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# ANALYSIS OF 3D DEFORMATION PROPERTIES OF WOVEN COMPOSITE REINFORCING STRUCTURES

***THESES***

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The review of this PhD dissertation and the protocols of the defense
can be found at the Dean's Office, Faculty of Mechanical Engineering,
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# 1. Introduction, Research Background

Fabrics are applied widely as reinforcing materials of polymer composites besides the conventional textile industrial application fields due to their excellent load bearing and deformation capability. Fabrics can deform significantly even if only small stress is applied, and therefore can show significant deformation already due to their own weight. This unique behavior is utilized in fields where fabrics are shaped to 3D forms or are put on 3D bodies. Formerly, conventional apparel industrial and home textiles were prepared from fabrics, however nowadays they have gained ground also as reinforcing materials of thermoplastic and thermosetting matrix composites. Mainly woven fabrics, i.e. weaves are widespread as the reinforcing materials of composites. One of the reasons for this usage is that fiber orientation is known in this case, therefore the deformation of products made of weaves can be planned more easily than in case of other textile structures.

In the last decades the investigation of the deformation capability of fabrics has been brought into focus again related to their application as reinforcing materials in composites. The first weave reinforced automotive industrial composite products, i.e. parts of an airplane were manufactured in the ‘50s. After weave reinforced composite materials were recognized to have high flexibility, strength and toughness besides their low specific weight, they began to spread widely. At first the reinforcing materials were mainly made of glass fibers, and later carbon, aramid, basalt and natural fibers also appeared. The need for preparing more and more complex geometry pieces also arose as composites were already used as structural materials. Simultaneously, designing the load bearing capacity of reinforcing materials was also highlighted, however the versatility of woven structures made it quite difficult. The aim of this type of research is to get to know the deformation of fabrics that take place during processing, and to estimate whether they can fit adequately to the desired form. Adequate fitting is not only important from aesthetic point of view, but it has also significance regarding the mechanical properties of the end product. The Kawabata fabric analysis system (KES-FB) has been applied since the ‘70s for the examination of mechanical properties, originally for the objective determination of fabric draping, however its measurement limits are restricted to the data of conventional textiles. Therefore reinforcing fabrics that have completely different properties than conventional textiles usually cannot be examined with the KES-FB device. Several methods – usually based on image processing – were developed for the investigation of deformation properties of reinforcing fabrics.

Image processing makes it possible to determine other deformations of the fabric structures besides elongation. Out of the deformation properties measured using image processing one of the most characteristic fabric deformations is shear angle that evolves due to shear stress. Another especially characteristic form of fabric deformation that is also studied by image processing is draping, a material property that characterizes the spatial behavior of fabrics globally, and can be measured in a simple way.

The description of spatial deformation of woven structures is a very complex problem. Although several research attempts were made to reveal the deformation mechanism of fabrics, a model that approximates the real behavior well is still not available. With the spreading of CAD systems the behavior of fabrics should be described and modeled regarding the requirements of design, therefore the research into the behavior of fabrics is still a current issue.

## 2. Critical analysis of literature, aims

Based on the analysis of literature in this field, the special investigation methods of fabrics can be classified into two groups based on the complexity of the stress: methods using uniaxial and multiaxial stresses.

Uniaxial stress investigations are tensile, compression, shear and flexural tests carried out on conventional equipment, as well as shear and shear angle determination investigations (bias extension, frame tests) using image processing methods.

Investigations applying multiaxial stress are biaxial tensile, special shear, ball impact tests, where deformation is induced by active external forces, and drape measurements where deformation takes place only due to gravity.

Deformation of woven structures is influenced by several mechanical properties that depend on different geometrical, structural characteristics, such as base material, area density, binding structure etc. Besides the structural properties that influence the spatial deformation of the fabric, yarn structure, and within that twist direction of yarns was not studied widely. However, yarn twist direction can play a significant role in the formation of the mechanical properties, therefore in the spatial deformation of fabrics.

