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Effects of needle punching process and structural parameters on mechanical behavior of flax nonwovens preforms

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Abstract. The production of nonwoven fabrics from natural fibers is already expanding at an industrial level for simple curvature semi-structural part in the automotive industry. To develop their use for technical applications, this paper provides an experimental study of the mechanical behavior of flax-fiber nonwoven preforms. A comparison between different sets of carded needle-punched nonwoven has been used to study the influence of manufacturing parameters such as fibers' directions, the area and the needle punching densities. We have found that the anisotropy observed between both directions can be reduced depending on these parameters. Furthermore, this work investigates the possibility to form double curvature parts such as a hemisphere as well as a more complex shape such as a square box which possesses four triple curvature points. We propose a forming process adapted to the features of the nonwoven structure. The purpose is to determine their behavior under high stress during various forming settings. The preforming tests allowed us to observe in real time the manufacturing defects as well as the high deformability potential of flax nonwoven.

Keywords: nonwoven preform; flax nonwoven; forming; fabric; mechanical characterization

1. Introduction

Nonwoven fabrics are used in the automotive industry for a variety of applications due to their lightweight, sound efficiency, flexibility, versatility and easy tailored properties, low process and materials costs as well as an attractive cost/performance ratio (Thilagavathi *et al*. 2010). They are playing a key role in the automotive market. They can be found in cabin air filters, in molded seat coverings, headliners, trunk liners and carpeting (Russell 2007). They can also provide interesting properties as lining materials because of their ease of handling, their shape adaptability characterized by a high formability potential (Soukupova *et al*. 2007, Misnon *et al*. 2014). In aerospace, the use of nonwoven reinforced composites is expanding as it provides weight and coast efficient materials (Kellie 2016).

Such materials can be manufactured by bonding together fibers or bundles to create a nonwoven network. They are made in one continuous process directly from the raw material to the

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finished fabric. This is particularly interesting to minimize the production cost and the impact on the environment (Smith 2000). Because of the low mechanical properties of composites manufactured from random nonwoven mats, researchers in recent years have been looking for highly aligned, yarn-based natural fiber reinforcement structures for the manufacture of composite components in load-bearing applications (Miao and Shan 2011). By using an Ashby method, Shah (2014) proved that the absolute and specific tensile properties of Plant Fiber Reinforced Plastics (PFRP) manufactured using nonwoven fabrics are globally 2 to 20 times lower than unidirectional reinforcement based composites. However, nonwoven fabrics outperform unidirectional and multiaxial PFRPs in terms of property per unit cost. If all these studies mainly deal with the tensile mechanical behavior of composites manufactured from nonwoven reinforcements, the identification of the mechanical properties of dried nonwoven preform has not been widely studied. Experimental analysis conducted by Farukh *et al*. (2014) showed significant tensile strain abilities in the 50% range. They also showed that strong anisotropy in mechanical property could be observed because of the non-uniform orientation distribution of the fibers within the nonwoven structure. High deformability properties which are an advantage during manufacturing processes of composite materials may therefore be observed as a consequence of the large tensile strain abilities of the nonwoven fabric.

In order to investigate the formability behavior of nonwoven fabrics during the preforming stage has been considered. This stage is first step of the Resin Transfer Molding (RTM), which is the main manufacturing processes to produce composite parts for the transport industries (Long 2007, Campbell 2006). A lot of experimental (Allaoui *et al*. 2014, Zhu *et al*. 2011) and numerical (Thomas *et al*. 2013, Boisse *et al*. 2011) studies concerning the draping stage of dry reinforcement, the first step of RTM process, were carried out to analyze the deformability of different reinforcements on more and more complex shapes. Many studies have been conducted about the preforming of carbon, glass and also natural fiber textiles in woven fabrics (Zhu *et al*. 2011, Ouagne *et al*. 2013), Non-Crimp- Fabrics (Bel *et al*. 2012), 3D interlock (Dufour *et al*. 2014) and weft-knitted fabric (Li and Bai 2009). However, the deformability of nonwoven reinforcements during the preforming step was not studied on the contrary to the resin flow characteristics of natural fiber nonwoven during the injection step (Zhang *et al*. 2012). The behavior of highly aligned reinforcements (woven, braided knitted, etc…) during the preforming step is characterized by complex coupled tensile, in-plane shear, bending but also and compaction deformations (Boisse *et al*. 2011). Criteria to define the feasibility to realize a particular shape are based on limits of these deformations, such as the locking angle (Boisse *et al*. 2011, Prodromou and Chen 1997) for the in-plane shear behavior.

