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Simulation of the Drapability of Textile Semi-Finished Products with Gradient-Drapability Characteristics by Varying the Fabric Weave

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Abstract
The design of 3D component parts made of fiber-reinforced composites for load bearing applications demands a load oriented fiber alignement. During the draping of the textile an undefined displacement of fibers up to wrinkle formation occurs. One possibility to influence fiber orientation during draping is the utilisation of the characteristics of different fabric weaves. By combining different weaves in a textile reinforcing fabric adjusted to the component part, gradient-drapability can be developed. This means that local zones with a high structural stability and zones with high drapability can be created in a textile semi-finished product. The design of these zones is done by simulation to produce a fabric structure suitable for the component part. For that purpose, material models for draping simulation developed at the Institute of Textile Machinery and High Performance Material Technology (ITM) are being improved. The material behaviour of each type of fabric weave is analysed and transformed to the simulation model. With the simulations performed the influence of the combination of different weave types on the shear behaviour of fabrics can be demonstrated.

Key words: *draping simulation, drapability, woven fabrics, gradient-drapability characteristics, Jacquard-weaving.*

Introduction

Continuous fibre-reinforced composites are characterised by high flexibility to adjust their reinforcing structure to existing loads and complex component geometry. By combining different fibre and matrix materials, the material characteristics in the composite can be adjusted for a specific application. The technology presently used for production is not economical, except in the case of the aviation industry [1], since the production costs of fibre composite components are about 20% higher than those of conventional materials [2].

In order to utilise the superior mechanical properties of fibre-reinforced composites efficiently, it is essential to align the reinforcing fibres in the component according to the distribution of the load. This can be ascribed to the high anisotropic characteristics of the high performance fibres. An undefined displacement of the fibres up to wrinkle formation can occur in the textile semi-finished product during the draping process. As a result, the position of the fibre cannot be reproduced, and therefore it is not possible to achieve the component quality desired. To avoid wrinkles, it is common to cut the textile semi-finished product in the areas where wrinkling occurs. Thus the fibres are cut and the load bearing capacity is interrupted. In order to guarantee component integrity, the material thickness needs to be increased. Consequently an increase in material cost and an oversizing of the component reduces the achievable effect of the lightweight construction. Another possibility to increase the structural stability and to systematically influence the fibre position during the draping process is a targeted structure modification of the textile semi-finished product. For this, different approaches exists. MITSCHANG and MOLNAR, for example, developed a process in which embroidery and sewing patterns are inserted in the textile semi-finished product to ensure yarn alignment [3, 4]. One of the current research projects at Technische Universität Dresden (TU Dresden) deals with the integration of thermoplastic-based hybrid yarn into the textile structure and the moulding of these to fix the structure [5].

The approach presented here avoids an additional process step by manufacturing fabrics with gradient-drapability characteristics. This can be achieved by combining different types of weaves in the reinforcement textile structure to use the different advantages of each weave type in the component. In this way, a textile structure adjusted to the end product can be created that has good drapability without interrupting the force transmission ability of the structure. According to requirements, zones with a high structural stability, which ensure reproducible manufacturing and zones, guaranteeing the necessary conformability for the component moulding, are created. Hence the further production process (handling, draping) as well as the mechanical char-

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acteristics of the final component (fibre positioning and alignment to ensure the transmission of force required) are improved. Furthermore the effect on the lightweight construction will be increased due to efficient material use. The selection of different zones relating to the components for improvement of the drapability and structural stability can only be made with the help of simulations, since an experimental analysis is too cost-intensive and time-consuming. For the manufacturing of such fabrics a Jacquard machine of the type UNIVAL from the Stäubli GmbH company in combination with a rapier loom from Lindauer Dornier GmbH are used.

