Mechanical properties evaluation and model finite element analysis of cork and felt based nanofilled phenolic resin composites

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Abstract: *The paper presents the development of numerical experiences using finite element commercial codes, based on experimental mechanical tests performed on ablative composite materials. The studied ablative materials were obtained using liquid phenolic resin matrix nanofilled with silicon carbide nanoparticles (added in different weight contents values: 0, 1 and 2 wt.% relative to the resin) that was impregnated into ablative preforms. The results of the numerical simulations are in accordance with the experimental data obtained for the tested specimens, showing that finite element analysis is a promising tool for development of a realistic simulation for advanced materials used in aerospace applications.*

Key Words: *ablative materials, compression strength, Young’s modulus of elasticity, finite element simulations*

1. INTRODUCTION

Recently the aerospace community has shown a great interest in developing some novel materials, the nanocomposites, because of the excellent properties of strength and stiffness of the nanoparticles embedded in the matrix. These improved materials are of great value for the aerospace structures, the aim being to produce long lasting components that can perform in the harsh environment. However, the mechanical properties and the material mechanics are yet to be fully discovered and encompassed. Therefore, in this work, a series of numerical simulations using the Finite Element Method (FEM) are developed in order to obtain more information about the material mechanics. In this method, the structure is decomposed in many simple and small elements and the behavior of each of them is described with a simple set of equations. An accurate discretization using FEM of a realistic structure may be composed of thousands and even millions of elements and nodes so they are now solved with commercially available software packages developed with similar methodology. The software used in this paper is PATRAN/ NASTRAN.

The experimental part of the laboratory study focused on mechanical testing of two classes of ablative materials with matrix consisting of phenolic resin (PR) with different weight loadings of nanometric silicon carbide (nSiC), based on carbon fiber felt preform and cork respectively. The ablative materials with nanometric loadings were obtained using ultrasonic homogenization, followed by a thermal treatment process with multiple temperature stages from room temperature to 150°C. The two ablative material sets differ by the reinforcing material.

One set is based on cork particles, one is based on carbon fiber felt, while both sets have the same matrix, consisting of phenolic resin (PR), simple or nanofilled with two nanofiller weight contents (1 and 2% nSiC).

The following nomenclature will be used for the sample: PR/cork and PR/felt for the control samples with no nanofiller and PR+1%nSiC/cork, PR+2%nSiC/cork for the samples with cork and phenolic resin with 1 and 2% nSiC respectively, PR+1%nSiC/felt, PR+2%nSiC/felt for the samples with carbon felt and phenolic resin with 1 and 2% nSiC respectively.

Nanometric silicon carbide was added to improve the properties of the basic carbon/phenolic materials, especially from thermal and tribological perspective. However, it is essential for the mechanical properties not to be negatively affected by the nanofiller presence; moreover one can aim for an improvement to be desirable, as conducted studies regarding phenolic resin with nanometric silicon carbide addition [1] proved that low contents of this nanofiller are able to improve mechanical, thermal and ablative properties.

Ablative materials are widely used in aerospace application as parts of thermal protection systems of space vehicles.

Although their main advantage is their excellent thermal and ablative resistance, during space missions they are subjected to different mechanical loadings (such as compression, bending etc.). Therefore, their mechanical strength and stiffness properties measurement and prediction are very important for the final application were these materials are used. The mechanical results obtained in the laboratory are compared with the numerical results obtained using FEM.

2. MECHANICAL TESTS

Mechanical properties experimental measurement consisted of 3-point bending and compression tests. The tests were performed on INSTRON 5982 mechanical testing machine equipped with 10 kN load cell, at room temperature, following specific international standards recommendations.

Three-point bending test was performed according to SR EN IN178 standard [2], at 2 mm/min speed rates, nominal span length and conventional deflection (1.5 of the specimen thickness). Five specimens of each sample were tested, all of them fractured before reaching conventional deflection.

