ESTIMATION OF FABRIC PROPERTIES AFTER FORMING

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SUMMARY: The increase of the use of continuous fibre reinforced composites in structural parts makes it clear that prediction of mechanical properties is needed in the design phase of structural components. With software programs the reorientation of fibres due to the placement can be predicted. One of the added benefits of these predictions is that mechanical properties of the composite structure can be estimated as well. Translating the fabric (or fibre) properties given by suppliers of these materials to FE based programs causes assumptions with respect to undulation and shearing to be needed. By using realistic values as found in literature for the Young's modulus perpendicular to UD fibre direction and the Poisson’s ratio it is possible to construct a usable set of mechanical properties for sheared fabrics.

KEYWORDS: Composites, fabric, forming, mechanical properties, CLT, deformation.

INTRODUCTION

When the performance/weight ratio is important in structural components, continuous fibre reinforced composites are more promising than short fibre reinforced composites. The control of fibre content and fibre placement is therefore very important, and designers should know what is possible within the materials-processes-component shape fields. These three aspects determine the possibilities of the continuous fibre reinforced composites. RTM and vacuum assisted processes shaping dry fibres together with press forming techniques shaping impregnated fibres show increased interest for producing structural composite parts.

The designer needs to know before the fabrication whether the composite part can be produced in the way he/she had in mind. Fibre placement prediction is one of the aspects that is needed. Therefore simulation software exists that predicts the fibre placement after forming. Whether the software is based on simple models, such as the fishermen’s net approach for fabrics, or more sophisticated approaches is not that important for the designer. He/She needs to know the limits of processes and the expected results when the production process is successful. The process itself is less important to the designer.

The simple approach is most of the time good enough for a designer. With some experience the designer is able to make the decision which material which product shape and which process to use for a certain design case.

A software program called DRAPE® developed at our faculty can predict the placement of fabrics & stitched UD’s on product shapes. This program is based on the geometrical placement of fibres on the surface of the structural part (often referred to as product shape). An example of a layer of fabric placed on a hemisphere is shown in figure 1. It is clear that the stiffness and the strength of the fabric layer changes for place to place.
In general the mechanical properties of the material covering the any 3D product will change from area to area. This is not only caused by the reorientation of the reinforcement, but also by the change in thickness caused by the forming process. Material properties used by Finite Element Programs, such as Abaqus®, Marc®, Nastran®, etc need to be specified, and since they change locally, the best way is to define them for every element.

FINITE ELEMENT ASPECTS

When the fibre reorientation is known from the simulation software, only the translation of the fibre/fabric properties from the undeformed state to the deformed state has to be performed.
For Uni Directional (UD) reinforcement (fibre & resin) this is done in a straight forward way, using the Classical Laminate Theory (CLT) and the layer possibilities of the FEM software. For fabrics this is less straight forward, since fabrics can not be specified in directly FEM software. Fabrics need to be translated into layered materials. In principle a simple two directional fabric can be defined in two ways:
1. Properties of the UD material in warp and weft direction and the weave type.
In way1 the properties of the UD material can be measured from real UD material or calculated from the fibres and resin content. The combination of the warp and the weft UD changed the properties, this according to the applied weave type.
The main effect of the weave type is the effect of undulation. For different weave styles this effect will be different (figure 2). By dividing the fibres into smaller parts, and estimating the properties of the smaller parts, an adapted set of properties is obtained (figure 3) [1, 2, 3, 4, 5]. For a plain weave the change in properties with and without undulation effect can be in the order of 10 %.
The main deformation found in fabrics when applied on three dimensional product shapes is the effect of the shearing of the fibres of the fabric. The reorientation of the fibres has the largest influence on the mechanical properties.

Figure 1: The varying stiffness along the product shape
Figure 2: The undulation of a fabric as sketched for different fabric weaves.

Figure 3: Unit cell, sub-unit cell and transformed sub-unit cell of a plain weave.

The other effect that causes quite some difference is the change in thickness (caused again by the shearing and the constant volume of fabric). For a designer these changes can be accounted for in several ways:

1. Find by testing the properties of the sheared fabric.
2. Deduce from non-sheared fabric properties sheared fabric properties.

The first way is obvious the best way to find reliable values for the properties, it is however very time consuming, and the test methods to be used are also not straightforward. Test on part levels are often needed and those are expensive. For a designer who wants to compose its own fabric from two UD’s in the design stage the first method is not practical, so the second method must be made available.

