1. Introduction

Woven, knitted, non-crimp and braided fabrics are popular reinforcements for moulding composite parts with complex double-curvatures. These fabrics are subjected to in-plane tensile and shear forces, and out-of-plane compression and bending forces during moulding process [1].

Knitted fabric composites are gaining interest because of the excellent drapeability of knitted fabric pre-pregs and hence the possibilities for near net shape manufacture of fibre preforms. As fibres in knitted structures are oriented not only in the in-plane directions, but also in the thickness direction, the through the thickness properties of knitted fabric composites are highest in comparison with unidirectional fibre reinforced composites and other textile (woven, braided) composites. However, the on-axis (wale or course) mechanical properties of knitted fabric composites are lower than the on-axis (weft or warp) mechanical properties of woven fabric composites. This is due to knitted fabric composites having a lower fibre volume fraction and fibres being less oriented to the wale or course directions. The on-axis mechanical properties of knitted fabric composites are comparable to the off-axis mechanical properties of woven fabric composites like in the bias directions. Depending on the fibre orientation in the knitted structure, the mechanical properties of knitted fabric composites vary from quasi-isotropic properties to anisotropic ones [2].

During manufacturing processes of polymer composites, transverse compaction of fibre preform results in changes in local micro-geometry such as inter-fibre spacing, porosity and pore dimensions, and in hence the fibre volume fraction. The compaction behaviour of fabric preform has significant effects on process ability in terms of the permeability and compressibility of preform, and on the quality and mechanical properties of final product [3, 4].

Another application of knitted fabrics is related to automotive glass forming. Design and production of automobiles with more intricate and fantasy shapes and appearance, necessitate the usage of more sophisticated production methods for manufacturing of automobiles and their components. Car glasses influence the visibility of driver, must satisfy strict safety rules and also have significant effect on the car aesthetics. New shaping technologies allow applying complicated shapes with double curvature to smaller areas of glass [5]. In press bending, the glass sheet is first heated to temperatures of about 650°C and subsequently vacuum pressed on a steel mould. Direct contact between the steel mould and the glass would lead to inadmissible defects in the glass. To ensure the quality of the glass, a heat resistant separation material (HRSM) is used. Nowadays knitted steel fibre fabrics cover the mould which itself is made out of steel [6]. The knitted steel fibre fabrics come in direct contact with the glass and thus play a primary role in the quality of the formed glass, for example windshield.

During fabric mounting onto the mould (so-called “draping”), tension variations occur across the fabric resulting in non-uniform deformation, which can change the evenness of the fabric thickness, local compression resistance and smoothness of the fabric surface. This can have a serious impact on the quality of the glass. Draping simulation methods, well developed for garment design and forming of composite materials [7] can be used for design and optimisation of the fabric itself (yarn structure, knitting parameters…) and the tensions during
mounting – providing that the deformation resistance laws of the material are known [8].
The challenge of the present work is to establish an experimental procedure for identification of the material laws for steel fibre knitted fabric deformation resistance, comparison with glass fibre knitted fabric, and to use those experimental results to simulate the deformation behaviour of the fabric during mounting.
The tests described here were performed at the room temperature. This, of course, deviates from the actual high temperature environment during the glass forming. However, our aim was to establish the experimental technique for identification of the fabric behaviour during draping on the mould, which is done at room temperature. With this challenge met, high temperature behaviour of the fabric will be the subject of future research.

Materials

Knitted fabrics used in this study are made by weft knitting on a circular knitting machine. Glass knitted fabric was produced using E-glass fibres. The fine steel fibres (12 µm diameter) are spun into yarns and then knitted into fabric. The parameters of the yarns and fabrics are summarized in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Steel knitted fabric</th>
<th>Glass knitted fabric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knitting pattern</td>
<td>Single Jersey</td>
<td>Single Jersey</td>
</tr>
<tr>
<td>Density [Thread/1 dm]</td>
<td>wale 92.3±0.5</td>
<td>96.6±0.5</td>
</tr>
<tr>
<td></td>
<td>course 82.1±0.5</td>
<td>83.3±0.5</td>
</tr>
<tr>
<td>Thread linear density [Tex]</td>
<td>179.2± 3.1</td>
<td>42 x 2 ±5</td>
</tr>
<tr>
<td>Fabric surface density [g/m²]</td>
<td>950±5</td>
<td>580±5</td>
</tr>
<tr>
<td>Thickness [mm]</td>
<td>1.10±0.07</td>
<td>1.11 ±0.07</td>
</tr>
</tbody>
</table>

Fig. 1. A) Steel fibres knitted fabric, B) Glass fibres knitted fabric.

