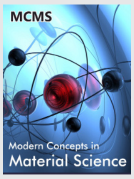

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Research article

Modeling and Simulation of Bending, Tensile and Impact Loads of Reinforced Thermosets with Carbon Fiber Fleece

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Abstract

Carbon fiber reinforced composites (CFRP) have very high strength to weight and stiffness to weight ratios. In addition to that, composites have excellent durability, heat and corrosion resistance which makes it the material of choice for the light weight sec- tor. During the production of composite parts, 10-30% waste is generated for example by offcuts and out of spec parts. Moreover a lot of aircrafts partially consisting of CF will soon reach their end of life cycle. So industry has to focus more on recycling of CF. Through new recycling methods the carbon fiber is regained from polymer matrix. The obtained fibers can only be used reasonably in chopped form, which can be reused for manufacturing an isotropic fleece by wet-laid process. Produced fleeces are impregnated with thermosets by resin transfer molding (RTM). This research shows the interrelation between several fiber length and fiber volume fractions in the composite with their specific values (flexural stiffness, tensile strength, Young's modulus, energy absorption). To design applications with this new material, the mechanical properties have to be forecasted. Hence the isotropy in the composite is simulated with AUTODESK HELIUS COMPOSITE 2017 by using the classical lamination theory (CLT) and a stacking order of unidirectional laminates. Following all of the specific values can be simulated and a comparison to the measured values gives a good approximation.

Introduction

In composite materials, combinations of properties can be achieved that could not be achieved with individual materials because of the inclusion of reinforcing material which is stronger and stiffer than bulk matrix. The reinforcing material of composites may be in the form of fibers, particles, or sheet laminates. Regarding to its lightweight construction potential, the key market of CFRP increases intensively and a market in automotive industry is developed.

In this sector, electric powered mobility and decrease in weight play a major role. On the one hand a greater extent of electric operated automobiles should be produced and sold. To compensate battery weight the best solutions are reinforced plastics (particularly carbon fiber reinforced plastics). On the other hand, there are stringent input requirements by EU referring to conservation and CO_2 reduction. Emission of combustion engines should be lowered from 141.8 gram CO_2 per kilometer (2012) until 2020 to 95 gram per kilometer [1].

Therefore, classic materials have to be substituted under conservation of physical and mechanical properties. This is possible with carbon fibers [2].

The composites market report 2017 forecasts that, in terms of volume, the global market for CFRP is projected to reach 210.19 kilotons by 2022, at a compound annual growth rate (CAGR) of 12.50% during the same period. The automotive application segment in Europe and the aerospace and defense industry in North America are the major growing sectors [3]. In consequence of production, 10 to 30% cost-intensive carbon fiber waste is accumulated. In addition to that, a lot of airplanes reach their end of life cycle with around 20 tons of CF waste per plane [4]. Since a land fill ban of CF waste, research in recycling CF gets more into focus [5]. Another reason for recycling is the energy-intensive manufacturing of CFRP. Costs can be reduced efficiently by using recycled carbon fibers (rCF) [6].

There are mainly three types of recycling: mechanical (crashing), thermal (pyrolysis) and chemical (solvolysis). Recent researches deal with supercritical solvolysis of water and other fluids [7-9]. One possibility to reuse chopped recycled fibers is through a fiber mat. Carbon fiber nonwovens can be fabricated by aerodynamics, hydrodynamics (wet-laid) or carding. Fabrication methods are much simplified if the reinforcement is in the form of chopped fibers. These can be blown onto a surface to form a mat and this technique is used in this study.

The disadvantage of a such reinforcement is that some of the reinforcing effect of the fibers is sacrificed because the average axial stress carried by fibers is less for short ones than long ones. The average axial stress in a fiber depends on its aspect ratio, d/l, where d and l are the fiber diameter and length, respectively. Manufacturing methods are numerous, examples are extrusions, injection moldings, and resin transfer molding (RTM). The main advantages of the former in-mold transformation technique are: an isotropic behavior by randomly oriented fibers, a low cost production, no dust and electrostatic problems, no respirable particulates

and low surface weight with maximum homogeneity [10].

Many previous studies have dealt with randomly oriened reinforcements. Giridharan [11] studied the mechanical performance of discontinuous carbon fibre reinforced composites through tensile testing of a wide variety of fibre architectures. Over the range of architectures tested (Vf = 20% - 55%), he found that tensile stiffness and strength increased linearly with fibre volume fraction but the influence of other parameters such the tow size, the fibre length, the thickness as well as the matrix properties was more complex. Zhu et al. investigated random flax fiber reinforced polypropylene composites made by two different techniques, namely, film-stacking and suspension impregnation [12]. The fiber volume fraction of the composite had a range of 0.10 to 0.44. The results showed that the tensile modulus had a maximum at about 0.28 fiber volume fraction. For the tensile strength, an irregular trend was observed. There seemed to be a lot of fluctuations in the results. The values went up and down before reaching a maximum at 0.44 fiber volume fraction. A critical fibre length has also been defined as the minimum fibre length which will allow tensile failure of the fibre rather than shear failure of the interface. Thomason et al. [13,14] examined the properties of glass fiber-reinforced polypropylene laminates. The fiber weight fraction ranged from 0.03 to 0.40, which corresponded to 0.01 to 0.19 in terms of volume fraction. In addition, different fiber lengths from 0.1 mm to 50 mm were used. Predictions from the Kelly-Tyson model[bureau] correlated well with the experimental data. The mechanical properties of the laminates increased linearly with the fiber weight content up to 0.40 and then the modulus improvement was considerably less due to fiber packing causing the increasing of void content and out of plane fiber orientation. Li and Mai [15] obtained experimental data on sisal/polystyrene randomly oriented composites. For the pure resin an at fiber weight contents of 0.10, 0.20 and 0.30 specimens, the corresponding ultimate tensile strengths were 34.9 MPa, 24.72 MPa, 31.14 MPa and 30.09 MPa, respectively. For the Young's modulus, the values were 390 MPa, 457.4 MPa, 543.3 MPa and 710.7 MPa. It can be seen that the strength of the composite was less than that of the resin. A decrease in strength was observed as the fiber weight fraction increased from 0.20 to 0.30. Further, there was little increase in modulus as the fiber content increased. Although different combinations of fiber/resin were used in the above studies, some common patterns can be seen. The fiber volume fraction of the random fiber composites was usually less than 0.40. This is the limit that ordinary manufacturing methods can achieve if a good randomness is expected. It is difficult to maintain a random dispersion at high fiber volume fraction. On the other hand, it has been found by different researchers that the tensile modulus/strength tends to show only small increase or even decrease at high fiber volume fractions.

