Development of quasi-unidirectional fabrics with hemp fiber: a competitive reinforcement for composite materials

Abstract

This study focuses on the development and mechanical testing of a quasi-unidirectional woven hemp fabric for composite applications. The fabric is designed to combine the advantages of easy handling, impregnability by resin and fiber alignment. In this sense, low twisted rovings, low crimping characteristics and a high roving density in the main direction were used. The results show that the manufacturing process proposed for this highly unbalanced woven fabric is less aggressive than that for a balanced pattern, and the effective tensile properties of the fibers are preserved. This innovative hemp fabric is also used to manufacture unidirectional and cross-ply laminated composites. The results indicate competitive properties relative to those of commercial flax-based reinforcements with rigidities similar to those of composites made with quasi-unidirectional woven fabrics, noncrimp fabrics and tapes.

Keywords

Natural fibers, Hemp, Weaving process, Textile composites, Polymer-matrix composites, Mechanical properties

1 Introduction

Currently, the environmental impact of materials is an increasingly important parameter in engineering applications. In the field of composite materials, manmade fibers, especially glass fibers, are conventionally used. However, even if these fibers have excellent properties, their production is generally energy intensive. For several applications, natural fibers, such as hemp fibers, are an environmentally friendly alternative to manmade fibers [1–3]. Although plant fibers have lower mechanical properties than glass fibers, they have lower densities than glass fibers, and thus, similar specific properties can be achieved [4–6]. Moreover, natural fibers have better thermal and acoustic insulation properties than glass fibers, which can be interesting for some applications, such as ground transportation and leisure [7, 8].

The mechanical properties of composite materials are mainly governed by the mechanical properties of the fibers and their affinity to polymers. Thus, to obtain the best properties in the loading direction, the ideal reinforcement should maximize the number of fibers aligned in this direction [9, 10]. Due to the discontinuous nature of natural fibers, one of the more obvious methods to build a continuous reinforcement with these fibers is to spin them into yarns [11, 12]. Several kinds of reinforcements with these yarns can thus be produced: woven fabrics, with balanced or unbalanced patterns, and braided and knitted fabrics. Braided fabrics have fibers aligned in two directions that are not perpendicular [13, 14]. For woven fabrics, if the pattern is highly unbalanced, a reinforcement, generally called a quasi-unidirectional (QUD) reinforcement, is obtained. Indeed, most of the fibers are aligned in the main direction, while the transverse direction is reinforced by thin yarns and/or yarns with a low density per centimeter. Pure unidirectional (UD) fabrics in the form of tapes have also been developed and commercialized recently with flax fibers, such as Flaxtape^{TM} by the company Lineo-Ecotechnilin [15, 16]. The fiber cohesion is ensured by using a process consisting of reactivating the pectin cement. Alternative methods were also recently proposed to produce continuous tapes from bamboo fibers [17]. Noncrimp fabrics (NCFs) made of flax fibers are also available on the market (such as Biorenforts by Terre de Lin). NCFs differ from woven fabrics by a stitching material that is introduced to bind a number of unidirectional tows while limiting fiber misalignment. The main challenge when fabricating reinforcements, in particular with plant fiber fabrics, is to combine fibers as unidirectionally as possible, to maintain the fiber integrity, ease of handling and drapability. In pure unidirectional tapes, all fibers are almost perfectly aligned in one direction, and thus, optimum properties can be expected. On the other hand, fibers are poorly bonded transversely, which makes the handling of the reinforcement challenging. This lack of cohesion in the transverse direction can also be problematic during composite processing and, specifically, during the forming stage of the liquid composite molding (LCM) process [18, 19]. Woven fabrics have better dimensional stability than other fabrics and excellent mechanical properties in the two main directions. However, yarns and fibers can be damaged during the weaving process (depending on the severity of the settings), thus decreasing the fiber properties in the composite [20–22]. Yarn crimp and interlacements between the warp and weft directions also lead to fiber misalignments and thus minimize the mechanical properties in the fabric plane [20–23]. In NCFs, the benefits of overlaying straight tows joined by stitching are that tow crimps can be avoided or at least limited. On the other hand, stitching can induce space between tows, leading to a heterogeneous composite structure at the mesoscale with matrix-rich and fiber-reach regions.

Flax-based UD composites are well documented in the literature, whether made of UD tapes, QUD woven fabrics or NCFs [24–30]. However, for this kind of UD or QUD reinforcement, there are only a few studies in the literature with hemp fibers [31, 32]. Moreover, when hemp fibers are used for composite reinforcements, they are mixed with other materials, such as thermoplastic polymers [31], or deposited between sheets of paper [32]. These modifications are due to the difficulties in producing the required rovings and yarns with hemp fibers, which are coarse and have lower mechanical properties than flax fibers. Indeed, to the best of the authors' knowledge, there are no data available in the open literature regarding QUD or UD fabric composites made of 100% hemp fibers. Nevertheless, our group recently showed that high-grade woven hemp fabrics can be manufactured for composite applications from low twisted hemp rovings [33]. As it is possible to produce low twisted rovings with hemp fibers, manufacturing of QUD fabric with similar low twisted rovings can be considered.

In this study, the focus is to develop a quasi-unidirectional woven fabric from hemp fibers. The weave pattern is optimized to limit fiber misalignment while keeping the properties of easy handling and drapability. Several characterizations are performed at the fabric and composite scales, including the determination of the textile and mechanical properties of the QUD fabric. Then, microstructural observations and mechanical characterization of the manufactured epoxy-based composites are conducted. The influence of the weaving process on the hemp yarn and fiber properties is also studied. Finally, the properties measured at the scale of the composite material are compared to those obtained with other materials with commercially available reinforcements to highlight the competitive properties of this innovative reinforcement.

2 Materials and methods

2.1 Manufacturing processes

2.1.1 Reinforcement manufacturing

A 100% hemp quasi-unidirectional fabric, later named QUDH, was produced in the GEMTEX laboratory on a manual Leclerc WeaveBird dobby loom, as seen in Fig. 1. Two types of linear structures, provided by Linificio e Canapificio Nazionale Company, were used: hemp twisted yarns and low twisted hemp rovings. Their properties are shown in Tab. 1. The linear density was measured according to NF G07-316 [34], and the twist level was measured according to NF G07-079 [35]. Thin hemp twisted yarns were used in the warp direction, with a very low yarn density (0.6 yarns/cm) to provide cohesion to the QUDH fabric and to limit the crimping level. In the weft direction, low twisted hemp rovings were inserted using a shuttle with the highest possible yarn density to maximize the fiber fraction in this direction. Indeed, more than 20 rovings/cm were introduced in the weft direction, which confers a fiber mass fraction of 98% in the weft direction and 2% in the warp direction. A picture of the final QUDH fabric, presented in Fig. 2.a), shows this high fiber percentage in one direction relative to the other. A simulated view of the interlaced pattern of warp and weft yarns was built with WiseTex® in Fig. 2.b). In the following, by analogy with the terminology used for UD materials, the direction made up of hemp rovings (i.e., the weft direction) will be called the "fiber direction", and that made up of twisted yarns (i.e., the warp direction) will be called the "transverse direction". In the fiber direction, there is almost no disorientation of fibers, and the shrinkage of the yarns inside the fabrics is equal to 0.286 ± 0.001% (measured according to the standard NF EN ISO 7211-3 [36]).

