NOVEL TESTING METHODS FOR THE EXAMINATION OF THE MECHANICAL PROPERTIES OF TEXTILES AND FLEXIBLE COMPOSITE SHEETS

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Abstract: In this paper, we present novel testing methods for examining the mechanical properties of textiles and flexible composite sheets based on the former related work of the research group. The novelty of the presented testing methods is that we examine mechanical properties with our custom designed and made testing equipment. In the case of apparatuses to perform draping and bending tests, we scan the 3D surface of samples, apply digital image processing, and calculate mechanical properties based on mechanical material models. The apparatus to perform shearing and yarn pull-out tests is a kind of gripper, which can be mounted on a universal load machine that provides force and deformation for the measurement. This paper presents our apparatuses for draping, bending, shearing, and yarn pull-out tests and methods for determining mechanical properties.

Keywords: textile testing, flexible composite sheet testing, mechanical properties, image processing, material models

Introduction

Our team's research area includes examining the mechanical properties of textiles and textile-reinforced flexible composite sheets, also called membranes. We have developed novel methods for testing mechanical properties for over 15 years.

Textiles and membranes undergo far greater deformation due to bending and shear loads than other solid structural materials, making it more difficult to examine their mechanical properties (Boos, 1994; Gyimesi, 1968; Kawabata, 1980). They bend considerably under their own weight, suffer considerable shearing deformation, and do not keep their shape. As a result of their fibrous structure, they are inhomogeneous and anisotropic. Therefore, their properties cannot be examined with the same methods as homogeneous structural materials, such as metals and ceramics. The mechanical properties are essential to simulate the mechanical behavior (Geršak, 2013; Kuzmina, 2005; Tamás, 2008; Vas, 2013; Vas, 2014).

Recently, we have witnessed an intensive modernization of testing methods, primarily due to the dynamic development of digital technology and to processing of huge amounts of data faster and faster. We have also used these possibilities to develop our novel testing methods.

In the paper, we want to present our equipment and methods to perform draping, bending, shear, and yarn pull-out tests and methods for determining mechanical properties.

Drape test

Our research team worked on a clothes design computer program from the beginning of the nineteen nineties (Geršak, 2013; Halász, 1999; Tamás, 2005; Tamás, 2008). The program includes the lifelike rendering of 3D model designs, which requires the simulation of how the textile of the garment behaves when it is worn, especially how it drapes and hangs under its own weight. The simulation requires the parameters of the applied material model. Measuring each parameter separately with separate devices is very labor-intensive (Boos, 1994; Gyimesi, 1968; Kawabata, 1980), and the need for a simpler, faster, and more direct testing method has arisen.

3D clothes design requires the exact shape and dimensions of the human body as well, therefore we also worked on developing a laser body scanner at the same time (Geršak, 2013; Szabó, 2008A; Tamás, 2003; Tamás, 2007; Tamás, 2008).

The mechanical properties of fabrics are complexly characterized by their draping behavior (Al-Gaadi, 2012; Al-Gaadi, 2013B; Cusick, 1965; Geršak, 2013; Kokas-Palicska, 2008; Militki, 2003; Moroka, 1976; Szabó, 2008B). Draping has been investigated for a long time, and attempts have been made to relate it to the various mechanical properties of textiles, but the result that can be used in the simulation is not known.

The work on the body scanner gave us a new idea for a novel drape test, with it possible to determine the parameters for the draping simulation in addition to the usual draping characteristics.

The generally used method for testing the draping of textiles, also used in the most common Cusick draping measuring device, is as follows (Cusick, 1965; Gyimesi, 1968). A 300 mm diameter circular sample is placed on a 180 mm diameter circular sample holder table top. The ring-shaped edge of the fabric that extends beyond the tabletop – hereafter referred to as the textile ring – bends down and drapes under its own weight. During the measurement, the projection of the draped textile ring on a horizontal plane must be determined. The draping ability of the textile is characterized by the draping coefficient (*DC [%]*) according to Equation 1, which is the ratio of the area of the planar projection of the draped textile ring to the area of the flat textile ring (Fig. 1).

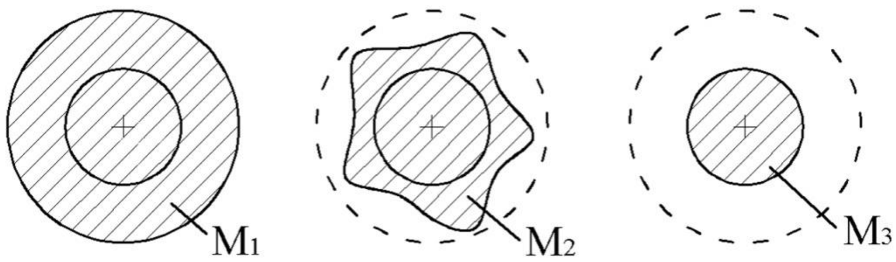


Figure 1 The sample holding table (M_3)**,** the flat textile ring (M_1), and the planar projection of the draped textile ring (M_2)

$$DC = \frac{M_2 - M_3}{M_1 - M_3} * 100 \ [\%], \tag{1}$$

where M_1 $[m^2]$ is the area of the flat textile ring, M_2 $[m^2]$ is the area of the planar projection of the draped textile ring, and M_3 $[m^2]$ is the area of the sample holding table.

