Contactless Optical Extensometer for Textile Materials

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Abstract

This paper presents a contactless extensometer. For some flexible materials, with great displacements and deformations, contact during measurement is not acceptable. In fact, contact measurement can modify the tensile behavior, as is the case for fibrous materials. Contactless extensometers usually have to print or glue some marks on the sample, which may cause problems during measurement. These extensometers typically use digital image processing to obtain deformation data. The principle used in this study uses the natural periodicity or surface patterns inherent in most textile materials without any image processing. During deformation the distance between two periods or pattern elements changes and allowing this method to measure the real-time modification of this in-plane distance. The extensometer consists of two parts: an optical device and a signal processing unit performing a Fourier analysis. Some results obtained during a tensile test on woven fabrics and nonwovens are presented here.

KEY WORDS: contactless extensometer, optical set-up, laser, Fourier analysis, textile fabrics, nonwovens

Introduction

The tensile properties of a material are among its main characteristics. Several parameters can be obtained from a tensile test: breaking strength, stress and mean elongation for each traction direction, etc. All these characteristics can be established on a usual tensile test machine. An extensometer is necessary to characterize the material more precisely: it allows the user to obtain the local strain. Some extensometers also helps to determine the lateral strain of the sample, i.e. contraction. Consequently, Poisson's ratio can be evaluated. It is of interest to know the tensile characteristics of a material in order to determine its behavior in use hence the present study of fibrous materials, such as woven fabrics or nonwovens.

Some devices allow the user to measure the longitudinal characteristics of a material. The most common one is the strain gauge. The gauge must be glued in the direction whose characteristics are required. As a result, if two gauges are used, the local longitudinal and lateral strains are obtained and so, Poisson's ratio can be calculated.

Another measurement method consists in using an image processing technique in order to evaluate the strain of a material during a tensile test. Several marks have to be put on the sample. Images are acquired throughout the test. By studying the mark location through simple image processing, the strains in the sample can be calculated. Hiver *et al.* [1] present the use of several dots in the tensile and lateral directions. The location of each mark is approximated by the location of its center of gravity and its displacement gives the longitudinal and lateral strains. They consider the material to be isotropic in order to assume that the thickness variations are equal to the lateral contraction. François *et al.* [2] determine the strain in the three directions precisely. The sample surfaces are marked with two lines in the tensile direction and one dot. The two lines allow the user to determine the longitudinal strain and the dot at the edge of both sides helps to evaluate the strain in the two other directions on the same location. The advantages of this method are that the strains are determined in the three directions of the material, in the same sample area, and without assuming that the material is isotropic.

A third principle, established by Fiedler [3] and used by Grellmann *et al.* [4], Casarotto *et al.* [5] and Chmelik *et al.* [6], consists in printing two marks at the surface of the studied material and analyzing the displacement of these marks. The real-time measurement of the dot locations is carried out with a laser beam focused on the sample. The intensity of the reflected beam is analyzed and used to calculate the strain between the two marks. Grellmann *et al.* [7] presents a device which uses the same measurement principle but with several laser sources in order to define the extensometrical characteristics on different parts of the material in a unique test.

Another principle is the digital speckle correlation between the images taken before the test and the images which can be taken at each displacement increment during the tensile test (Amodio *et al.* [8] - Laraba-Abbes *et al.* [9]). The speckle pattern can be generated by a coherent light source or using paint. The image processing technique consists in determining the displacement of the different dots on the material surface. This measurement principle is used by Anwander *et al.* [10] to characterize the strain properties of materials at high temperature and by Zhang *et al.* [11] for the characterization of arterial tissue.

Another image processing technique is the stereoscopic correlation which determines the strain characteristics through the determination of the 3D coordinates of the surface points of the object, as proposed by Luo *et al.* [12] and Mistou *et al.* [13]. Dumont *et al.* [14] characterize woven fabrics using this method.

The strain gauges and the methods which use marks on the sample surface require sample preparation before the test. Furthermore, for some materials, these marks can modify the tensile behavior and so, the strain results. For materials with great deformations, an element stuck on the surface must elongate with the material tested without changing the material behavior. Moreover, the adherence between the material and the stuck element must be perfect. For all these reasons, a stuck element, a strain gauge or a mark is not suitable for fibrous surfaces. A painted mark presents the same disadvantages as a stuck element. The use of a mark with a dyeing method also has some disadvantages: the dependence on the initial fabric color and the significant mark deformation during the test. The use of a speckle pattern on a fabric surface is not suitable because of the natural texture of the fabric. The stereo correlation which consists in evaluating the displacement of some points of the surface, is very interesting but for fabrics with surface hairiness, due to fibers on the surface which have escaped the cohesion process, can be difficult to follow the displacement of some chosen points.

This paper describes a method using the proper sample structure without any image processing and presents some results obtained with a woven fabric and a nonwoven.

Structure of Textile Materials

In this study, two different kinds of materials are tested: a plain woven fabric and a spunbonded nonwoven.

A woven fabric consists of interlaced warp yarns and weft yarns. The type of interlacing determines the kind of fabric.The plain woven fabric tested in the present case is described in Fig. 1. The main characteristics of a fabric are the way warp and weft yarns are interlaced, the number of warp and weft yarns per 10^{-2} m, the yarn mass per unit length, called the yarn count in tex (1 tex = 10^{-6} g.m^{-1}), and the raw material of yarns. This kind of fabric is usually used to make shirts.

Another type of fibrous surface is a spunbonded nonwoven. A nonwoven is made up of a fiber or filament web; a filament has an infinite length contrary to a fiber which is several millimeters or centimeters long. The web cohesion is obtained either chemically or thermally or mechanically. The spunbonded nonwoven is composed of filaments, projected in a pseudo-random direction on a conveyor belt. The cohesion of this filament web is then obtained by a thermal process called calendering. The web is compressed between two cylinders, a smooth one and a patterned one which heat the polymer making up the web to its melting temperature. Therefore the fibers melt at the contact point between the two cylinders, i.e. at the calendering points (Fig. 2).