Biaxial tension

Fig. 2 shows the configuration of the biaxial tension test. A square fabric specimen (dimensions 270x270 mm) is clamped in a tensile machine with four independent arms, allowing simultaneous tension in course and wale direction with a given ratio of extension speeds \((v_c, v_w)\) in two directions \(k = v_c/ v_w\), for \(k = 1/0, 2/1, 1/1, 1/2 \) and 0/1. The maximum velocity in the pair \((v_c, v_w)\) is 10 mm/min for all the tests. The clamp width is 200 mm. The fabric is pretensed with the force of 20 N, applied in the both directions; the value of pretension corresponds to the elimination of the initial fabric slack, which is determined by laser measurement of the position of the fabric surface. The strains in the middle of the specimen are measured optically using digital image correlation (DIC) technique (LIMESS system) [9]. Because of changing texture of the fabric surface during deformation it was not possible to use the natural grey scale contrast of the fabric image to resolve displacement fields by full-field DIC. The DIC system registered displacement of a grid of
points, marked on the fabric surface, and the average surface strain was determined based on the measured displacements of these points. The result of each test is dependency of the force per 1 mm of the clamped fabric width, applied in the course and wale directions on the average strain in the central part (120x120 mm) of the specimen. For any given $k$ ratio four tests were done. In each test two force-strain dependencies are registered:

$$F_c = F_c(\varepsilon_c, \varepsilon_w | k); F_w = F_w(\varepsilon_c, \varepsilon_w | k)$$  \hspace{1cm} (1)

where $F_c$ and $F_w$ are forces per unit length in the course and wale direction respectively, $\varepsilon_c$ and $\varepsilon_w$ are average deformations measured using DIC. Note that in these equations $\varepsilon_c$ and $\varepsilon_w$ are interdependent, as both curves are registered in the same test with the given $k$. Because of the difference between the deformations in the middle of specimen and the relative displacements of the grips, $\varepsilon_c/\varepsilon_w$ ≠ $k$ exactly (even if the ratio is close to the $k$ value).

Dependencies (1), combined for all the values of $k$, used in the test, allow derivation of a generic functions

$$F_c = F_c(\varepsilon_c, \varepsilon_w); F_w = F_w(\varepsilon_c, \varepsilon_w)$$  \hspace{1cm} (2)

as interpolation of all the data points. The scatter of the points used for the least square interpolation is as follows: strains $\varepsilon_c$ and $\varepsilon_w$ at any given data point (determined by the global loading conditions) have a coefficient of variation (standard deviation to average ratio) of not more than 10%; force values of not more than 8%; each data point is the average result in four measurements.

Fig. 3 illustrates the final result of the measurement: the material law, describing the fabric deformation resistance in in-plane biaxial tension (only the graph for the force in the course direction is shown). The response surfaces (2) are approximated with polynomial functions to be used in FE simulations.

**Shear: Picture frame**

During draping on a double-curvature mould (close to hemisphere; box shapes near corners etc.) a fabric shears. Shear leads to densification of the fabric fibrous structure, with possible “locking” leading to wrinkling, which is inadmissible for the glass forming. Shear deformation changes the local pattern of the knitted loops, with a potential imprint effects on the glass. Finally, the shear resistance, together with the tension forces, defines in-plane (“membrane”) deformation response of the fabric, and the material laws for these two types of deformation constitute the full system of equations necessary for finite element modelling of the draping.