Fig. 1. Picture of the weaving operation of the QUDH fabric on a Leclerc Weavebird loom

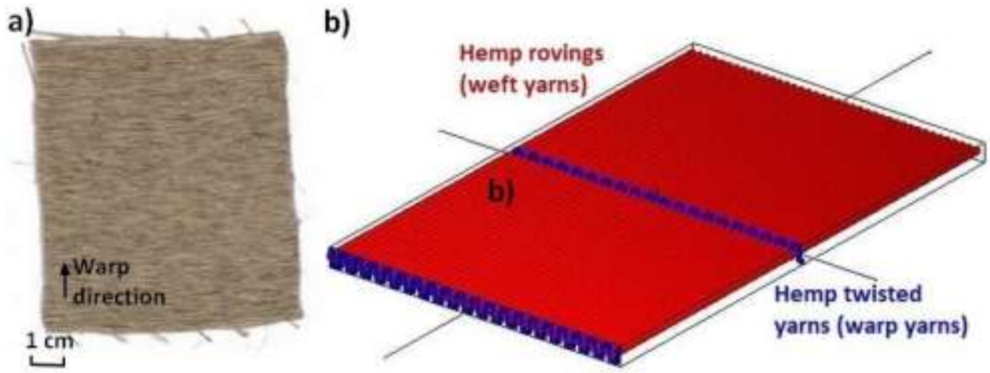


Fig. 2. Picture of QUDH fabric a) and a simulated 3D view of QUDH fabric (WiseTex® software) b)

Tab. 1. Properties of the yarns and rovings used to manufacture the QUD fabrics

	Type of yarn	Linear density [Tex]	Twist level [turns/m]	Yarn density [yarns/cm]	Shrinkage [%]
Warp direction	Twisted yarns	153 ± 14	222 ± 13	0.6	-
Weft direction	Rovings	288 ± 8	39 ± 2	20	0.286 ± 0.001

2.1.2 Composite manufacturing

2.1.2.1 Fabrication process

This QUDH woven fabric was used with a thermoset epoxy system to manufacture composite plates using thermocompression. A partially biosourced epoxy prepolymer (GreenPoxy 56®) and its hardener (SD7561) provided by Sicomin® were chosen. A prepolymer to hardener ratio of 0.37 was used.

Two different composites were produced with this reinforcement: a quasi-unidirectional composite (QUDC) and a cross-ply laminated composite (CPC). Each composite was composed of two plies. The dimensions of the produced plates were approximately 300 x 200 mm². Hand lay-up and impregnation were performed in an open mold following the protocol proposed in [27]. In short, the matrix was poured onto the center of the first ply and along its warp direction. The same operation was carried out with the second ply. The top part of the mold was placed on the impregnated plies. The mold was then placed in an Agila® 100 kN thermocompression press. The curing cycle was divided into two steps: precuring at 40°C for 15 minutes and curing at 60°C for 1 hour. Once the temperature reached 40°C, a pressure of 3 bars was applied on the plate. The precuring step allowed the resin viscosity to decrease to facilitate its transfer within the fabric. A postcuring process at 130°C was applied for 1 hour. The fiber and void volume fractions were calculated following the procedure described in [26], and they are equal to 60 and 4%, respectively.

2.1.2.2 Sample preparation

Samples were cut in both material directions using a Trotec® speed 3000 laser cut machine. The sample dimensions are 190 mm in length, 15 mm in width and 1.3 mm in thickness. Immediately after cutting, all samples were stored in a climatic chamber at 23°C and 50% relative humidity for a minimum of 30 days to ensure that they reached moisture content equilibrium.

2.2 Characterization steps

2.2.1 Textile and mechanical properties of hemp quasi-unidirectional reinforcement in a dry state

To study the textile properties, the areal density, thickness and air permeability were measured according to the standards NF EN 12127 [37], NF EN ISO 5084 [38] and NF EN ISO 9237 [39], respectively. The air permeability test is used to determine the air flow rate that can pass perpendicularly through the fabric with a defined area (20 cm²), time (1 minute) and pressure drop (200 Pa). The mechanical properties, bending and tensile properties were studied. Bending properties were measured by a cantilever test according to the standard ISO 4604 [40], as shown in Fig. 3. The sample is first placed on the horizontal side of the test bench and then moved forward. The fabric gradually bends, and when it touches the 41.5° sloping side, the length of the advance is measured. A bending rigidity factor is then calculated with Eq. (1), and the bending rigidity modulus is obtained with Eq. (2). Tensile tests were conducted according to the standard NF EN ISO 13934-1 [41] on an MTS Criterion 45 tensile machine with a load cell of 10 kN, a gauge length of 200 mm, a width of 50 mm, a pretension of 5 N and a crosshead displacement rate of 20 mm/min.

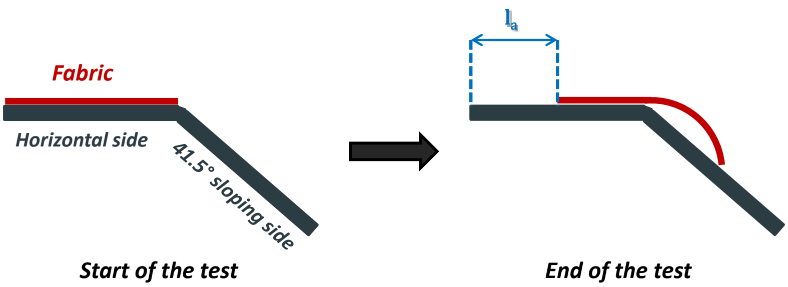


Fig. 3: Schematic representation of the bending rigidity test

$$G = 9{,}81 \times a_d \times \left(\frac{l_a}{2}\right)^3 \quad (1)$$

$$G_{MPa} = \frac{12}{t^2} \times G \quad (2)$$

With: G: Bending rigidity factor (N.mm)

a_d: Areal density of the fabric (g/m²)

l_a: Measured length of advance at the end of the test (m)

G_{MPa}: Bending rigidity modulus

t: Thickness of the fabric (mm)

2.2.2 Roving tensile tests

The roving properties were determined using tensile tests according to the standard NF EN ISO 2062 [42]. An MTS Criterion 45 tensile machine was used with a load cell of 10 kN, a gauge length of 200 mm, a pretension of 0.5 cN/Tex and a crosshead displacement rate of 200 mm/min. Tests were performed on rovings before and after weaving using rovings from the bobbins, allowing the fabrication of the QUDH fabric and rovings extracted from the QUDH fabric in the weft direction.

2.2.3 Impregnated fiber bundle tests (IFBTs)

IFBT tests were conducted according to the method developed by the CELC [43] and described in [44] to evaluate the effective mechanical properties of fibers. IFBT specimens were prepared with rovings from the bobbins used in the weaving process as well as with rovings extracted from the QUDH fabric. Specimens were manufactured with the GreenPoxy 56® epoxy resin and the SD SurfClear hardener from Sicomin®, with a weight ratio of 100/37. The curing cycle was performed in two stages: the first stage occurred in a thermocompression press Dolouets® at 60°C for 7 h 30 with a pressure of 2 bars on the samples, and the second stage occurred in an oven Memmert® at 60°C for 16 h 30 without pressure. Samples were then conditioned at ambient temperature for at least 7 days before testing. They were mechanically tested with an Instron® tensile machine, with a load cell of 250 kN, a gauge length of 150 mm, a width of 10 mm and a crosshead displacement rate of 1 mm/min.