Manufacturing of fabrics with gradient-drapability characteristics

The challenge of combining different types of weave is the processing of technical fibres as warps on Jacquard weaving machines. When classical yarns are used, differences in length occurring temporarily between the warps during shedding are compensated by straining the yarn of the fibre material. In the case of the warp i being interwoven from the warp beam on Jacquard weaving machines, the weave has to be designed in a way that the demand for yarn is the same for every warp within the pattern. For the processing of high performance fibre material with a high Young´s modulus by Jacquard technology, the essential length adjustment can normally not be achieved. Due to this, glass and carbon fibre yarns have so far only been interwoven with a few heddle shafts and hence into comparably simple weaves. However, with the newly developed UNIVAL-Jacquard-technology, complex weaves can also be woven with technical fibres. This technology is characterised by the fact that each warp yarn can be raised and lowered independently with respect to the lift height by the servo motor. Thus the shed geometry can be adjusted so that the differences in length occurring due to different weaves can be compensated systematically. Furthermore, this technology allows precise regulation of the local crimp of the warps to influence local drapablity characteristics of the fabric. The mechanical characteristics can also be established by the degree of crimp of warp and weft yarns. It was possible to produce fabrics made of high performance fibres with changing weaves by this technology in our initial experiment. However, further scientific research is necessary to use these theoretical possibilities in practice and to establish a reproducible manufacturing process.

Draping simulation of textile structures

Determination of the areas in which different types of weaves are formed must be done with the help of simulation. The simulation of draping is a challenge due to the inhomogeneous structure and orthotropic characteristics of textile fabrics. For this reason, the mechanisms that occur during draping have to be taken into consideration in a suitable simulation model. In practice, different models exist for the simulation of forming textiles. These can be divided into geometric, discrete and continuum-mechanic models, which reflect the macromechanic and mesomechanic material behaviour. Geometric or kinematic approaches (also known as fish net-algorithms) represent the textile fabric on a geometric surface. Generally such algorithms do not account for boundary conditions, loads or friction effects. Examples of commercially available software packages on a geometric base are PAM-QUIKFORM, FiberSIM, Interactive Drape and Composite Modeler [6]. Geometric approaches are only partly suitable for draping tests of different weave types in a textile structure since the specific mechanical characteristics of the structure are not sufficiently taken into consideration [7, 8].

In the discrete models, single yarns are shaped as springs, which are connected to mass elements at the cross points [9, 10]. Since an enormous computational effort is required, this type of model is only suitable for the simulation of gradient-fabric structures.

In continuum-mechanic models, the textile fabric is regarded as a flexible and thin shell. These models are well-suited for the draping simulation of textile structures [11, 12]. To describe the deformation behaviour of the shell, an adequate material model is needed which defines the macro mechanic characteristics of the textile structure. On the one hand, determination of the input parameters of the material model or values of the material characteristic can be diagnosed with the help of textile testing technology (e.g., a uniaxial or biaxial tensile test, angular tensile test, picture frame test etc.). On the other hand, they can be determined with multiscale simulation, in which the deformation mechanisms on the meso level (stretching, bending, buckling and lateral contraction) and the interaction of the yarns is considered. Multiscale modelling based on the representative volume element (RVE)-model consists of yarns of a repeating structure on the meso-mechanic level and can be modelled by beam elements, shell elements or volume elements [13]. Determination of geometric and mechanical model characteristics is very time-consuming. However, it can be used for the presentation of multifaceted structures of the same fabric forming process for a single yarn weave type when sufficiently parameterised [14]. The material design is, for example, based on the calculation of the material behaviour using multiscale simulation [15, 16]. Modelling of the entire structure for simulation of the drapability on different and complex component geometries is, in general, very time-consuming with respect to the calculation. Therefore the draping simulation on a RVE-base is hardly ever used in practice. In research works, the use of shell elements has turned out to be very success-

