STIFFNESS OF THE SKINS OF 3D-KNITTED COMPOSITES

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SUMMARY: Open 3D-knitted composites have been around for several years now. So far, most of this time was used to adapt the 3D-knitted textiles for composite applications. Some preliminary work was presented earlier on the bending properties of these materials [1]. In this paper, one takes a closer look at the skin stiffness which depends on the material properties but also to a large extent on the geometry of the unit cells. One of the most important parameters will be the degree of expansion of these cells. The properties of the skins are studied by 3point bending tests on the full sandwich structure. These results are then compared with the stiffness obtained from tensile tests on the skins. The relation between the results of these two methods seems to be linear but the bending tests always underestimate the real skin stiffness. A third method to determine the skin stiffness uses Finite Element Modelling. Here, the influence of all kinds of parameters was examined and these results were then compared with those from experiments.

KEYWORDS: Knitted fabrics, textiles, sandwich structures, stiffness, modeling, skin.

INTRODUCTION

Since several years research has been done on open 3D-knitted composites. These composites are based on knitted distance fabrics which resemble the more known classical honeycomb structures (Fig. 1). So far, most publications explained the concept of 3D-knits and described the processing of the textile into a composite. Some early results on bending and compression properties have been reported and the main parameters were pointed out [1].

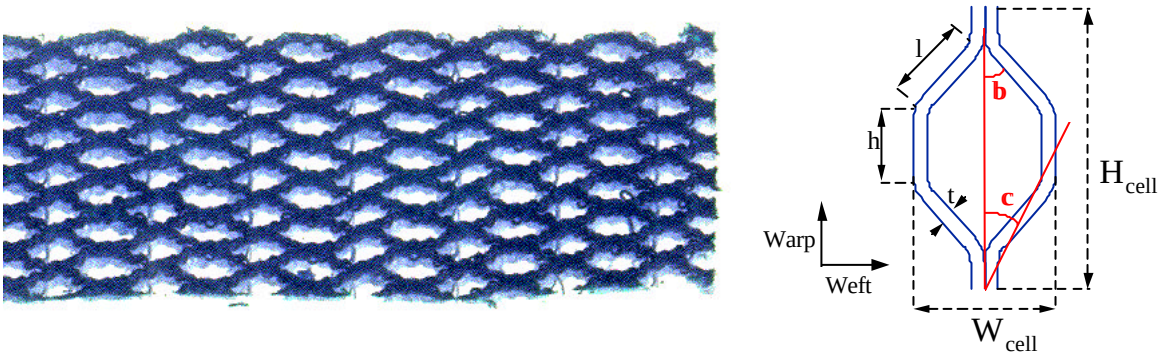
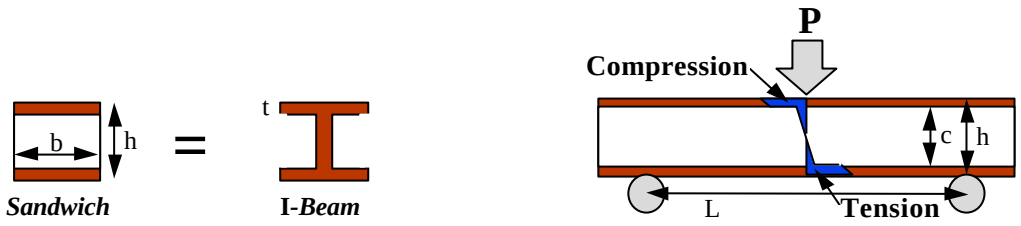


Fig. 1: 3D-knitted composite sample used for bending and compression tests. The basic parameters for the hexagonal unit cell are indicated in the right figure. ***b*** *is the hexagonal degree of expansion,* ***c*** *is the rhombic degree of expansion.*

However, understanding the bending behavior of these materials is not so easy because the material does not completely behave like standard sandwich structures. Sometimes the stiffness of the skins obtained by tensile tests deviates from the values that were calculated from bending tests. To get a better understanding of the mechanics of the skins, tensile tests were carried out and a model was set up to study the influence of geometrical parameters.