To define a field of application for thermosets, which are reinforced by wet-laid fleeces, material properties are extremely important. The focus lies particulary on flexural stiffness, tensile strength, Young's modulus and energy absorption. The greatest effect is the fiber volume fraction and a secondary effect is the fiber length. Therefore these factors should be simulated and compared to the measured values. Commercial software work with unidirectional (UD) arranged fibers embedded in a matrix. For designing the isotropic fleece the classical lamination theory is a suitable model, because this model gives the opportunity to stack UD laminates over each other using different angles. By this method an isotropic behavior can be simulated. The results show a good approximation for all mechanical properties.

Experimental Approach

Chemicals

Dispersing Agent and Defoamer

For each vessel a solution with hydroxyethyl cellulose from SE Tylose GmbH & Co. KG and water is prepared a day before. To inhibit foam formation three gram BYK 021 from BYK Additives & Instruments is added.

Carbon fibers

TENAX-A HT C124 carbon fibers with a fiber length of 3 mm, 6 mm and 12 mm from TOHO TENAX EUROPE GmbH are used. They are prepared by the manufacturer with an unknown water soluble sizing. Fleece with 1 g fibers are laid down so that a areal weight of

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30 g/m^2 is realized.

Epoxy resin system

A bisphenol-A resin (BAXXORES 5500) and an amine based two-component hardener (BAXXODUR 5530 and 5520) from BÜFA COMPOSITE SYSTEMS GmbH & CO. KG are applied. Reaction time is adjusted by mixing ratio of both hardeners. In the experiments this ratio is 50 to 50, this adds up to a reaction time of 3 hours and a good manageability.

Wet laid process

For the fleece a process based on paper manufacture is used. At first the short fibers are suspended with a stirrer in water with the dispersing agent and surfactant. Then the dispersion is pumped from two tanks via a rotary distributor onto an inclined wire section. There a fiber mat (or nonwoven) is formed. The water is extracted by vacuum and fed back into two empty tanks where it is available for renewed use. A continuously moving screen conveyed the mat to a heated roller for drying. The result is a process-ready web about 20 m long and 300 mm wide.

Figure 1: Pilot plant for CF nonwovens from Andritz Küsters GmbH (Krefeld).

Resin-Transfer-Molding (RTM)

Subsequent a composite with compounded fleeces and epoxy resin is manufactured by RTM. For this purpose the injection installation IJECT TOUCH 2.0 (Figure 2 left side) from Wolfangel GmbH is utilized. This machine ensures a resin hardener ratio of 100 to 30. In addition to that different parameters as pressure, temperature and material quantity can be varied. Increasing pressure during injection causes entire impregnation and replacement of air in the composite. Moderate temperatures arrange for flowability, while accurate quantities avoid waste. The injection unit is connected to a tool with a squared cavity. (Figure 2 right side) On top and bottom are heating panels to control reaction rate. After insertion of the fleece the tool is closed and the mold cavity is filled under pressure (maximum 6 bar). Then the chemical reaction takes place. If the disk is cured it can be removed from the mold. A post curing is not necessary. The disks have a final thickness of 1.5 mm and fiber volume content up to 40%.

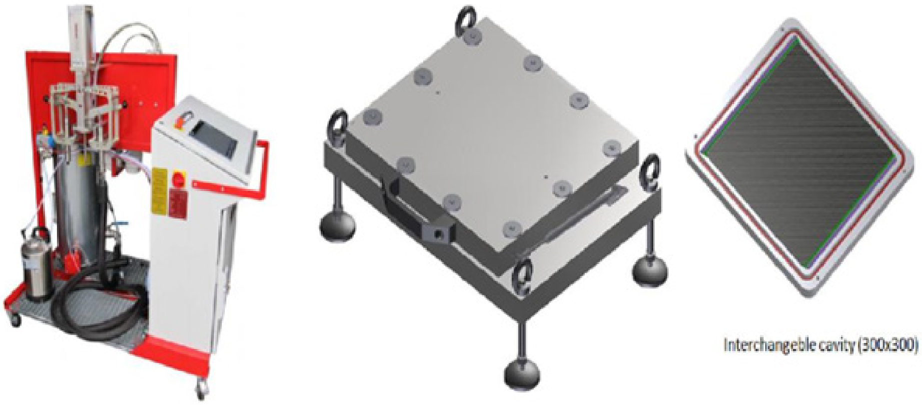

Figure 2: Injection unit (left side) and aluminum tool with interchangeable cavity (right side)

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Mechanical Characterization

Bending Test

Flexural stiffness of the material is analyzed by a four-point bending test in dependence on DIN 14125. In this test, two different specimen geometries are used. Firstly a round sample which is divided into 20° -parts (viewed in Figure 3.a) is measured. Every part is bent nondestructively and in each case the flexural modulus is calculated between 0.5 mm and 1 mm elongation. The results verify whether the fibers in the composite are isotropic or not. For unidirectional fibers the flexural stiffness increases in only one direction, for orthotropic arranged fibers the flexural stiffness increases in two directions and for isotropic fibers the increase is consistent in all directions. Secondly specimens with 30 mm width and 130 mm length are bent nondestructively and their flexural modulus is calculated as described before.