The purpose of this paper is to analyses the mechanical behavior of nonwoven made with flax fibers by tensile and forming tests conducted at the dry scale. The influence of process parameters like the area density, the needle punching settings and the fibers direction was studied.

2. Materials and methods

2.1 Material selection

Das and Pourdeyhimi (2014) has described several technologies to manufacture nonwovens fabrics; they are defined as sheet or web structures bonded together by entangling fibers or filaments and by perforating films mechanically, thermally or chemically. In general, to manufacture the nonwoven fabric from the fiber material or the extruded thermoplastic, two

Table 1 Main properties of the flax fiber

Reinforcing Fiber	Flax
Origin	France
Average fiber length (mm)	80
Density (g/cm^3)	1.45
Color	Natural

Table 2 Main properties of flax-fiber reinforced nonwoven

	Ratio Flax (%)	Needle Punching Settings	Area density (g/m^2)	Thickness (mm)
NW-1	100	Set A	450	3.52
NW-2	100	Set A	600	3.39
NW-3	100	Set B	600	4.30
NW-4	100	Set A	1000	5.53

processes are needed, web forming and web bonding. Concerning the web forming, the fibers are laid on a forming surface that can be either dry, air, wet or spun (drylaid, airlaid, wetlaid and punlaid). The fibers are transformed into continuous layers of loosely arranged webs or networks (Wilson 2010). In general, the formed web exhibit poor physical properties. To improve the web physical properties during production, web bonding is an important step. Mechanical, thermal or chemical systems are employed to achieve the needed cohesion between fibers. Various types of fibers and filaments, such as staple fibers and synthetic polymers in chips and flakes, can be used to make nonwovens for technical applications. Thus, the choice of the web forming system has to be adapted to the characteristics of the fibers and the final product.

Among these manufacturing systems, three-dimensional needle-punching allows to produce complex net-shape/near-net-shape preforms to be produced (Chen *et al*. 2016). In addition, needle punched nonwoven natural fibers have excellent through the thickness properties that reduce delamination problems (Andre *et al*. 2017). Therefore, in this study, nonwovens have been manufactured according to the carding/over lapping/needle punching technology. It is a dry-laid process starting with carding during which the small tufts are separated into individual fibers that are bound together, parallelized and delivered in the form of a web. Then, the mechanical consolidation is provided by needling where the board containing a plurality of metal needle moved through the thickness direction so that the needles come pierce the mat to entangle the fibers. The fibers alignments in the nonwoven fabric can be in various directions, depending on the fibers' initial alignment during the web forming process and the fibers' courses changes during the bonding process (Wilson 2010). So, the fibers' orientation can be described by their angles in two or even three dimensions. Although fiber orientations in a nonwoven fabric are potentially in any direction, the manufacturing process can lead to the emergence of a preferential direction. Thus, for this nonwoven structure, it is necessary to define the concept of directions where the machine direction (MD) represent the direction of implementation of the material and the cross direction (CD) is the perpendicular to the machine direction.

Concerning the tested material, flax-fiber nonwoven was provided by EcoTechnilin SAS in France. Four sets of nonwoven, denoted (NW) and manufactured from the same origin of flax-fiber with different areal densities, were tested. The description of the used fibers is presented in Table 1. For this series, the samples are needled from both sides but the needle punching settings is