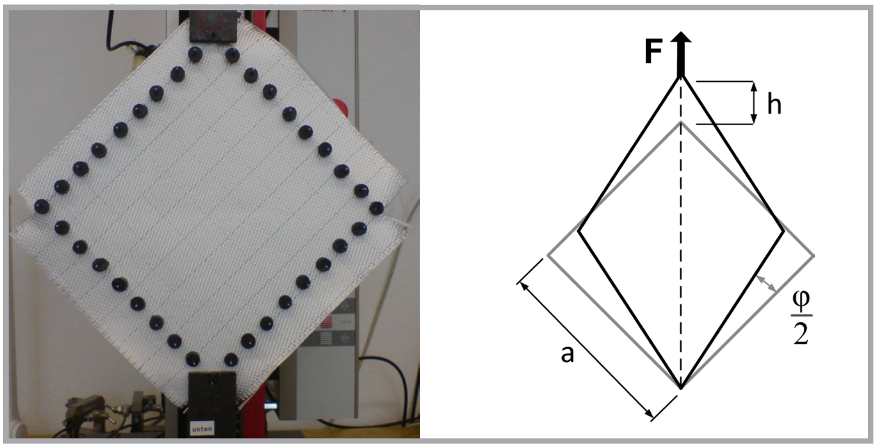

***Figure 1.** Picture frame test.*

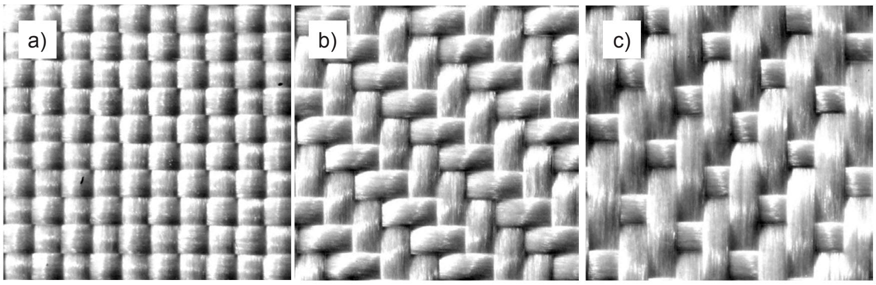

***Figure 2.** Weave types studied; GF 300 tex, 8.2 yarns/cm; a) plain, b) twill 2/2, c) satin 1/4.*

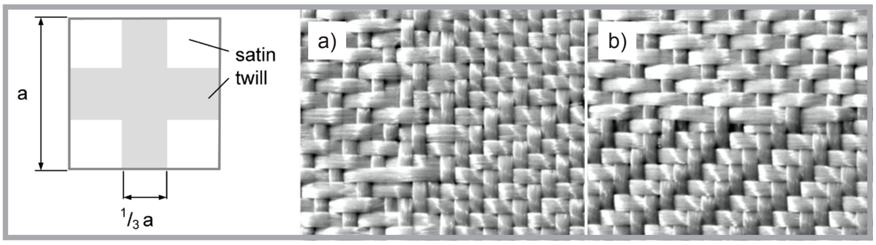

***Figure 3.** Gradient-fabric specimen and transition zones of satin to twill; a) transition in weft direction, b) transition in warp direction.*

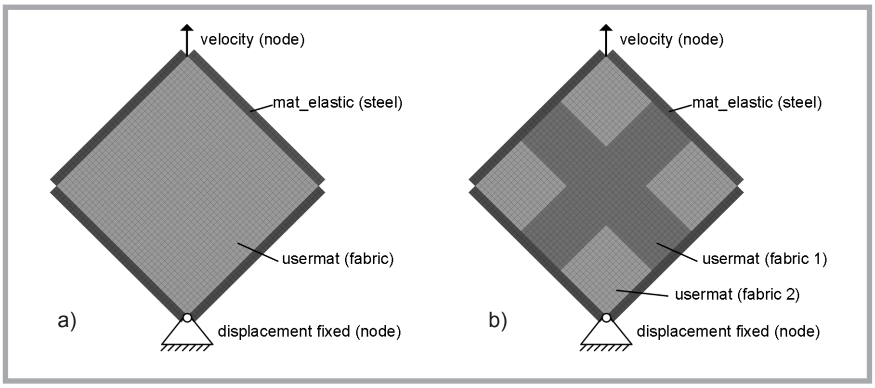

***Figure 4.** Picture frame test simulation model: a) consistent type of weave b) combination of weave types in cross pattern.*

ful for the draping simulation of textile structures. In [7] a shell based draping simulation was set up for multiaxial non-crimp structures as well as for woven structures. Using the methods developed, extensive simulation calculations were made and the draping processes could be modelled and simulated realistically. The simulation calculations were carried out considering the material and geometric non-linearities as well as the variable states of contact during the draping process. Very good correlations between the results of the simulation and those of the experimental tests were achieved even for complex component geometries.