Spatial deformation of fabrics is most widely described by draping. However, draping was often measured in a modified way in case of textile material investigation, for example the sample was rotated in order to approximate the scenarios that take place in reality. Image processing applied in the evaluation of the examinations made it possible to carry out unconventional measurements. More studies refer to the fact that drape coefficient can depend on the circumstances of drape formation, although only gravity affects the examined fabric during the measurement. Therefore the consequence that fabric draping can change in a wide range depending on the circumstances of the measurements and external effects even in case of one single material can be drawn.

Several studies dealt with the description of draping with mechanical properties the main aim of which was to determine the properties that influence the spatial deformation of fabrics to the greatest extent. Measurements necessary for this purpose were carried out mostly with the KES-FB equipment. These investigations revealed unambiguously that draping is in an especially strong relation with the shear and flexural properties of the fabric. Reinforcing fabrics usually have larger stiffness and looser structure compared to conventional fabrics, and their deformation is usually small in case of drape measurements that is therefore difficult to measure. However, the determination of drape properties is also essential in case of reinforcing fabrics, since it provides important information regarding the spatial deformability that is crucial from the point of view of shapability during processing.

According to the studies deformation in reinforcing fabrics during composite processing is mostly influenced by shear properties and the strongly related friction among yarns. Determination of the friction coefficient among yarns of a fabric is a really complex task, and that is why there are only a few special methods and equipment mentioned in the literature. Shear properties are characterized with the shear angle among yarns as well as the shear force. More devices and methods were developed for the examination of shear deformation in case of which the determination of the deformation to be measured is carried out with image processing. One of the simplest and most frequently used measurement methods is bias extension in case of which more solutions are already worked out for the evaluation of shear angle. Further shear investigation methods are the frame investigation, and the solution applied in the KES-FB equipment. It was also concluded that shear strength values obtained from bias extension coincide well with the values measured on the KES-FB equipment. The advantage of bias extension method compared to the one with a frame is its simplicity and that the yarn ends remain in the pure shear zone and therefore the process is closer to the real one. Although deformation process during frame investigation is closer to the one that takes place when composite parts are formed than in case of bias extension, the latter provides faster and more reliable results. The methods revealed that there is no uniform, widely available shear test method for reinforcing fabrics that can be applied for all kinds of textile materials.

Several other investigation methods were developed for the examination of deformation behavior during processing such as biaxial tensile and ball impact tests, usually amended with optical examinations. However, these measurement methods can be reproduced only in a difficult way, and only parts of the total deformation are characterized during evaluation. In these literatures shear stiffness was considered to be the most influential regarding deformation. Their results were usually used in finite element modeling in order to pre-estimate the shape of the product to be formed.

Based on the review of the literature in this field, the aim of my dissertation in general is to analyze the spatial deformation of woven reinforcing structures with easy to measure elementary mechanical properties and to reveal relations based on the results with the help of which the spatial shapability of the reinforcing structure with given properties can be determined and relations that can contribute to the preparation of a model that approximates the real behavior of fabrics in a better way.

In order to realize this general goal, the following detailed research aims were set:

1. Investigation of deformation behavior of fabrics using image processing examination methods.
2. Analysis of the impact of fabric structure, i.e. yarn twist direction on draping.
3. Improvement of drape tests carried out with the Sylvie 3D Drape Tester in order to examine the dependence of drape coefficient on effects that influence draping and to reveal the reasons for that.
4. Development of a shear property determination method for reinforcing fabrics using image processing.
5. Improvement of the method for the determination of yarn-yarn friction coefficient in fabrics.
6. Analysis of the relation between fabric deformation – draping and shear angle – and yarn-yarn friction coefficient.

# 3. Examined materials, equipment and methods used

Examined materials and methods used in my research work important from the point of view of the theses are detailed below. The KES-FB measurements were carried out in the Apparel Industrial Engineering Laboratory at Maribor University, while the flexural tests in the Textile Testing Laboratory of Óbuda University, and all other measurements were executed in the laboratory at the Department of Polymer Engineering, BME.