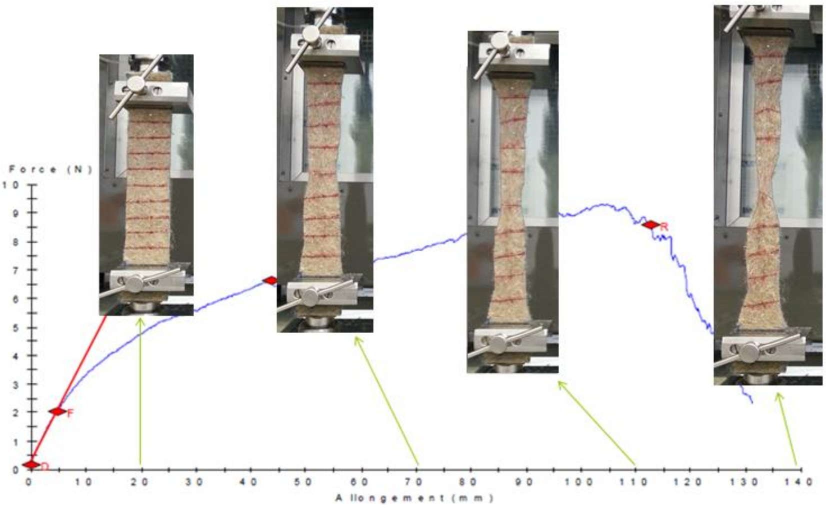


Fig. 1 Example of a tensile test of a nonwoven

modified into two sets (Set A and Set B) as shown in Table 2. The needle punching setting relates the needling density (p/cm²) and the speed production. For confidentiality reasons, values of needling densities cannot be given, but the needling density of "Set A" is higher to "Set B". The main properties of the flax-fiber nonwoven fabrics are given in Table 2.

2.1 Experimental method

For all samples, we are carrying out a namely textile characterization associated to the determination of the area density followed by a mechanical characterization especially in tensile conducted on dry reinforcement. The area density and the thickness of nonwoven were measured according to the standard methods EN 29073-1 (1992) and EN ISO 9073-2 (1997) respectively. Due to the nonwoven significant unevenness and variability, in comparison with the standard fabric, the measurement of the nonwoven area density and thickness requires a great accuracy in sampling and testing.

The nonwoven area density and thickness can determine the fabric packing density. This parameter influences the fibers' freedom of movement and the proportion of voids, called porosity, in the structure. Fabric bulk density is an important property as it can define the propagation and the penetration of fluid, heat and sound into the structure (Kellie 2016). The packing density of a nonwoven is defined as the ratio of the volume occupied by fibers to the total volume. It can be calculated as presented in Eq.(1). Thus, the total porosity of the fabric, defined as the ratio of the void volume to the total volume of nonwoven, is equal to (1- Packing density) × 100 %.

$$Packing\ density\ (\%) = \frac{V_{fibers}}{V_{fabric}} \times 100 \equiv \frac{W_{fabric}}{\rho_{fiber} \times t_{fabric}} \times 100 \qquad (1)$$

V_{fibers} = Volume of fibers
V_{fabric} = Volume of the fabric/ nonwoven
W_{fabric} = Weight of the fabric
ρ_{fibers} = Fiber density
t_{fabric} = Fabric thickness