When a fabric is modelled as two UD materials (with undulation accounted for) the CLT provides simple means to account for the shear effect. Just by rotating the two UD directions in the weave, a set of properties can be found. A problem that can arise is the problem of symmetry. Some fabrics are symmetrical and some are not. Translating these usable layers for the CLT often gives non-symmetrical solutions, and when the symmetry is forced (by doubling and mirroring the layers, and making them half the thickness) the bending properties must be adjusted, so realistic values are calculated.

When a fabric is defined by its own (measured) properties, the effect of the shearing is more difficult to account for. Since the CLT expects layered materials, a fabric is usual defined by two UD materials. The UD materials are called the warp UD and the weft UD (just as in reality). When the stiffness properties are considered for instance, a non-sheared fabric will be specified by $E_x$, $E_y$, $G_{xy}$ and $V_{xy}$, where $x$ and $y$ denote the main material directions (in most cases these are the fibre directions). While for the warp and weft UD two sets of these stiffness properties are needed ($E_1$, $E_2$, $G_{12}$, $V_{12}$, where 1 is the fibre direction of the UD material). A lack of properties arises, so assumptions are needed to
overcome this shortage of data. In the following three methods will be shown how an 
estimation can be made, which is usable for the designer.

**METHOD I:**

This method uses estimations obtained from micro mechanics to establish an approximation 
of the stiffnesses of the warp and weft UD’s. With the CLT the stiffness matrix of the 
weave and the combined UD’s are calculated:

\[
Q_{\text{weave}} = \begin{bmatrix}
E_x & v_{xy}E_x & 0 \\
\frac{1}{1-v_{xy}v_{yx}} & \frac{1}{1-v_{xy}v_{yx}} & 0 \\
v_{yx}E_x & \frac{v_{yx}E_x}{1-v_{xy}v_{yx}} & G_{xy} \\
0 & \frac{1}{1-v_{xy}v_{yx}} & 0 \\
0 & \frac{v_{yx}E_x}{1-v_{xy}v_{yx}} & G_{xy}
\end{bmatrix}
\]

(1)

\[
Q_{\text{warp}}(0) = \begin{bmatrix}
E_{1}^{\text{warp}} & \frac{V_{12}^{\text{warp}}E_{1}^{\text{warp}}}{V_{21}^{\text{warp}}} & 0 \\
\frac{1}{1-V_{12}^{\text{warp}}V_{21}^{\text{warp}}} & \frac{1}{1-V_{12}^{\text{warp}}V_{21}^{\text{warp}}} & 0 \\
\frac{V_{21}^{\text{warp}}E_{1}^{\text{warp}}}{V_{12}^{\text{warp}}} & \frac{V_{21}^{\text{warp}}E_{1}^{\text{warp}}}{V_{12}^{\text{warp}}} & G_{12}^{\text{warp}} \\
0 & \frac{1}{1-V_{12}^{\text{warp}}V_{21}^{\text{warp}}} & 0 \\
0 & \frac{V_{21}^{\text{warp}}E_{1}^{\text{warp}}}{V_{12}^{\text{warp}}} & G_{12}^{\text{warp}}
\end{bmatrix}
\]

(2)

\[
Q_{\text{wef}}(90) = \begin{bmatrix}
E_{2}^{\text{wef}} & \frac{V_{21}^{\text{wef}}E_{2}^{\text{wef}}}{V_{12}^{\text{wef}}} & 0 \\
\frac{1}{1-V_{21}^{\text{wef}}V_{12}^{\text{wef}}} & \frac{1}{1-V_{21}^{\text{wef}}V_{12}^{\text{wef}}} & 0 \\
\frac{V_{12}^{\text{wef}}E_{2}^{\text{wef}}}{V_{21}^{\text{wef}}} & \frac{V_{12}^{\text{wef}}E_{2}^{\text{wef}}}{V_{21}^{\text{wef}}} & G_{12}^{\text{wef}} \\
0 & \frac{1}{1-V_{21}^{\text{wef}}V_{12}^{\text{wef}}} & 0 \\
0 & \frac{V_{12}^{\text{wef}}E_{2}^{\text{wef}}}{V_{21}^{\text{wef}}} & G_{12}^{\text{wef}}
\end{bmatrix}
\]

(Q rotated over 90 degrees) (3)