## 3.1. Examined materials

In my research work I have examined glass, carbon, aramid, cotton and polyester (PES) base material fabrics. The fabrics were classified into two groups based on their significantly different mechanical properties, and the materials of the groups were examined mainly using different methods, and were also evaluated as two, separate groups.

The basic structural properties of materials were determined based on the relevant standards, and their data are listed in Tables Table 1 and Table 2 .

| Notation | Material | Weave type | Area density [g/m$^2$] | Linear density [tex] | | Yarn density [1/10 mm] | |
|---|---|---|---|---|---|---|---|
| | | | | Warp | Weft | Warp | Weft |
| **G163** | glass | 2/2 twill | 163 | 70 | 70 | 12 | 12 |
| **G220** | glass | plain | 220 | 220 | 220 | 5 | 5 |
| **K170** | aramid | 2/2 twill | 170 | 130 | 130 | 6 | 6 |
| **C160** | carbon | plain | 160 | 200 | 200 | 4 | 4 |

*Table 1 Characteristics of examined reinforcing fabrics*

| Notation | Material | Weave type | Area density [g/m$^2$] | Linear density [tex] | | Yarn density [1/10 mm] | | Twist | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Warp | Weft | Warp | Weft | Warp | Weft |
| **P** | Cotton | plain | 156 | 29 | 29 | 26 | 22 | Z | Z |
| **K** | Cotton | plain | 156 | 29 | 29 | 26 | 22 | Z | S |
| **F** | Cotton | plain | 156 | 29 | 29 | 26 | 22 | Z | Z+S |
| **R** | Polyester | plain | 92 | 5 | 18 | 31 | 43 | - | - |

*Table 2 Characteristics of examined conventional fabrics*

The glass fabrics were produced by PD Interglas and Saint Gobain Vetrotex, while carbon and aramid fabrics were prepared by company Sigratex. These reinforcing fabrics are applied in elements of different composite parts, such as vehicles, sports equipment.

The yarns of the three samples made of 100% cotton have different twist directions so that the impact of twist direction on the mechanical properties of the fabric can be studied. All other structural characteristics of these three samples are the same, however, due to the different yarn twist directions the thickness of fabrics also differs. These special cotton fabrics were produced by Csárda-Tex Kft. in Hungary, while the polyester fabric woven from untwisted multifilament yarns in plain weave was prepared by Lurotex Kft. These fabrics can be used mainly for conventional textile industrial purposes, but may also appear as reinforcements. Cotton fabric is present in the developing field of biologically degradable composites, while PES fabric coated with PVC is generally used in canvas production.

The warp yarns of all the three cotton fabrics have twist direction Z, and the difference lies in the twist direction of weft yarns. Material P contains Z twist direction yarns also in the weft direction; while material K has S and material F alternately Z and S weft yarn twist direction. Polyester material R has untwisted warp and weft yarns.

## 3.2. Investigation methods

### *3.2.1. Determination of friction coefficient among yarns*

The friction coefficient among the yarns of the reinforcing fabrics was determined with the help of yarn pull-out measurements. During yarn pull-out measurements a yarn that is not clamped from the bottom is pulled out upwards from the fabric sample clamped from the bottom and the two sides, while the force needed for yarn pull-out is measured as a function of yarn displacement. Since the warp and weft yarns of the fabric cross each other and this way have a curved shape, using this curve and the forces obtained from the yarn pull-out measurements and based on formula Euler used for the calculation of rope friction formula (1) can be used for the determination of friction coefficient among yarns in the fabric:

$$\mu = \frac{\ln(K_i / K_k)}{\alpha \cdot 2 \cdot (k - i)} \tag{1}$$

where $K_i$ and $K_k$, are the yarn pull-out forces that belong to the $i^{th}$ and $k^{th}$ peak of the force - yarn displacement curve registered during the yarn pull-out examination and for which $K_i > K_k$ is valid, while $(k - i) \geq 1$ is the difference of the number of the two selected peaks (Figure 1), and $\alpha$ is the central angle of the contact arc of the yarn to be pulled out and the yarn that crosses it measured in radian determined from an image taken of the cross section of the fabric with an electron microscope.