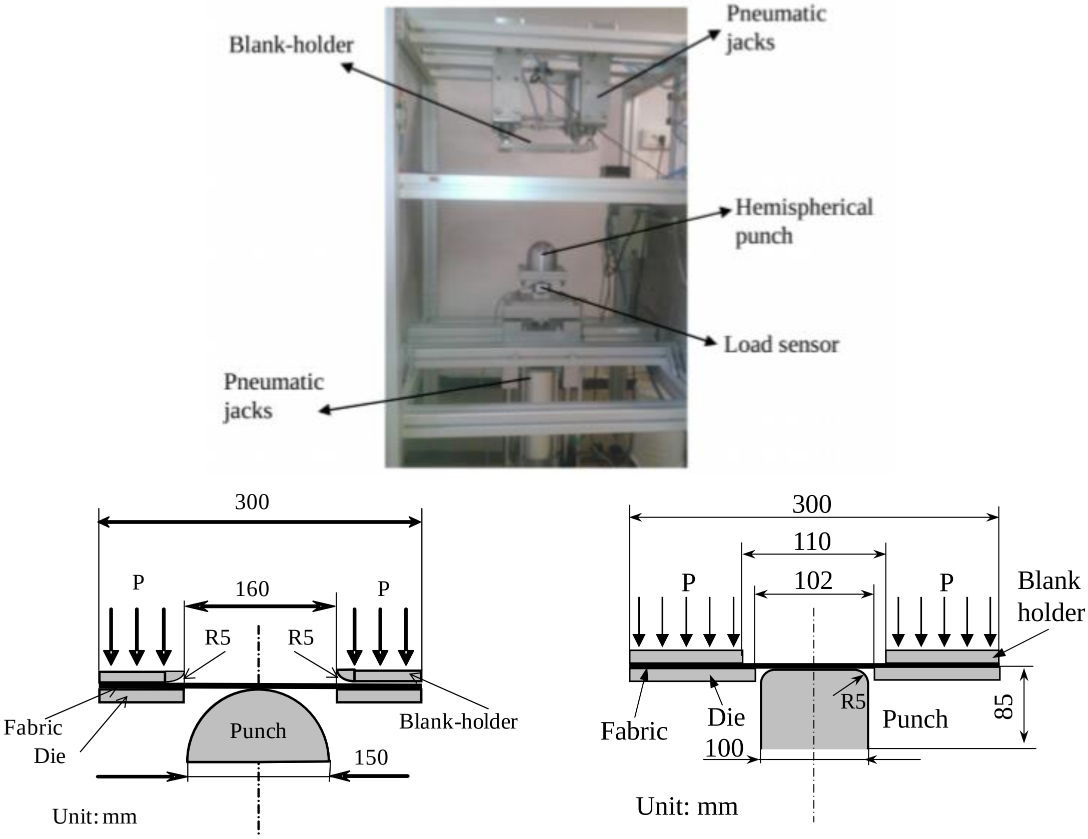


Fig. 2 The hemispherical and square box preforming device

We have also measured the nonwoven air permeability according to the standard method EN ISO 9073-15 (2008). It depends on the nonwoven structure and represents the void capacity through which the air can flow. The test consists on a volumetric rate of air flowing through the nonwoven of unit cross sectional area and at a certain pressure (100 Pa). It is measured in l/m²/s.

The tensile test for the dry reinforcement follows the standard EN ISO 9073-3 (1989). The specimen (300×50 mm²) is placed between the two clamps at a distance equal to 200 mm and loaded with a speed of 100 mm/min. Several tests are realized in each direction: Machine direction MD, cross direction CD and ±45° direction Bias. Fig. 1 shows an example of the tensile test of a nonwoven as a dry reinforcement.

Due to the nonwoven manufacturing processes leading to a non-uniform orientation distribution of their fibers, the anisotropy and non-uniformity of nonwovens cannot be avoided. Consequently, the definition of criteria characterizing the deformability during the preforming stage cannot be the same to the ones of highly aligned reinforcements used in literature. Consequently, this study has developed an experimental approach on the deformability of dried natural fiber nonwovens on a preforming device. A punch and die system was used to form hemispherical geometry and also a more complex square shape (Fig. 2).

For this purpose, the test specimens were laid in 0/90° and in ±45° directions, where 0° being MD and 90° being CD. The surface dimensions of the specimens are 250×250 mm². A mark

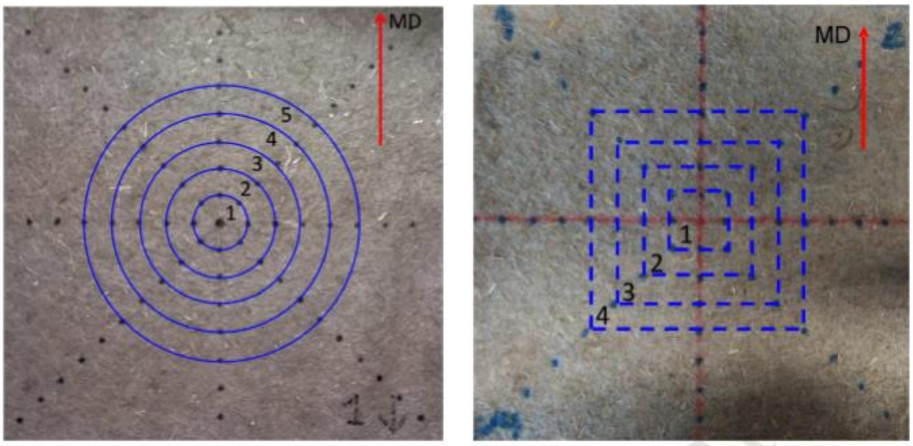


Fig. 3 Nonwoven samples with marked for the hemispherical and square box preforming

tracking technique was used to monitor the local deformations of the preform during the forming. The positions of the markers points are presented in Fig. 3. These markers are placed from the center of the reinforcement to the edges every 15 mm. A video camera installed on the forming device is used to measure the evolution of the markers position. Local zones are defined on the specimens. The evolution of local area density can be performed during forming. Two different preparations of specimen are shown in Fig. 3 with round or square zones, depending on the shape of the device.