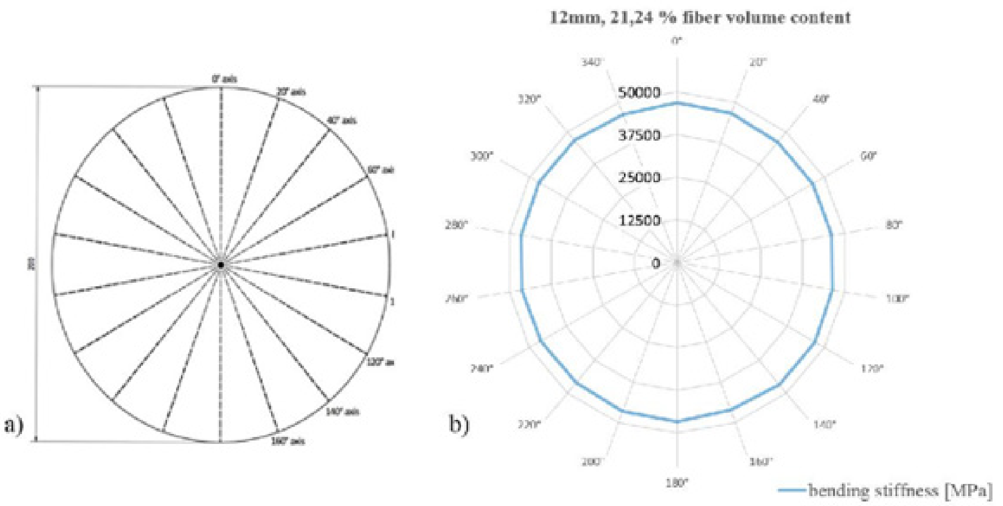

Figure 3: (a)Sample with 20°division for isotropy analysis, (b) Isotropy of composites with carbon fiber fleece.

At each fiber length isotropy could be proved as pictured in Figure 3.b. Fiber volume content has the greatest effect as visible in Figure 4. It shows the relative improvement of flexural stiffness reinforcement with 12 mm fibers in comparison to the pure resin (corresponds to the value 1). With 20% fibers an improvement of 400% is achieved and with maximum fiber volume fraction of 40% the properties increase more than six times. when the fiber volume content is raised from 5.31% to 24.78%. Standard deviations are negligible with 1.8 - 6.3%.

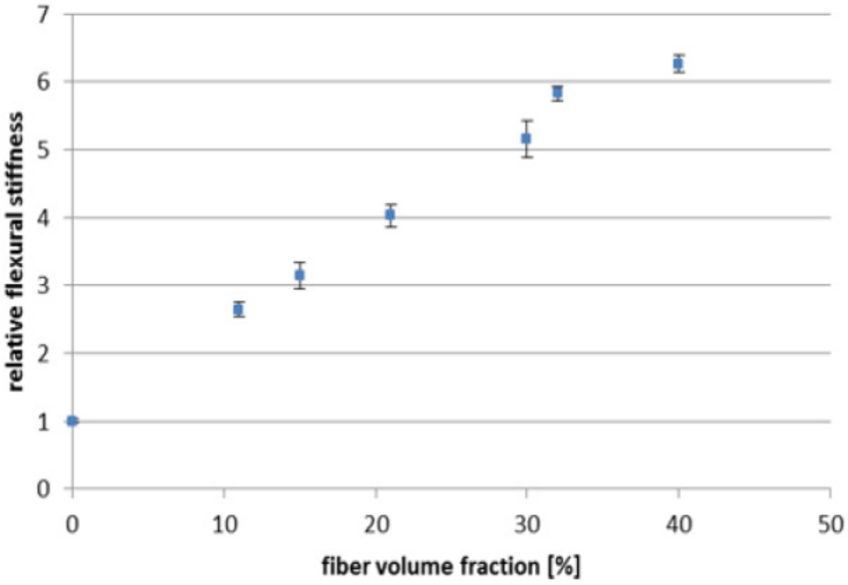

Figure 4: Relative bending properties as a function of fiber volume fractions.

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Tensile Test

Tensile strength, Young's modulus and elongations are determined by tensile test according to DIN 527-4. Due to the fact that the sample has a dimension of 200 mm, tests are conducted with smaller geometries. Samples were repeatedly recessed with a CNC milling cutter from CNC-STEP E.K. They have a length of 150 mm, a width of 15 mm and a thickness of 1 mm. Previous investigations showed that a narrowed size has no effect on the test results [16]. There are five samples per disc which are exposed in standard climate for one day and are analyzed afterwards. Their data are displayed by average. Again the fiber volume content has the major effect on material properties. The properties for the pure resin are 1851 MPa for Young's modulus, 56 MPa for tensile strength and elongation around 7%, elongations of reinforced samples are typically around 3-4% (Figure 5). In Figure 6 the linear increase of Young's modulus and tensile strength with 12 mm fibers are illustrated. When 40% of the composite consist out of CF fleece an improvement of 464% for Young's modulus is achieved. Tensile strength can nearly be quadrupled. Standard deviations increase with increase of fiber volume fraction, however, they are still low with 1.3-12.7%.

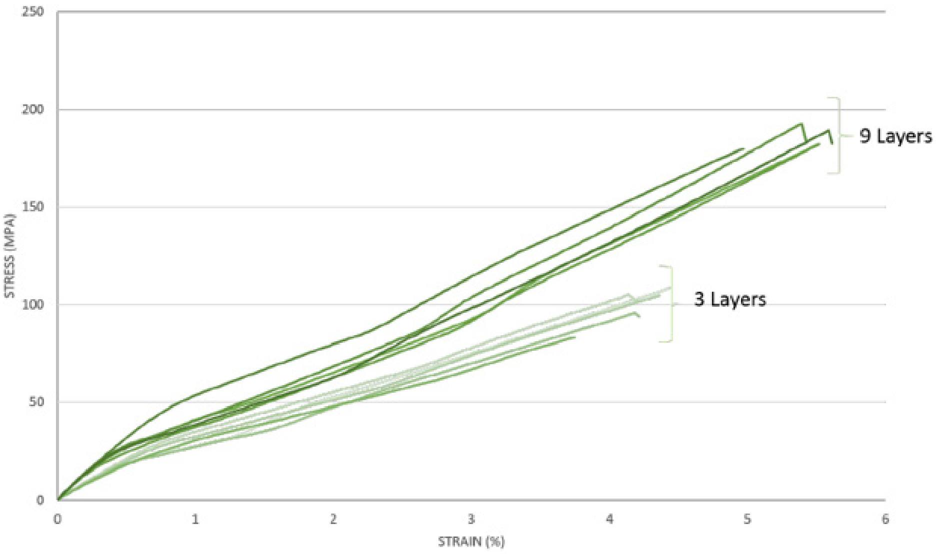

Figure 5: Stress-Strain charts of the 3 and 9 layers specimens.