The expressions (1,2,3) are expressions from the CLT, defining the stiffness matrix of a 
material. Since the weave is build up from the warp and weft fibres expression (4) is found.

\[
Q_{\text{weave}} = \alpha Q_{0}^{\text{warp}} + \beta Q_{0}^{\text{wef}}
\]

with \( \alpha \) and \( \beta \) as multipliers for unbalanced weaves. From (4) four expressions can be found. 
When the terms \( (1-V_{pq}V_{qp}) \) are neglected (they are near unity, table 1 and therefore 
neglectable) expressions (4,6,7 & 8) are found. Incorporating the terms \( (1-V_{pq}V_{qp}) \) make 
these expressions non-linear, and therefore a bit more difficult to solve. For sake of clarity 
this is not shown.

\[
G_{xy} = \alpha G_{12}^{\text{warp}} + \beta G_{12}^{\text{wef}}
\]

(5)

\[
v_{xy}E_x = \alpha v_{xy}E_{1}^{\text{warp}} + \beta v_{xy}E_{2}^{\text{wef}}
\]

(6)

\[
E_x = \alpha E_{1}^{\text{warp}} + \beta E_{2}^{\text{wef}}
\]

(7)

\[
E_y = \alpha E_{2}^{\text{wef}} + \beta E_{1}^{\text{warp}}
\]

(8)

From micro mechanics [6] the following estimations are used:
\[ E_{1}^{\text{warp}} = E_{f}^{\text{warp}} V_{f}^{\text{warp}} + E_{m} V_{m} \]  
(9)

\[ E_{2}^{\text{warp}} = \frac{E_{f}^{\text{warp}} E_{m} (1 + 2V_{f}^{\text{warp}}) + E_{m} E_{m} (2 - 2V_{f}^{\text{warp}})}{E_{f}^{\text{warp}} (1 - V_{f}^{\text{warp}}) + E_{m} (2 + V_{f}^{\text{warp}})} \]  
(10)

\[ E_{1}^{\text{weft}} = E_{f}^{\text{weft}} V_{f}^{\text{weft}} + E_{m} V_{m} \]  
(11)

\[ E_{2}^{\text{weft}} = \frac{E_{f}^{\text{weft}} E_{m} (1 + 2V_{f}^{\text{weft}}) + E_{m} E_{m} (2 - 2V_{f}^{\text{weft}})}{E_{f}^{\text{weft}} (1 - V_{f}^{\text{weft}}) + E_{m} (2 + V_{f}^{\text{weft}})} \]  
(12)

Expressions (7) to (12) contain 6 unknowns: \( E_{1}^{\text{warp}}, E_{2}^{\text{warp}}, E_{1}^{\text{weft}}, E_{2}^{\text{weft}}, E_{f}^{\text{warp}}, E_{f}^{\text{weft}} \) of which only the first four need to be known, that is when we suppose that \( E_{m} \) and the volume fractions are known. Supposing that \( v_{12} \) is the same for warp and weft UD, expression (13) can be deduced from expression (6).

\[ v_{12} = \frac{v_{xy} E_{y}}{\alpha E_{2}^{\text{warp}} + \beta E_{2}^{\text{weft}}} \]  
(13)

Supposing that

\[ \frac{E_{2}^{\text{warp}}}{E_{2}^{\text{weft}}} = \frac{G_{12}^{\text{warp}}}{G_{12}^{\text{weft}}} \]  
(14)

and combining this with expression (5) the shear stiffness (G) of warp and weft can be estimated. In this way the properties of two UD’s can be determined from a fabric.

**METHOD II:**

This method takes a different approach and is based on the assumption that the \( v_{12} \) of the warp and weft UD is the same and has a value of 0.27, as is often seen in literature [7,...,13]. This value is close to most values of glass/aramid and carbon UD’s. Combining this with expression (6), (7) and (8) leaves on extra expression needed to find values for \( E_{1}^{\text{warp}}, E_{2}^{\text{warp}}, E_{1}^{\text{weft}}, E_{2}^{\text{weft}} \). The forth expression is found by assuming that the weft contribution in the warp direction and the warp contribution in the weft direction can be neglected (dividing expression (7) by expression (8) and neglecting the small terms):

\[ \frac{E_{x}}{E_{y}} = \frac{\alpha E_{1}^{\text{warp}}}{\beta E_{1}^{\text{weft}}} \]  
(15)

The value for \( G_{12} \) is estimated in the same way as in method I.