Our novel idea for a drape test to determine the material parameters is the following (Geršak, 2013; Tamás, 2006; Tamás, 2008):

Since the surface of the draping textile is a 3D surface, similar to the human body, it is scanned like the human body, and its 3D virtual model is created. At the same time, the simulation of the drape test is made. Instead of measuring the necessary material parameters one by one, we use a numerical, iteration mathematical method to determine the real simulation data. The parameters of the simulated textile are modified and tuned until the simulated surface is as close to the scanned surface as possible. This way, the real material parameters necessary for the simulation of the textile are obtained.

Figure 2 shows our computer-controlled drape tester built similarly to our body scanner (Geršak, 2013; Tamás, 2006; Tamás, 2008).

The circular table of the tester is initially lowered into the platen, and they are in the same plane. The center of the tested circular piece of textile is fastened to the center of the table with a pin. A computer-controlled motor raises the table so that the draping in the textile always forms at the same rate in the same dynamic conditions. During testing, the four line lasers on the frame project a horizontal line on the textile. This laser line is recorded by four cameras located on the frame above the line lasers. The photos are uploaded to the computer after each shot. The height of the frame is changed with preprogrammed steps; hence, the draping textile is scanned. The equipment is built into a black case, which ensures a black measuring space and good contrast during operation.

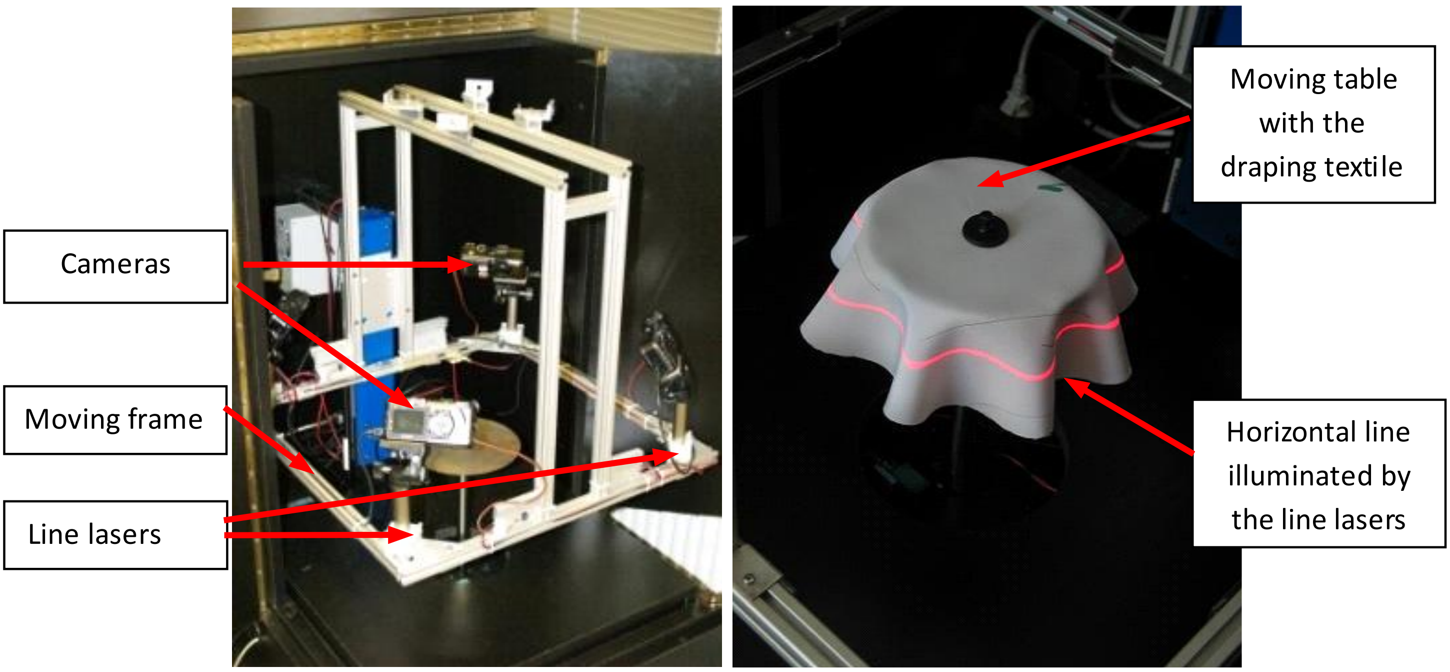
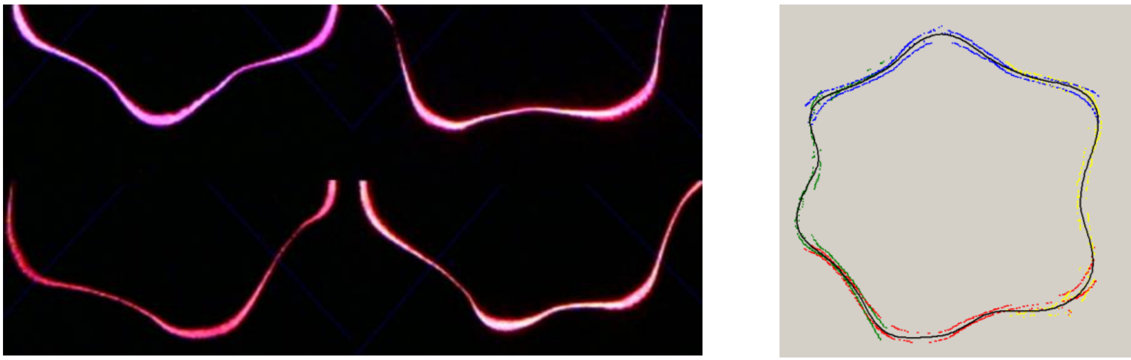