Experimental method

Optical device

The optical device uses a principle presented by Bueno *et al.* [15]. The material is clamped on a rotating sample carrier like in a record player. A laser line is projected onto the sample surface. The reflected beam is concentrated onto a photodiode. In extensometry, the sample cannot rotate; therefore, the optical set up has to generate a light ring. The device presented (Fig. 3) uses a 632.8 nm He-Ne laser and darkness is not required for operation. The beam is expanded and the collimated beam goes through a cylindrical lens. A system composed of two parallel mirrors allows the user to offset the beam. The beam with radial deviation is focused on the sample. The suitable eccentricity direction is parallel to the cylindrical lens axis with the result that the beam describes a ring at the surface of the material. Because of the synchronized rotation of the cylindrical lens and the mirror system; the laser line is always radial. The light reflected by the sample surface follows the same optical path in the opposite direction, up to a beamsplitter cube which sends it onto a photodetector. The light intensity variations during measurement depend on the structure of the textile surface. For example, for the case of the plain woven structure, while the laser line describes the ring, it is sometimes parallel or quasi-parallel to the weft and sometimes to the warp. So the frequency of these phenomena can be evaluated with an appropriate signal processing technique.

Several parameters can be changed and adapted to the tested fabric characteristics. Light intensity can be changed with a neutral-density filter, which could be important for fabrics with different brightness because of the color. An iris diaphragm allows the user to choose the length of the laser line. The length can be adjusted from 5 mm to 10 mm. In the test presented in this paper, the laser line was 7 mm. The distance between the two mirrors is the parameter that determines the diameter of the ring on the surface of the textile sample; it can be adjusted from 45 mm to 90 mm. For the tests presented in this paper, the laser ring diameter was 84 mm. Then the distance between the sample and the optical device must be adjusted so that the laser line is focused on the tested surface. In fact, the great difference in thickness between different textile materials modifies this adjustment. The device allows the user to change the rotation speed of the rotating part from 0.1 rps to 1.35 rps.

In order to determine the strain characteristics, the sample is clamped in the crossheads of a tensile test machine. The optical device is translated in the tensile direction at half the speed of the crosshead speed, so as to always analyze the same part of the sample and not to be next to the clamps of the tensile test machine. The load vs elongation curve provided by the tensile test machine completes the study.

Signal processing

The signal processing technique uses the periodicity of the textile surface; it can be a structural periodicity (fabric) or due to calendering patterns (nonwovens). When the laser line describes and highlights the surface, the reflected light changes. The reflected pattern is acquired by a photodiode. The corresponding electrical signal is sent to a spectral analyzer. The received signal is a voltage value directly linked to the intensity variation of the reflected beam. The Fourier Transform of this type of signal is:

$$X(f) = \sum_{k=-\infty}^{k=+\infty} x(k) \exp(-j \times 2\pi f k) \tag{1}$$

with: x(k): temporal signal,

X(f): Fourier Transform of the signal x(k).

This study considers the Power Spectral Density of the signal:

$$PSD(f) = \left| X(f) \right|^2 \tag{2}$$

A time-frequency diagram represents the evolution of the PSD in the frequency domain versus time. The times and the frequencies are plotted on the two main axes and the third axis shows the amplitude of the PSD (Eq. 2). The graphs obtained exhibit peaks whose frequencies correspond to the periodical structure patterns and the changes of these frequencies can be measured with the displacement of these peaks, linked to fabric deformation, versus time.

The theoretical formula which gives the structure frequencies (Fig. 4) is:

$$P = \pi\phi \tag{3}$$

with P: average perimeter of rotation (10^{-3} m),

ϕ: average ring diameter (measured in the middle of the laser line) (10^{-3} m).

$$V = P f_r \tag{4}$$

with V: linear speed of the laser beam (10^{-3} m.s^{-1}),

f_r: rotation speed of the laser line (rps).

$$F = Vn \tag{5}$$

with F: frequency of the element (Hz),

n: number of structure elements by unit of length (10^{-3} m^{-1}).

Therefore:

$$F = \pi\phi f_r n \tag{6}$$

It is also possible to determine the peak width compared with the laser line length:

$$\Delta F = \pi f_r n(\phi_{max} - \phi_{min}) \tag{7}$$

For instance, for a plain woven fabric, the warp and weft yarns give the structure frequencies (Fig. 1). With the spunbonded nonwoven, the frequencies are defined by the distances between the calendering points in the two main directions. This calendering pattern and its parameters are shown in Fig. 2.

To analyze strain during a tensile test, it is important to follow the variations of the frequencies with time. In the time-frequency diagram (Fig. 5) each interesting zone is represented by a gray spot whose gray level depends on the intensity of the phenomenon. In this study, the central point of each zone is used. These zones are obtained by thresholding the data. This threshold depends on the kind of textile surface, the color of the sample and the test conditions (speed, light intensity, …). Then, frequency is recorded out of the center of the ellipse. It is then recorded all along the test measurement, in order to obtain the strain in both tensile and lateral directions during the test procedure.

Strain measurement

Measurements are realized on samples whose dimensions are 200 x 160 mm^2. The diameter of the light ring is about 84 mm. The bigger the ring is, the more precise the measurement is. Nevertheless, the diameter of this ring is limited by the optical system and the sample size. The width of the sample is chosen in order to remain superior to the ring diameter at the maximum contraction

For each direction (tensile and lateral directions), the measurement is about two areas in opposition relative to the laser ring diameter, i.e. with a distance of 42 mm from the center of the sample during the tests presented in this paper. These two areas give information about the same direction with a gap of an half of rotation of the laser line. The considered and interesting area are 10 mm (direction of the measurement) by 7 mm (length of the laser line).

These 2 x 2 measurement zones allow the user to obtain the strain in the two main directions during the test.

During the tensile test, the frequencies of the structure elements change. In the tensile direction, the sample enlarges, then the distance between two elements increases, i.e. the frequency decreases. In the lateral direction, there is a contraction, so the frequency between two elements in this direction increases. The analysis of these variations helps to evaluate longitudinal and lateral strain. Actually, from the initial characteristics of the studied textile material (the number of warp and weft yarns per unit length for the plain woven fabric and the number of calendering points per unit length for the nonwovens, and the size of the tested sample), the frequency variation helps us to determine the strains in the tensile and lateral directions through a simple calculation at a distance from the center of the sample equal to the rotation radius of the laser line. Measurement is performed at a distance from the clamps in order to remove the boundary conditions effects in the sample.

In the lateral direction, the length variation of a structure element orthogonal to the tensile direction is:

$$\delta l = \left(\frac{V}{F_1} - \frac{V}{F_0}\right) \Rightarrow dl = \left(\frac{V}{F_1} - \frac{V}{F_0}\right) nl \tag{8}$$

with δl: length variation of one structure element orthogonal to the tensile direction(10^{-3} m)

dl: width variation of the sample (10^{-3} m),

l: width of the sample (10^{-3} m),

V: linear speed of the laser beam (10^{-3} $m.s^{-1}$),

n: number of studied structure elements by length unit (10^{-3} m^{-1}),

F_0: frequency of the studied element before deformation (Hz),

F_1: frequency of the studied element at time t_1 (Hz).