The fiber modulus is back-calculated from the IFBT results using the rule of mixtures following Eq. (3) [45]. Two moduli are back-calculated: E_{f1} between 0.01% and 0.1% of strain and E_{f2} between 0.3% and 0.5% of strain.

$$E_c = (\eta_0 \eta_1 V_f E_f + V_m E_m)(1 - V_p)^n \quad (3)$$

With: V_f : Fiber volume fraction

V_m : Matrix volume fraction

V_p : Porosity volume fraction

E_c: Composite modulus

E_f: Fiber modulus

E_m: Matrix modulus

η_0 : Fiber orientation factor, $\eta_0 = cos^2(2\alpha)$ [46]

α : Surface twist angle, $\alpha = tan^{-1}\left(10^{-3} \cdot T \cdot \sqrt{4\pi \frac{1}{Nm \cdot \rho_f \cdot \theta}}\right)$ [46]

θ: Yarn packing fraction, $\theta = 0.71(1 - 0.78e^{-0.195T})$

η_1: Fiber length factor, $\eta_1 = 1$ (Fiber length/fiber diameter > 50) [47, 48]

n: Porosity factor, n = 2 (approximation) [47, 48]

T: Twist level of roving (turns/m)

1/Nm = kTex: Linear density of roving in kTex

ρ_f: Density of hemp fibers, $\rho_f = 1.504$ g.cm^{-3}

2.2.4 Microscopic observations

Some composite samples were observed through an optical microscope. A piece of composite was cut and placed in a coating resin. The coated sample was then polished. An optic microscope Nikon Eclipse LV-150 was used to observe the microstructure of the material in the two material directions.

2.2.5 Tensile testing of composites

An MTS Criterion 45 machine equipped with a 5 kN cell load was used to carry out tensile tests on the conditioned samples. The crosshead speed was fixed at 1 mm/min. Each sample was installed on the tensile machine with wedge action grips. The strain was measured by an Instron® 2620-601 contact extensometer with a gauge length of 50 mm and a full range of ±10%. Stress was calculated as the ratio of the measured force to the initial sample cross section. The tensile tests were carried out on the composite until failure and according to the ASTM D3039 standard [49]. During a monotonic tensile test in the fiber direction, this type of material is characterized by biphasic behavior [26]. Therefore, two apparent moduli, E_L^{app1} and E_L^{app2}, were defined for each phase in the following strain ranges: 0.01 to 0.15% and 0.4 % to failure, respectively [50].

2.2.6 The rule of mixtures and classical laminate theory

A simple rule of mixtures was used to compare the stiffness and tensile strength obtained on our materials and in the literature for an equivalent fiber volume ratio of 0.6. Under the hypothesis of a strain at failure of the fibers weaker than that of the matrix and an isotropic behavior of the matrix, the following equations use the expression of the law of mixtures for a 0° stacked composite:

$$E_L = V_f E_{fL} + (1 - V_f)E_m \quad (4)$$

$$\sigma_L = V_f \sigma_{fL} + (1 - V_f)\varepsilon_L E_m \quad (5)$$

With: E_L: Longitudinal modulus of the composite (MPa)

σ_L: Longitudinal stress at failure of the composite (MPa)

ε_L: Longitudinal strain at failure of the composite (-)

E_{fL}: Longitudinal modulus of the fiber (MPa)

σ_{fL}: Longitudinal stress at failure of the fiber (MPa)

E_m: Modulus of the matrix (MPa)

V_f: Fiber volume ratio

For a 90° stacking sequence, these equations are written as:

$$E_T = \frac{E_{fT} E_m}{(1 - V_f) E_{fT} + V_f E_m} \quad (6)$$

$$\sigma_T = \frac{\sigma_{fT} \varepsilon_T E_m}{(1 - V_f) \sigma_{fT} + V_f \varepsilon_T E_m} \quad (7)$$

With: E_T: Transverse modulus of the composite (MPa)

σ_T: Transverse stress at failure of the composite (MPa)

ε_T: Transverse strain at failure of the composite (-)

E_{fT}: Transverse modulus of the fiber (MPa)

σ_{fT}: Transverse stress at failure of the fiber (MPa)

In view of the large number of matrices used by the authors and the dependence of the modulus of elasticity of the matrix on the manufacturing process, the choice was made to fix E_m at 3 GPa, a value representative of the elastic behavior of epoxy resins [51]. From the values of the longitudinal modulus of the composite E_L and the fiber volume fraction $V_{fauthor}$, both determined by the author, the longitudinal modulus of the fiber E_{fL} was calculated using Eq. 4 (cf. Fig. 4). This value was then reintroduced into Eq. 4 by taking a fiber volume fraction of 0.6 to obtain the estimation of the longitudinal stiffness of the composite. A similar method was applied to determine the estimated values of the transverse modulus and the longitudinal and transverse stress at failure of the composite using Eqs. 6, 5 and 7, respectively.

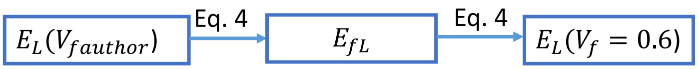


Fig. 4. Methodology used to estimate the longitudinal modulus of composites for a fiber volume fraction of 0.6

The estimation of the modulus for a cross-ply composite requires the use of the following equation, obtained with classical laminate theory:

$$E_{CP} = \frac{1}{2}(E_L + E_T) \quad (8)$$

With: E_{CP}: Apparent modulus of the cross-ply composite (MPa)

The longitudinal and transverse moduli of the fiber were determined from the ply modulus and using the above equations. These values are then reintroduced into Eqs. 4 and 6 to obtain the estimated ply stiffness for a volume fraction of 0.6. Eq. 8 then gives access to the estimated value of the cross-ply apparent modulus.

3 Results and discussion

3.1 Properties of the fabric

3.1.1 Textile properties

Regarding textile properties, the first property studied is the areal density. An average value of 649 ± 3 g/m² was measured. This areal density is high compared to most of the flax unidirectional reinforcements available on the market [52]. This is mainly due to the high roving density (Tab. 1) in the fiber direction. This high number of rovings per centimeter confers a thickness of 2.97 ± 0.14 mm to the QUDH fabric, which is also quite high for composite reinforcement. Regardless, the areal weight could be optimized for targeted applications in the future. Even if the warp density is very low (0.6 yarns/cm), QUDH fabric has a weaker permeability than woven fabrics traditionally used for composite reinforcement, approximately 424 ± 19 L/m²/s, which is still due to the high weft density.

3.1.2 Mechanical properties

The bending modulus of the QUDH fabric is determined in the fiber and transverse directions (i.e., the weft and warp directions, respectively). The values are presented in Tab. 2. The fiber fraction in the weft direction gives stiffness in this direction, more than 150 times higher than that in the transverse direction. In the latter case, the low rate of twisted yarns cannot support the weight of the high number of rovings, and the QUDH fabric bends immediately. The high bending modulus in the fiber direction is mainly due to the high fiber content in this direction but is also a consequence of the high thickness of the QUDH fabric. As presented previously in Eq. (2), the thickness of the fabric plays an important role in the bending rigidity modulus. However, a high bending modulus can be a drawback for the drapability of the reinforcement during manufacturing of composite parts with complex shapes. In the future, the thickness of the quasi-unidirectional reinforcement needs to be improved.