The adequate clamping of the examined sample was ensured and the splitting of yarns was prevented by the laminated parts created on the sample (Figure 2).

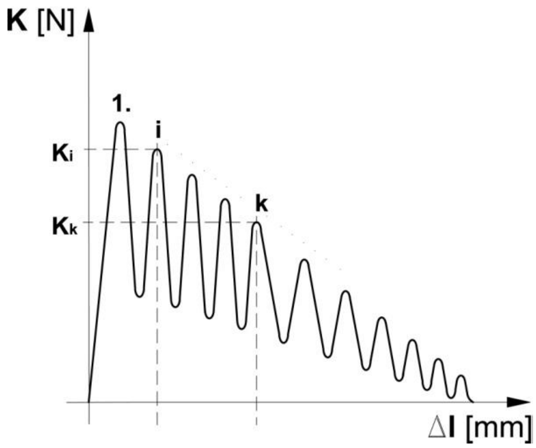


*Figure 1 Theoretical force - yarn displacement curve of yarn pull-out tests*

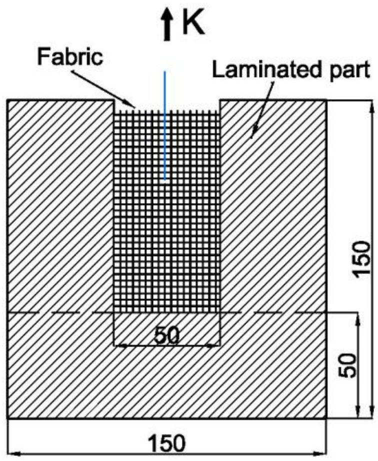


*Figure 2 Sketch of the specimen prepared for a yarn pull-out test*

Yarn pull-out is carried out on a Zwick Z005 universal, computer controlled tensile tester using a 20 N force measuring cell at ambient temperature. When clamping in the tensile tester the bottom part of the laminated sample was clamped with a general 60 mm wide jaw, the yarn to be pulled out was fixed with a yarn clamper from the top, while lateral clamping was automatically solved by the laminated edges of the sample. Before starting the measurement the lower end of the yarn to be pulled out from the fabric was cut after the number of crossing yarns that was to be examined.

### *3.2.2. Bias extension test*

During bias extension shear force (*N*) and shear deformation are the determined from the tensile tests of the sample cut from the fabric in a ±45° angle compared to the weft direction. Shear deformation is often characterized by the change in the angle of the fabric yarns ($2\Theta$), called shear angle ($\gamma$) (Figure 3).

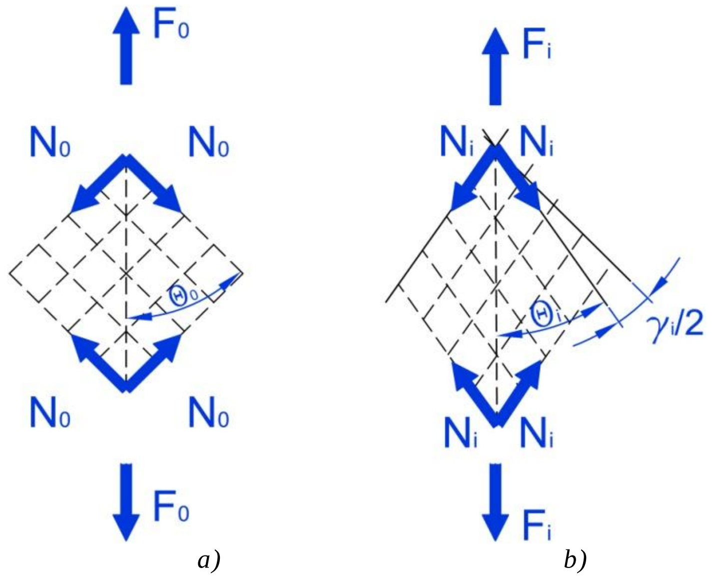


*Figure 3 Shear angle and shear force change due to loading*
*a) Angle of the warp and weft yarns of the fabric in an unloaded state*
*b) Shear angle and angle of the warp and weft yarns of the fabric in a loaded state*

Bias extension tests were carried out on a universal, computer controlled tensile tester, type Zwick Z005 equipped with a 5 kN force measuring cell. During the examination tensile force is recorded as a function of the crosshead displacement. The shear angle was determined as a function of crosshead displacement with methods based on geometry and image processing – already described in the literature -, and also with a new own developed method. A Messphysik ME-46 Full Image type video extensometer was used for the own developed, new method, while the camera that belongs to the video extensometer was applied for the image processing method.