The specimen geometry was rectangular (70x15x5 mm). The testing principle scheme is presented in Fig. 1, where N represents the applied load, while L is the span length set as a function of the sample thickness (16 x thickness).

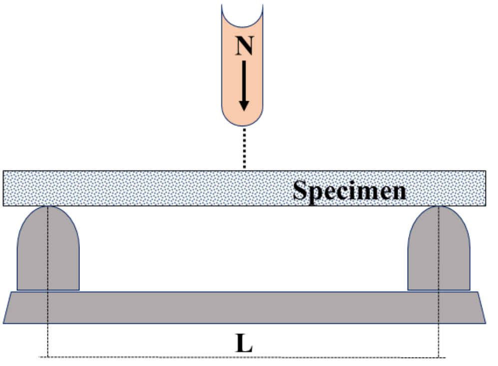


Fig. 1 – 3-point bending test scheme

Below, Fig. 2 and Fig. 3 present the bending curves obtained during the materials testing. In both sets of samples, the positive effect of the nanometric particles is observed. It is noticed that bending strength (its values are marked on the stress-strain curves graphics) increases, lower contents leading to higher increments.

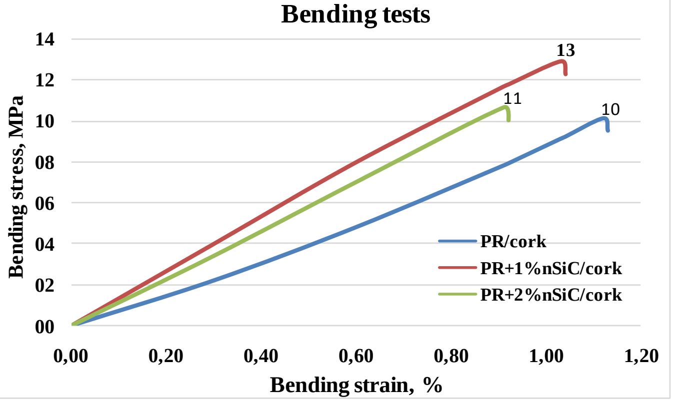


Fig. 2 – Stress-strain curves during bending tests of PR/nSiC/cork materials

It can be observed that the materials experience a linear behavior, the curves present a slope increase that is approximately linear, and the break occurs at maximum bending stress value. This suggests, as it was expected, the brittle nature of both carbon felt and cork based materials.

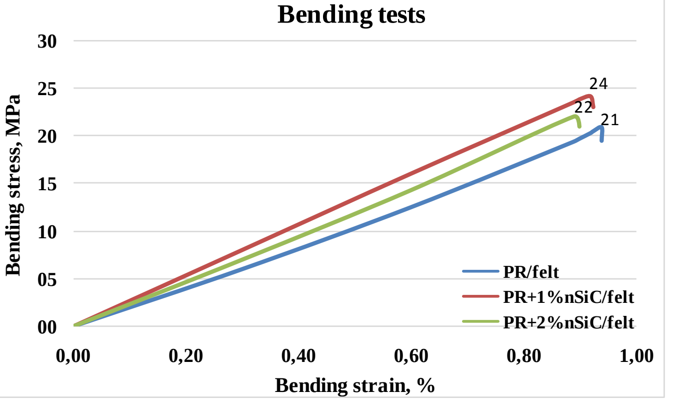


Fig. 3 – Stress-strain curves during bending tests of PR/nSiC/felt materials

From Table 1, it can be observed that along with the bending strength increase, the bending modulus exhibits the same increment trend, as a function of nSiC contents into the matrix. Also, the strain value decreases with modulus increase, as expected, confirming one again the brittle nature of the materials.