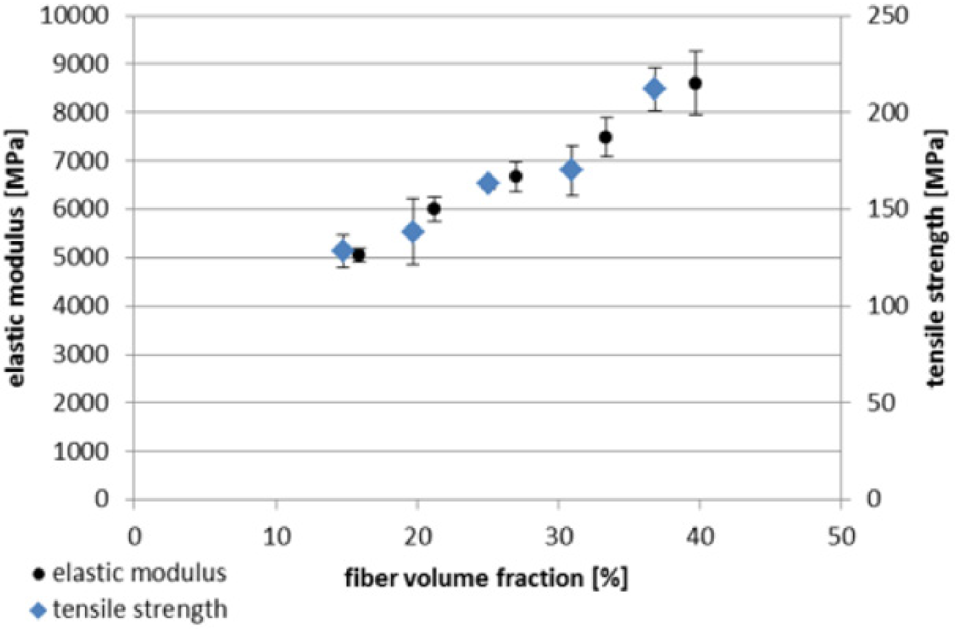

Figure 6: Young's modulus and tensile strength as a function of fiber volume fraction.

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Impact Test

Energy absorption and fracture behavior of the composites were tested for possible crashresistant applications. A force-deflection diagram is measured with an instrumented impact test from CEAST (Figure 7.a). A bolt shown in Figure 7.b falls from a height of 1 m with a total weight of 17.6 kg. For each test, four squared specimens with an edge length of 60 mm are examined according to DIN EN ISO 6603-1. From the data obtained, the average of the maximum force, deformation and energy consumption can be calculated. Additionally the fracture behavior and fragment formation can be optically analyzed.

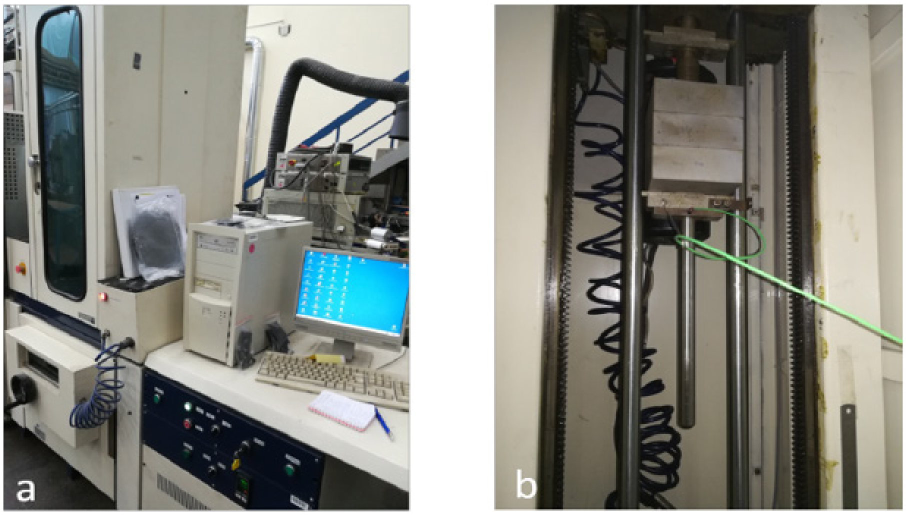

Figure 7: a) Impact machine, b) hemespherical impactor.

The deformation of all test specimens was about 11 mm. Once again, a linear increase with increasing fiber volume fraction was recorded (Figure 8 left). The results show that a tripeling of energy absorption can be realized with a maximum reinforcement of 40 %. The fracture pattern is also of particular importance, since epoxy resin is a brittle material. Test specimens produced from fibers shorter than 12 mm also show this characteristic splintering. Apart from that specimens based on 12 mm fibers get through impact penetration without splintering. Fragments remain attached to the specimen, so that the risk of injury in a crash situation can be minimized (Figure 8 right and Figure 9).