The tensile properties in both directions for the QUDH fabric are also presented in Tab. 2. The maximal load in the fiber direction is approximately 24 times higher than that in the transverse direction. To determine the maximal force supported per yarn, the maximal load is also divided by the number of yarns in each tested sample. The calculated maximal load per yarn is then similar in both directions. Afterwards, the strain at the maximal load is two times higher in the fiber direction than in the transverse direction. The low twist level of rovings allows more fiber elongation before break than a high twist level of yarns. Indeed, rovings can stretch more than yarns, and fabric deformability is higher in the fiber direction than in the transverse direction.

Tab. 2. Mechanical properties of QUDH fabric

		Fiber direction	Transverse direction
Bending modulus [GPa]		3.09 ± 0.25	0.02 ± 0.01
Tensile properties	Maximal load [N]	2493 ± 259	105 ± 16
	Maximal load/yarn [N/yarn]	25.2 ± 2.6	26.2 ± 4.0
	Strain at maximal load [%]	4.4 ± 0.5	2.3 ± 0.2

3.2 Impact of the weaving process on the roving and fiber properties

The weaving process for 2D and 3D woven fabrics is known to reduce yarn properties [20–23, 33]. As this process has been used for QUDH manufacturing, its impact on roving and fiber properties was investigated in this work.

After the weaving process, the linear density of the rovings extracted from the fabric in the weft direction is 272 ± 27 Tex, which is slightly lower than the linear density before weaving. The successive passages in the various components of the weaving loom led to the removal of some impurities in the rovings, which resulted in a slight decrease in the linear density.

The tensile properties of the rovings were also determined before and after weaving. The recorded curves are shown in Fig. 5. Previous studies [23, 33] have shown that the weaving process damages weft yarns and especially decreases their breaking load. In the case of quasi-unidirectional fabric, roving properties are not affected by the weaving process even if the yarn is inserted in the weft direction. In fact, no significant differences can be observed in the tensile curves before and after weaving. During the manufacturing of more classical woven fabrics, due to a higher yarn density in the warp direction, there is considerable friction between the two orthogonal yarns during weft insertion and packing in addition to the friction between the juxtaposed crowded warp yarns. In quasi-unidirectional woven fabrics, such as the one considered in this work, there is less friction between the yarns, as the warp density is smaller than in a woven fabric, and it is twisted with less hairiness, which causes hanging between rovings and a loss of fibers under friction. Thus, weft yarns (in this case, the hemp rovings) are not damaged during the weaving process.

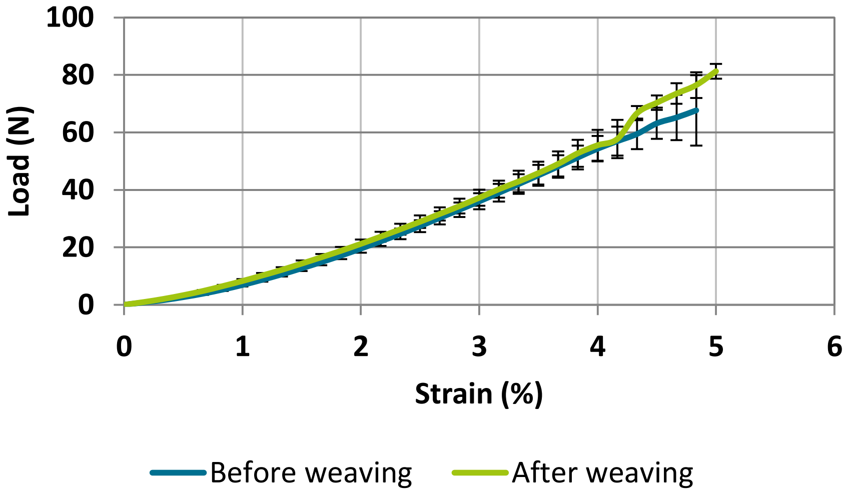


Fig. 5. Tensile curves of hemp rovings before and after weaving

For woven fabrics, a previous study [33] showed that fiber moduli also often decrease after weaving, mainly due to fiber damage during the process. Therefore, the impact of the weaving process on the fiber properties was also studied in the present work using IFBT tests. The fiber moduli were back-calculated according to Eq. (3). The results are presented in Tab. 3. Despite a similar fiber volume fraction, the IFBT samples manufactured with rovings extracted from the bobbins (before weaving) exhibit a porosity volume fraction slightly higher than the samples manufactured with rovings extracted from QUDH fabric (after weaving). The two fiber moduli are similar before and after weaving, which means that fibers have not been damaged during the weaving process. This is one of the advantages of manufacturing and using a quasi-unidirectional fabric as reinforcement: the integrity of rovings and fibers is preserved during processing.

Tab. 3. IFBT test results for rovings collected before and after weaving

	V_f	V_p	E_{f1} [GPa]	E_{f2} [GPa]
Before weaving	0.38 ± 0.03	0.12 ± 0.05	53.7 ± 5.9	37.7 ± 5.9
After weaving	0.39 ± 0.01	0.08 ± 0.02	53.8 ± 1.7	39.8 ± 2.5

3.3 Properties of the composite

To estimate the fabrication quality of the QUDC material, the microstructure of the composite was studied in both material directions. Pictures are presented in Fig. 6. It can be observed that the distribution of fibers inside the composite is not completely homogenous along the warp (see Fig. 6 a) and b)) and weft (Fig. 6 c) and d)) directions. Some matrix- and fiber-rich zones can be distinguished. These heterogeneities at the mesoscale are explained by the presence of warp yarns. Their presence also induces disorientation of the fibers at their boundaries. However, this effect is mild and localized. The micrographs also reveal the good impregnation of the plies by the matrix. Only a few pores are visible in the microstructure, in accordance with the porosity ratio measured at approximately 4%. The microscopic view presented in Fig. 6 d) highlights some cracks within the warp yarn. This is certainly due to the local impregnation restriction resulting from the high twist level of yarns. This could be further attenuated by optimizing the warp yarn features.