Different pressures were used during the forming: A low (0.01 MPa) and a high pressure (0.2 MPa). In order to measure the evolution of local area density and monitor the forming defects by optical measurement, the “open-die” forming system is proposed. Another electric jack imposes the punch displacement. The punch displacement in hemispherical and square box forming tests was respectively 65 mm and 80 mm. A load sensor measures the punch force during the forming.

3. Results and discussion

3.1 Physical properties

The nonwoven area density and thickness vary in different locations in the fabric which can explain the variation of local packing density, fabric porosity and air permeability. These physical properties influence greatly the performance of nonwoven applications: Tensile behavior, shape forming, light opacity, liquid and air penetration, thermal and sound insulation. The packing density is an indication of the fibers’ web compactness and the nonwoven solidity (Kellie 2016). The testing results are shown in Fig. 4. The packing density of the sampled nonwoven is from 10 % to 15 %. It is considered as a high fibers’ volume ratio for a carded needle punched nonwoven in dried form. Usually, this type of product has an average porosity of 95 %.

Indeed, the increase of the mass per unit area leads to the increase of the fibers’ packing density consequently the nonwoven is much less permeable. Thus, the evolution of air permeability is inversely proportional to that of the packing density. For the needle punching settings, the change in the needling density between set A and set B, particularly for NW-2 and NW-3, leads to a