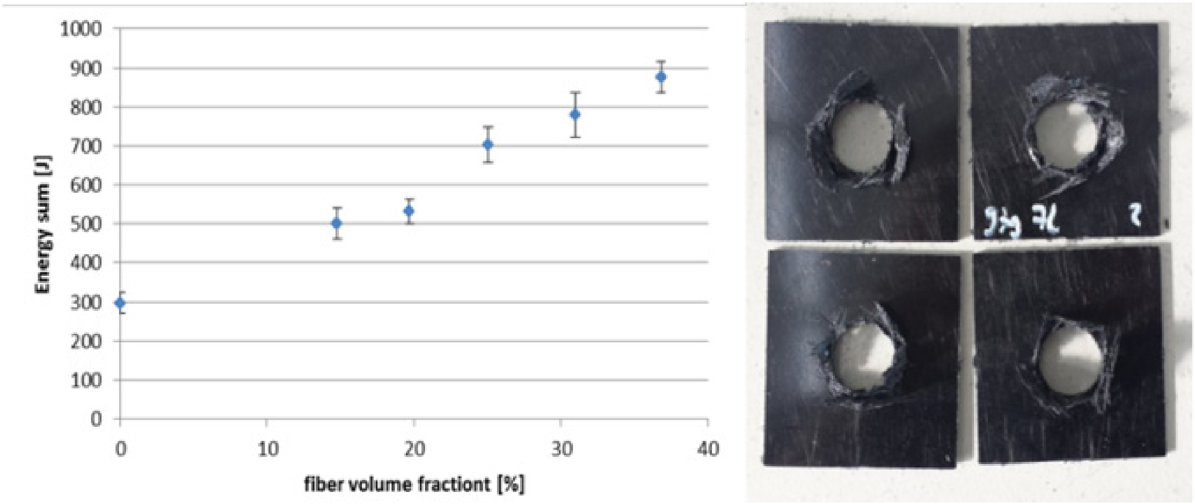

Figure 8: Energy absorption as a function of fiber volume fraction (left) and the penetrated sample with attached fragments (right)

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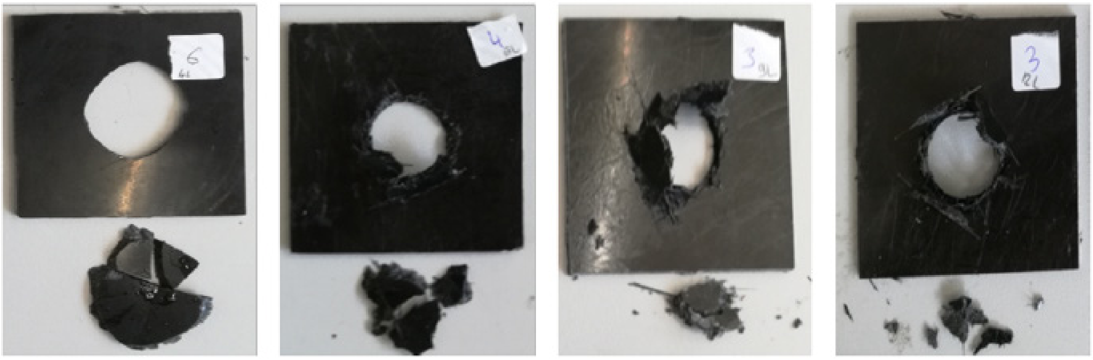

Figure 9: Impact specimen for each configuration (4, 6,9 and 12 layers).

Numerical Model

The measured values should be simulated to forecast mechanical properties for designing different structures. AUTODESK HELIUS COMPOSITE 2017 based upon CLT and micromechanics gives detailed information on composites and their behavior. The basic element in CLT is the monolayer which consists of unidirectional arranged fibers and is embedded in a matrix. At first the mechanical properties of the monolayer are calculated by the rule of mixtures. Therefore fiber volume content is used to describe elastic modulus in fiber direction E_1, across fiber direction E_2, shear modulus G_{12} and Poisson's ratio ν_{12} [17]. Then with summation of the disk-plate stiffness matrices of every monolayer the whole laminate can be characterized. The equation of elasticity for the disk-plate element is shown in equation 1, consisting of three matrices, disk stiffness matrix A, plate stiffness matrix D and coupler stiffness matrix B.

$$\begin{Bmatrix} \{n\}_0 \\ \{n\}_0 \end{Bmatrix} = \begin{bmatrix} [A] & [B] \\ [C] & [D] \end{bmatrix} * \begin{Bmatrix} \{\in\}_0 \\ \{\kappa\}_0 \end{Bmatrix} \qquad (1)$$

Finally with inverse disk-plate matrix engineer constants can be determined:

$$\overline{E_x} = \frac{1}{A_{1,1}} \qquad (2)$$

$$\overline{E_y} = \frac{1}{A_{2,2}} \qquad (3)$$

$$\overline{G_{xy}} = \frac{1}{A_{6,6}} \qquad (4)$$

$$\overline{G_{xy}} = \frac{A_{1,2}}{A_{1,1}} \qquad (5)$$

As most established software AUTODESK HELIUS COMPOSITE 2017 only works with unidirectional laminates, on that account several unidirectional laminates with variable orientations were stacked on top of each other to simulate an isotropic laminate. The numbers of layers and angels are viewed in table 1. A convergence (Figure 10) test showed that at least ten layers are needed. In this case results achieve a deviation of less than 3 % to the measured Young's modulus.

Table 1: Layer structure of the model in AUTODESK HELIUS COMPOSITE 2017 [18].

Number of Layers	Angles [°]
1	(0)
2	$(0/90)$
4	$(0/\pm 45/90)$
6	$(0/\pm 30/\pm 60/90)$
8	$(0/\pm 22.5/\pm 45/\pm 67.5/90)$
10	$(0/\pm 18/\pm 36/\pm 54/\pm 72/90)$
20	$(0/\pm 9/\pm 18/\ldots\ldots/\pm 72/\pm 81/90)$
30	$(0/\pm 6/\pm 12/\ldots\ldots/\pm 78/\pm 84/90)$