Using the same principle, the strain in the longitudinal direction can be calculated:

$$\delta L = \left(\frac{V}{F_1} - \frac{V}{F_0}\right) \Rightarrow dL = \left(\frac{V}{F_1} - \frac{V}{F_0}\right) nL \tag{9}$$

with δL: length variation of one structure element in the tensile direction (10^{-3} m),

dL: length variation of the sample (10^{-3} m),

L: length of the sample (10^{-3} m).

It is obvious that during the tensile test the behaviors in the tensile and in orthogonal directions are opposite. The frequency of the element in the tensile direction will decrease while it will increase in the lateral direction. This is of importance for nonwovens as the same structure is analyzed in both directions, because of the 90°-rotational symmetry of the calendering patterns.

These structures composed of perpendicular elements help to determine the strain characteristics of the textile surface in both the lateral and longitudinal directions. Each test helps to plot two curves in each main direction insofar as measurements are carried out every half rotation. These two curves are then averaged in order to obtain a representative curve of the local strain.

Results

Results obtained with the fabrics

The curves corresponding to these tests are shown in Fig. 6 and 7. Three curves are drawn with each sample. One curve which is directly obtained with the tensile test machine shows the evolution of the mean deformation of the sample according to the applied force. The two other curves represent the lateral and the longitudinal strain according to the mean strain, i.e. corresponding to the crosshead moving. It is assumed that the textile surface characteristics are the same all over the sample and that the structure moves symmetrically according to the center of the sample which corresponds to the center of the light ring.

The curves obtained with both plain woven fabric and spunbonded nonwoven show the local lateral strain due to contraction and the local longitudinal strain due to extension.

Repeatability of the measurement method

The repeatability of the method has been evaluated by tests realized on several samples. The results of these samples of the plain woven fabric are reported Fig 8. The bundles of curves show small dispersion of the curves and thus the good repeatability of the measurement.

Comparison with a commercial extensometer

We have realized some tensile tests with the same plain fabric but by using a commercial laser extensometer [3] in order to compare the results. The obtained curves are drawn Fig. 9. It is interesting to see that the values obtained with this method are approximately equal to those ones obtained with our system. Nevertheless, this commercial extensometer is only able to do measurements in tensile direction without changing the system configuration. Some problems occurred during the test. Firstly, it was difficult to glue the reflecting marks on the surface of the sample. Then, during the test and the contraction of the sample, the marks made wrinkles, which could modify measurement results. Sometimes, the sensor does not find the marks anymore mostly because of these wrinkles of the glued marks, with the lateral contraction of the textile surface.

Discussion

The tensile curve of a woven fabric is typically J-shaped, and so can be divided into two parts: the first one gives a great deformation for a low strength and the second one corresponds to smaller deformations but with an increase in strength. The first part corresponds to a decrease in the waviness of the yarns in the tensile direction. Therefore, at the same time, the yarns in the lateral direction are forced to increase their waviness. In fact, a woven fabric is the result of a balance between two perpendicular yarn webs. The second part of the curve is mainly due to the traction of the yarns in the test direction.

As shown in Fig. 7, with the plain woven fabric, strain is higher for a tensile test in the weft direction than in the warp direction. For most woven fabrics, the waviness of weft yarns is higher than for warp yarns. For the plain woven fabric tested, as the yarn counts for both weft and warp directions are quasi equal, only the number of yarns per centimeter modifies the waviness. The present fabric consists of more warp yarns. Consequently, the results are coherent.

The strain of the spunbonded nonwoven is of the same order of magnitude as the strain of the plain woven fabric. Because the structures of these two kinds of textile surfaces are very different, the tensile behavior mechanisms are not similar. In the nonwoven used the filaments present a kind of highly irregular waviness that gives a great elongation potential which, however, is reduced by the calendering points. Thus, this filament entanglement allows a movement which is different but of the same order of magnitude as in a woven structure. The structure is nearly locked and the rearrangement of the structure element is not really easy for this kind of nonwoven.

In all the tests, the local strain was almost equal to the global strain. It is obvious that the lateral contraction next to the clamps is smaller and consequently, the longitudinal extension in the same zone is also smaller. The global strain of the sample evaluated by the tensile test machine is a mean value of the strain all along the material. Then, the closer to the center the measurement is carried out, the higher the strain is, and the weaker the boundary condition effects are. On the other hand, for the nonwoven, strain is very different in the longitudinal direction, i.e. the machine direction and in the lateral direction, i,e. the cross direction. That is probably due to filament orientation.

Conclusion

This paper has described a new contactless extensometer. This device allows the user to measure strain during a tensile test for textile surfaces. It does not need a preparation of the surface sample such as painting or gluing marks. The principle used in this study consists in considering the natural periodicity of the patterns present on the surface of most fibrous materials and more precisely the change of these periods during tensile test. During deformation the distance between two periods or pattern elements changes and this method measures the real-time modification of this distance. The extensometer consists of two parts: an optical device and a signal processing unit based on a Fourier analysis. The values obtained are local strains at a distance from the center of the fabric equal to the radius of rotation of the optical device.

Some results from tensile tests for a plain woven fabric and a spunbonded nonwoven have been presented. For the plain woven fabric, the global and local strains for traction in the warp direction are lower than in the weft direction. Moreover, the local strain in the lateral direction is weaker than the one in the tensile direction, whether for a warp or weft tensile directions. For the nonwoven, during a tensile test parallel to the machine direction, the elongation in the machine direction is strongly higher than the contraction in lateral direction.

The device gives quite good results for plain woven fabrics or for nonwovens whose structure elements are parallel to the lateral or longitudinal directions proved by tests realized with a commercial laser extensometer. When structure elements form an angle with the tensile direction, for instance in the case of twill woven fabrics, a direct interpretation of the results is not possible; further calculation are necessary.

The device described in this paper presents a good repeatability but it could be improved in order to lower the vibrations (due to the optical device rotation and to the crosshead displacement) and to increase the signal to noise ratio.

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Figure legends

Figure 1. Diagram of a plain woven fabric.

Figure 2. Diagram of a spunbonded nonwoven.

Figure 3. Diagram of the optical system.

Figure 4. Schematic of the light ring on a plain woven fabric showing the main parameters.

Figure 5. Time-frequency diagram during a tensile test.

Figure 6. Longitudinal and lateral strains obtained in a) weft and c) warp direction for the plain woven fabric and their associated force-strain curves in b) and d).