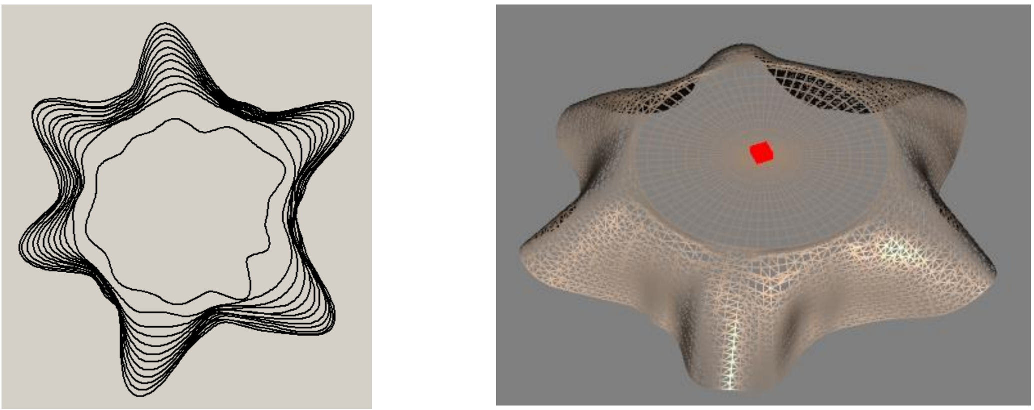
Figure 2 The 3D Drape Tester

Figure 3 shows the four photos taken of the laser-illuminated cross-section and the cross-section of the textile reconstructed based on the photos. Figure 4 shows the geometry of the draping textile. On the left are the laser contour lines; on the right is the reconstructed surface.



a) b)

Figure 3 The four photos taken of the laser-illuminated cross-section (a) and the cross-section of the textile reconstructed based on the photos (b)



a) b)

Figure 4 The geometry of the draping textile with the laser contour lines (a) and the surface reconstructed based on the photos (b).

Several material models could be used for the simulation, but we found only one fast enough for real-time rendering (Geršak, 2013; Halász, 2008; Kuzmina, 2005; Tamás, 2008). It is based on a model of a network of mass points and combined coupling elements (springs and dashpots connected in parallel) connecting them, also known as the Kelvin-Voigt element (Fig. 5).

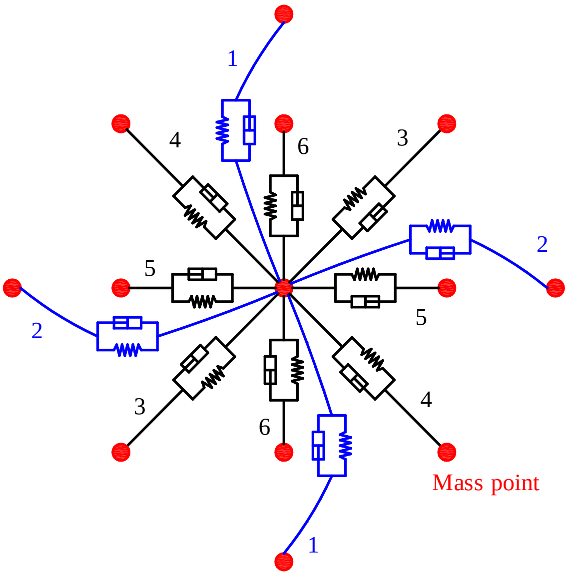


Figure 5 Coupling elements affecting one mass point

1, 2 bending elements 3, 4 shearing elements, 5, 6 structural elements

The mathematical model of a mechanical oscillating system can be described with the Lagrange equation (Eq. 2).

$$\underline{\underline{M}}_p \cdot \ddot{\underline{q}} + \underline{\underline{K}} \cdot \dot{\underline{q}} + \underline{\underline{S}} \cdot \underline{q} = \underline{F}(t) \tag{2}$$

where $\underline{q}$ is the vector of the coordinates, $\underline{F}(t)$ is the vector of the forces affecting the mass point as a function of time, $\underline{\underline{M}}_p$ is the matrix of the masses of the mass points, $\underline{\underline{K}}$ and $\underline{\underline{S}}$ are the matrices of the parameters of the dashpots and springs.