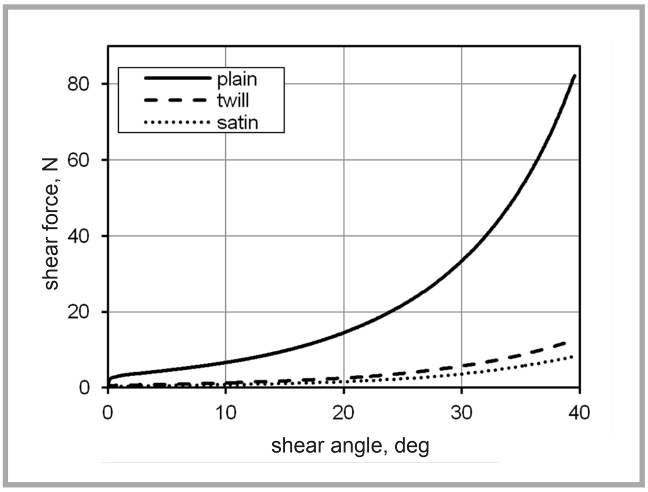

***Figure 5.** Comparison of shear force vs. shear angle of different weave types.*

Materials and methods

Draping is the forming of a two-dimensional textile into a preset three-dimensional geometry. Knowledge of the mechanisms occurring during shaping inside the fabric is essential to analyze and improve the draping behaviour via simulation. The different mechanisms which occur during the draping of fabrics are as follows:

- hearing ('Trellis'-Effect),
- stretching of fibres,
- straining of fibres and
- shifting of fibres towards each other [17].

Due to the special characteristics of technical fibres and the relatively low shaping force mechanisms, such as the straining of fibres have no or only little influence on the drapability. Shearing has the greatest influence on the drapability of technical fabrics, which is the change in angle between the warp and weft under the influence of force. In this case, the critical shear angle indicates that no more in-plane deformation is possible in the section and when this angle is exceeded wrinkles may form.

Determining the in-plane shear behaviour

One possibility to influence the shear behaviour of fabrics is the variation in the type of weave. To analyse their influence on the shear behaviour and, therefore, the draping behaviour, the shear force vs. shear angle curve of three basic types of weave - plain, twill and satin was determined with the picture frame test, developed at the Institute of Textile Machinery and High Performance Material Technology (ITM) [18]. The picture frame consists of four hinged bars in which the textile specimen is clamped by needles (***Figure 1***, see page 89). The needles allow the textile to rotate, thus decreasing the influence of the clamping. With the vertical displacement *h* the global shear angle φ can be determined. This global shear angle is an average value over the entire specimen. Hence this method is not suitable for the characterisation of fabrics with gradient-drapability characteristics.

The fabric specimens in plain, twill and satin weave studied are shown in ***Fig-***

ure 2. They only vary in the type of weave; all other parameters such as the fibre material, warp and weft density and yarn count are identical. To study the influence of the combination of different weave types, the picture frame test was also performed on a specimen which combines twill and satin weave in a cross pattern (***Figure 3***). The area ratio from twill and satin is 4:5.

Simulation of shear behaviour of fabrics

In order to simulate the shear behaviour of textile structures, the finite element method (FEM) program LS-DYNA, which contains an explicit solver, is used. To represent the macro mechanic behaviour of textile structures, a shell-based simulation model was set up. A four-node shell element with uncoupled mechanical properties is used in the simulation to represent the nonlinear characteristics of textiles.

In ***Figure 4*** a model of the picture frame test simulation is shown. The frame as well as the fabric are built of shell elements.

To represent the material behaviour of the frame a standard elastic material model is used, while for the fabric behaviour – a user defined material model, which describes the nonlinear orthotropic characteristic of the fabric.