A new method was developed for the evaluation of bias extension tests with the help of which shear angle can be determined in a simple and accurate way. An essential element of the new method is that not only the longitudinal elongation of the examined sample is used for the calculation of shear angle $\gamma$ but also the decrease of cross directional width. In order to determine the dimensional change in two directions longitudinal and crosswise lines were drawn on the middle of the sample, where pure shear deformation takes place, as shown in Figure 4 before the examination. Then during the examination, the length of segments denoted by *a* and *b* in the figure have to be recorded continuously by a video extensometer.

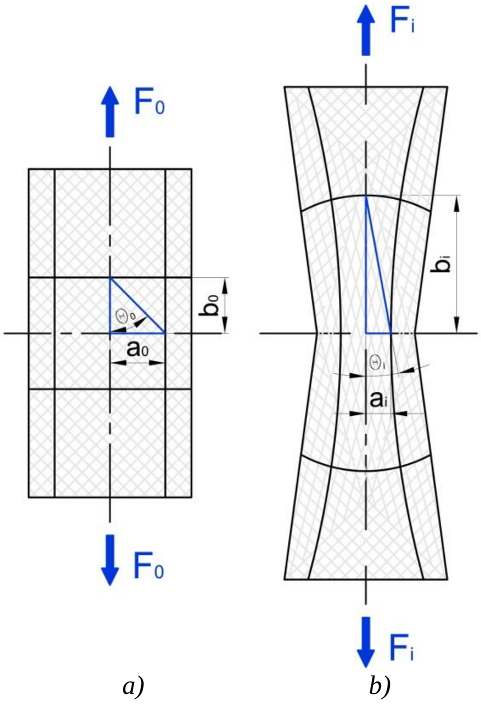


*Figure 4 Determination of shear angle γ using bias extension test and a video extensometer a) Marked sample in unloaded status b) Marked sample in loaded status*

### *3.2.3. Drape measurement*

Draping was measured with the Sylvie 3D Drape Tester that uses 3D optical reading, computer control and evaluation and was developed by the Department of Polymer Engineering in cooperation with the Department of Mechatronics, Optics and Engineering Informatics at the Budapest University of Technology and Economics. The geometrical dimensions of the equipment correspond to standard MSZ 93-4, and the evaluation software determines – among other data – the parameters according to this standard.

Different mechanical impacts can be exerted on the examined samples during drape formation, even if only gravity affects the examined sample during the measurement, and they modify the result of drape measurement. In order to be able to study this phenomenon in a reproducible way, the Sylvie 3D Drape Tester was amended with a new device with the help of which draping can be examined after well-defined, step-like deformation excitation. The supplementary device is a changeable sheet in a shape of a ring that was made in 3 different sizes, 210, 240 and 270 mm inner diameter. The conventional measurement carried out without a ring was executed with a ring of 300 mm inner diameter – that has no impact on the 300 mm diameter fabric sample – and this way was considered as one of the measurements (Figure 5).