To obtain the material parameters, we must first calculate the G difference (Eq. 3) between the area of the surface reconstructed based on the measurement and the area of the simulated surface as a function of the P vector of the material parameters. The minimum of function G must be found because it will have a minimum at the parameter vector describing the real material.

$$G(\underline{P}) = minimum \tag{3}$$

The minimum can be found with iterative simulation. An expert system helps make the iteration faster. The database of the expert system stores the results of thousands of simulations. The system selects the simulation result closest to the textile based on the number of waves, the minimum, and the maximum radius. The parameters of this selected simulation are used as the initial parameters of the simulation.

The measuring equipment with the novel method made it possible to measure the parameters of textile draping more accurately than with traditional methods and to determine the parameters of the material model directly and fast (Al-Gaadi, 2009; Al-Gaadi, 2010; Al-Gaadi, 2012; Geršak, 2013; Tamás, 2008).

Bending test

Measuring the flexural strength of textiles and textile-reinforced composite sheets is difficult due to their little resistance to bending. It is also difficult to determine their cross-section because they are not continuous and homogeneous due to their fibrous structure. Therefore, the D flexural rigidity is used instead of the E $[N/m^2]$ flexural elasticity modulus. Their relationship is shown by Equation 4, where I $[m^4]$ means the second-order moment of the cross-section.

$$D = I \cdot E\ ,\ [N \cdot m^2] \tag{4}$$

There are two widely used methods to measure bending. In the first method, also used in the well-known KES system (Bilbao, 2008; Kawabata, 1980; Kocik, 2005), the necessary bending moment is measured as a function of bending deformation, that is, the curvature. In this case, flexural rigidity is the ratio of bending moment and curvature. Based on the bending moment over the width of the sample (M_f $[N \cdot m/m]$) and the curvature ($\rho[1/m]$), Equation 5 can directly yield the flexural rigidity of the sample, specific for the width of the sample:

$$D_f = M_f / \rho\ ,\ [N \cdot m^2/m] \tag{5}$$

The other method is Peirce's Cantilever test (Peirce, 1930). In this case, no force or moment is measured as a function of deformation, but also simple deformation caused by gravity is measured, and flexural rigidity is calculated from this with a mechanical model. This method is widespread due to its simplicity, speed, and sufficient accuracy.

The method we also worked out to measure bending does not require force measurement, but bending deformation and parameters are calculated based on a material model (Halász, 2012; Tatár, 2013). When working out the method, we used the idea applied in creating the simulation parameters of draping. Bending deformation is made in the flexible sheet-like material and scanned with the method used in the draping test. Since deformation is only limited to bending in this case, so it is possible to create an analytical model using the deformed shape. Then the computer can calculate flexural rigidity and modulus based on the mechanical model.

Based on these principles, we built our Bending Tester device (Fig. 6). The test strip sample is 100 mm wide and 500 mm long. It is laid on the table of the device. The clamps are pushed towards each other, which bends the material in a bell shape. Three line lasers project a laser line each on the material, and two cameras take a photo of the material. Figure 7 shows the device in operation.