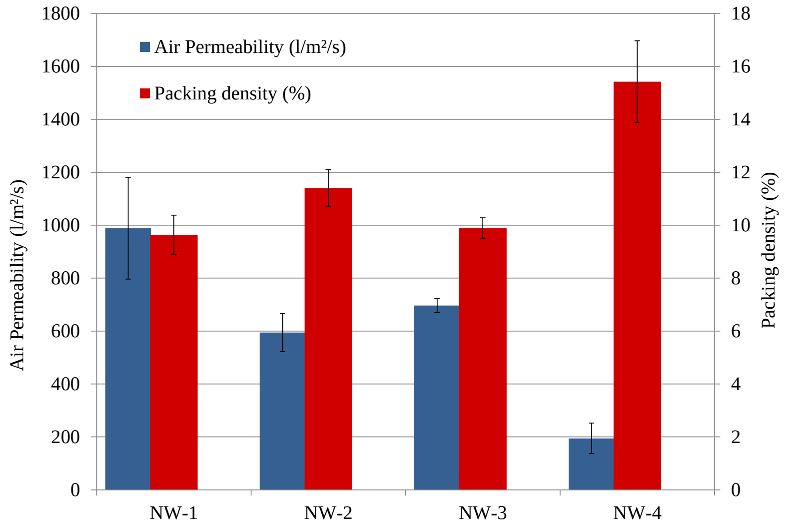


Fig. 4 Air permeability and packing density for nonwoven samples

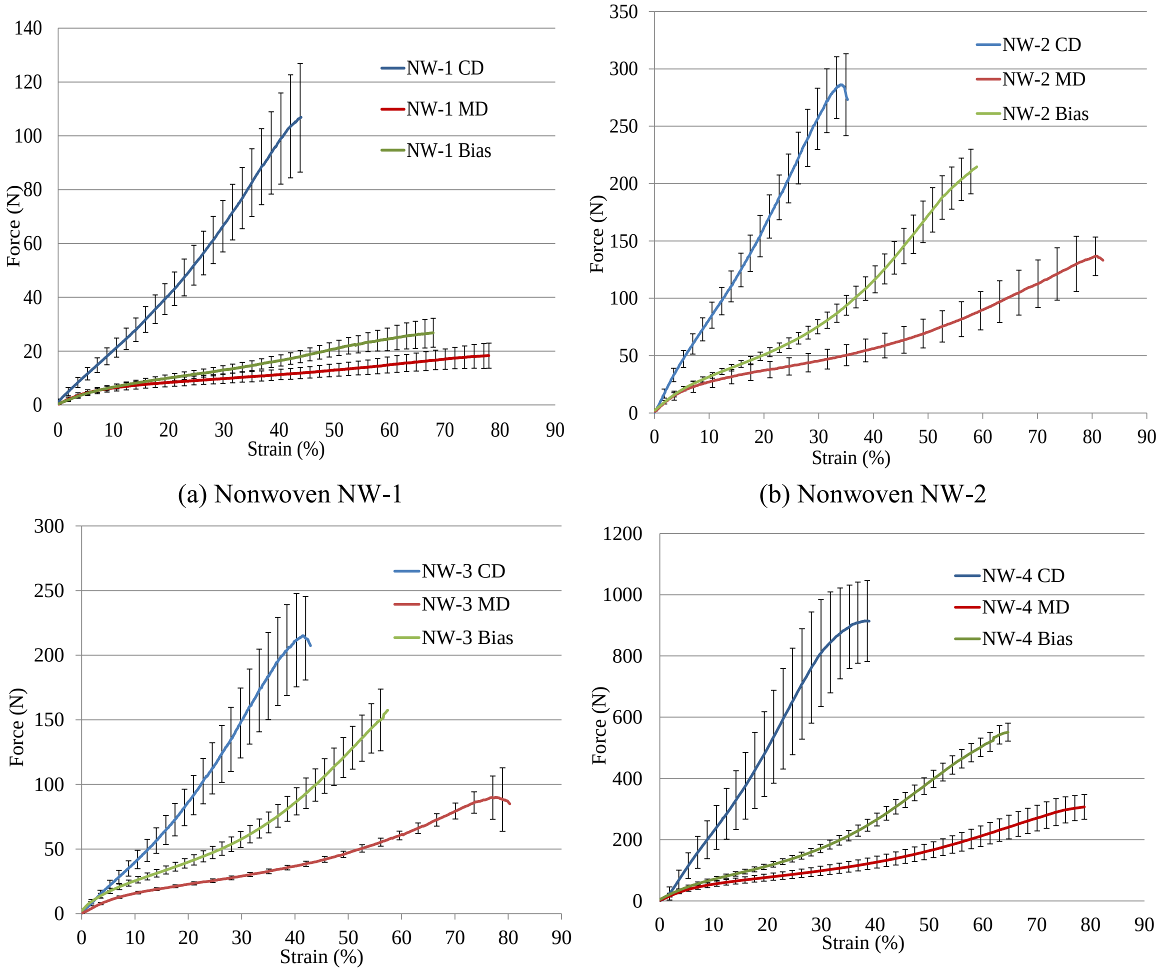
significant variation of the packing density. The results show a change in the area density that influences consequently the air permeability and the packing density.

3.2 Mechanical properties

Fig. 5 shows the tensile behavior identified to the dry nonwoven, in each orientation (MD: for Machine Direction, CD: Cross Direction and Bias direction). The average tensile tests and the standard deviation are also specified. The mechanical behavior of a nonwoven structure, at the dry scale, is characterized by a dissociation of the fiber network reflecting a non-linear behavior in large strain. The figure below highlights an anisotropic behavior in both directions (MD and CD). However, the standard deviation in the machine direction is larger than in the cross direction. This can be explained with reference to the higher variation of the local fiber density along with higher strain at break in the machine direction, in comparison to those in cross direction. From these curves, three different parts can be distinguished. A first linear part associated with the orientation of the fibers in the load direction, followed by a second part characterized by a higher slope until the breaking phase. This phenomenon is associated to a stiffening of the tensile behavior.

For all samples, a high deformation capacities are shown as the strain at maximum load can be attaining 80% in the machine direction. However, the cross direction shows better mechanical performance than the machine direction. In MD+45° and CD+45°, the mechanical behavior seems to be the average between the two mains directions (CD and MD) in terms of maximal load and strain. This result can be explained by the manufacturing process where, after the carding and cross-lapping process, the fibers are more oriented in the CD direction. Moreover, the analysis of the curves shows that this anisotropy of the behavior increases with the mass pert unit area: the cross direction tends to be more rigid, therefore a higher maximum force and an increasingly lower deformation at break, contrary to the machine direction which shows a greater deformation. The difference between the directions for NW4 (1000 g.m2) reaches up to 198% for the MD direction and 66% for the Bias direction.