Table 1 – Bending modulus and strain values corresponding to the ablative materials

Sample	Bending modulus, MPa	Strain, %
PR/cork	918 ± 15.3	1.12
PR+1%nSiC/cork	1145 ± 18.8	1.03
PR+2%nSiC/cork	1106 ± 18.9	0.91
PR/felt	2190.21 ± 38.9	0.94
PR+1%nSiC/felt	2393.32 ± 68.5	0.92
PR+2%nSiC/felt	2469.1 ± 112,5	0.89

Compression test was performed according to ASTM D1074 standard [3], at 1.3 mm/min speed rates, using cylindrical specimens with 12.7 mm diameter and 4 mm thickness. The compressive strength and stiffness values were obtained calculating an average of the obtained results after testing 5 specimens of each sample. The compression testing principle scheme is presented in Fig. 4, where N represents the applied load.

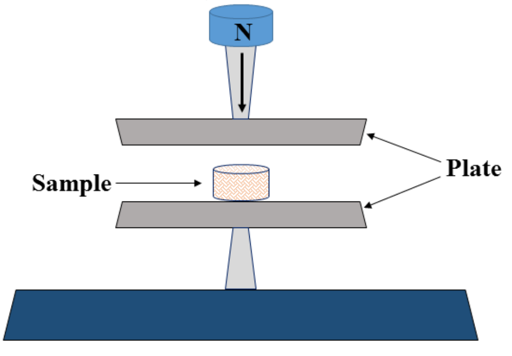


Fig. 4 – Compression test scheme

Fig. 5 and Fig. 6 show the compression curves obtained during the materials testing. The same trend as in bending is observed, 1% nSiC content generates the higher strength increments, but both nanofilled samples show superior properties. Also in terms of compression, the stress-strain curves are characteristic to brittle materials [4].