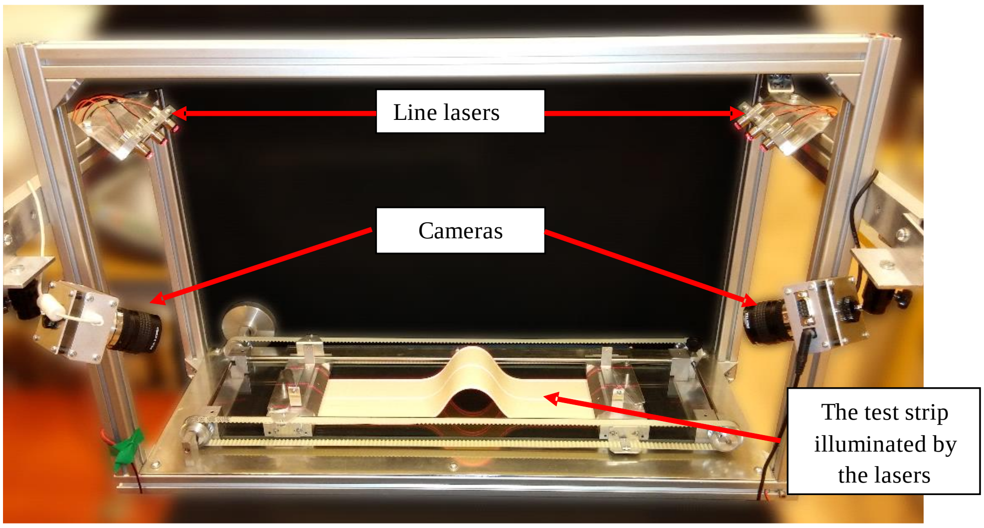


Figure 6 Bending Tester

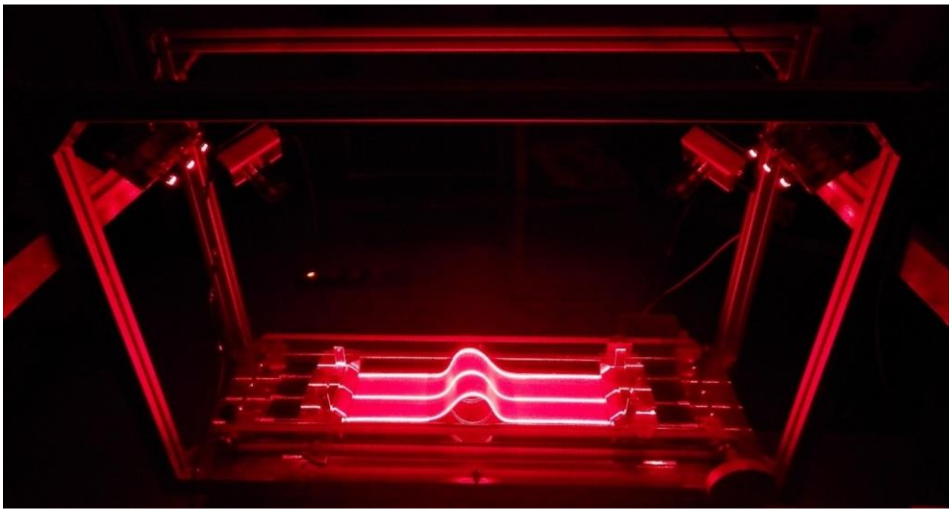


Figure 7 Bending Tester in operation

The images are transferred to the computer, and image processing software determines the coordinates of the curved shape of the test strip. Based on these coordinates, the *y(x)* function must be defined, well-approximating the curved shape. Our experience shows that an eighth-order polynomial is suitable for this purpose. If the function is known, the mechanical model necessary for calculating bending properties can be made. The deformed test strip is in equilibrium; therefore, the equilibrium equations of statics apply (Fig. 8).

If we use the notations in Figure 8, for an arbitrary fixed point *P* of the test strip, the M_h bending moment of forces left of point *P* can be calculated with Equation 6:

$$M_h(x) = N_x \cdot y(x) - \frac{G}{2} \cdot x + Q(x) \cdot S(x) \tag{6}$$

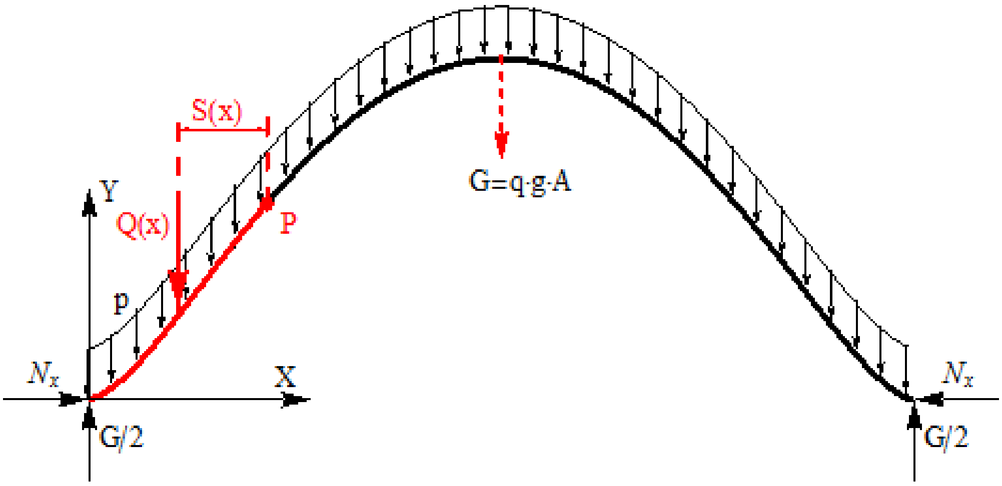


Figure 8 Forces affecting the strip bent to a bell shape

where: *P* is an arbitrary fixed point on the test strip with the coordinates *x* and *y(x)*; N_x *[N]* is the horizontal force affecting the sample; *G [N]* is the weight of the sample; *S(x) [m]* is the distance of the center of mass of the red curve section from point *P*; *Q(x) [N]* is the weight of the red section of the curve; *q* $[kg/m^2]$ is the surface density of the sample; *g* $[m/s^2]$ is gravitational acceleration; *A* $[m^2]$ is the area of the whole sample; *p [N/m]* is the weight of a unit length of the sample.

