Definition and quantification of drapeability through the measurement of constituent effects

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Abstract. Although considerable work has been carried out in the field of drapeability research, both the definition of what drapeability comprises as well as the tools to measure and quantify it must be further developed. This paper presents a definition of drapeability that is meant to broaden its scope to include not only the important effects of shearing and wrinkling, but all constituent effects such as gap formation, undulations, loops (tow buckling) and fabric anisotropy. This definition is completed by an experimental test device to measure and quantify all of these effects in a single, standardized setup (available as the Textechno Drapetest). The Drapetest utilizes optic measurement technology coupled with digital image analysis software to detect and measure fibre positions and orientation, and fabric topology. For each of the defined drapeability effects characteristic values were generated from this optical data that can describe the intensity, distribution and extent of the effect in question. The device and methodology was empirically validated using a set of 72 specially manufactured glass fibre NCF. The interdependencies between textile design, process parameters and drapeability effects as well as a semi-analytical equation for them are shown. A method to use these semi-analytical equations in the composite design process is introduced [1].

1. Introduction

The usage of fibre reinforced plastics (FRP) is further increasing every year. It has by now become a standard material in all areas of aircraft design, in wind turbine blades and even serial production of automobiles. In parallel with this development the sophistication of the design and manufacturing processes has increased. Moving away from metal emulating designs with quasi-isotropic stacks of woven fabrics the manufacturing and design processes now increasingly incorporate fibre conscious technology and techniques to maximize the fibre based material’s potential.

Including fabric specific material properties such as drapeability in the testing, design, manufacturing and quality control is one aspect of such fibre conscious design. The increasing sophistication of fabrics, e.g. usage of multiaxial non-crimp-fabrics instead of plain woven fabrics, creates the necessity to deepen the knowledge of the drapeability of the involved materials. This can be achieved through a re-evaluation of the definition of and how the choice of this definition effects testing and design methodologies.

This paper introduces a drapeability definition that includes all relevant effects. Furthermore a set of indicator numbers is shown that might be used to assess these drapeability effects quantitatively. These characteristic values can be measured by using the automated Textechno Drapetest. To validate the chosen drapeability definition empirical studies were conducted with said testing device to show usefulness of the indicator numbers. As a conclusion it is shown how these empirical results can be used to formulate a semi-analytical material model of all drapeability effects included in the definition.
2. Definition of Drapeability and Characteristic Values

Previous definitions of drapeability focussed on the shearing behaviour of fabrics and defined good drapeability as adherence to a double curved shape without the formation of wrinkles. The reason for this definition is historic. In tightly woven fabrics shearing is the only relevant deformation mechanism and fabric shear is that case the cause of wrinkles, so this narrow definition of drapeability can be applied correctly. However, in different fabrics, a large number of drapeability effects have been identified [2, 3], as shown in Figure 1 for NCF.

![Deformation mechanisms in NCF](image)

**Figure 1.** Deformation mechanisms in NCF [2]

Drapeability is in fact not the adherence of a fabric to a curved shape without a wrinkle. Drapeability must encompass all effects since even without a wrinkle changes in the fabric structure might be changing the preforms properties. Under the classical definition of drapeability, a fabric that shears considerably but avoids any wrinkles possesses “Good” drapeability. In reality though, a fabric that easily changes its fibre direction might lead to a preform with fibre orientations that differ greatly from the presupposed directions and thus also load directions. For sheared fabrics orthogonality can also not be assumed. A better approach to define drapeability would be to quantify effects and present a quantitative description of the observed effects.

Furthermore, looking at reinforcement fabrics with a wider scope, non-crimp-fabrics (NCF) must also be considered, and thus, other drapeability effects beyond shearing cannot be neglected anymore. In NCF the yarns can exhibit three modes of motion: rotational (by fabric shear), translational and axial.

To grasp the drapeability of a fabric it is necessary to define three terms: the draping parameters, the draping behaviour and the drapeability effects. The draping parameters are determined by the selection of fabric and its design, and by the requirements for the final component shape. They can usually be quantified as simple geometric parameters such as curvature. The interaction between the textile design parameters determine the fabric specific draping behaviour. The draping behaviour can be derived from empirical results (as long as not complete mechanical material law for textiles is available) in the form
of functions that include the draping parameters as variables and the empirically determined material coefficients. The drapeability effects are the resulting effects observed in the draped fabric. They can be characterised by a set of indicator numbers in intensity and extent, either as a result of empirical experiments or by solving the determined draping behaviour functions of the fabric used. The importance of choosing a comprehensive drapeability definition is compounded by the fact that it influences the next steps of drapeability research. The design of a drapeability tester will be based in the chosen drapeability definition. In production, the quality testing of preforms will also only be able to find drapeability effects that have previously been incorporated in a definition. In fact, this can become a self-enforcing circular definition in which a testing device only detects those effects its underlying definition includes which in turn is validated by this testing. Instead the definition must be chosen as broadly as possible and a testing device must be able to test for all defined effects. Only after the fact of quantifying the effects in a fabric can it be concluded that in a particular case the definition of drapeability can be narrowed to a smaller subset of effects.