Figure 7. Longitudinal and lateral strains in a) and its associated force-global strain curve in b) obtained in machine direction for the spunbonded nonwoven.

Figure 8. Bundle of curves corresponding to successive tests for longitudinal and lateral strains obtained in a) weft direction for the plain woven fabric and in b) the associated force-strain curves

Figure 9. Longitudinal strain obtained in a) weft and b) warp direction for the plain woven fabric with commercial laser extensometer in comparison with the optical extensometer.

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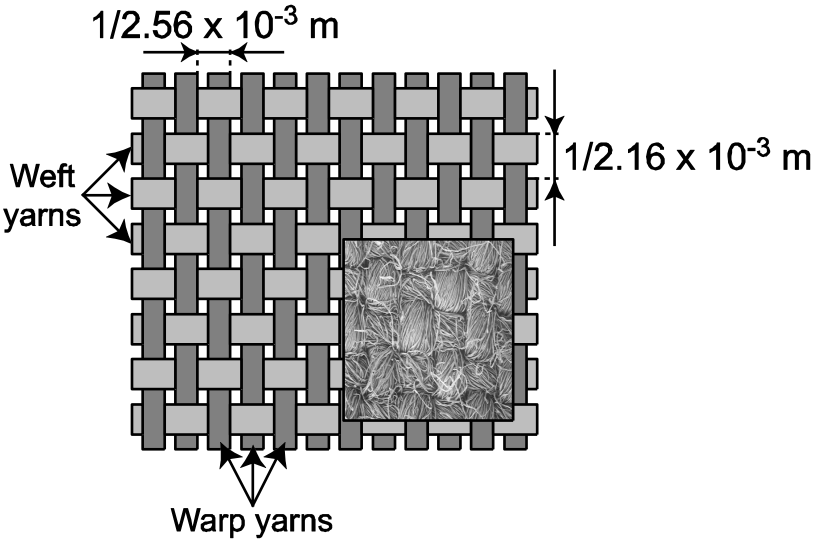
Figure 1:



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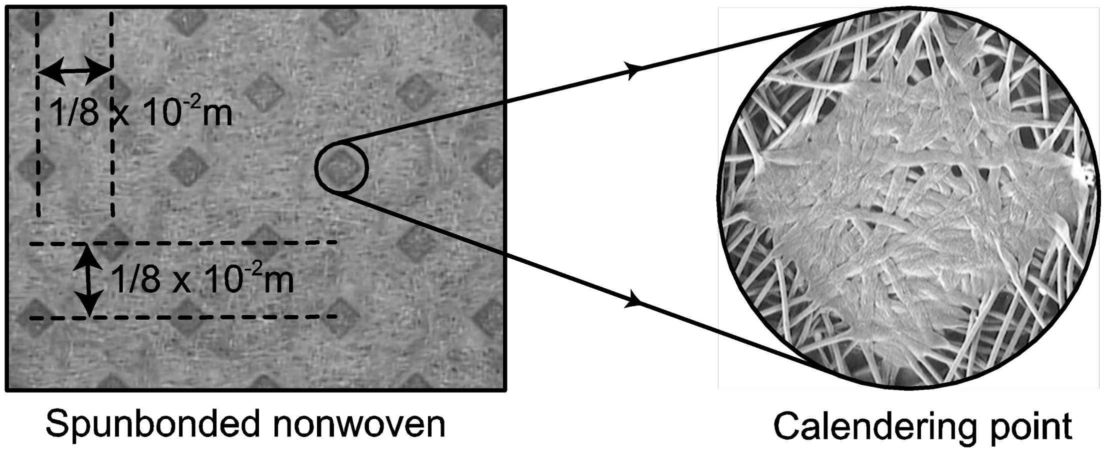

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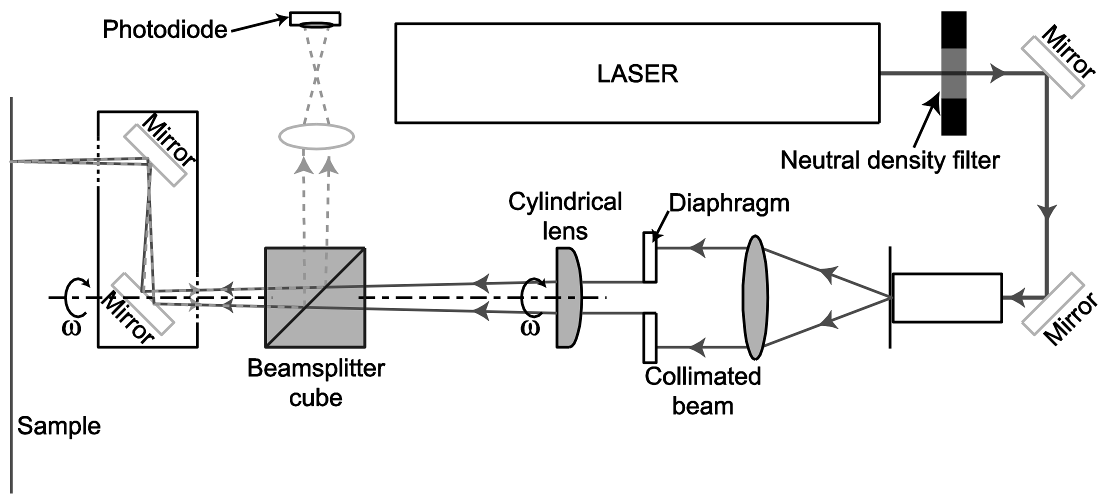
Photodiode
LASER
Mirror
Neutral density filter
Mirror
Cylindrical lens
Diaphragm
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Mirror
ω
Beamsplitter cube
Collimated beam
Mirror
Sample