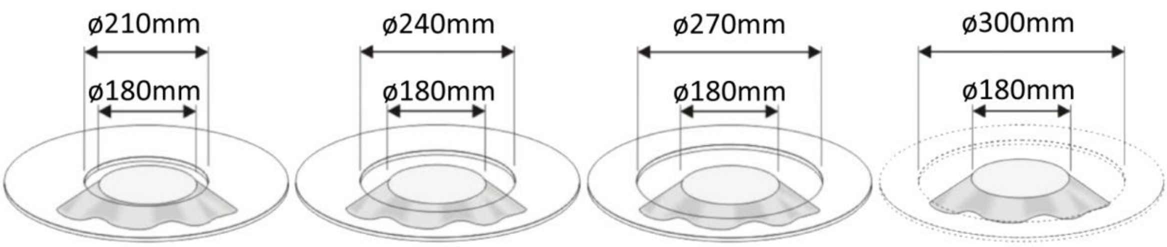


*Figure 5 Rings with different inner diameters*

The measurement equipment raises the sample through the ring as shown in Figure 6, before the optical scanning of the draped fabric shape and as a result, the draping of the sample changes. In my research work this change was studied as a function of different parameters.

Large deviations experienced during conventional drape measurements are usually accompanied by the unevenness of formed waves and asymmetric draping image that looks random (Figure 7). In order to be able to describe the geometrical asymmetry of the draping fabric and the unevenness of waves formed during draping numerically a new property was introduced that has not been used in this field yet. This new property is drape unevenness denoted by DU that is mathematically the relative deviation of the wave lengths of waves formed on the perimeter of the planar projection of the examined draping fabric (2).

$$DU = \frac{\sqrt{\frac{\sum_{i=1}^{n}(WL_i - \overline{WL})^2}{n-1}}}{\overline{WL}} [-] \quad (2)$$

where $WL_i$ is the central angle between two adjacent maximum amplitudes (i.e. the wave length of single waves, Figure 7), $\overline{WL}$ is the average central angle of one single wave (i.e. average wave length, $\overline{WL}$ = 360/n), and $n$ is the number of waves.

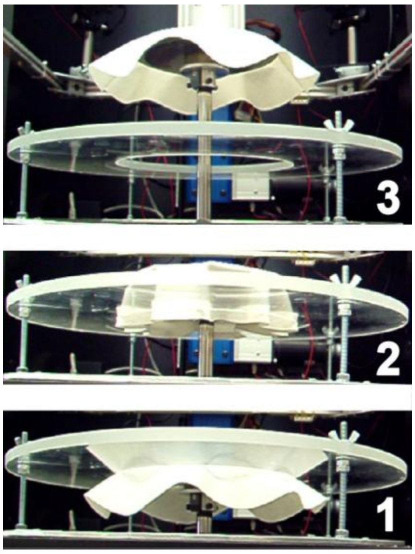


*Figure 6 Drape measurement amended with a ring*

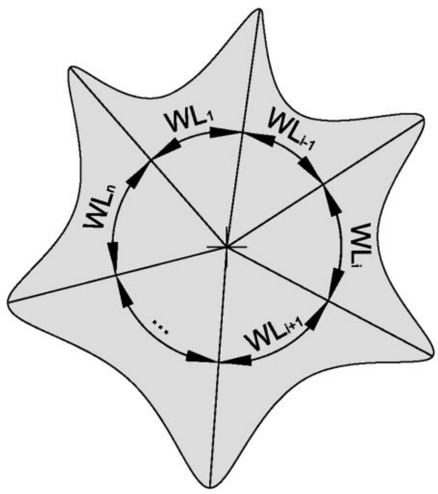


*Figure 7 Wave length of waves formed on the perimeter of the planar projection of the draped sample*

The smaller is the value of drape unevenness, the more even draping the examined fabric has. The calculation of drape unevenness was integrated into the evaluation software of the Sylvie 3D Drape Tester, and this way the program calculates drape unevenness automatically, besides drape coefficient, number of waves, minimum and maximum amplitudes and the deviation of amplitudes.