The influence of the needle punching settings is traduced by a different tensile behavior



(c) Nonwoven NW-3 (d) Nonwoven NW-4

Fig. 5 Tensile behavior of nonwoven reinforcement in Cross Direction (CD), Machine Direction (CD) and Bias Direction (Bias)

between NW-2 and NW-3. Despite having a similar mass per unit area, the set A seems to improve the breaking stress of the nonwoven as well as reduce the dispersion within the same samples. However, the second needle punching setting, set B, leads to having a more homogenous tensile behavior. This observation can be confirmed with the reduction of the difference between the three directions.

3.3 Forming

As an open matrix is used, it is possible to observe the local and general behavior of the nonwoven fabrics during forming. To achieve both hemispherical and square box shapes, several investigations of a preliminary nature were performed. It was observed first that the bending stiffness of both reinforcements is too high in both directions to allow their forming without the

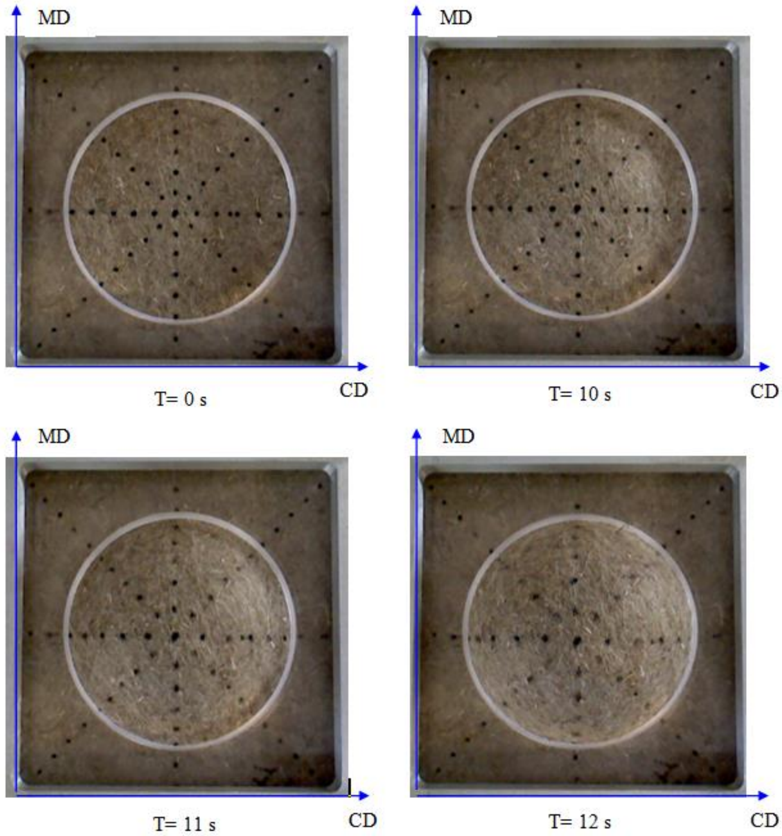


Fig. 6 Forming evolution of a NW-1 nonwoven fabric using a hemispherical geometry (0.2 MPa)

use of a blank-holder device. When the blank-holder is used, it was observed that the shape can be obtained even though a careful choice of pressure is necessary to avoid the presence of defects.

During forming, it was observed that both local and global deformations of the reinforcement take place. Local deformation of the nonwoven fabric takes place first. This mechanism is characterized by local movement or migration of fibers and bundles of fibers within the fibrous structure. The local areas of the reinforcements are increased and the density of fiber decreases. This phenomenon is particularly visible for the hemispherical forming where the size of markers points increases in the useful zone, like shown in Fig. 6.