Generally accepted device for measurement of shear deformation resistance of textile materials is so-called picture frame, shown in Fig. 4. A square fabric specimen is clamped in the frame, installed on a tensile machine. The course and wale directions are aligned with the frame sides, which initially are orthogonal. With the movement of the machine the frame, thanks for the hinged sides, imposes a shear deformation on the fabric. The speed of the tensile machine was 20 mm/min. As demonstrated in [10,11] the pre-tension of the fabric, created during its mounting on the frame, largely determines the
shear resistance. Even simple mounting of a knitted fabric sample on the frame presents considerable difficulties due to rolling up of the fabric edges and slackness of the fabric. To avoid initial wrinkling of the heavy fabric, it is pretensed prior to the picture frame test on the biaxial tester with deformation 10% in the both directions; the fabric is fixed with a cardboard frame, taken off the biaxial tester and clamped in the picture frame; the cardboard is cut out (leftovers of the cardboard are seen in Fig. 4).

![Fig. 4 Picture frame test: (a) picture frame: 1 – clamps, 2 – hinges, 3 – fabric specimen, the block arrow shows the upper hinge direction of movement, bottom hinge is stationary; thin arrows indicate the course and the wale directions](image)

The shear angle of the fabric during the picture frame test normally well correspond to the kinematic shear angle of the frame [10, 11]. However, this was checked using optical observations of the initially square grid drawn on the fabric (see Fig. 4), and the difference between the shear angle determined kinematically and measured on the fabric was found to be below 1°. During the test a force-displacement curve is registered by the tensile machine. It is processed as follows: (1) the force-displacement registered in the test without fabric sample is subtracted to account for the frame weight and friction in hinges; (2) the displacement is transferred into shear angle using the kinematics of the frame; (3) tension force is transferred into shear force applied per unit width of the fabric.

Three subsequent cycles of shear are registered. The first cycle considered as “conditioning” of the specimen, which relaxes tensions created by misalignments in the specimen mounting. The second and the third cycle are very close one to another. The second cycle is normally taken as characterisation of the fabric behaviour [10]. Tests with five fabric specimens are done, and the average of the five is taken as the final result of the test:

\[ T = T(\gamma) \] (3)

where \( T \) is the shear force per unit width, \( \gamma \) is the shear angle. The dependency (3) is illustrated in Fig. 5. The scatter in the values of the shear force for a given shear angle does not exceed 10% (coefficient of variation). The dependency (3) constitutes the material law, describing the fabric deformation resistance in in-plane shear.

![Fig. 5. Shear test result: shear force – shear angle diagram, three loading cycles](image)

**Compression**

During vacuum glass forming the fabric, draped over the mould, undergoes through- the thickness compression under a pressure of about 1 bar. As any fibrous/textile material, the fabric is highly compressible, and its thickness under 1 bar pressure can be 60...70% of the initial thickness. The compressibility theoretically changes with the local change of the fabric tension. The corresponding change of thickness may affect deviations of the local glass shape from the design surface, which may lead to unwanted optical distortions. Fig. 6 shows the arrangement of a compression test. Compression force was exerted on a fabric sample using a cylindrical head with the diameter of 70 mm. The fabric was placed on a spherical pivot; compression action without a sample was used to align the pivot to the compression head and to produce a “calibration” curve subtracted from the test force- displacement diagram to account for the
machine compliance and to establish the zero thickness point.

The test speed was 1 mm/min. The fabric was tested in the relaxed state and after pre-tension on the biaxial tester with pre-strains of 5x5%, 10x10%, 15x15%, 0x10%, 10x0%, 0x20%, 20x0%.

The test results are expressed as glass fabric thickness – applied pressure diagrams (Fig. 7). Three pressure cycles were done on each of the specimens and the third cycle was taken as the compression characteristic.

Note that the first cycle is not representative because of the considerable fabric hairiness. The second compression cycle was taken as characteristic of the fabric behaviour. The fabric undergoes several hundreds of compression acts during its life on the glass-forming mould. The tests with large number of cycles (up to 150) have shown that after the third cycle of compression the fabric thickness at 1 bar pressure changes not more than by 5%. The change of compression behaviour during cyclic loading can be characterised by the resilience coefficient (RC), which is the ratio between the area under the reloading compression curve to the area under loading compression curve. The RC values change with the cyclic loading as follows: 1st cycle 45%, 3rd cycle 83%, 10th cycle 86%, 100th cycle 88%.