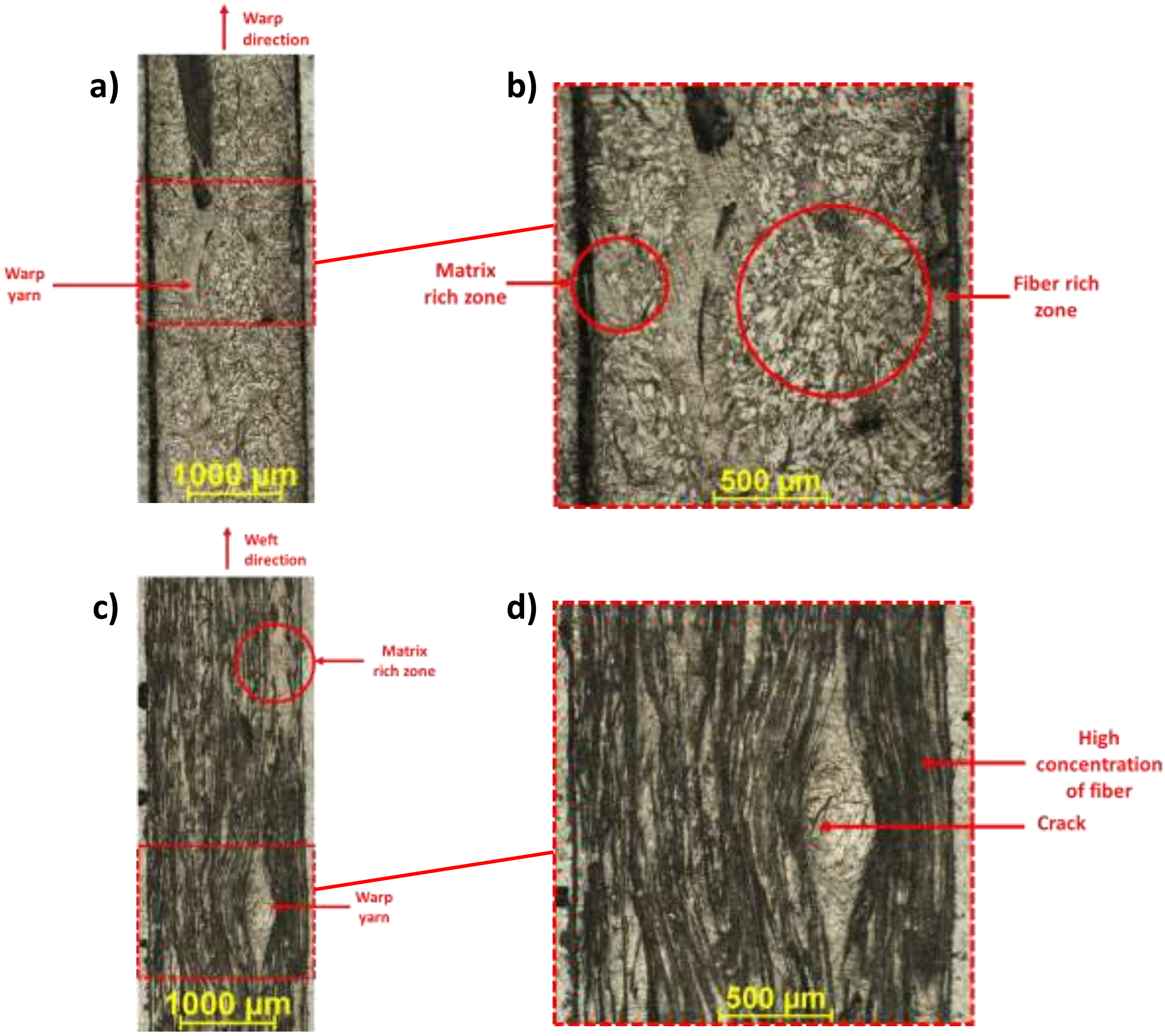


Fig. 6. Cross-sectional views of the microstructure of the QUDC material along the warp direction (a) and b)) and along the weft direction (c) and d))

The results of the mechanical characterization of the UD laminates are presented in Figure 5. Specimens tested in the fiber and transverse directions are labeled as H_WF649_0_E and H_WF649_90_E, respectively. The stress-strain curves of the H_WF649_0_E specimens are represented in Fig. 7 a). The typical biphasic behavior of plant fiber composites is observed with a yield point around a stress level of 50 MPa. The mean values of the apparent initial modulus, stress and strain at failure are equal to 31 GPa, 287 MPa and 1.1%, respectively, in the fiber direction. In the transverse direction, these values are 6 GPa, 17 MPa and 0.38%, respectively.

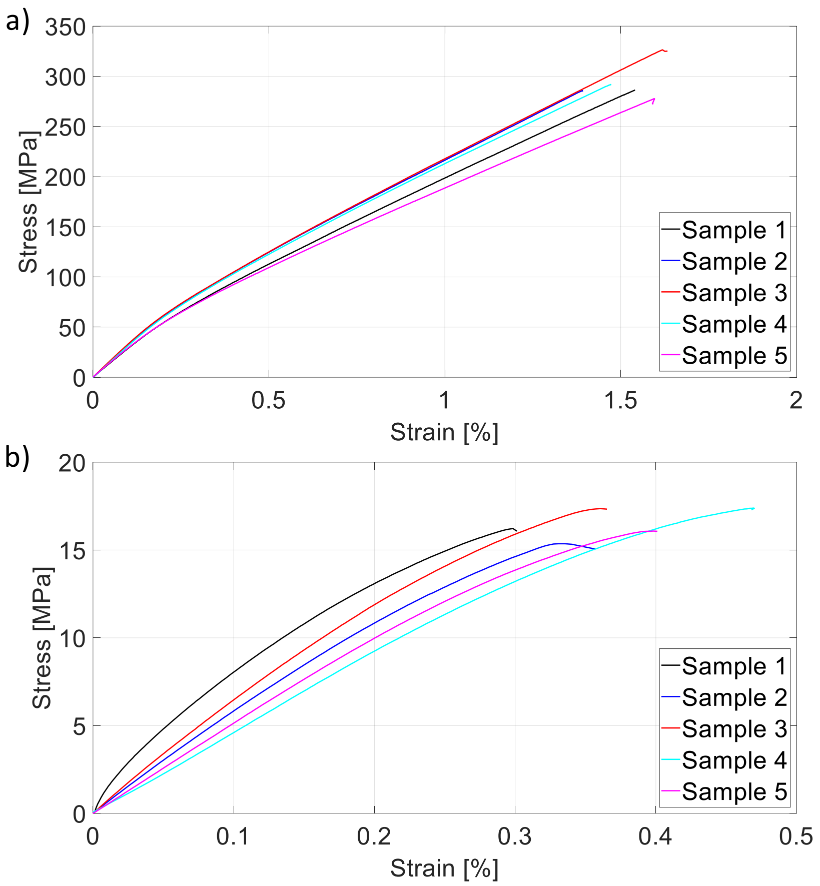


Fig. 7. Tensile stress-strain curves of the H_WF649_0_E composite a) and the H_WF649_90_E composite b)

These properties are compared to data from the literature obtained for composites reinforced with flax reinforcements already available on the market, such as UD tape, QUD woven fabrics and NCFs. All the reinforcements and their characteristics are described in Tab. 4. The details of the process used by the authors to produce composite plates are shown in Tab. 6, and the resulting mechanical properties are presented in Tab. 4. The features of the fabric and composite materials used in the present work are also listed in these tables for comparison. A material identity code is introduced in the form of X_YZ, where X represents the fiber type (H for hemp and F for flax), Y represents the reinforcement type (WF, woven fabric; NCF, noncrimp fabric; and T, tape) and Z represents the areal weight of the considered fabrics. In these tables, only UD and QUD fabrics and their UD or cross-ply laminates are considered. It is also important to note that the direction with the greatest number of yarns is the weft direction for the hemp QUD fabric, while it is generally the warp direction for commercial QUD flax fabrics. Tab. 6 summarizes the matrix system, the ply orientations and the process fabrication used by the authors to manufacture the composites. Indeed, beyond the fiber and reinforcement types, in the comparison study, it is also important to consider the matrix type and the manufacturing process. For composite material identification, two letters are added to the fabric code to indicate the matrix type and the stacking sequence, which leads to the code X_YZ_S_M, where S is the stacking sequence and material direction (0 and 90 are the fiber and transverse directions in a UD laminate, and 090 is one of the two main directions in a cross-ply laminate) and M is the matrix type (E for epoxy, PP for polypropylene). To fairly compare the composite properties, the fiber volume fraction should be similar. Thus, all the data from the literature were used to estimate the mechanical properties for a given fiber volume ratio of 0.60 using the rule of mixtures. Although the rule of mixtures has also been used to determine the ultimate stresses of plant-fiber-reinforced composites [53], the biphasic response of the material under tensile loading and the distribution of the fiber ultimate stress values tend to show the high uncertainty level in the use of the rule of mixtures. However, these recalculated values of tensile strength are used only as estimates.