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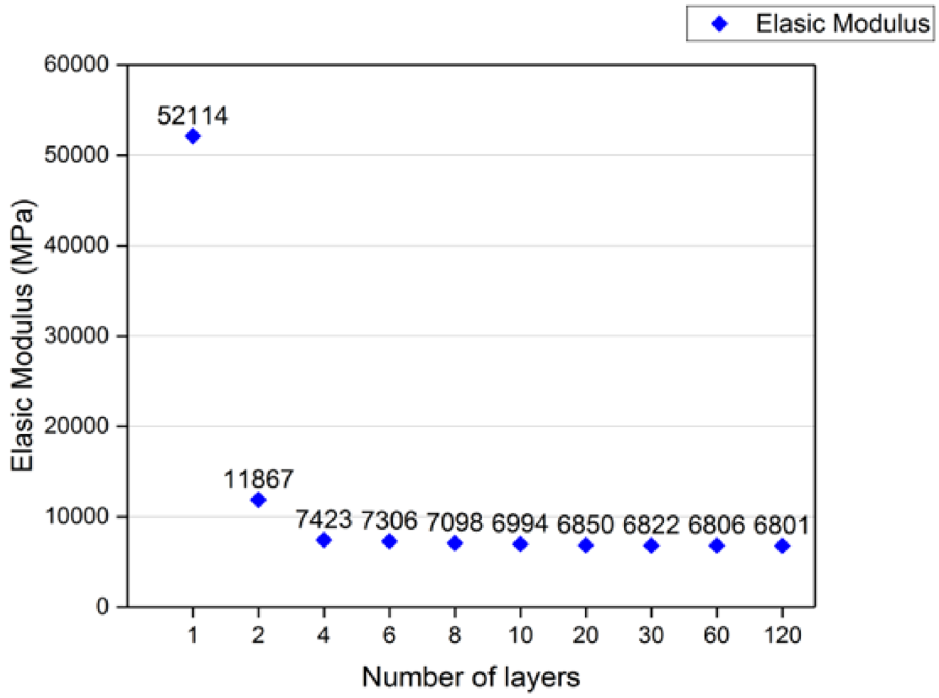

Figure 10: Convergence test to define the minimum number of layers for simulation [18].

Simulation Results

Bending Test

The bending test was reproduced by FEM softwares ANSYS and Autodesk Inventor Professional 2018 and results in terms of load-displacement curves are examined. The same model based on the real boundary conditions is introduced in the two cases (Figure 11) and material engineering data are used directly from the results of Autodesk Helius Composite 2017 [18].

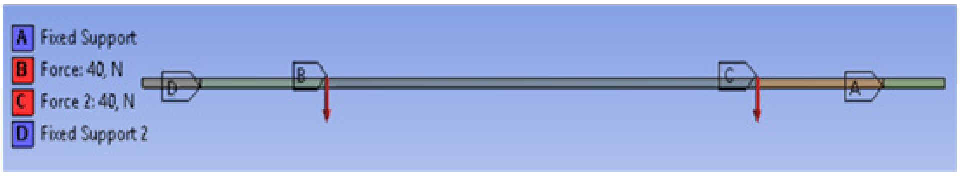

Figure 11: Boundary conditions review of the ANSYS model.

The results from the ANSYS simulation are presented in Figure 12 as the normal displacement of all the points of the nodes under a 80 N normal load.

The comparison of the experimental test results and the numerical simulations is presented in Figure 13. In fact, the experimental curves show a non linear behavior which can't be reproduced by the linear analysis system. The slight difference is due to the analysis system being used and the mesh type which can not be controlled in Autodesk Inventor.

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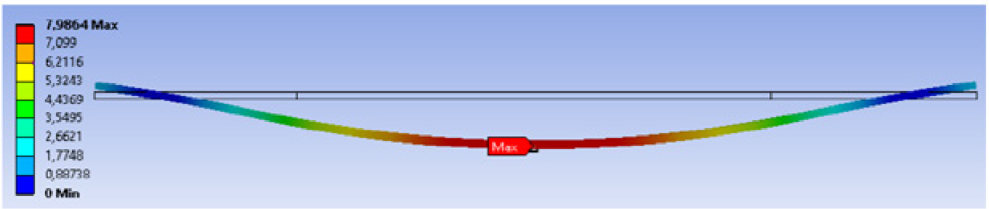

Figure 12: Results of the simulation: Total deformation in normal direction.

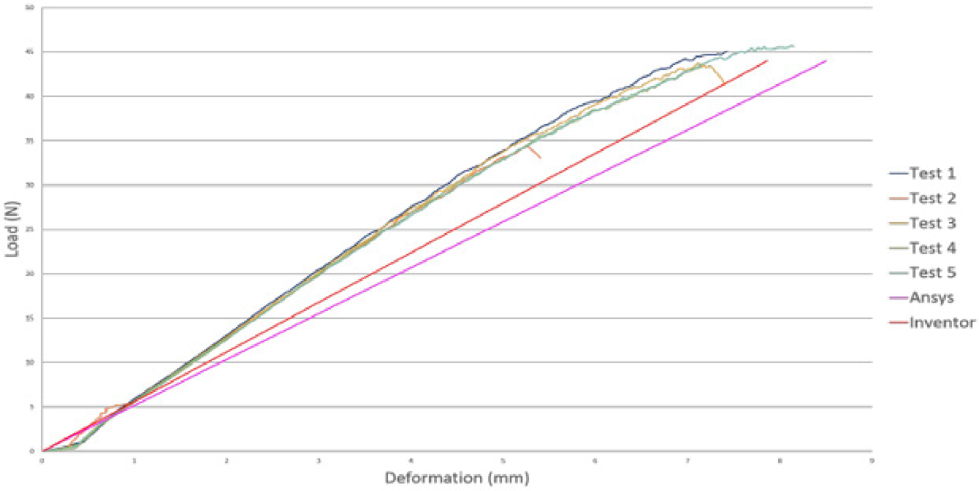

Figure 13: Comparison of the experimental and numerical results of the bending test.

Tensile Test

Like the bending test, the tensile test was reproduced under ANSYS and Autodesk Inventor in order to validate the predicted materials properties of the CFRP. A simple geometry model is implemented into a static structural analysis system and stress-strain curves are then extracted. Figure 14 represents the geometry of the model, the boundary conditions and a capture of the results for the two types of the simulations and Figure 15 shows the comparison between the experimental and numerical results with Autodesk Inventor