## 4. New scientific results – Theses

**<u>Thesis 1:</u>** I have worked out a new drape measurement method that influences drape formation of the examined fabric samples with different inner diameter, changeable rings and that approximates the real usage circumstances, while increases the extent of draping compared to measurements carried out without a ring, makes the image of draping more regular and decreases the deviation of drape coefficient. The essence of the new measurement method is that the equipment raises the fabric at constant speed through a ring, and this way influences the shape change of the fabric with a step-like deformation excitation before optical scanning, and this way reduces the randomness of the factors influencing drape formation. I proved with measurements that in case of drape tests influenced by a ring, based on image processing, the 156 g/m2 area density, plain woven cotton fabrics the warp and weft yarns as well as the warp and weft yarn densities of which are identical the deviation of the drape coefficient measured with the 210 mm inner diameter ring is in average 39% less than the drape coefficient measured without a ring. [1-4]

**<u>Thesis 2:</u>** I revealed with measurements that draping of cotton fabrics becomes more even as a consequence of step-like deformation excitation exerted with rings that have smaller and smaller inner diameter, this way drape unevenness decreases, and the drape image becomes more even. The dependence of drape unevenness on the ring diameter can be described with a linear trend approximated by formula (T1).

$$DU = aD + b \tag{T1}$$

where *DU* is drape unevenness [-], *D* is the inner diameter of the ring [m] and D≥210 mm. The value of parameters and the determination coefficient value of the approximating line in case of fabrics made of yarns with identical twist directions (Z-Z) is: a=0.0378; b=0.085; $R^2$=0.907; in case of fabrics made of opposite twist direction yarns (Z-S): a=0.0345; b=0.2064; $R^2$=0.9338 and in case of fabrics made of identical (Z) twist direction warp yarns and alternately changing twist direction weft yarns (Z/S): a=0.0183; b=0.1542; $R^2$=0.9308. [1-4]

**<u>Thesis 3:</u>** I proved with measurements that if the inner diameter of the ring that influences drape formation decreases, the drape coefficient also decreases. In case of cotton and polyester fabrics the change in the drape coefficient is described by logistic curve (T2) if 210 mm or larger inner diameter rings are used.

$$DC = \frac{1}{1+e^{aD-b}} - c \tag{T2}$$

where *DC* is the drape coefficient [%] and *D* is the inner diameter of the ring [m]. The value of parameters in case of cotton fabric made of yarns with identical twist directions (Z-Z) is: a=0.15; b=42.42; c=6.54, in case of cotton fabric made of opposite twist direction yarns (Z-S): a=0.12; b=33.21; c=6.25, in case of cotton fabric made of identical (Z) twist direction warp yarns and alternately changing twist direction weft yarns (Z/S): a=0.16; b=45.92; c=6.92 and in case of polyester fabric made of non twisted yarns: a=0.14; b=35.71; c=29.67. [1, 2, 4-6]

**THESIS 4:** I proved with measurements that the twist direction of yarns influences the drape coefficient. I revealed based on the examination of fabrics made of cotton raw material and woven from Z-Z, Z-S and Z-Z/S twist direction warp and weft yarns that the drape coefficient is in average 7% higher in case the twist direction of warp and weft yarns is the same than if the twist directions are different. This can be explained by the fact that the twist direction of yarns influences the turning of crossing yarns on each other, i.e. friction and this way the shear resistance that hinders drape formation as well. In case the crossing yarns have the same twist direction, and due to the twist the elementary fibers on the surface of the crossing yarns meet almost parallel and therefore can penetrate into each other and this way hinder the turning of yarns on each other, and hence result in average 37% higher shear resistance than in case of opposite twist direction yarns, where due to the opposite twist direction the elementary fibers on the surface of the crossing yarns cross each other and this way cannot penetrate into each other. I proved the penetration of elementary fibers into each other in case of same twist direction crossing yarns also by the fact that fabrics woven from this kind of yarns is in average 16% thinner than fabrics made of opposite twist direction yarns. [1, 7, 8]

**THESIS 5:** I developed an evaluation method that uses a video extensometer for the determination of the shear angle that characterizes the shear deformation of reinforcing fabrics in case of bias extension tests. The essence of the new method is to record the longitudinal and crosswise distances between the marked points with a video extensometer continuously during the whole examination of the sample that is cut in 45° compared to the weft direction of the fabric. The change of the shear angle, i.e. the angle of the yarns of the fabric due to shear stress can be calculated with formula (T3) from the longitudinal and crosswise size changes of the fabric.