Tab. 4. Characteristics of the reinforcements (data from this work and from the literature)

Type of fabric (Y)	Type of fiber (X)	Weight of fabric (Z) [g.m^{-2}]	Weft/warp ratio	Reference	Reinforcement ID: X_YZ
Woven Fabric (WF)	Hemp	649 ± 3	98/2	This work	H_WF649
	Flax	400	0	[30]	F_WF400
	Flax	300	10/90	[24]	F_WF300
	Flax	223	0	[30]	F_WF223
	Flax	180	1/19	[30]	F_WF180
	Flax	154	1/19	[26]	F_WF154
	Flax	115	1/8	[30]	F_WF115
Noncrimp Fabric (NCF)	Flax	140	0	[54]	F_NCF140
Tape (T)	Flax	200	0	[55]	F_T200
	Flax	110	0	[27, 50, 52, 56]	F_T110

Tab. 5. Fabrication characteristics of the composites (data from this work and from the literature)

Reinforcement ID (X_YZ)	Matrix system (M)	Stacking sequence/plies orientation (S)	Fabrication process	Reference	Composite ID: X_YZ_S_M
H_WF649	Greenpoxy	0°	Thermocompression	This work	H_WF649_0_E
		90°			H_WF649_90_E
		[0°,90°]			H_WF649_090_E
F_WF400	Epoxy Huntsman LY 5150	0°	Curing at atmospheric pressure	[30]	F_WF400_0_E
F_WF300	Epoxy Epikote 828 LVEL	0°	RTM	[24]	F_WF300_0_E
		[0°,90°]			F_WF300_090_E
F_WF223	Epoxy Huntsman LY 5150	0°	Curing at atmospheric pressure	[30]	F_WF223_0_E
F_WF180	Epoxy Huntsman LY 5150	0°	Curing at atmospheric pressure	[30]	F_WF180_0_E
F_WF154	Epoxy Huntsman LY 5150	0°	Thermocompression	[26]	F_WF154_0_E
		90°		[26]	F_WF154 _90_E
F_WF115	Epoxy Huntsman LY 5150	0°	Curing at atmospheric pressure	[30]	F_WF115_0_E
F_NCF140	Epoxy Sicomin SR820	0°	Thermocompression	[54]	F_NCF140_0_E
		90°			F_NCF140_90_E
		[0°,90°]			F_NCF140_090_E
F_T200	Epoxy Epikote 828 LVEL	0°	RTM	[55]	F_T200_0_E
		[0°,90°]			F_T200_090_E
	MAPP	[0°,90°]	Compression molding	[55]	F_T200_090_PP
F_T110	Greenpoxy	0°	Thermocompression	[52]	F_T110_0_E[1]
	DGEBA	0°	Thermocompression	[27]	F_T110_0_E[2]
		90°	Thermocompression	[56]	F_T110_90_E
	Epoxy Huntsman XB3515	0°	Thermocompression	[50]	F_T110_0_E[3]

Tab. 6. Tensile properties of composite specimens tested in the fiber direction (mean ± standard deviation)

Composite ID	Reference	Vf	E_L^{app1} [GPa]	E_L^{app2} [GPa]	Stress at failure [MPa]	Strain at failure [%]
H_WF649_0_E	This work	0.60	31 ± 2	19 ± 1	287 ± 42	1.36 ± 0.17
F_WF400_0_E	[30]	0.57	26.3 ± 2.1	-	260 ± 27	1.58 ± 0.11
F_WF300_0_E	[24]	0.40	22.9 ± 0.5	15.9 ± 1.1	235 ± 31	1.51 ± 0.40
F_WF223_0_E	[30]	0.60	27.5 ± 2.9	-	298 ± 20	1.69 ± 0.09
F_WF180_0_E	[30]	0.60	33.1 ± 0.4	-	357 ± 13	1.93 ± 0.10
F_WF154_0_E	[26]	0.45	32.9 ± 3.2	19.6 ± 3.1	327 ± 10	1.45 ± 0.15
F_WF115_0_E	[30]	0.46	23.1 ± 1.4	-	235 ± 16	1.51 ± 0.12
F_NCF140_0_E	[54]	0.44	22.8 ± 1.0	-	318 ± 12	1.65 ± 0.05
F_T200_0_E	[55]	0.40	26.6 ± 2.6	20 ± 2.6	249 ± 9	1.16 ± 0.10
F_T110_0_E[1]	[52]	0.51	36 ± 2	24 ± 1	311 ± 21	1.18 ± 0.10
F_T110_0_E[2]	[27]	0.46	30.8 ± 0.8	21.3 ± 0.5	328 ± 23	-
F_T110_0_E[3]	[50]	0.61	35 ± 0.8	24.6 ± 0.8	387 ± 22	1.52 ± 0.09

As a result, Fig. 8 presents all the measured and estimated values for the hemp-based composite developed in the present study as well as for flax-based QUD woven fabric, NCF and UD tape reinforced epoxy composites. For the flax composites, only the composites with the highest and lowest stiffness reported in the literature are presented in this figure. These values allow a relevant range to be built.

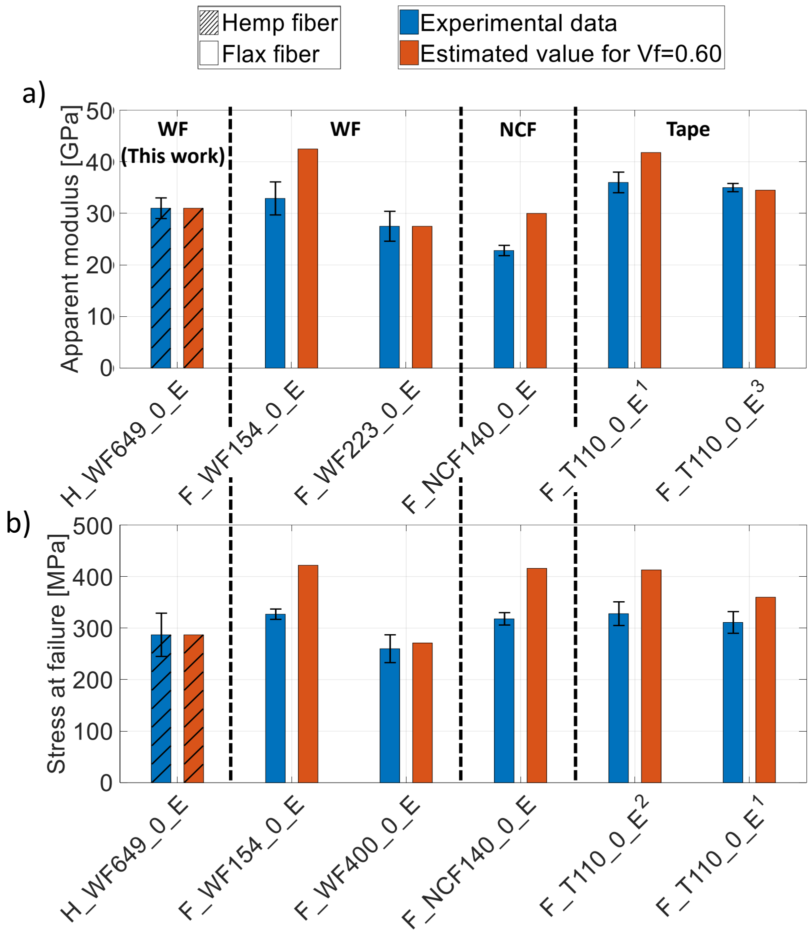
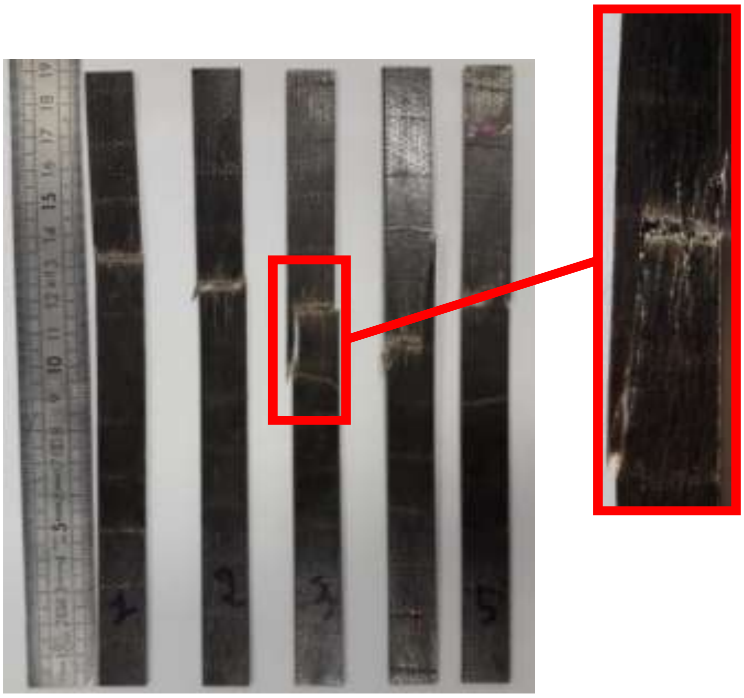