The input parameters are the Youngs modulus in the warp and weft direction and the shear modulus. The nodes in the contact area are dubbed, hence the displacement of the frame and fabric is linked and the rotation is free, analogous to the experimental tests. The displacement h is realised by the velocity at the top of the frame.

The picture frame test was simulated for plain, twill and satin weave as well as for a gradient-fabric with a combination of different types of weave, analogous to the experiment. The objective was to find out the local shear behaviour. For the cross pattern specimen the combination of twill and satin and that of plain and satin were simulated in order to determine the influence of different combinations of weave types. The implementation was carried out by adjusting the material properties of the shell elements to the types of weave.

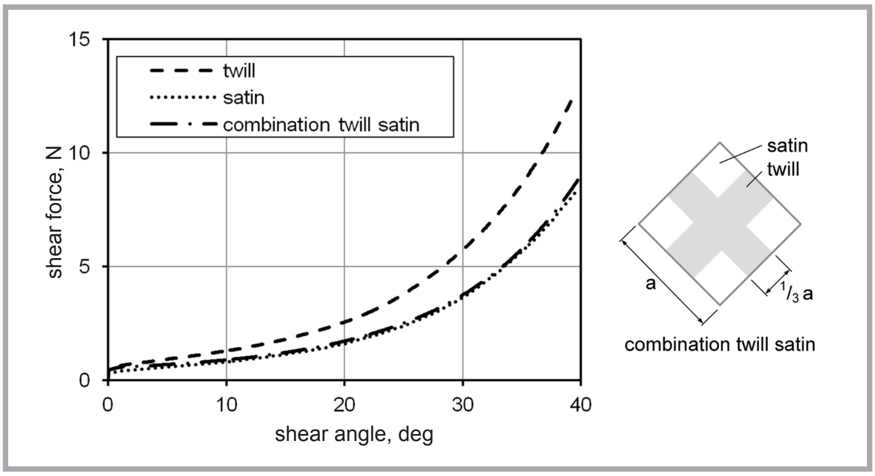

Figure 6. *Picture frame test of fabric with combined types of weave (twill and satin in cross pattern).*

Results and discussion

Experiment

The shear force vs. shear curves of the picture frame test for the three weave types: plain, twill and satin are presented in ***Figure 5***. The relationship between weave type and shear behaviour can be clearly seen. Furthermore satin and twill weaves show less shear resistance than the plain weave, which can be attributed to the weave structure. Due to the lower number of fibre interlaces in satin or twill weave, the critical shear angle is higher and the shear force lower, respectively. Hence it can be derived that fabrics in satin weave possess a better drapabiltiy than those in plain weave. It can be concluded that with a combination of different types of weave the drapability can be influenced. Test results of the gradient-fabric specimen show that the global shear behaviour thereof is close to the one with satin weave (***Figure 6***). This test also confirms that determination of the local shear behaviour of fabrics with gradient drapability-characteristics is not possible with the picture frame test.

Simulation

The shear force vs. shear angle curves from the simulation of the plain, twill and