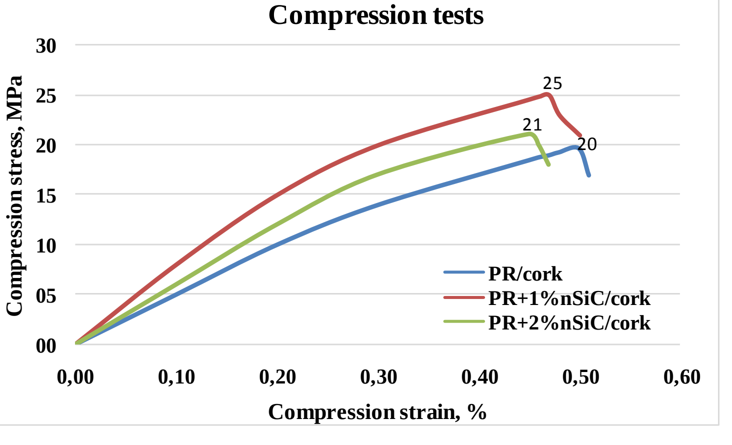


Fig. 5 – Stress-strain curves during compression tests of PR/nSiC/cork materials

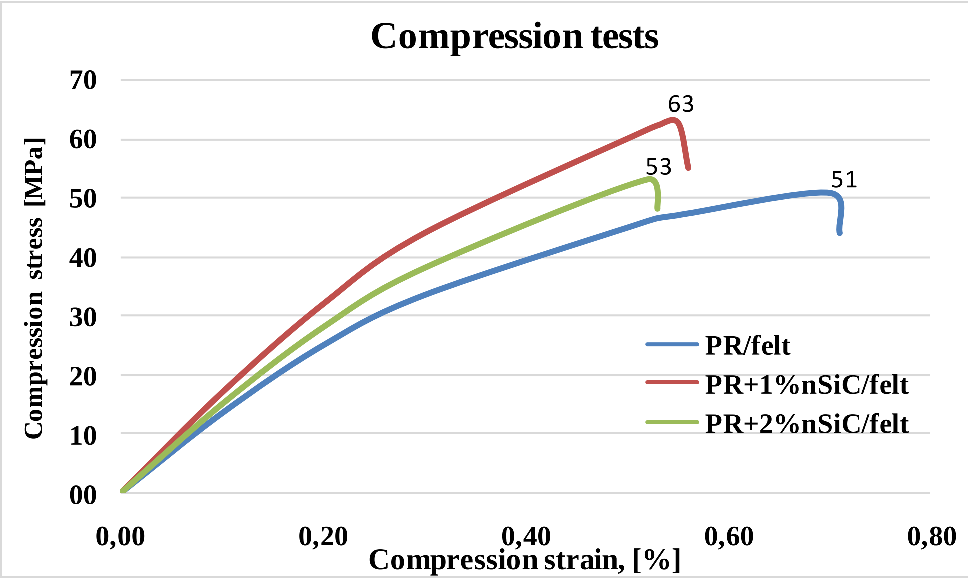


Fig. 6 – Stress-strain curves during compression tests of PR/nSiC/cork materials

From Table 2, it can be observed the same trend as in bending tests, along with the compression strength increase, the compressive modulus exhibits the same increment trend, as a function of nSiC contents into the matrix.

Table 2 − Compressive modulus values corresponding to the ablative materials

Sample	**Compressive modulus, MPa**
PR/cork	342.5 ± 20.9
PR+1%nSiC/cork	553 ± 29.3
PR+2%nSiC/cork	505.8 ± 15.5
PR/felt	585.47 ± 19.9
PR+1%nSiC/felt	664.98± 9.3
PR+2%nSiC/felt	659.64 14.6

3. NUMERICAL SIMULATIONS OF THE MECHANICAL TESTS

Using the commercially available software package PATRAN/NASTRAN we intend to investigate the stresses appeared in the structure to see if it is a powerful tool for predicting the mechanics of the material and, therefore, modeling nanocomposite space structures.

In this early stage it is introduced a homogenous material characterizes by a Young modulus equal with the mean value obtained from the laboratory experiences and a Poisson ration common for non-metallic materials.

The discretization is made using solid elements.

3.1 Bending tests

The main characteristics of the finite element model of the bending sample are presented in Fig. 7.

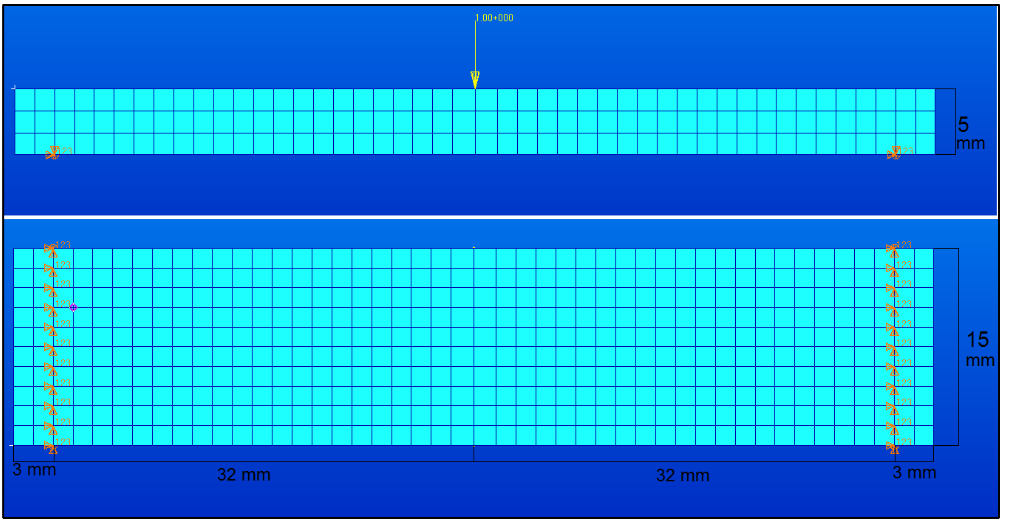
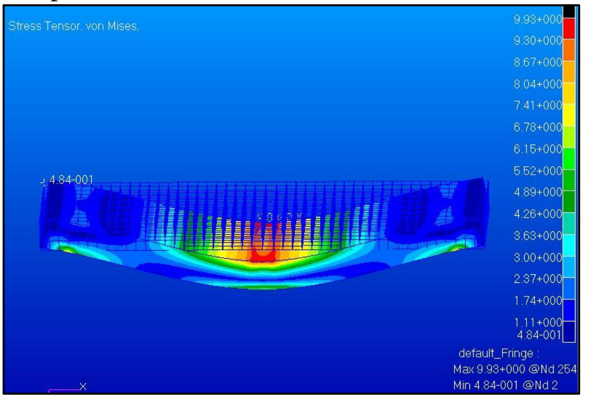