Fig. 8 shows the difference of the fabric compressibility, expressed by the fabric thickness under 1 bar pressure, with the different tension conditions. With increase of the tension the thickness can decrease by up to 70 µm, or by about 12% of the relaxed fabric thickness. For thin glass this difference can be significant for the glass optical properties. The pressure – thickness relation can be described using van Wyk formula \[ t = t^* (p^*/p)^3 \] (4)

where \( p \) is the pressure, \( t \) is the fabric thickness, \( t^* \) and \( p^* \) are parameters, identified by the least square fit to the experimental diagram.

Fig. 8. Fabric thickness under 1 bar pressure for different pre-tension A) Steel knitted fabric; B) Glass knitted fabric

Difference of thickness of fabrics after pre-strain is between 50-60 µm (10%).
Draping over a model mould and finite element simulations

Identification of the in-plane “membrane” material model (equations (2) and (3)) allows finite element modelling of the draping process. The aim of such a simulation is determination, for certain loading scenario, the distribution of local tension and shear deformations. As described above, this information leads to estimations of the local distortions of the knitted pattern, identification of the loading scenarios which can lead to wrinkling or fabric rupture. Uniform distribution of deformation over the mould surface is a desirable feature of the production process. After validation of the draping simulations they can be used for optimisation of the loading scenario in a (future) automatisation of the draping.

Equations (2) and (3) offer themselves readily to be used in the draping simulation. However, it is important to remember that the tension and shear resistance was measured in macro-scale tests, whilst during FE simulation they are applied to micro-scale behaviour. Another deviation of a model, based on (2-3) from reality may be in coupling of the tension and shear resistance, which was not taken into account during the tests described below. Finally, numerical difficulties of the draping simulations cannot be underestimated: we deal with highly non-linear behaviour of the material, with the presence of low stiffness deformation regimes, which may lead to numerical instabilities.

To validate the FE simulations, a test program on the draping of the fabric on a model mould was performed. Fig. 9 shows the configuration of the test. The mould, made of hard foam, was punched on the fabric, held by a blank holder. The deformed shape of the fabric was registered using DIC optical system with two cameras, which allow resolution of the full strain fields on the fabric surface.

The same deformation was modelled in FE ABAQUS package, using explicit simulations. The user defined material routines (UMAT), implementing the material laws (2) and (3), and objective differentiation for large fabric deformations were used. The results of the experimental registration of the strains and FE simulations are compared in Fig. 10. The simulations correctly predict the strain distribution over the mould. For the central area of the mould (defined by its rounded edges) the maximum strain in the wale direction is predicted as 9.8%, experimental value is 9.0%; for the course direction the predicted maximum strain is 18%, measured 19%. These results show that the model correctly describes the deformation behaviour and correctly estimates the distribution of strains over the mould – the parameter most important for the practical optimisation of the draping process. However, the reaction force is predicted with a large error (several times), which can be attributed to the fact that in the identification of the material resistance parameters pretension was used both for biaxial tension and shear. The actual boundary conditions in the draping experiment (blankholder force governed by friction) are difficult to identify, as well as a difficult-controlled slack of the fabric. In spite of these difficulties, adequacy of the simulations is supported by the fact that the ranging of resistance of different fabrics is correctly represented in the simulations.

Fig. 9. Draping experiment; 1) mould, 2) fabric sample in the blank holder on a mechanical testing machine, 3) DIC cameras
Fig. 10. Draping experiment results DIC registration (above) and FE simulation (below) of strains on the fabric surface, strain in horizontal (wale) direction.

Conclusions

An experimental procedure is described for study of deformation resistance of weft-knitted fabrics. The procedure includes biaxial tension, shear (picture frame) and compression tests. The experimental procedure has been validated as a tool for identification of material laws, necessary for finite element draping simulations.

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References