The classic differential equation of elastic chords shows the relationship between deformation and moment. We need the equation form that can also describe great deflections (Eq. 7).

$$y''(x) = -\frac{M_h(x) \cdot (1 + y'^2)^{\frac{3}{2}}}{\mathrm{D}} \tag{7}$$

where: $D[Nm^2] = I_z \cdot E$ is flexural rigidity; $I_z[m^4] = \frac{b \cdot h^3}{12}$ is the second-order moment of the cross-section; *b [m]* is the width of the test strip; *h [m]* is the thickness of the test strip; *E [Pa]* is the elasticity modulus.

Substituting Equation 6 into Equation 7 and rearranging it, we get a complicated two-variable integral differential equation. The two unknowns are the horizontal force N_x and the flexural rigidity *D*.

The equation cannot be solved in a closed form, but if the function *y(x)* describing the shape of the test strip is known, and the equation is written for two different P points, we get two equations with which the two unknown parameters can be determined. The two-variable system of equations can be solved numerically with suitable mathematical software, and flexural rigidity *D* and bending elasticity modulus *E* can be obtained.

Shearing and yarn pull-out test

In addition to bending resistance, the ability of textile sheets to take up the shape of a 3D object is primarily defined by their resistance to shearing. Therefore, it is very important to know this property (Al-Gaadi, 2013A; Al-Gaadi, 2013B; Karádi, 2021; Mohammed, 2000; Potluri, 2006; Prodromou, 1997; Rothe, 2019). The shear deformation of the flexible sheet-like materials is always measured in the plane of the sheet.

The most widespread method to measure shear is the principle also used in the KES equipment (Fig. 9) (Kawabata, 1980).

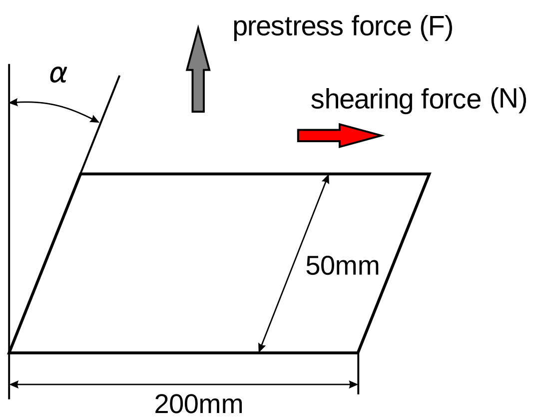
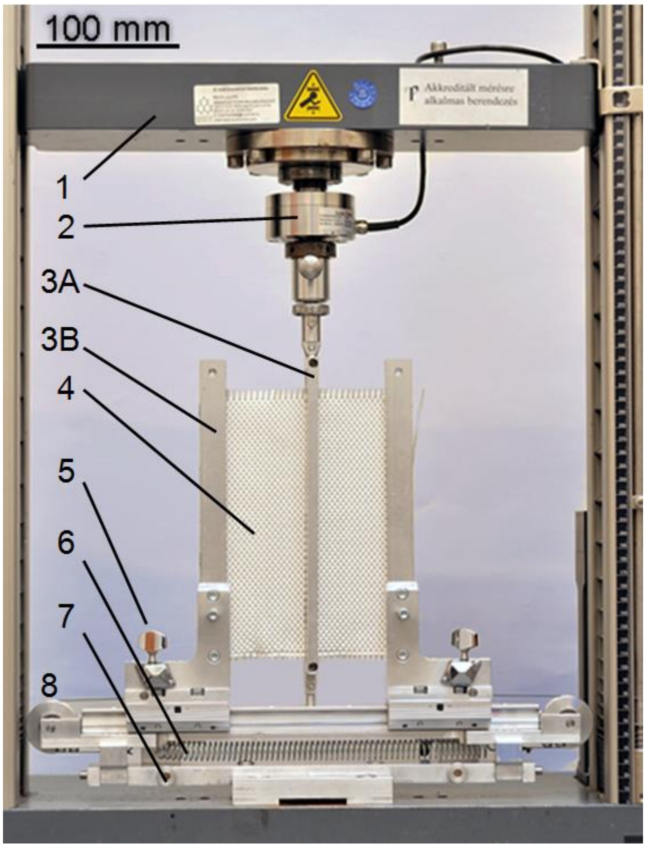


Figure 9 The principle of the KES shear tester

The two long sides of the sample are moved parallel to each other and in the opposite direction, while the force necessary to do this is measured as a function of displacement. A constant pretension perpendicular to the shear force direction is provided by a torque-controlled roller during the test. Based on the width of the sample and the displacement, the shearing angle α as the shear deformation can be calculated.

We used this principle, too, when designing our shear tester. Our device is essentially a special clamp that can be connected to a universal load machine, and this way, the force can be measured in a wide range, and test speed can also be varied in a wide range (Molnár, 2020).

The photo in Figure 10 shows the clamping device.