$$\gamma_i = 2\theta_0 - 2\theta_i = 2\theta_0 - 2arctg\frac{a_i}{b_i} \qquad \text{(T3)}$$

where $\gamma_i$ is the actual shear angle [°], $\theta_0$ is half of the initial angle of the warp and weft yarns [°], $\theta_i$ is half of the actual angle of the warp and weft yarns [°], $a_i$ is half of the actual crosswise distance between the marks [mm], while $b_i$ is half of the actual longitudinal distance between the marks [mm]. The precision of the new method is the same as that of the well known and already accepted evaluation method based on ‘image processing’ and is better than the accuracy of the method ‘based on geometry’. I verified with measurements that the square error of the results obtained from the own developed method using a video extensometer compared to the results of the method ‘based on image processing’ is in average 30% smaller than in case of results achieved using the method ‘based on geometry’. A further advantage of the method developed by me is that it can be applied using a universal tensile tester and a video extensometer without any additional device. [9, 10]

**<u>THESIS 6:</u>** I revealed through examinations that there is a strong relationship between the friction coefficient among yarns and the specific shear force. I proved with measurements that specific shear force determined at 8° shear angle characteristic of plain and twill woven fabrics grows exponentially if the friction coefficient among yarns increases according to forumla (T4) in the friction coefficient range between 0.64 and 0.89, where the determination coefficient is $R^2$=0.999.

$$f = 0{,}0098(e^{7{,}28\mu} - 1) \tag{T4}$$

where $f$ is the specific shear force [N/m], and $\mu$ is the friction coefficient among yarns [-]. [9, 11]

**<u>THESIS 7:</u>** I revealed with examinations that the drape coefficient difference of the examined reinforcing fabrics grows exponentially according to formula (T5) if the friction coefficient among yarns also grows, in the friction coefficient range of 0.64 and 0.89 at $R^2$=0.993 determination coefficient.

$$\Delta DC = 0{,}101(e^{5{,}65\mu} - 1) \tag{T5}$$

where $\Delta DC$ is the drape coefficient difference [%] that means the difference between the drape coefficient measured without the step-like deformation excitation effect of a ring and measured with a – 210 mm inner diameter – ring, while $\mu$ is the friction coefficient among yarns [-].

A similar tendency can be revealed in case of the examination of cotton fabrics, where 0.5 N/m increase in shear stiffness that is in strong relation with the friction coefficient among yarns results in average 0.5% increase in the drape coefficient difference. [9, 11]

# 5. List of Own Publications


[1] **Al-Gaadi B.**, Göktepe F., Halász M.: A new method in fabric drape measurement and analysis of the drape formation process. Textile Research Journal, **82**, 502-512 (2012). IF: 1,122

[2] **Al-Gaadi B.**, Halász M., Tamás P.: Textiles dynamically influenced drapability. Materials Science Forum, **659**, 361-366 (2010).

[3] **Al-Gaadi B.**: 3D-s szkennelés alkalmazása a redőződés mérésére. Magyar Textiltechnika, **2**, 56-59 (2010).

[4] **Al-Gaadi B.**, Halász M., Tamás P.: Textíliák dinamikusan befolyásolt redőződése. in 'Proceeding of Országos Anyagtudományi Konferencia. Balatonkenese, Magyarország' poszter, (2009).

[5] **Al-Gaadi B.**, Geršak J., Göktepe F., Halász M., Tamás P., Göktepe Ö.: Fabric drape examination using ring-controlled equipment. in 'Proceeding of 4th International Technical Textiles Congress. Isztambul, Törökország' 9 oldal (2010).

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[10] **Al-Gaadi B.**, Halász M.: Analysis of shear behaviours of woven fabrics with image processing. in 'Proceeding of International Joint Conference on Environmental and Light Industry Technologies. Budapest, Magyarország' 6 oldal (2010).

[11] **Al-Gaadi B.**, Halász M.: Effects of yarn-yarn friction on shear behavior and on drapability of reinforcing fabrics. Fibers and Polymers, **(benyújtva)**, (2012). IF: 0,836

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