Fig. 8. Apparent modulus a) and stress at failure b) determined by the authors with their confidence intervals and the values of these properties estimated using the ROM for a fiber volume ratio of 0.60 for the composites oriented at 0°

The stiffness in the fiber direction of the QUD woven hemp fabric composite developed in this study (approximately 31 GPa) is similar to that obtained for flax fibers with the NCF and is in the range of the values obtained with a QUD woven fabric (28-42 GPa), see Fig. 8 a). This value remains below the stiffness obtained with the flax tape (35-42 GPa). Two reasons can explain this difference: (i) the slight disorientation of hemp fibers within the QUDH fabric (due to the twist level and the crimp, even if significantly limited) and, more importantly, (ii) the difference in apparent rigidity between flax and hemp fibers [1]. Indeed, the literature reports moduli for flax fibers processed industrially equal to or higher than 60 GPa [55] when compared to the value of 53 GPa for the hemp fibers used in the present study.

In terms of strength in the fiber direction, the measured value for the QUD woven hemp fabric composite is less than or equal to the low range of all the UD and QUD flax-based composites (see Fig. 8 b). A maximum difference of almost 33% is observed when considering pure UD flax tape composites. This moderate strength can be attributed partly to the presence of warp yarns. Fig. 9 shows the fracture profile of the tested samples. It can be observed that the initiation of the failure occurs in the region where warp yarns are located. These zones constitute weak points, particularly when yarns are incompletely impregnated. It can be concluded that even if the fabric presents a lower ratio between weft yarn and warp yarn (see Fig. 8.b)), the yarns in the transverse direction still play a role in the failure mechanisms of the material when loaded in the fiber direction.



1 2 3 4 5

Fig. 9. Fracture profile of H_WF649_0_E samples

Beyond the reinforcement structure, this difference can also be mainly attributed to the intrinsic properties of hemp and flax fibers. The average tensile strength of the hemp fibers used to manufacture the fabrics is approximately 550 MPa compared to the traditional 800 MPa reported for flax industrially processed using single fiber tensile tests [44].

The stress-strain curves and the properties for the transverse direction are presented in Fig. 7. b), Fig. 10 and Tab. 7. Interestingly, the transverse modulus of the QUD hemp woven fabric composite is equal to that obtained for the flax QUD woven fabric and NCF composites and higher than that obtained for flax tape composites. This could be due to the presence of the warp yarn, which endows a stiffer transverse direction, and to a difference in the transverse modulus of hemp and flax fibers. This property has never been measured directly for hemp or for flax fibers and clearly deserves to be investigated in the future. On the other hand, the tensile strength in the transverse direction is lower than that of the other flax composites, with a difference of up to 10 MPa. However, an estimation at an equivalent fiber volume fraction shows a higher or equal stress at failure than for other woven fabric, tape and NCF composites (cf. Fig. 10). Moreover, the strain at failure can be half that of flax-based composites. These moderate properties at failure in the transverse direction were attributed to the initial cracks observed in the warp yarns.

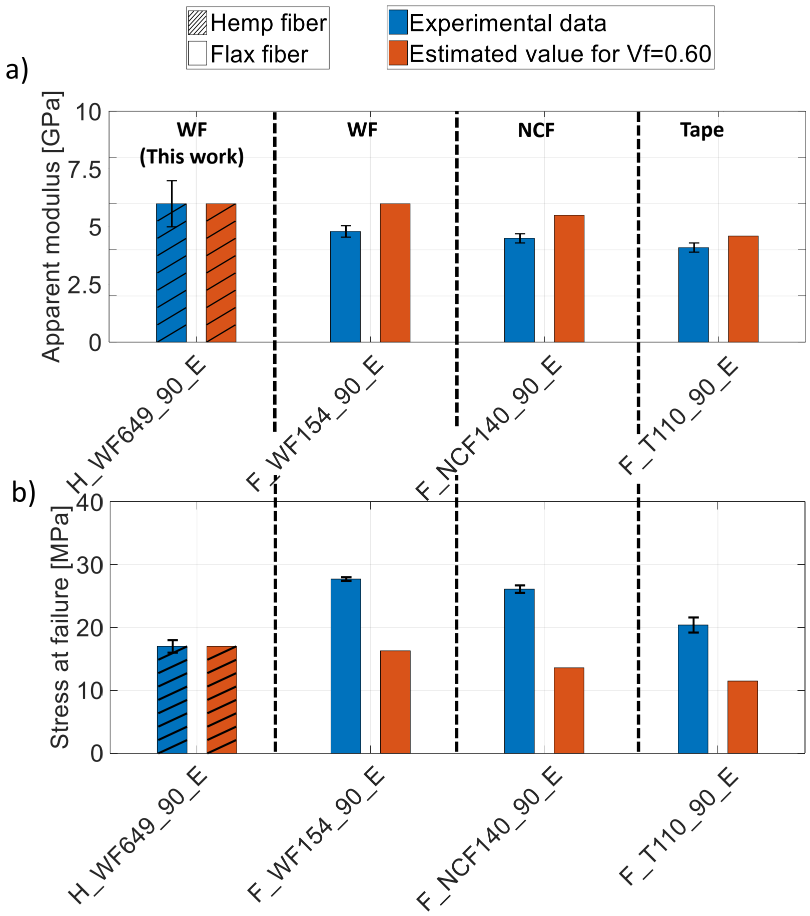


Fig. 10. Apparent modulus a) and stress at failure b) determined by the authors with the confidence intervals and property values estimated using the ROM for a fiber volume ratio of 0.60 for the composites oriented at 90°