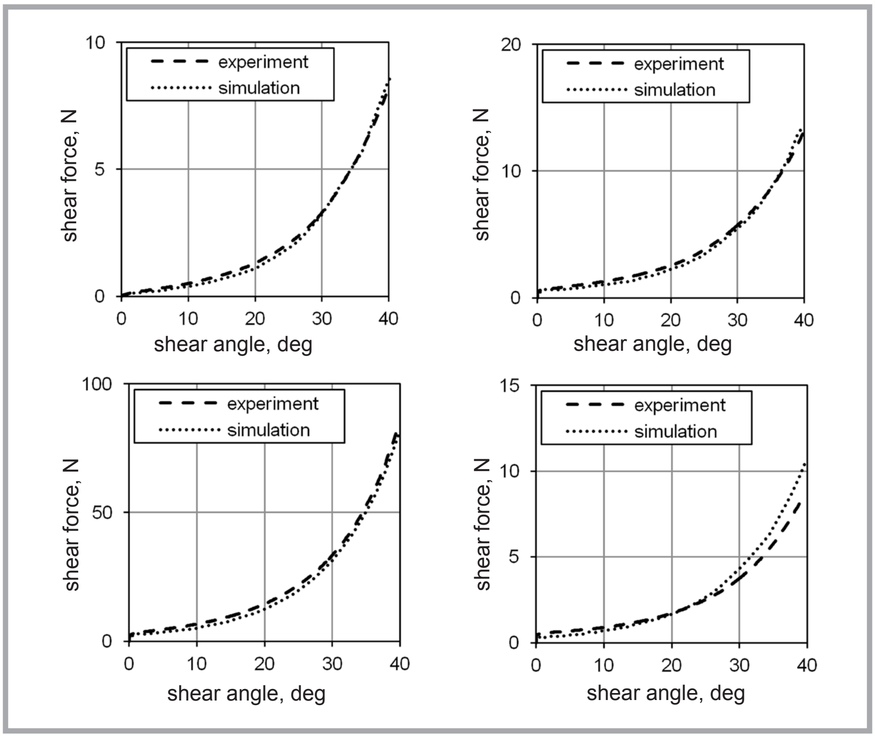

Figure 7. *Simulation picture frame test: a) satin b) twill c) plain d) combination of twill and satin.*