1. moving crosshead of the universal load machine
2. load cell
3. clamps:

3A: central clamp connected to the load cell

3B: side clamps

4. sample
5. lever to adjust the prestress force
6. steel prestress spring
7. fastening bolts
8. rollers with bearings

Figure 10 Clamping device with a central clamp for shear tests

The side clamps fixing the sample can move sideways and are connected to the tensile tester with rails. Since they can move sideways, clamping width can be varied in a wide range, and a constant prestress force can be applied to the sample. The prestress force is provided by a helical steel spring under the rails. The force of the spring is transferred to the clamps by a thin steel cable. The prestress force can be set with levers.

The sample first has to be clamped with the side clamps. While the sample is being clamped, the side clamps can be fastened so that they cannot move sideways, and the whole device can be turned into a horizontal position for easier access.

After the sample is clamped with the side clamps and positioned exactly to the center, the central clamp can be attached. It is connected to the load cell on the moving crosshead of the tensile tester. During testing, the central clamp pulls the center of the sample upwards at the preset constant speed and thus produces shear in both sides of the sample.

Figure 11 shows the principle of measuring shear. The left side shows the sample in the unloaded state, while the right shows it under shear load. Since the rails allow a sideways motion of the side clamps, they can follow the deformation of the sample the way the length of the initially horizontal yarns remains the same throughout the test. So, the side clamps move nearer to each other as shear increases while keeping the preset preload force.

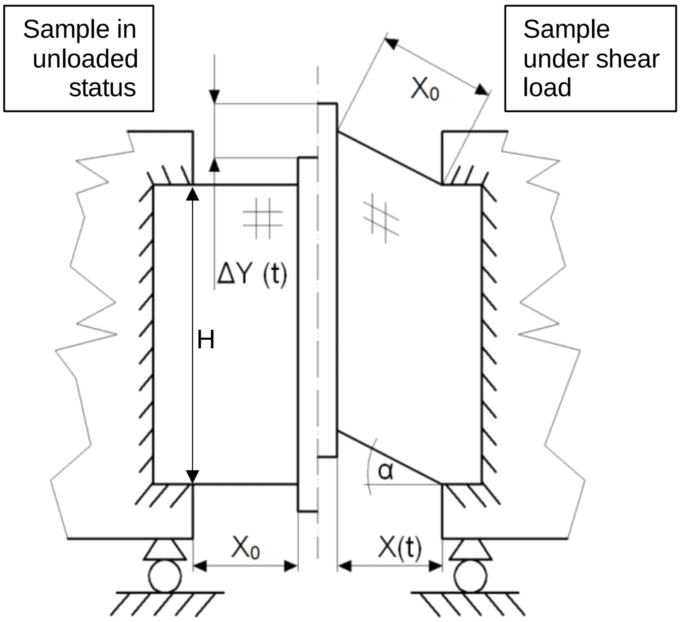


Figure 11 The principle of measuring shear

The shear angle α can be calculated from the displacement ΔY of the central clamp with Equation 8:

$$\alpha = arc\ sin\ (\Delta Y/X_0)\cdot 180/\pi, \quad [°] \tag{8}$$

As opposed to the KES equipment, however, the directions of the shear test cannot be separated here since the testing of the samples right of the central clamp and left of the central clamp is done simultaneously, with opposite shearing directions. So, the shear force for one side is half of the measured force F. The specific shear force N_f is the shear force divided by the sample length H (Eq. 9).

$$N_f = F/(2H), \quad [N/m] \tag{9}$$

The specific shear force – shear angle diagram can be produced from the results in the usual way. Figure 12 is a typical diagram of a cycle shear test.

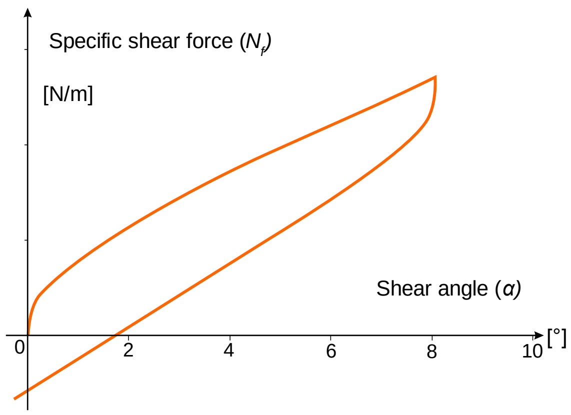


Figure 12 Typical diagram of a cycle shear test

The device can also perform yarn pull-out tests (Molnár, 2020). The yarn pull-out test can measure the interaction of yarns in the woven textiles, the force necessary to pull out a yarn against friction between the yarn and the yarn across it. Friction between the yarns plays an important role in determining the material's properties; therefore, it is essential for modeling the mechanical behavior of the woven textile (Al-Gaadi, 2013A; Al-Gaadi, 2013B; Bilisik, 2011; Dong, 2009; Pan, 1993; Virág, 2019).