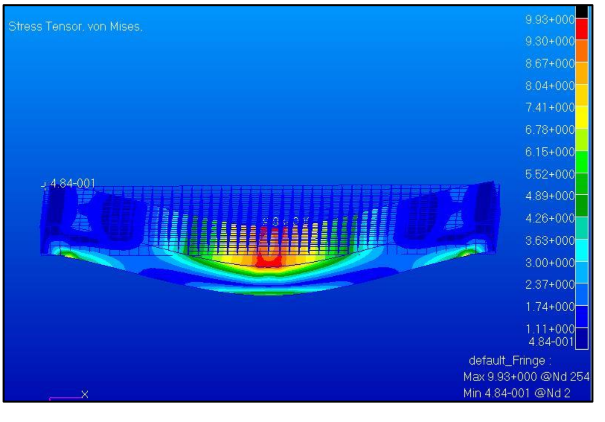
Fig. 7 – Geometry description for bending tests

The results obtained using FEM are presented in Fig. 8 for:

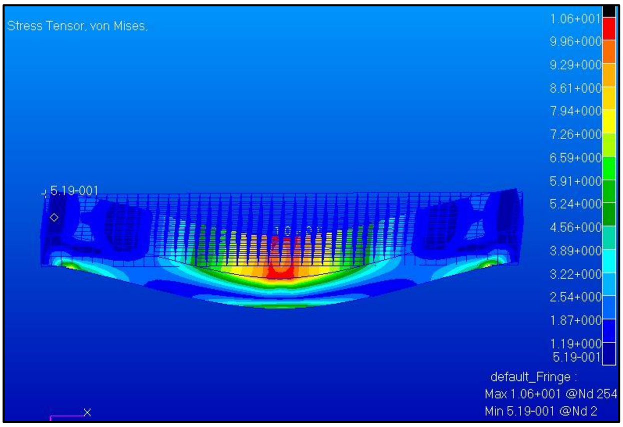
a) Cork and phenolic resin
b) Cork and phenolic resin with 1%nSiC
c) Cork and phenolic resin with 2%nSiC



a) PR/cork



b) PR+1%nSiC/cork

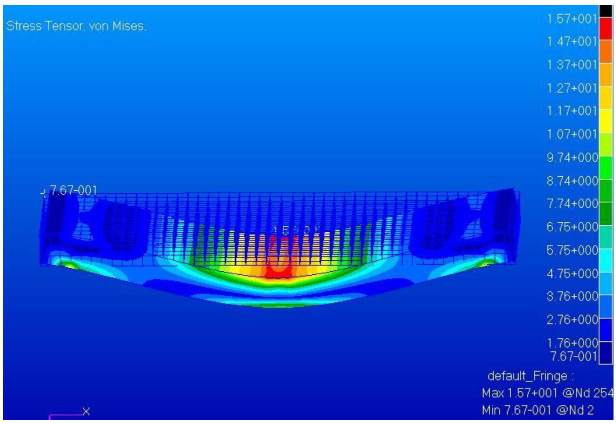


c) PR+2%nSiC/cork

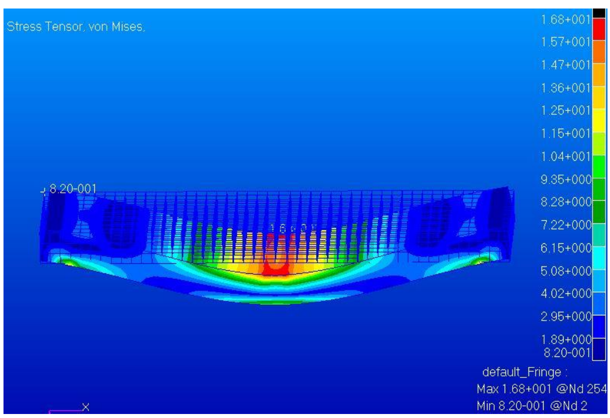
Fig. 8 –FEM results for bending samples with cork as reinforcement material