One of the most common defects that can be observed frequently in woven reinforcement forming is wrinkling (Allaoui *et al*. 2014, Boisse *et al*. 2011 and Wang *et al*. 2015). Boisse *et al*. (2011) have pointed out that wrinkling is a global phenomenon that depends on all strains and stiffness's. It also depends on the forming boundary conditions. The wrinkles are due to an out of plane deformation mechanism that takes place because too much matter tries to come in a certain zones of the shape. With nonwoven fabric, the notion of in-plane shear does not exist and wrinkles appear. The wrinkling phenomenon can be observed in Fig. 7(a) and Fig. 8(a) for the square box forming of respectively NW-1 and NW-4 under 0.01 MPa blank-holder pressure. When a low blank-holder pressure is applied during the forming, the tensile load is too weak to prevent wrinkles.

(a) 0.01 MPa blank-holder pressure (b) 0.2 MPa blank-holder pressure

Fig. 7 Wrinkling phenomenon in NW-1 nonwoven fabric during forming

(a) 0.01 MPa blank-holder pressure (b) 0.2 MPa blank-holder pressure

Fig. 8 Wrinkling phenomenon in NW-4 nonwoven fabric during forming

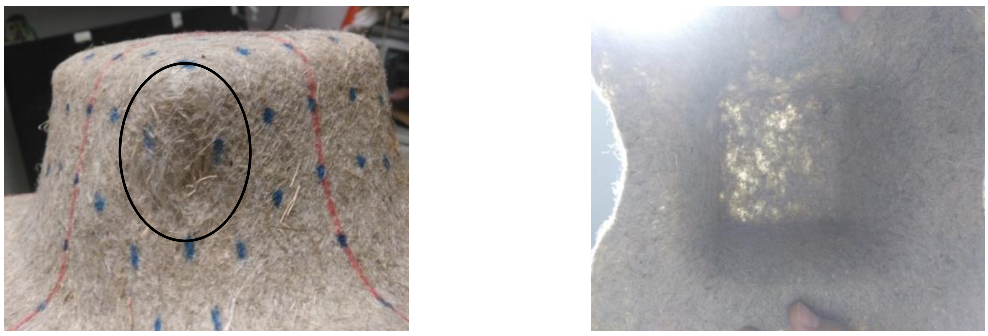


Fig. 9 The slippage/damage of network in NW-1 nonwoven fabric forming

However, the wrinkles disappear when a sufficient load is applied. For example, no wrinkles were observed when a blank-holder pressure of 0.2 MPa was applied (Fig. 7(b) and Fig. 8(b)). When a sufficiently large blank-holder pressure is applied, the tension of the membrane increases, and local deformations also increase.

Another defect may be observed in zones where the fabric shows low fiber area density or fiber vacancies. In fact, the slippage/damage of network is a typical problem in the nonwoven fabric forming, which depends strongly on the fiber density (area density) of fabric and blank-holder pressure. These types of defects are illustrated in Fig.9 for the NW-1 nonwoven in box forming under a high blank-holder pressure (0.2 MPa). It shows a lack of fiber densities conducting to severe damages and a loss of the fabric integrity.

5. Conclusions

In the present work, an experimental study has been proposed for the mechanical behavior of flax nonwoven reinforcement at the dry scale. Two sets of carded, needle-punched nonwoven reinforcements have been studied. They are made with a ratio of 100 % flax fibers, but differ with the process parameters as area density and needle punching settings.

The tensile tests have shown a significant anisotropy between the machine and the cross directions, as classically noted in literature. For a constant area density, the variation of the needle punching density helps reducing the anisotropy between fibers' directions. An increase in mass per unit area of the nonwoven leads to the increase of the tensile resistance but at high density, such as 1000 g.m^{-2}, the anisotropy between directions is accentuated.

The forming test has established the high deformation potential of the nonwoven fabrics. The specific behavior of the nonwoven fabrics is studied by analyzing the local and global deformation mechanisms of the reinforcement during forming. During the process, the global deformation is characterized by the draw-in under the blank-holder. The variation of the local surface area as a function of the local fiber density will be an important parameter to characterize the deformability of nonwoven fabric and its consequence on the permeability during resin injection step. The specific behavior of the nonwoven fabric should be taken into account for future modelling of the forming and impregnation processes. By choosing the right process parameters and reinforcements with sufficiently large enough areal weights, it is demonstrated that it is possible to form the expected shapes without any apparent defect such as vacancies or wrinkles.

Acknowledgments

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