In the yarn pull-out test, the textile is clamped on two sides, and a central yarn parallel to the clamped sides is pulled out from the top. It is important that the other side of the pulled-out yarn must be free (Fig. 13). For the yarn pull-out test, the central clamp of the shear tester apparatus has to be replaced with a conventional yarn clamp. Clamping the sample is the same as in the shear test, but instead of using the central clamp, one must clamp the end of the yarn that will be pulled out.

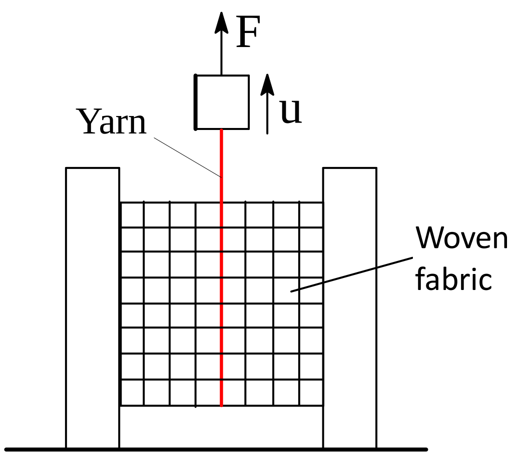


Figure 13 Method of yarn pull-out test

Figure 14 shows the device during the pull-out test.

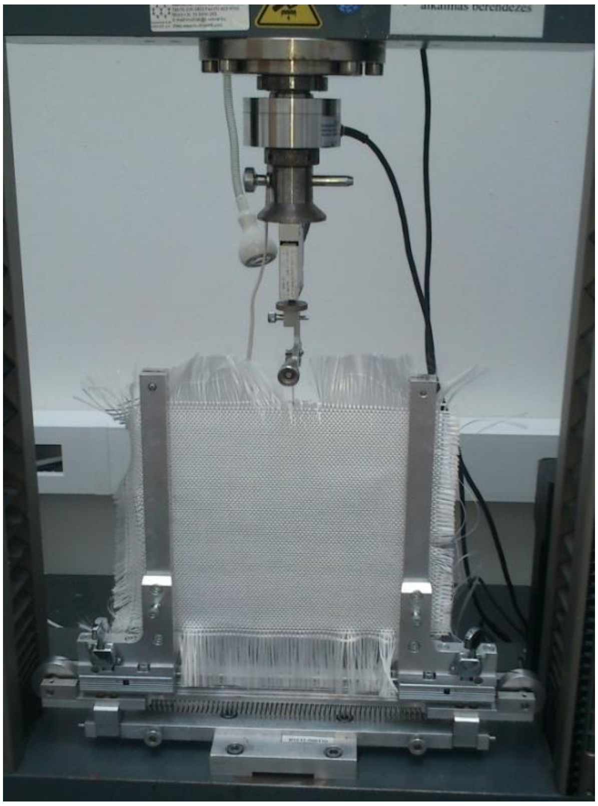


Figure 14 The clamping device with a central yarn clamp for yarn pull-out tests

This test also has the advantage that cross-directional preload, clamping length and width, and pull-out speed can be varied in a range.

Figure 15 is a typical diagram of a yarn pull-out test.

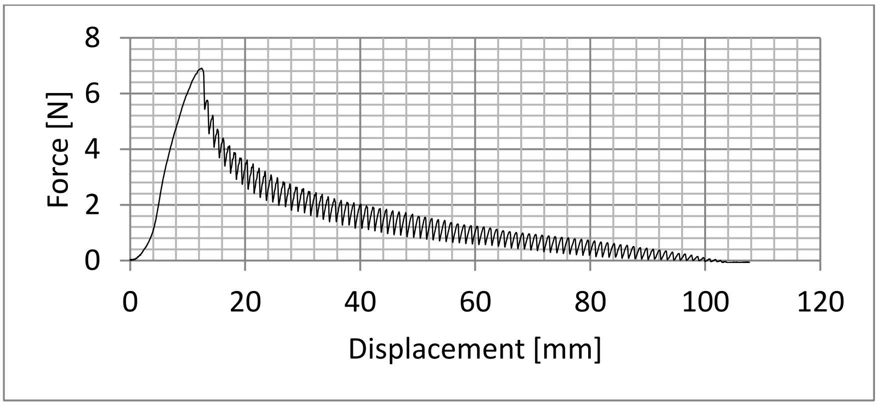


Figure 15 Typical diagram of a yarn pull-out test

Conclusion

Our research team developed novel testing equipment and measuring techniques using digital image recording and processing, modeling, and high-speed data processing. We have presented our devices used for draping, bending, shear, and yarn pull-out tests of these novel tools.

The devices for drape tests and bending tests both scan the 3D shape of the specimen that takes its shape due to gravity. Then the required material parameters are calculated with these shapes with special material models. The advantage of these devices is that since force does not have to be measured, there is no need for expensive equipment that measures force.

The device for shear and yarn pull-out tests has to be attached to existing universal testers. It is a special complex clamping device, and to the measuring with this, the universal load machine provides the deformation and the measuring of force.

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