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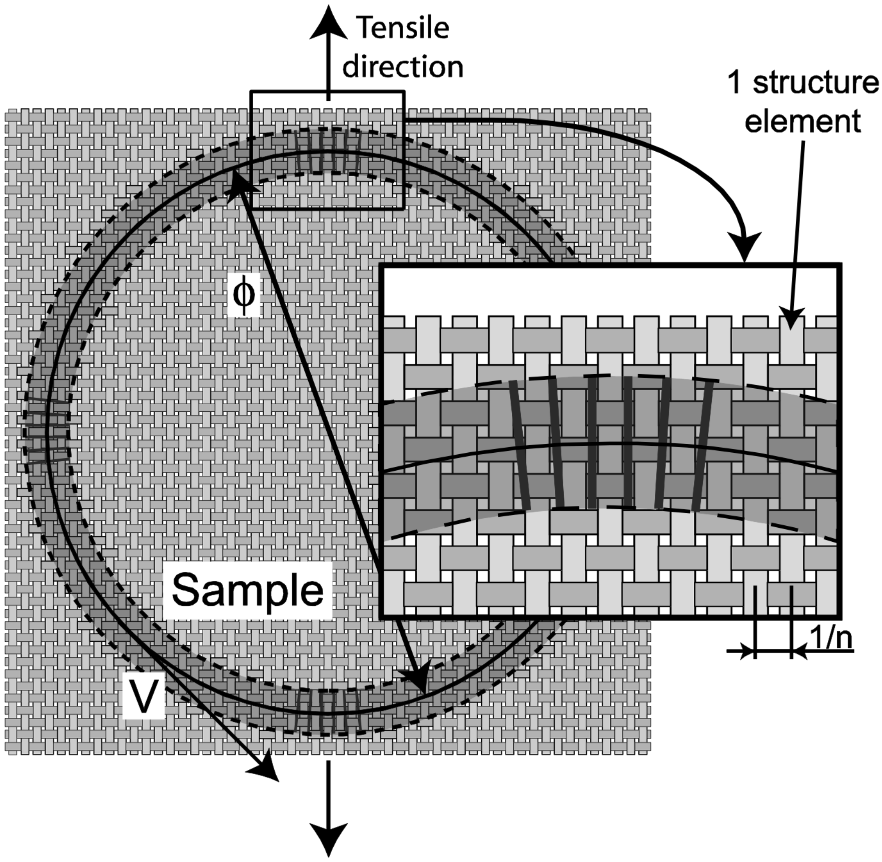
Figure 4:



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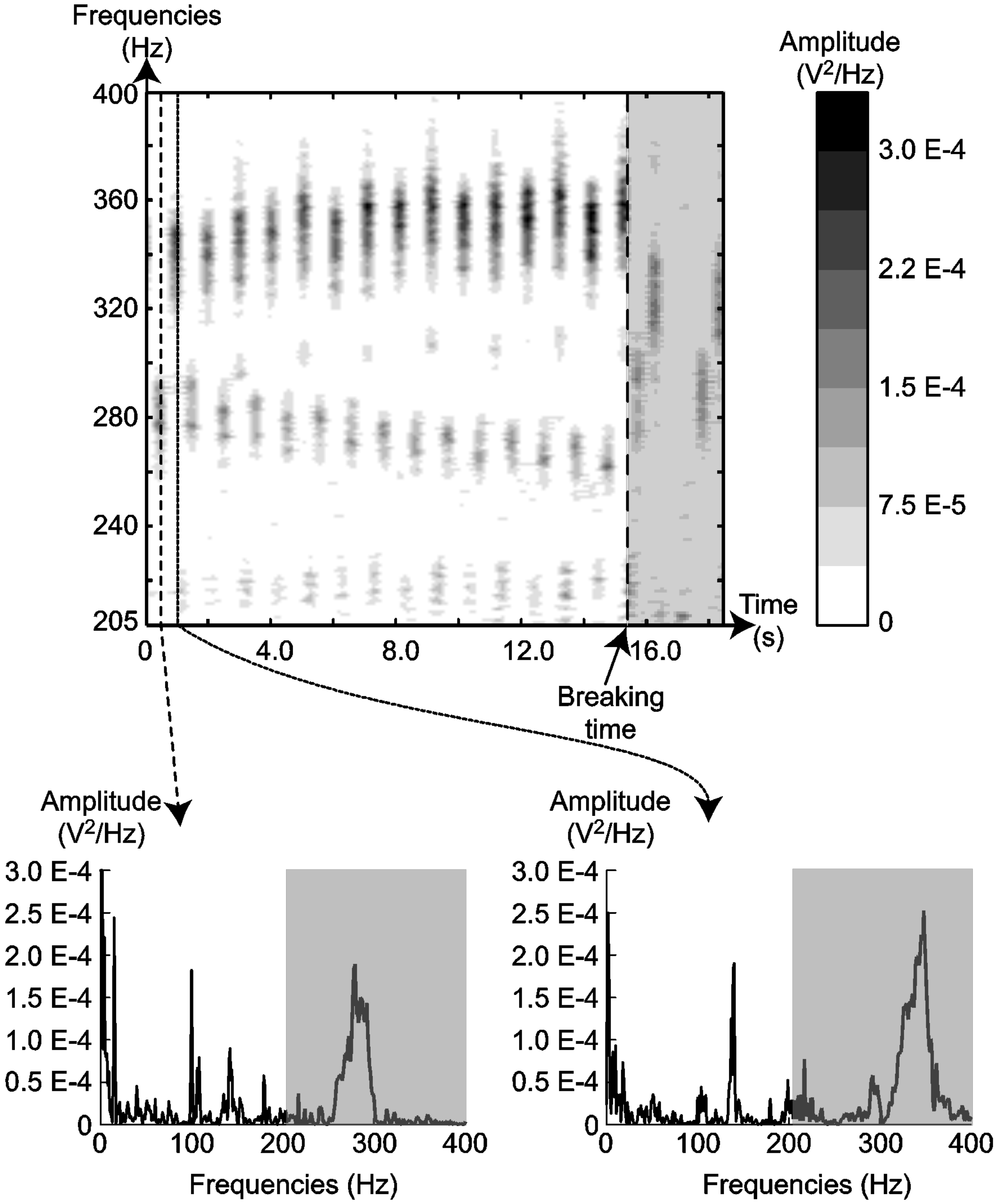
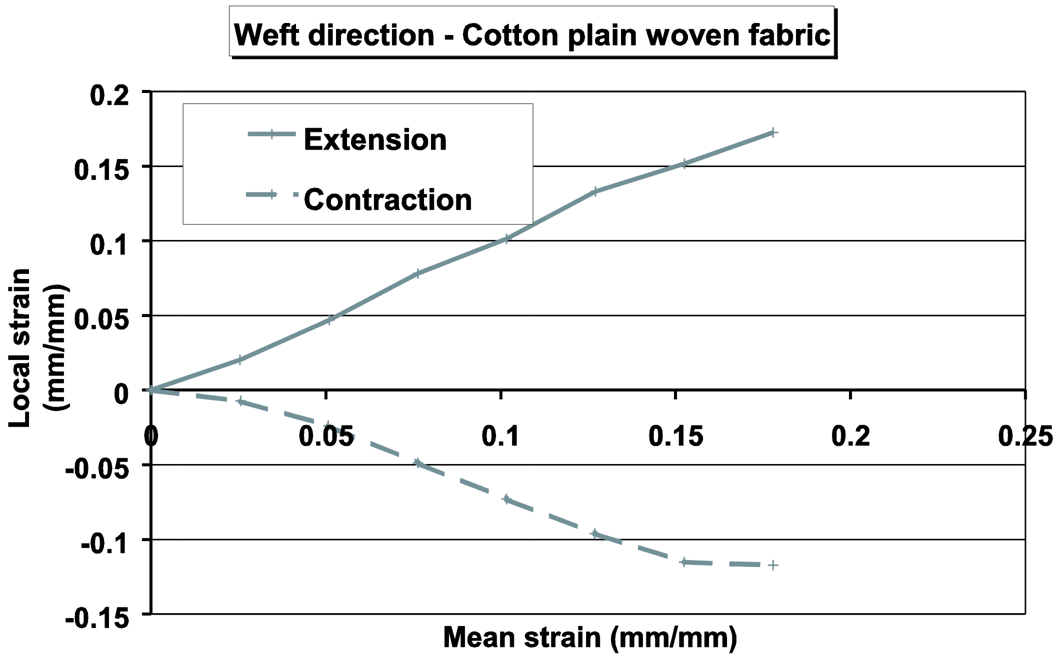