And in Fig. 9 are presented the results for:

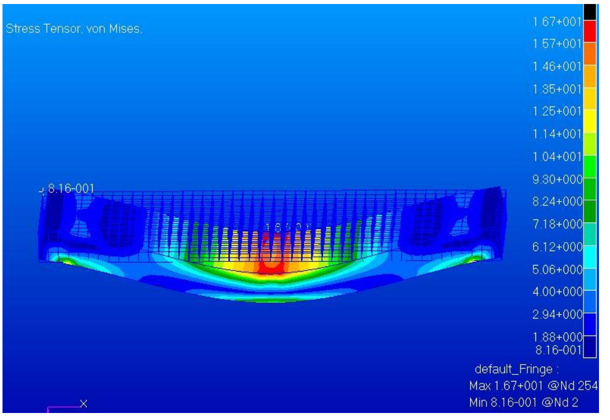
a) Carbon felt and phenolic resin
b) Carbon felt and phenolic resin with 1%nSiC
c) Carbon felt and phenolic resin with 2%nSiC



a) PR/felt



b) PR+1%nSiC/felt



c) PR+2%nSiC/felt

Fig. 9 –FEM results for bending samples with felt as reinforcement material

Table 3 − Results for bending tests and simulations

Material	nSiC content	Young modulus [MPa]	Poisson ratio	Applied forces [N]	Stresses [MPa]	
					Lab tests	Numerical results
PR/cork	0%	1026	0.33	47.00	10.10	9.98
PR+1%nSiC/cork	1%	1083	0.33	46.75	12.93	9.93
PR+2%nSiC/cork	2%	1107	0.33	50.08	10.63	10.60
PR/felt	0%	2235	0.33	74.01	20.92	15.70
PR+1%nSiC/felt	1%	2393	0.33	79.14	24.13	16.80
PR+2%nSiC/felt	2%	2500	0.33	78.74	22.05	16.70

3.2 Compression tests

The main characteristics of the finite element model of the compression sample are presented in Fig. 10.

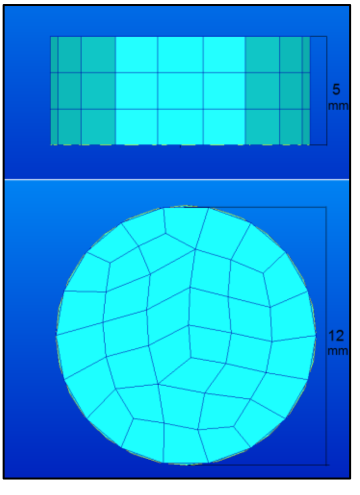
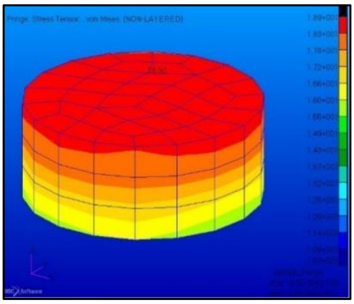


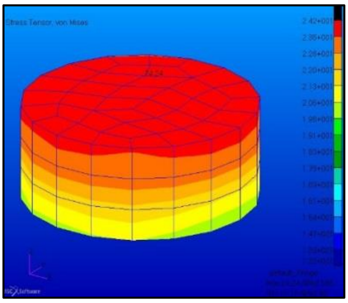
Fig. 10 – Geometry for compression tests

The results obtained using FEM are presented in Fig. 11 for:

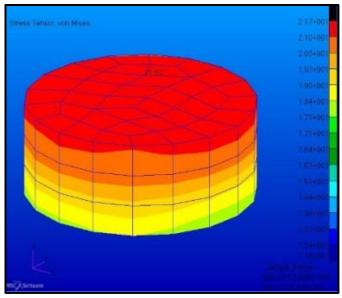
a) Cork and phenolic resin
b) Cork and phenolic resin with 1%nSiC
c) Cork and phenolic resin with 2%nSiC



a) PR/cork



b) PR+1%nSiC/cork

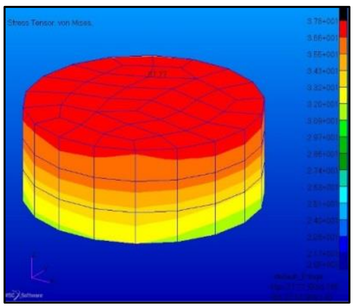


c) PR+2%nSiC/cork

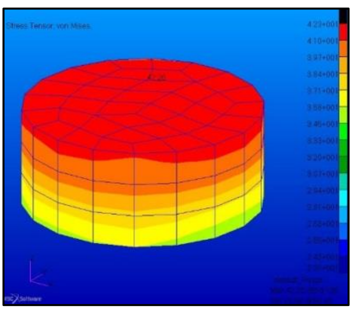
Fig. 11 – FEM results for compression of samples with cork as reinforcement material

And in Fig. 12 are presented the results for:

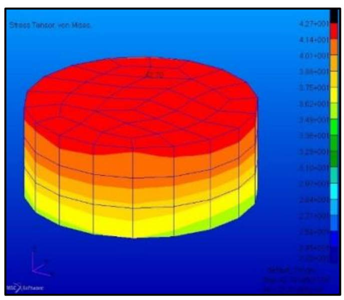
a) Carbon felt and phenolic resin
b) Carbon felt and phenolic resin with 1%nSiC
c) Carbon felt and phenolic resin with 2%nSiC



a) PR/felt



b) PR+1%nSiC/felt



c) PR+2%nSiC/felt

Fig. 12 – FEM results for compression of samples with felt as reinforcement material

Table 4 − Results for compression tests and simulations

Material	nSiC content	Young modulus [MPa]	Poisson ratio	Applied forces [N]	Stresses [MPa]	
					Lab tests	Numerical results
PR/cork	0%	342.5	0.33	2039.5	19.68	18.90
PR+1%nSiC/cork	1%	533	0.33	2616.0	23.45	24.20
PR+2%nSiC/cork	2%	506	0.33	2338.0	20.59	21.67
PR/felt	0%	593	0.33	4076.0	50.79	37.80
PR+1%nSiC/felt	1%	665	0.33	4560.0	62.62	42.30
PR+2%nSiC/felt	2%	660	0.33	4607.0	53.45	42.70

As it can be observed the biggest differences appear for the Carbon felt and phenolic resin cases, thus implying that the constitutive equations have to be improved or some other effects like clustering or particle-particle interaction must be considered.

4. CONCLUSIONS

Regarding the experimental results, both sets of samples exhibit the same trend in bending and compression, adding 1 % nanoparticles filler to the phenolic resin generating higher increments than the ones generated by 2 % contents. This could be due to eventual particle-particle interaction that can lead to agglomeration (similar to clustering) of the nSiC nanoparticles, causing the appearance of stress concentration sites that lead to lower mechanical properties. The difference between carbon felt and cork based materials in numerical results compared to experimental test results could be owned to the different form of the reinforcing agent, that can lead to eventual void formation in different contents, as cork agent is in form of powder and can be mechanically/ultrasonically homogenized in the phenolic resin mixtures, while carbon felt is a mat shape preform, that has to be impregnated with the phenolic resin mixtures. This leads to different composite morphologies and microstructures, thus could be a reliable explanation for the observed differences between numerical and experimental results in carbon felt based materials. Considering all the aspects presented above, the finite element method is a reliable tool for modeling real nanocomposite structures loaded in real conditions and obtaining preliminary results that can lead to a first phase of sizing and designing.

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