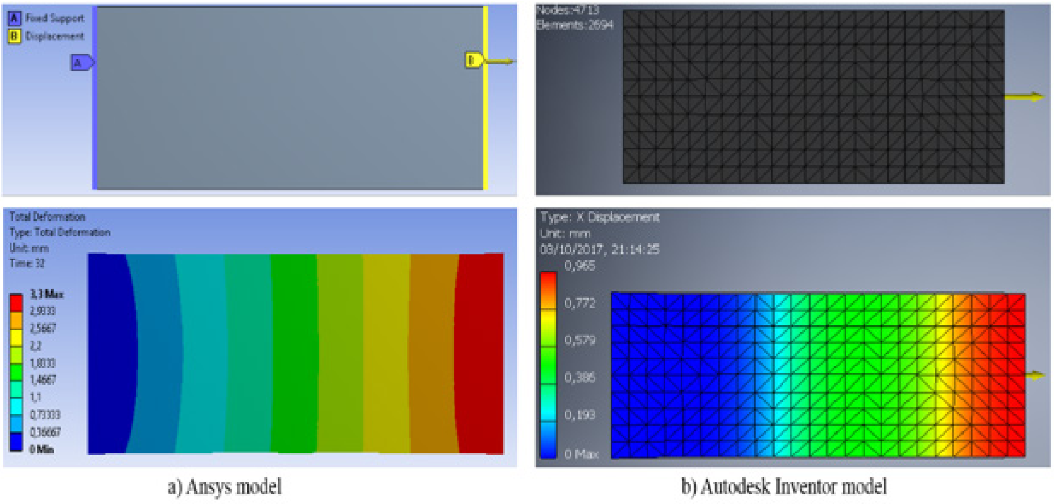

Figure 14: Boundary conditions and results of the tensile simulation: a) with ANSYS b) with Autodesk Inventor

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A first interpretation of Figure 15 shows the lack of information after 1% of strain, this is due to the nature of the analysis system used in the simulations. In fact the non-linear behavior of the CFRP can't be reproduced under a steady-state or a static structural analysis so the test crosshead speed is not being considered. But the linear part of the curves is nearly reproduced, this leads to a validation of the E-modulus of the experimental and predicted model.

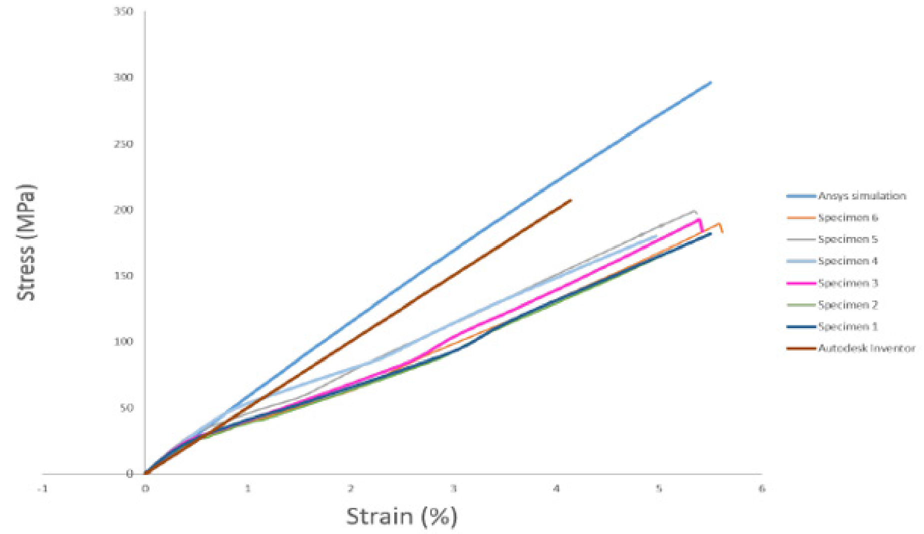

Figure 15: Comparison of the experimental and numerical results of the tensile test.

Impact Test

The drop-weight impact test was reproduced by a numerical simulation using an explicit dynamic analysis system. The aim of this simulation is to validate, in addition to the linear properties, the non-linear mechanical properties of the short-chopped fibers composites and to define the accuracy of the produced model in the determination of the behavior of CFRP under show loading. Under the quasi-isotropic assumption, the model is reduced to the quarter in order to reduce the run time as presented in Figure 16.a. The structure is meshed

uding an explicit solid element type, the mesh is refined only under the impactor area in order to reduce the runnig time (Figure 16.b). A total of 20019 elements and 24775 nodes are used for this explicit dynamics study.

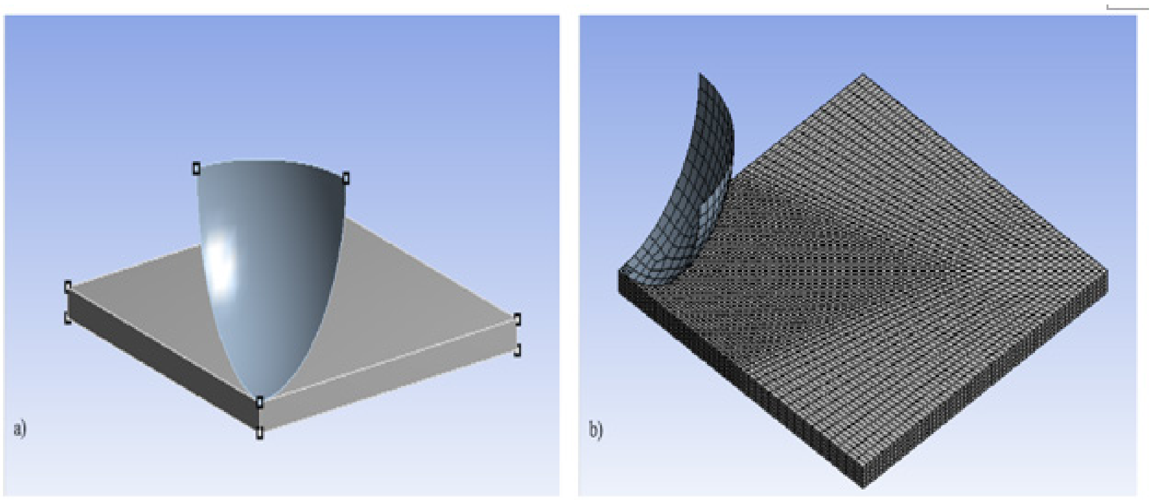

Figure 16: Impact test model: a) reduced geometry b) refined mesh.

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This low-velocity analysis system is solved using an Autodyne solver, the equivalent stress and the displacement of the impactor are presented in Figure 17.a and the comparaison of the different experimental and numerical results is presented un Figure 17.b.