Figure 6:

Figure 6a:



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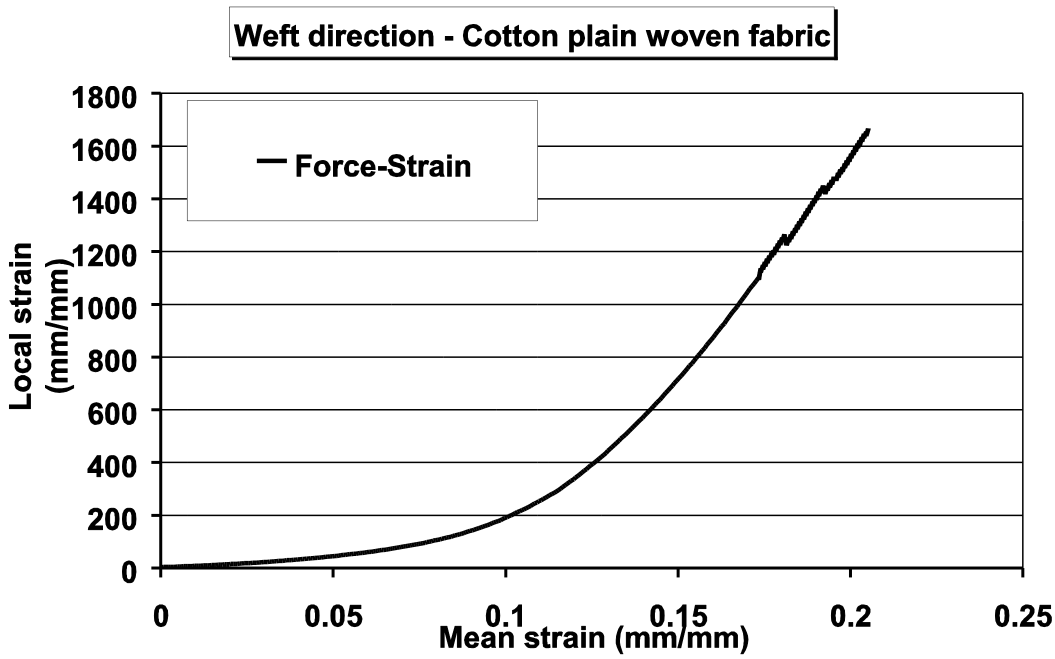

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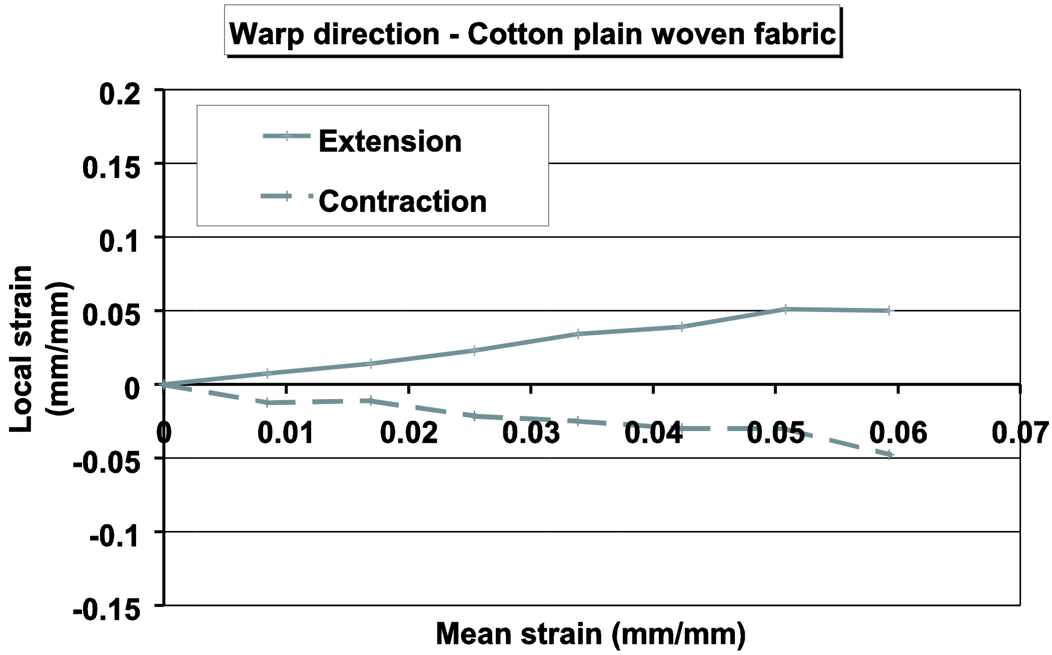