**METHOD III:**

This method takes the same approach as method II, only the fourth expression is obtained from a different assumption: The stiffness of the warp and weft UD perpendicular to the fibre direction is the same:

\[ E_{2}^{\text{warp}} = E_{2}^{\text{weft}} \]  
(16)

The value for \( G_{12} \) is estimated in the same way as in method I. Note that since \( E_{2}^{\text{warp}} = E_{2}^{\text{weft}} \) \( G_{12}^{\text{warp}} equals G_{12}^{\text{weft}} \)
COMPARISON OF THE METHODS I, II & III

From literature [7,..., 13] many values for different UD’s can be found. In table 1 some reasonable average values are listed.

<table>
<thead>
<tr>
<th>material</th>
<th>property</th>
<th>$E_1$(GPa)</th>
<th>$E_2$(GPa)</th>
<th>$G_{12}$(GPa)</th>
<th>$v_{12}$</th>
<th>$1-v_{12}v_{21}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass epoxy (Vf 45%)</td>
<td></td>
<td>38.6</td>
<td>8.27</td>
<td>4.14</td>
<td>0.26</td>
<td>0.9855</td>
</tr>
<tr>
<td>Carbon epoxy (Vf 50%)</td>
<td></td>
<td>181</td>
<td>10.3</td>
<td>7.17</td>
<td>0.28</td>
<td>0.9955</td>
</tr>
<tr>
<td>Aramid epoxy (Vf 60%)</td>
<td></td>
<td>79</td>
<td>4.1</td>
<td>1.5</td>
<td>0.31</td>
<td>0.9950</td>
</tr>
<tr>
<td>Average resin</td>
<td></td>
<td>3.4</td>
<td>3.4</td>
<td>1.3</td>
<td>0.35</td>
<td>-</td>
</tr>
</tbody>
</table>

The comparison is done in the following way:
1) Combine the properties of two original UD materials into one set of properties for a non sheared fabric.
2) Derive from the non sheared fabric properties two sets of derived UD materials properties.
3) Combine the properties of two original UD materials into one set of properties for a sheared fabric.
4) Combine the properties of two derived UD materials into one set of properties for a sheared fabric.
5) Compare the properties of the fabrics as found by step 3 and step 4.
The first step is done for the three UD’s, creating seven fabrics (glass-glass; carbon-carbon; aramid-aramid; glass-carbon; carbon-glass; aramid-carbon; carbon-aramid), which are balanced in three different ways (90-10, 70-30, 50-50 and 10-90), giving a total of 28 fabrics.
The second step derives from these twenty eight different fabrics UD properties which are calculated according to method I, II and III.
The third step is to combine the original UD’s to sheared fabrics with shearing angles from 0 degrees (not sheared) to 85 degrees (5 degrees between the UD’s)
The fourth step is similar to the third, only the derived UD’s are used.
The fifth step compares the values of the step three and step four. From the stiffness matrix found for every fabric, the $E_x$, $E_y$, $G_{xy}$ and $v_{xy}$ are estimated, and although many of the fabrics are not balanced, and the axes used are not the main material axes, so these engineering properties are not what they should be, comparisons can still be made. The x-axes is defined for all fabrics as the direction of the warp UD. The $E_x$, $E_y$, $G_{xy}$ and $v_{xy}$ are compared and the errors found are shown in table 2. Comparing these properties is not that wrong, since they all originate from the stiffness matrix which is valid in all cases.
From the values found in table 2 it is clear that Method I can not predict unbalanced fabrics in a reasonable way. Even for balanced fabrics Method I is less then Method II.
It is also found that Method II and Method III give the same results for balanced fabrics, as could be expected.
An overall result is that Method III gives in most cases the best prediction.
It is also clear that fabrics with aramid fibres show larger errors in the results. This is most probably due to the fact that aramid fibres themselves are anisotropic as well.
<table>
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<tr>
<th>Material &amp; Property</th>
<th>Glass/Cloth</th>
<th>Carbon/Cloth</th>
<th>Aramid/Carbon</th>
<th>Glass/Cloth</th>
<th>Carbon/Cloth</th>
<th>Aramid/Carbon</th>
</tr>
</thead>
<tbody>
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<td>Unbalanced: Warp 10% of the fibres, Weft 90% of the fibres</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ex I</td>
<td>16.99</td>
<td>3.73</td>
<td>34.69</td>
<td>4.35</td>
<td>12.56</td>
<td>22.99</td>
</tr>
<tr>
<td>Ex II</td>
<td>3.09</td>
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<td>1.60</td>
<td>24.93</td>
<td>8.17</td>
<td>36.35</td>
</tr>
<tr>
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<td>1.91</td>
<td>2.76</td>
<td>1.36</td>
<td>0.99</td>
</tr>
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<td>15.31</td>
<td>12.60</td>
<td>58.67</td>
<td>11.42</td>
<td>15.80</td>
<td>12.69</td>
</tr>
<tr>
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<td>5.42</td>
<td>10.19</td>
<td>29.38</td>
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<td>45.80</td>
</tr>
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<td>1.81</td>
<td>6.72</td>
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<td>1.05</td>
<td>2.00</td>
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<td>7.37</td>
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<td>10.77</td>
<td>17.52</td>
<td>54.79</td>
</tr>
<tr>
<td>vxy II</td>
<td>14.67</td>
<td>38.23</td>
<td>4.64</td>
<td>35.57</td>
<td>20.76</td>
<td>44.84</td>
</tr>
<tr>
<td>vxy III</td>
<td>3.08</td>
<td>2.23</td>
<td>8.12</td>
<td>2.58</td>
<td>2.90</td>
<td>6.42</td>
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</tbody>
</table>
Table 2 Continued Error percentages caused by the three different methods