Table 1. Drapeability effects and their characterising indicator numbers

| Drapeability effect | Indicator | Symbol | Unit |
|---------------------|-----------|--------|------|
| Gaps                | Gap Percentage | $G_p$ | %    |
|                     | Gap Width   | $G_w$ | mm   |
|                     | Gap Shape   | $G_S$ | -    |
| Fibre Angle Change  | Angle Difference | $\Delta$ | °    |
|                     | Undulations  | $\Lambda_{loc}$ | °    |
| Fabric Shape Change | Out-of-roundness | $\Theta$ | %    |
| Out-of-plane effects| Waviness    | $\Lambda$ | mm   |
|                     | Loops       | $\Omega$ | mm²  |

3. Measurement technology

Fabric forming tests can be assorted according to their specificality: from the generic drapeability test setups to the more specific preforming test setups [4]. The generic test setups such as the trellis frame (also known as picture frame) test or the bias extension test attempt to elicit a singular drapeability effect in a fabric by creating a generic load condition e.g. a pure shear loading. This approach is similar to the test setups used to measure mechanical properties of stiff materials (laminates or metals), the bias extension test is close to the setup for measuring the shear modulus of biaxial laminates. The results of these generic drapeability tests is also similar to those for usual engineering materials as they essentially measure the shear modulus of a fabric. On the other end of the scale, preforming tests use a very specific geometrical condition to elicit all drapeability effects that will be present in a later application by using a test geometry that is as similar as possible to the final tool shape. The advantage of this approach is, that no question arises how to apply the laboratory experiments to the production environment because the laboratory geometry and production geometry are very similar or even the same. On the other hand, the results of one test can hardly be applied to another geometry because the observed effects are only applicable to the specific geometry used in this instance. Also preforming tests often rely on quantitative descriptions of the observed fabric state and do not lend themselves to gain insights into the material mechanics behind the formation of drapeability effects. In between these setups are those that use a generic reference body such as a hemisphere or tetrahedron to induce drapeability effects and then either record deformation forces or optically measure the fabric surface. They are more complex in their conditions and results as the generic test setups yet more universal than the preforming test.
The requirements for a drapeability test setup that allows for verification of the proposed drapeability definition can be summarised as such:

1. Measuring the fibre orientation as this is the most important attribute of reinforcement fabrics
2. Measuring the position of yarns to detect lateral yarn movement
3. Detection of out-of-plane yarns
4. Recording of necessary forming force
5. Using a generic test condition for universal application of test results
6. Measuring at different degrees of drape
7. Generating a defined clamping condition

The development of a drapeability tester to fulfil these requirements resulted in a test setup that takes the classical reference body setup as described above and equips it with measuring technology to quantify all resultant drapeability effects [5]. Going beyond the usual laboratory setups the technology is available in a guaranteed build and quality in the form of the Textechno Drapetest while the testing method is available as the DIN SPEC 8100 in an open access manner. This combination means that the drapeability test can be standardised to maximise interlaboratorial comparability.

The Drapetest relies heavily on optical image technology to detect and quantify the drapeability effects (see Figure 2). This has the advantage of offering the capabilities to detect all effects that are visible. To measure in-plane-effects a detail camera takes images of the fabric surface from which an image analysis software can discern small-scale effects. Out-of-plane effects are measured by scanning the fabric topology with a triangulation laser and generating a 3D-representation of it. Additionally, an overhead camera photographs the entire fabric sample to measure larger scale fabric deformations. The fabric sample is clamped by pneumatic tube, which means the clamping conditions are constant and user definable.

![Diagram of Drapetest setup](image)

**Figure 2.** Drapeability tester Textechno Drapetest (left) and utilised optical measurement technology to quantify drapeability effects (right)

The images and height profiles recorded by the tester are analysed with an automated image analysis software. This is capable of detecting and measuring all the defined effects and generate the defined indicator numbers that are then communicated to the user. The indicator numbers are meant to give the user a clear and complete overview of the present drapeability effects and their intensity. By communicating these numbers this information can then be conveyed to other involved e.g. textile manufacturers or part designers.
4. Equations of constituent effects

The goal of the empirical testing was to validate the usefulness of the proposed drapeability definition. A useful definition can describe not only the drapeability effects but also the drapeability behaviour of a fabric. The drapeability behaviour describes how a specific fabric responds to the external constraints, (i.e. like the component geometry) due to its internal structure i.e. its textile design. To test this capability of the definition a set of NCF was manufactured whose design parameters were chosen to full out a fully parametric design space with the variables, stitch length (in machine direction MD), stitch point distance (in cross direction CD), weight per area, and stitching pattern. The fabrics were all of the two layer biaxial +45°/-45° type manufactured by Karl Mayer Malimo with a constant stitch yarn tension. These fabrics were tested with the Drapetest on a hemispherical reference body that had its height varied to investigate different degrees of drape. Due to the symmetrical nature of the reference body, the influence of fibre orientation to the curvature of the body could also be investigated. The clamping forces were kept constant.