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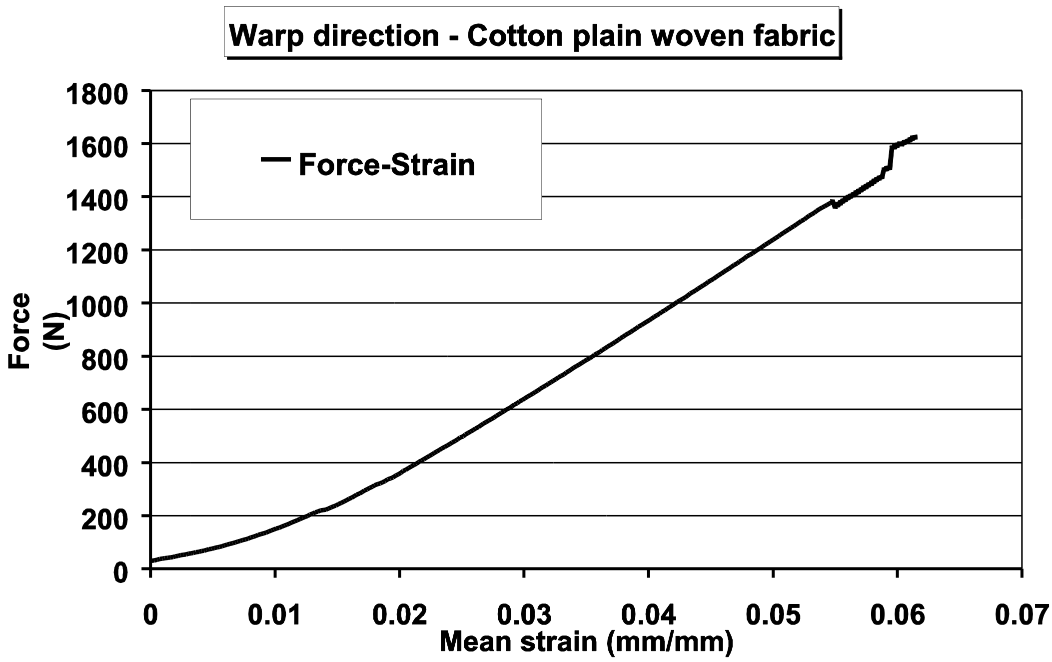
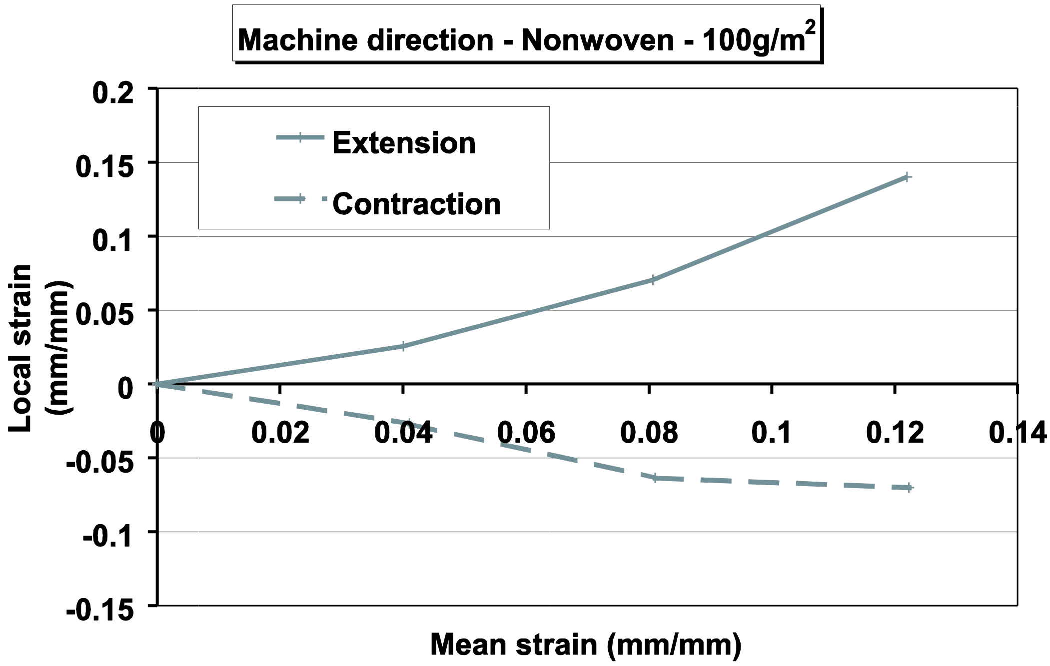


Figure 7:

Figure 7a:



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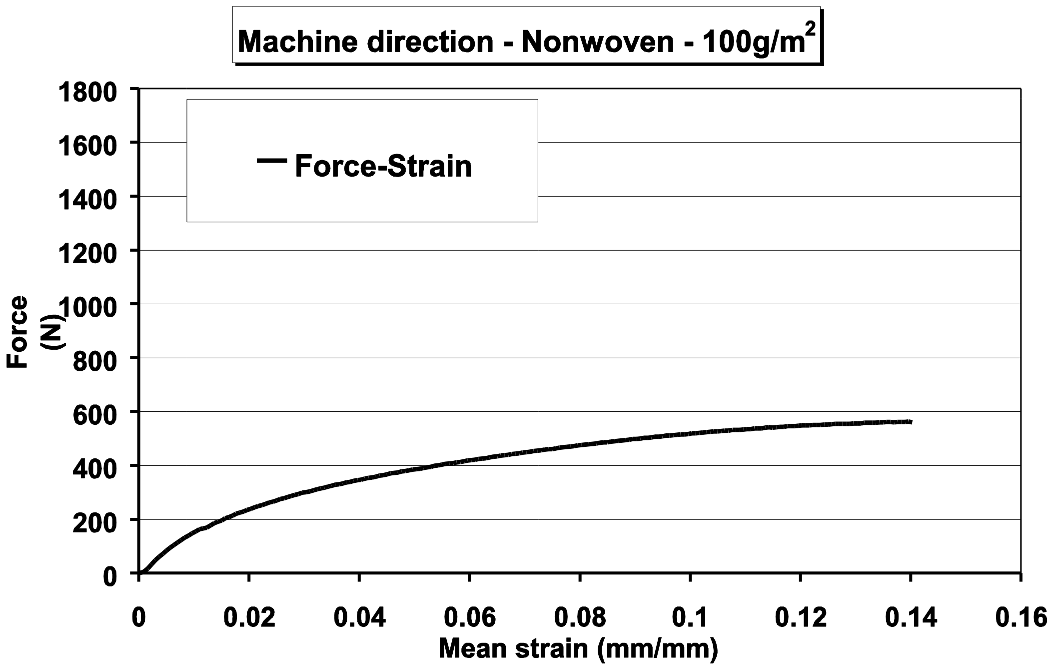

Figure 8:

Figure 8a:

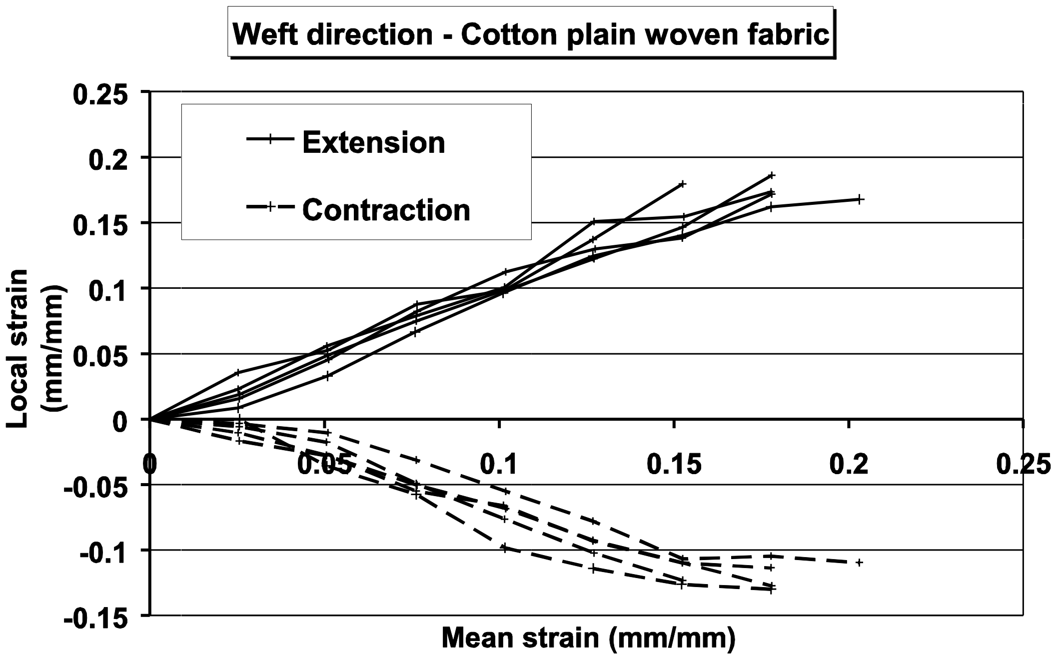

Figure 8b:

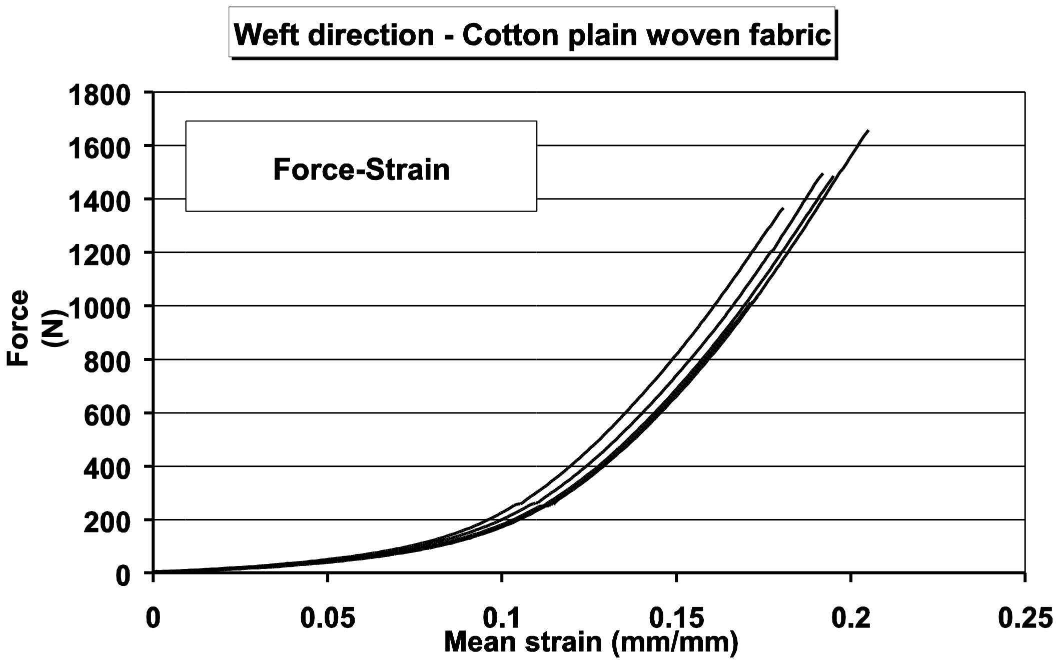

Figure 9:

Figure 9a:

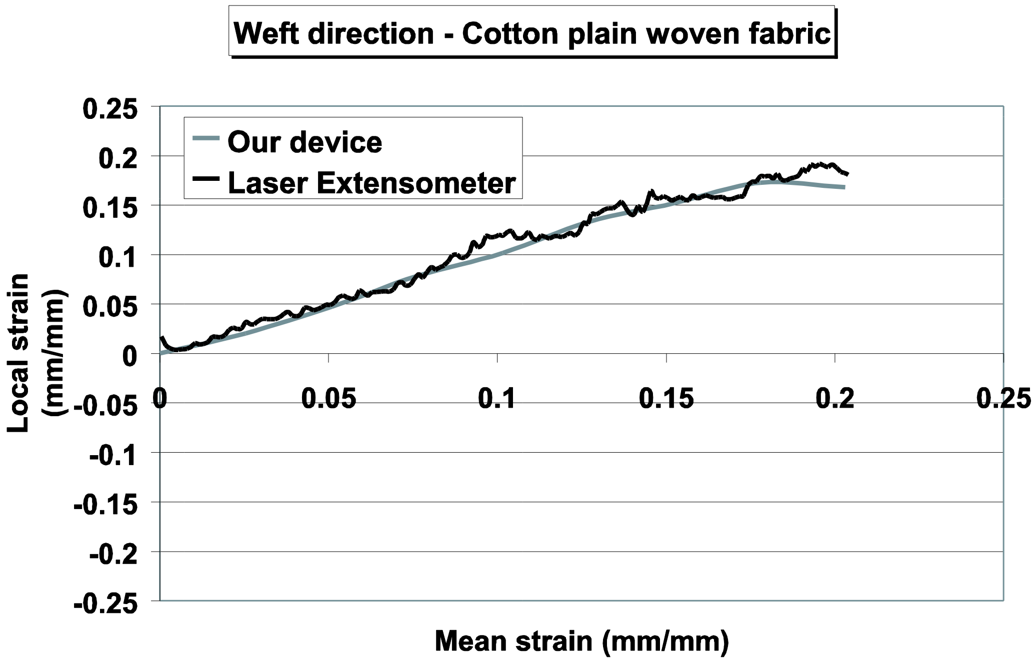

Figure 9b: