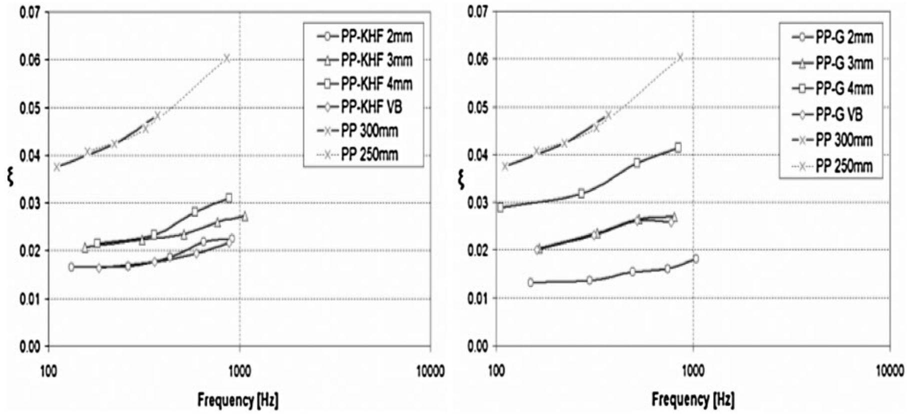

Figure 7.
PP-KHF and PP-G damping ratio variation.

In the same tests the damping properties of NFC and GFC were measured (Figure 7). We noted an increasing damping for higher frequency at the same thickness for both materials. Once again, the data show that tested NFC have damping properties higher than GFC at the highest compaction level (e.g. thickness 2 mm); opposite trend is presented at lower compaction.

Tensile and dynamic mechanical analysis performed show a particular engineering interest to composites with higher compaction levels, which present a good compromise in terms of dynamic and mechanical properties. In non-structural applications, when better vibration and acoustic damping capacity is required, instead, composites produced with the vacuum bagging techniques may be employed.

Vibration-damping tests were performed on NFC and GFC composites following the new method in order to characterize the behavior at higher frequencies. Three specimens were tested for each compaction level (thickness 2 mm, CM and VB) and length considered. Samples tested according to this method had a width of 40 mm and a free length of 200 to 250 mm. All the samples were cut with length parallel to roll direction (L). In Table 8, experimental damping of 2 mm thick PP-KHF (length 250 mm) is presented. With this technique only the 1st mode was not measured.

Table 8.
Results of the new vibration-damping test on 2 mm thick PP-KHF.

No. Mode	PP-KHF 01		PP-KHF 02		PP-KHF 03	
	resonance frequency [Hz]	damping ξ	resonance frequency [Hz]	damping ξ	resonance frequency [Hz]	damping ξ
1	14.4	–	12.9	–	13.9	–
2	66.9	0.0173	63.8	0.0181	69.8	0.0169
3	189.2	0.0167	184.3	0.0165	196.3	0.0164
4	376.7	0.0175	369.3	0.0172	384.8	0.0173
5	635.0	0.0198	610.3	0.0199	641.4	0.0188
6	946.5	0.0206	918.4	0.0195	951.4	0.0196
7	1316.1	0.0227	1290.6	0.0215	1328.0	0.0212
8	1745.0	0.0243	1700.2	0.0217	1761.0	0.0218
9	2242.6	0.0281	2179.2	0.0240	2247.4	0.0250
10	2785.8	0.0300	2730.9	0.0301	2815.6	0.0276

Table 9.
Numerical-experimental correlation on 2 mm thick PP-KHF.

No. Mode	Numerical resonance frequency [Hz]	Experimental resonance frequency [Hz]	Δ (Experimental-Numerical) frequency [%]
1	13.7	14.4	4.6
2	66.8	68.0	1.7
3	189.9	188.9	−0.6
4	376.9	372.3	−1.3
5	628.9	618.6	−1.7
6	938.8	926.8	−1.3
7	1311.5	1295.4	−1.2
8	1735.4	1722.4	−0.8
9	2223.1	2205.8	−0.8
10	2777.4	2748.2	−1.1

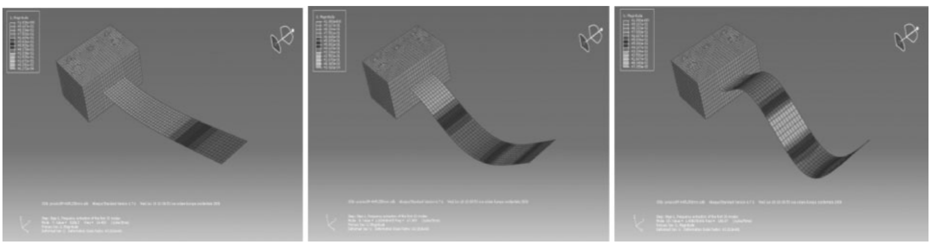

Figure 8.
Modal Analysis: first three vibration modes.

A numerical-experimental correlation was performed (Table 9, Figure 8) to check the frequency of the experimental flexural modes obtained. Subspace iteration method was used for calculating the frequencies. The agreement between numerical and experimental frequencies was quite good.

Figure 9 and 10 show the damping variation of NFC and GFC for the compaction levels selected. The data were obtained according to ASTM E756 and the new method. Once again we noted an increasing damping at higher frequency, at the same thickness for both materials; moreover, the

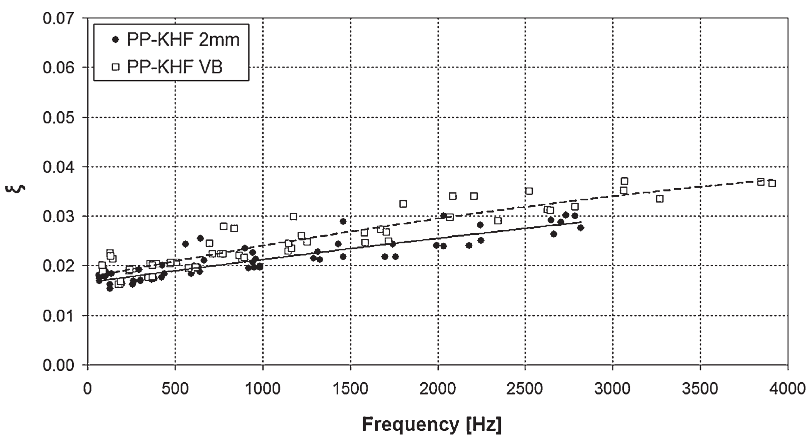

Figure 9.
PP-KHF damping ratio.

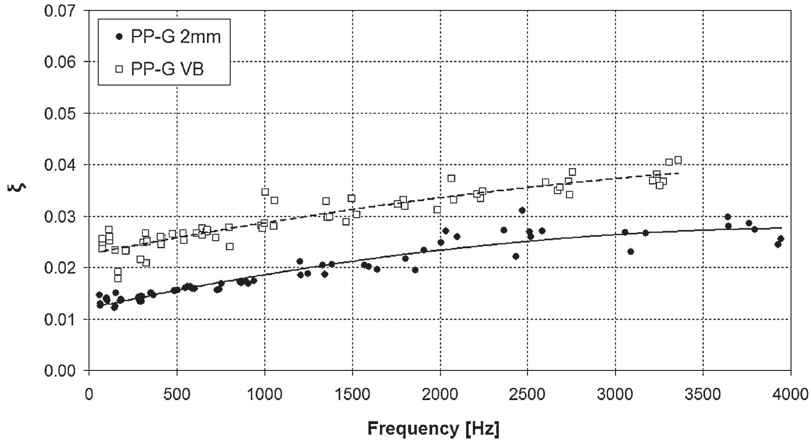

Figure 10.
PP-G damping ratio.

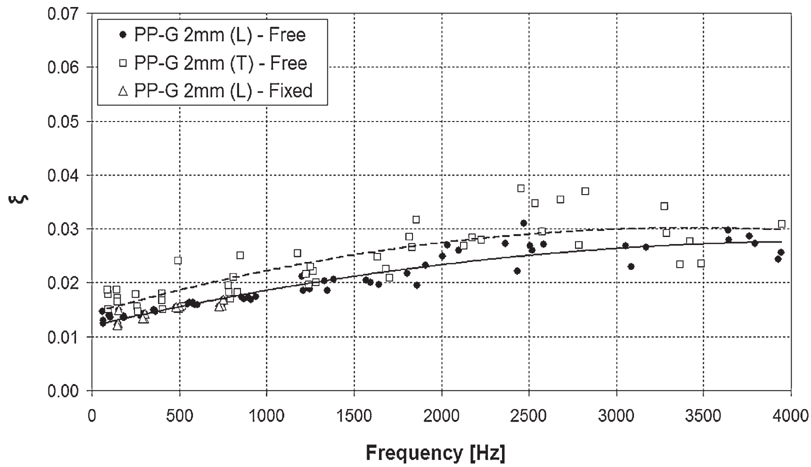

Figure 11.
PP-G damping ratio (L - longitudinal, T - transverse direction).

data show that tested NFC have damping properties higher than GFC at the highest compaction level (e.g. thickness 2 mm); opposite trend is presented at lower compaction (VB). The new method has allowed to extend significantly the frequency range up to three/four times the range previously investigated.

The effect of direction on damping ratio was further investigated. Figure 11, by way of example, shows the damping ratio of PP-G, 2 mm thickness, for longitudinal and transverse directions. The measurements show higher data scatter in transverse direction. In general the average damping ratio in transverse direction is approximately the same as longitudinal direction.

Conclusion

In this research, different mechanical and dynamic characterizations of natural and glass fiber composite are presented, directed toward the exploration of possible composite materials for structural and non-structural applications. The research showed that NFC, based on thermoplastic matrix and natural fibers, have mechanical and damping properties that are comparable and sometimes superior to glass fiber composites. These results show that NFC have a potential to be used instead of conventional GFC in engineering applications where low weight, easily recyclable and environmental friendly materials are desirable.

Composites with higher compaction levels appear to give a good compromise in terms of dynamic and mechanical properties. In non-structural applications that require better vibration damping capacity, instead, composites produced with the vacuum bagging techniques can be employed. Operational flexibility and cost advantages of this technology are expected to surpass those of conventional methods.

Acknowledgements: The authors gratefully acknowledge the financial support provided by Fondazione Cariplo. Grateful acknowledgements are given to Professor G. Ghiringhelli for his support in the new vibration-damping test method.

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