To assess the drapeability behaviour each fabric is measured at ten degrees of drape with the reference body being moved outward of the textile plane in 10 mm steps. At each step the surface of the fabric sample is measured with the described optical technologies and quantitative data of the extent and intensity of each drapeability effect is gathered by the image analysis software. The formation of the drapeability effects can then be described as a function of the reference body displacement (i.e. the degree of drape) as shown in Figure 3 on the left side. Between a reference body displacement of 10 mm and 80 mm the results can be linearised and described by the linear slope $k_E = dE/dh$ for each effect $E$ over the displacement of the reference body $h$. By varying a textile design parameter this slope is changed, so it can be used to describe the drapeability behaviour of a specific textile in regard to a certain drapeability effect. The $k$-coefficients may now be used as data points to model the drapeability of NCF as a function of a design parameter. As shown in Figure 3 on the right, for certain conditions a linear function can be chosen that models the influence of a design parameter onto the drapeability behaviour with a very high degree of confidence.

In the shown example the formation of gaps is dependent on the stitch length of the warp-knit stitching. A longer stitch length leads to a low amount of initial gaps, due to less stitch points, but shows a faster growth of gaps because of the lower stiffness of the reinforcing warp-knit structure.

In the next step these semi-analytic functions can be combined even further to model the entire multi-dimensional process space of draping NCF materials.
5. Drapeability Modelling

As described the slope coefficients $k$ gathered during the empirical testing can be displayed as a function of a textile design parameter or even several design parameters. These functions include in effect a drapeability effect, one or more geometric parameters (the degree of drape and/or the fibre orientation) and one or more textile design parameters. This way, if all textile design and draping process parameters with their coefficients are combined, a model of the drapeability behaviour can be setup that is analytic in nature but based on empirically gained material laws. Due to its analytical nature such a model is simple and fast to calculate. No expertise of numerical methods such as FEM is required. The problem of measuring fabric properties as input parameters is also circumvented because all input parameters (the k-coefficients) are generated by one test, the standardised drapeability test with the Drapetest.

The complexity of modelling the drapeability of NCF stems from its multi-dimensionality. The fabric’s drapeability behaviour can be influenced by numerous interdependent design parameters. For the formation of the drapeability effects these parameters then interact further with the process parameters such as the tool curvature and the preform orientation. An example how a semi-analytical modelling of these interactions look is shown in Figure 4. For the sake of clarity only one process parameter, the reference body displacement and one design parameter, the stitch length. But for the semi-analytical model further combinations are possible but do not lend themselves to graphical representation (due to them existing in a space higher than the $\mathbb{R}^2$). Further refinement of the model and application to such conditions in which the drapeability behaviour in non-linear requires further material testing to populate the design space more thoroughly.

![Figure 4. Graphical representation of the semi-analytical model of the fibre angle change in a NCF dependent on the stitch length l and the displacement h](image-url)
6. Conclusion

This paper concerned the challenge of defining, testing, and modelling the drapeability of non-crimp-fabrics (NCF). Classical definitions of drapeability can well be applied to woven fabrics but are insufficient for fabrics whose yarns not only possess rotational (through fabric shear) but also axial and lateral movability. In the classical definition the effects of shearing and subsequent wrinkling are considered to evaluate the drapeability of a fabric.

A novel definition of drapeability includes a number of further drapeability effects such as gaps and preform deformation due to axial yarn slippage. To evaluate the drapeability of a fabric all effects must be considered by using quantitative indicator numbers that are gained by empirical testing. A defined set of indicator numbers can be used to describe the state of the fabric and effects present in their extent and intensity.

A drapeability tester is introduced that is able to deliver these indicator numbers by measuring a fabric sample in different degrees of drape using optical measurement technology coupled with a digital image analysis software. The tester uses the classical reference body method but expands upon it by allowing for several degrees of drape through displacement of the reference body and a quantitative drapeability analysis by employing two cameras and a laser scanner.

Through experiments empirical relationships between various NCF design parameters and the defined drapeability effects could be found. These relationships can be expressed in the form of semi-analytical functions which can be combined into a model of the draping process of NCF. The model can used as a simple tool during material selection or, when more parameters are included, as the basis for a fast computer-based modelling of the complex problem of NCF drapeability.

References

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