<table>
<thead>
<tr>
<th>Material Property &amp; method</th>
<th>Glass/ Glass</th>
<th>Carbon/ Carbon</th>
<th>Aramid/ Aramid</th>
<th>Glass/ Carbon</th>
<th>Carbon/ Glass</th>
<th>Aramid/ Carbon</th>
<th>Glass/ Aramid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unbalanced fabric: Warp 70% of the fibres, Weft 30% of the fibres</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Ex</td>
<td>0.65</td>
<td>0.12</td>
<td>2.20</td>
<td>0.56</td>
<td>0.17</td>
<td>3.85</td>
<td>4.14</td>
</tr>
<tr>
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<td>1.62</td>
<td>0.97</td>
<td>0.24</td>
<td>8.51</td>
<td>0.67</td>
<td>6.91</td>
<td>3.35</td>
</tr>
<tr>
<td>III</td>
<td>0.83</td>
<td>0.27</td>
<td>0.82</td>
<td>0.27</td>
<td>0.14</td>
<td>0.88</td>
<td></td>
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<tr>
<td>Ey</td>
<td>14.33</td>
<td>14.62</td>
<td>171.85</td>
<td>12.77</td>
<td>17.29</td>
<td>89.21</td>
<td>30.28</td>
</tr>
<tr>
<td>II</td>
<td>1.98</td>
<td>5.51</td>
<td>8.69</td>
<td>16.85</td>
<td>7.01</td>
<td>42.89</td>
<td>12.37</td>
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<td>2.21</td>
<td>9.08</td>
<td>0.72</td>
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<td>3.71</td>
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<td>17.92</td>
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<td>6.88</td>
<td>30.47</td>
<td>5.44</td>
<td>11.79</td>
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<td>2.48</td>
<td>2.17</td>
<td>2.58</td>
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</table>

CONCLUSIONS

Fabrics sheared and non sheared are unknown types of materials to the current FEM based programs. Therefore the properties of the (sheared) fabrics must be provided in such a way that FE programs can handle them. One way of accomplishing this is by splitting a non sheared fabric into two UD materials. The shearing effect can then be provided by stacking the UD materials under the right angles. Since the properties of a non sheared fabric are not sufficient for calculation of the UD properties directly, assumptions need to be made so reasonable values for the properties of UD materials can be established. It appears that:

- by defining the Poisson’s ratio to a value of 0.27 and
- by assuming the same value for the Young’s modulus in the transverse direction of the two UD’s as well as
- by assuming the ratio of the shear modulus of the two UD’s equals to the ratio of the Young’s modulus in the transverse direction of the two UD’s

a set of stiffness properties for sheared fabric material can be obtained, that will satisfy the designer needs for estimations of product properties.

REFERENCES

4 Miravete A. 3-D Textile reinforcements in composite materials, Woodhead publishing limited, 1999
6 Jones R.M., Mechanics of composite materials, Hemisphere publishing corporation, 1975
8 Phillips, L.N., Design with Advanced Composite Materials, The Design Council/Springer-
Verlag, 1989