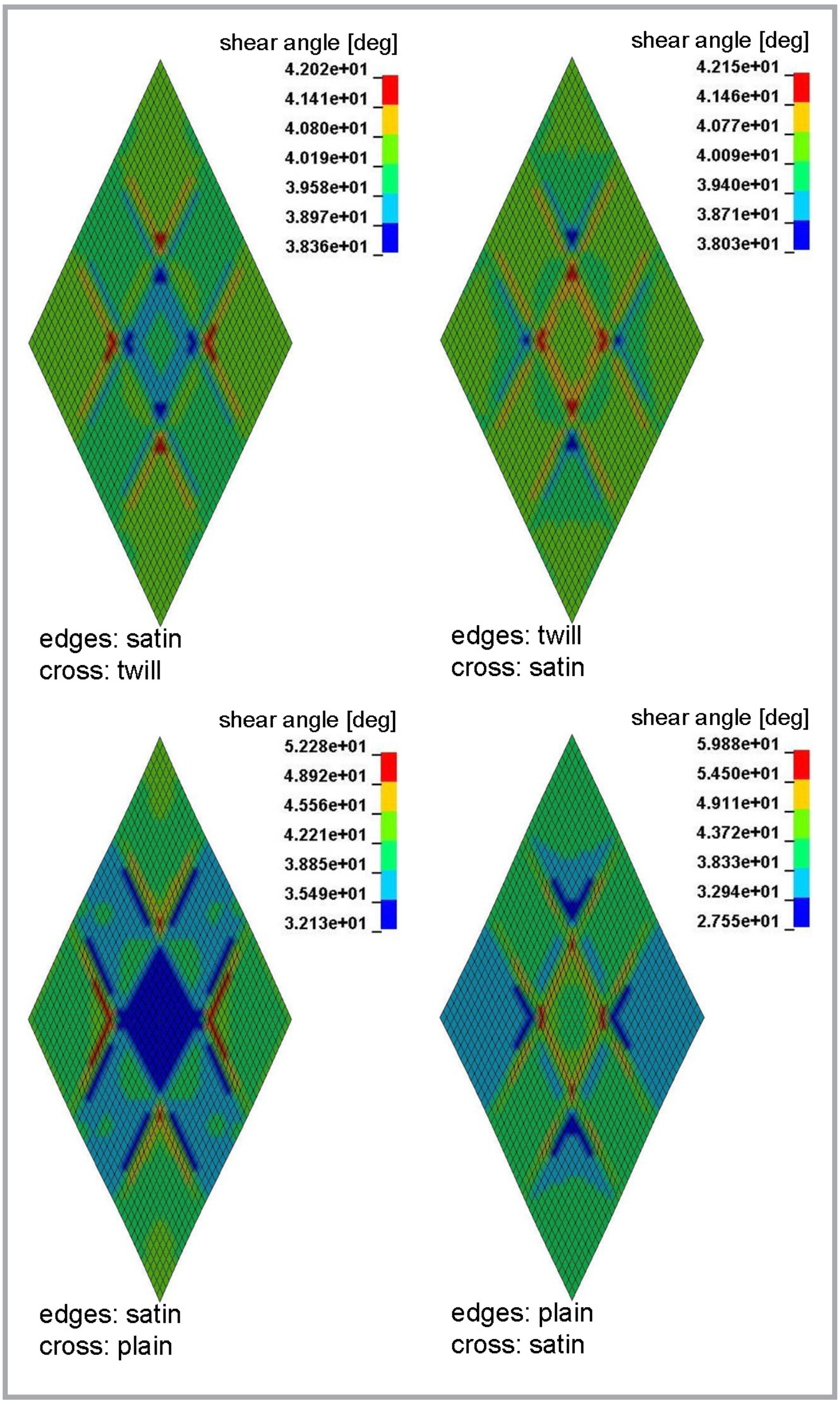

Figure 8. *Shear angle distributions in woven fabrics with gradient drapability properties (shearing of 40 degrees).*

satin weave show a good correlation with the experimental results (***Figure** 7*, see page 91). The shear curve of the picture frame test simulation of the fabric with a combination of twill and satin weave shows a discrepancy with the experiment. Especially at shear angles higher than 30 °, the shear force simulated exceeds the experimental one. The most influential factor on this seems to be the zone between the different types of weave. In ***Figure 8.a*** it can be seen that the shear angle shows the greatest range (38 - 43 °) in this zone. Furthermore the zone in twill weave shows a shearing of up to 2 ° lower than the zones in satin weave. To analyse the shear behaviour in different combinations, the picture frame test was simulated with a reverse assembly of the weave types and with a combination of satin and plain weave as they have a high convergence in their shear behaviour (***Figures 8.b** - **8.d***). Especially the combination of plain and satin weave shows how the shear behaviour can be influenced by combining different weave types. In ***Figure 8.c*** it can be seen that the shear angle can be reduced by up to 10 ° in the zone with plain weave and a global shearing of 40 °. This reduction is compensated by the zones in satin weave, where higher shear angles occur. This example clearly shows that the shearing in textile semi-finished products can be systematically directed into areas which undergo a lower mechanic load with the help of gradient-fabric structures.

Furthermore the investigations show that the influence of the transition zone between the different types of weave could not be simulated with the current model. This transition zone can vary according to the weave and the demand with respect to its size and the number of yarn interlaces. In order to determine the influence of this zone on the drapability as well as its implementation into the simulation model of the ITM, further research is necessary. A special challenge is the characterisation of the material behaviour in the transition zone. Established characterisation set-ups like the picture frame test are only suitable for a global characterisation and thus cannot be used for th characterisation of fabrics with different types of weave. In order to analyse the draping behaviour efficiently, further development of suitable test methods is therefore essential.

Conclusions

Modification of the reinforcing structure is appropriate for the manufacture of components according to the requirements for the load-oriented embedding of textile semi-finished products for complex three-dimensional structures. The possibility of achieving this goal without an extra process step is provided by the creation of zones with different drapability characteristics within a fabric by combining different weave types. In this way, a fabric structure with zones of high structural stability as well as those with a high drapability can be realised. Experimental realisation for the production of such fabric structures was made on a single motor Jacquard weaving machine at the ITM. Determination of the weave zones required for the component was carried out with the aid of simulation. Simulation of the in-plane shear behaviour was realised with shell elements. Furthermore basic knowledge is gained about the material behaviour of gradient-fabric structures. The transition zone between different weave types should be integrated in the simulation model in further research. The aim is to characterise the material of the transition zone, since its characteristics cannot be measured using standard textile test methods. In order to characterise and determine the drapability of the transition zone between the different weaves, there is a high demand for research with respect to measuring and simulation techniques. If an extensive explanation of the material behaviour of fabrics with gradient-drapability characterisations is successful, it would be a major step in creating a basis for engineering constructions with complex shaped component geometries in the field of textile-reinforced composites. As a result, an innovative component-adjusted textile structure with predictable characteristics would be available on the market.

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