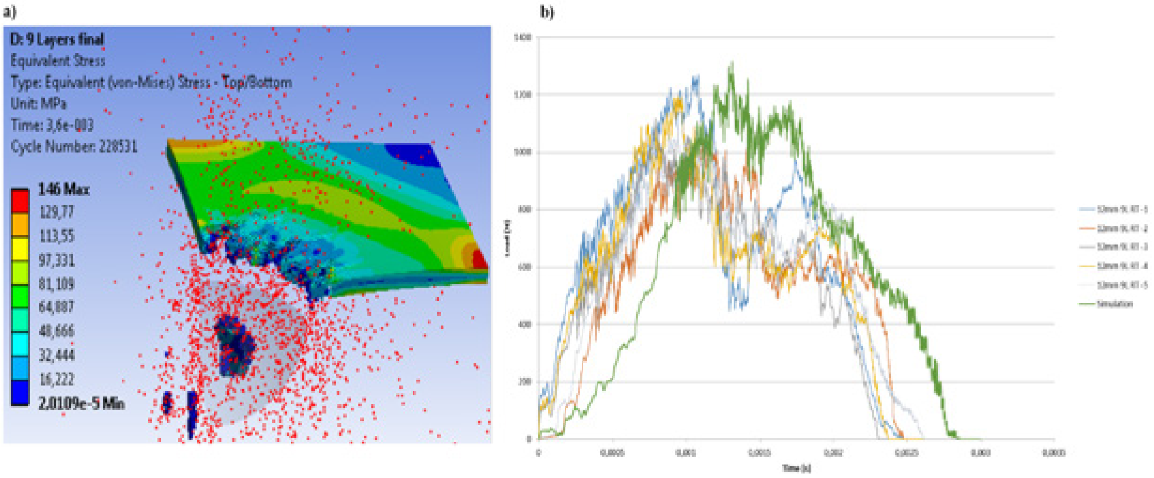

Figure 17: Simulation results: a) Equivalent stress b) Comparison of the curves.

The analysis of the curves shows that they are slightly slipped to the left and this could be because of defects and irregularities during manufacturing phase and also that the clamping forces are not being taken into calculations.

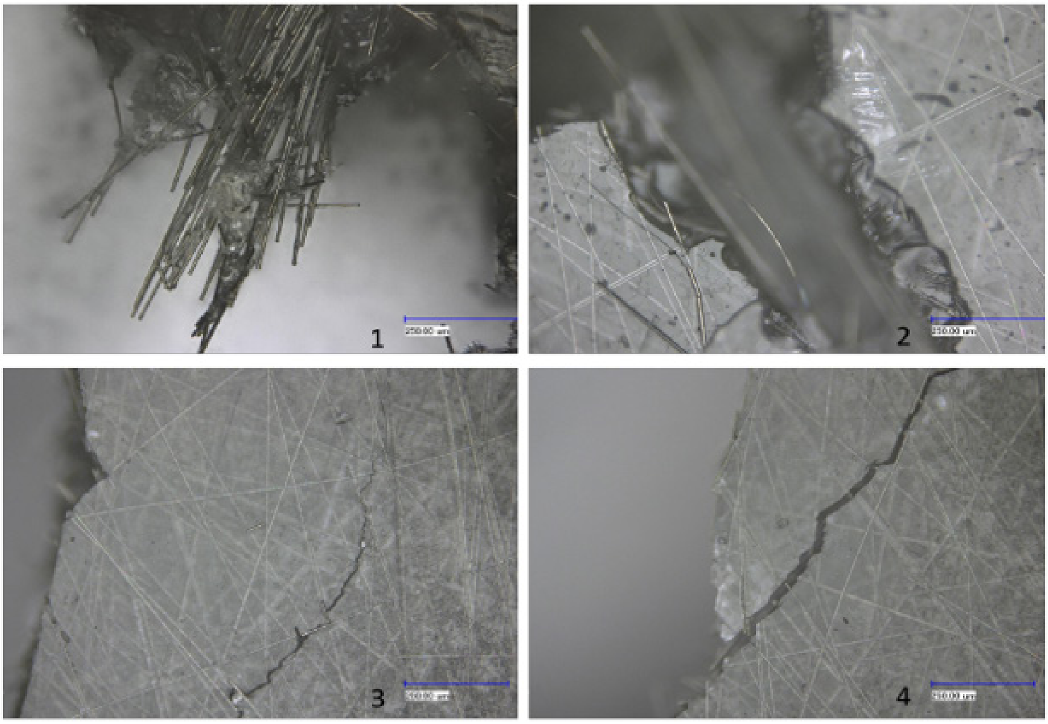

Figure 18: SEM observations of the failure modes.

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The failure process caused by low-velocity impact in composites is a complex phenomenon. Different failure modes and mixed damage modes may occur. Matrix cracking, delamination, fiber debonding and fiber breakage are examples of various failure modes. Figure 18 recapitulates some of those modes. In fact, picture 1 represents the debonding of the fibers in the area where the sample was impacted and picture 2 shows the matrix breaking

after being subjected to the impact load. Pictures 3 and 4 represent the propagation of the crack near the impacted area. After initiation, cracks usually propagate between fibers, primarily along the fiber-matrix interface. Cracks are generally perpendicular to the direction of load and extend over the entire thickness of a ply.

Conclusion

Carbon fiber fleece can be impregnated until a fiber volume content of 40%. There is a linear correlation of fiber volume content and the mechanical properties of the tested fiber volume contents. So a heightening of fiber volume content has positive effect on all mechanical properties. In addition to that 12 mm fibers show the best mechanical properties. The course of mechanical properties confirm that the results obtained with glass fiber can be transferred to carbon fibers [19]. Furthermore first insights into the properties of composites with carbon fiber fleece and epoxy resin are obtained so that they can be transmitted to recycled fibers. Experimental tests are reproduced by simulation and mechanical properties of the material are verified. For the bending and tensile tests, a satisfying correlations are obtained. Thus, for the impact test, a significant difference between the experimental and numerical results is mainly do to the non linearity of the CFRP which is not studied at this stage.

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Conflict of Interest

None.

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