Tab. 7. Tensile properties of composite specimens tested in the transverse direction (mean ± standard deviation)

Composite	Reference	Fiber volume ratio	E_L^{app1} [GPa]	Stress at failure [MPa]	Strain at failure [%]
H_WF649_90_E	This work	0.60	6 ± 1	17 ± 1	0.38 ± 0.06
F_WF154_90_E	[26]	0.45	4.8 ± 0.25	27.7 ± 0.3	1.00 ± 0.15
F__NCF140_90_E	[54]	0.44	4.5 ± 0.2	26.1 ± 0.6	0.62 ± 0.04
F_T110_90_E	[56]	0.46	4.1 ± 0.2	20.4 ± 1.2	0.57 ± 0.06

Finally, the hemp fabric was studied as reinforcement in a composite with a cross-ply laminate stacking sequence. The tensile stress-strain curves are presented in Fig. 11. The tensile mechanical properties are shown in Tab. 8. The mean values of the apparent modulus, stress and strain at failure are 16 GPa, 148 MPa and 1.70%, respectively. Literature data for cross-ply laminates produced from flax QUD woven fabrics, NCFs and tapes are also summarized Tab. 8. The estimated values for a given Vf of 0.60 are presented in Fig. 12. The stiffness of the hemp-based cross-ply laminate is similar to the mid-range of all the other flax-based laminates. The strength is slightly lower, with a mean value equal to the low range of the flax-based cross-ply laminates (see. Fig. 12 b)).

Tab. 8. Mechanical characteristics of the cross-ply composites (mean ± standard deviation)

Composite	Reference	Fiber volume ratio	E_L^{app1} [GPa]	E_L^{app2} [GPa]	Stress at failure [MPa]	Strain at failure [%]
H_WF649_090_E	This work	0.62	16 ± 1	7 ± 1	148± 16	1.70 ± 0.24
F_WF300_090_E	[24]	0.40	12.9 ± 0.8	9.0 ± 0.6	145 ± 14	1.53 ± 0.30
F_NCF140_090_E	[54]	0.43	14.5 ± 0.8	-	170 ± 20	1.72 ± 0.13
F_T200_090_E	[55]	0.40	14.5 ± 0.8	11.8 ± 2.5	126 ± 7	1.08 ± 0.16
F_T200_090_PP	[55]	0.40	10.8 ± 1.1	7.4 ± 0.7	89 ± 12	1.09 ± 0.06

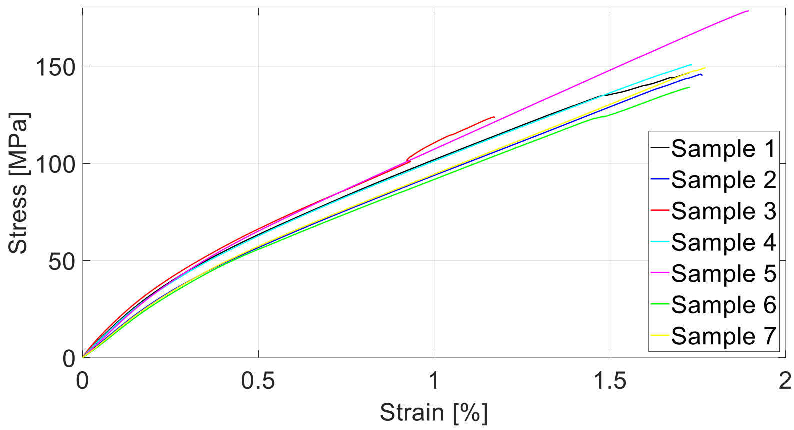


Fig. 11. Tensile stress-strain curves of the H_WF649_090 composite

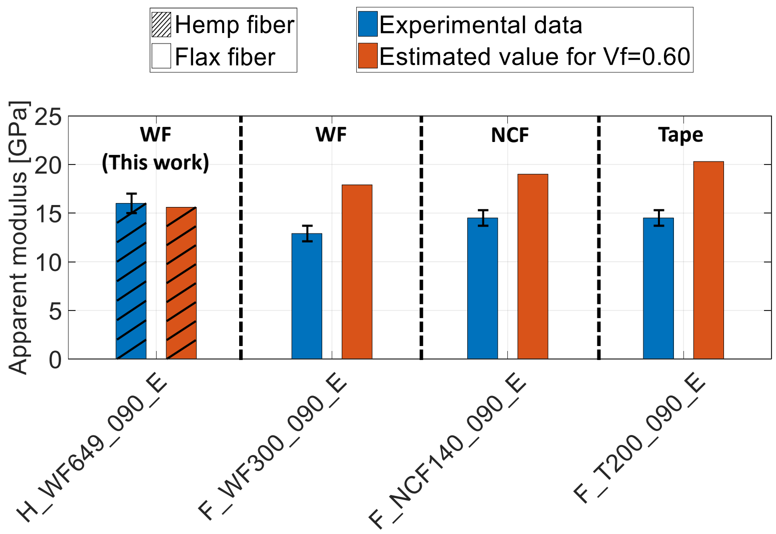


Fig. 12. Apparent modulus determined by the authors with the confidence intervals and property values estimated using the ROM for a fiber volume ratio of 0.60 for the cross-ply epoxy-based composites

Thus, the quasi-unidirectional fabric developed in this study with hemp fibers allows competitive mechanical properties to be achieved compared to those obtained with commercially available flax reinforcements, thus showing promise for the future. This new reinforcement is made with hemp fibers, which are known to have lower mechanical properties than flax fibers. Moreover, the manufacturing of QUDH fabric is conducted at a laboratory scale with a manual weaving machine. In the future, this process can be improved with the use of an industrial weaving machine and optimization of the production parameters. At the scale of the composite plate, the manufacturing cycle can also be improved to maximize the mechanical properties of the final composite.

4 Conclusion

In this work, a quasi-unidirectional fabric was produced by the weaving process with hemp fibers using low twisted rovings in the weft direction and only a few small twisted yarns in the warp direction to bring cohesion to the fabric. The obtained reinforcement is heavier and thicker than conventional flax unidirectional fabrics available on the market due to a high yarn density in the weft direction. This parameter could be tuned and optimized in the future. This fabrication process allows a high fiber content in one direction while retaining low crimping of fibers. Another advantage in the manufacturing of quasi-unidirectional fabric is that the properties of the fibers and rovings are less affected than those of a more standard and balanced woven fabric by the manufacturing process. It is then possible to obtain a composite reinforcement that maximizes the fiber fraction in one direction, with sufficient cohesion for composite processing and without damaging the fibers. The fabric was then used as reinforcement in a composite and compared with data in the literature obtained with unidirectional flax tapes, noncrimp fabrics and quasi-unidirectional woven fabrics made of flax fibers. The results highlighted the competitiveness of this hemp-based quasi-UD composite in terms of stiffness in both material directions compared to composites reinforced with flax-based quasi-UD and NCF fabrics. The modulus of the unidirectional composite still remains slightly higher. The stiffness of the cross-ply laminate is comparable to the mid-range of the flax cross-ply laminates reported in the literature. The tensile strength remains lower, which is attributed to the intrinsic properties of hemp fibers; these properties are generally reported to be significantly lower than those of flax fibers. Indeed, the development of this new quasi-unidirectional reinforcement with hemp fibers is promising since it allows competitive properties to be achieved, and it can be optimized.

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6 Declaration of conflicting interests

The authors declare that there are no conflicts of interest.