SKIN STIFFNESS OBTAINED FROM 3POINT-BENDING TESTS

The stiffness of 3D-knitted composites can be described according to the so-called sandwich theory (Fig. 2). From the classical sandwich theory follows that when a force P is applied during a three-point bending test then the resulting displacement (Δ) is given by equation 1:



$$\Delta = \Delta_{bending} + \Delta_{shear}$$

$$= \frac{PL^3}{48D} + \frac{PL}{4N} \qquad (1)$$

P: applied force

L: span length in a bending test

D: bending stiffness of the skins ($D = \frac{Eb(h^3 - c^3)}{12}$)

N: core shear stiffness (= G.A = G$\frac{b.(h-t)^3}{c}$)

E: E-modulus for the skins

G: core shear modulus

Fig. 2: Schematic presentation of a sandwich structure during 3point-bending tests. The corresponding formulas are shown as well.

With equation 1 it should be possible to calculate the Youngs' modulus E of the skins and the shear modulus G of the core by doing only two bending tests with different span lengths. Two parameters are unknown so that at least two tests are needed to find them. This method is very simple, but it is unlikely that it will lead to good results unless it is known that one span length is large enough to make sure that the deflection is mostly due to bending. The other span length should be small enough to ensure that the deflection is mostly due to shear [2].

One method to improve reliability is by doing more bending tests on different span lengths and following a specific data reduction scheme. The disadvantage is of course that it takes more time to do the tests, but the results will be more reliable. In this study span lengths of 80, 100, 120, 140, 160 and 180mm were applied. In fact, this choice of span lengths is not yet optimal because the variation is not large enough. However, when the span length would be chosen larger, then the measured force would be very low. Span lengths shorter than 80mm are not possible either because the thickness of the samples has to be much smaller than the span length.

$$\frac{\Delta}{PL} = \frac{L^2}{48D} + \frac{1}{4AG} \qquad (2)$$

$$\frac{\Delta}{PL^3} = \frac{1}{48D} + \frac{1}{4AGL^2} \qquad (3)$$

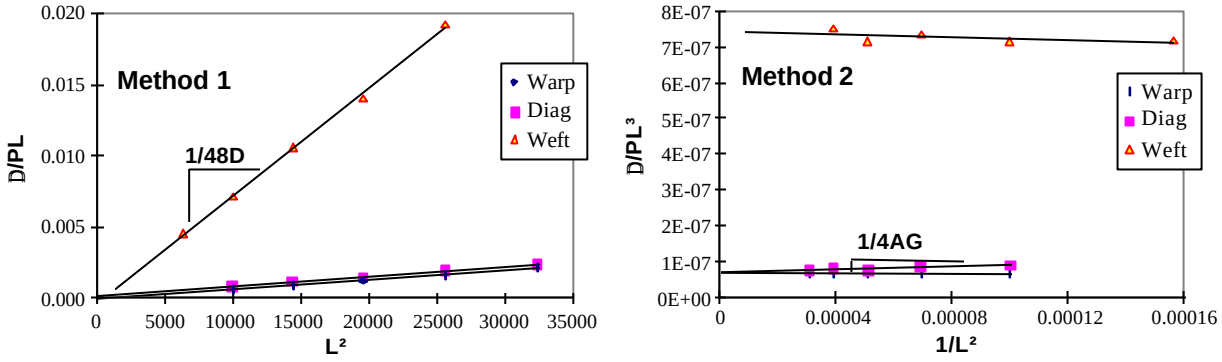


Fig. 3: Bending results plotted according to the two calculation methods.

To calculate the skin bending stiffness D and the core shear stiffness G, the previous formula will have to be rewritten like in equation 2 & 3. In the left graph, the different experimental values of Δ/PL are plotted versus their respective L^2 and the experimental points are then fitted with a straight line. From this it is clear why more data points are needed: the more points and the more widely they are spread, the better the fit will be. The slope of this line is equal to 1/48D in the case of a three-point bending test while the intercept of this line with the y-axis equals 1/4AG where A equals $b(h-t)^2/c$. Because the slope of a line is calculated by interpolation between data points and the intercept is calculated by extrapolation, this method will give the best results for estimating the value of D.

Another reason why this intercept method does not always lead to good results for G is that for small span lengths, the local bending of the skins can become important. The value of G can hence better be calculated with a second method. Here the second formula is used and Δ/PL^3 is plotted versus $1/L^2$. The slope of the fitted line is 1/4AG and the intercept with the y-axis is 1/48D.

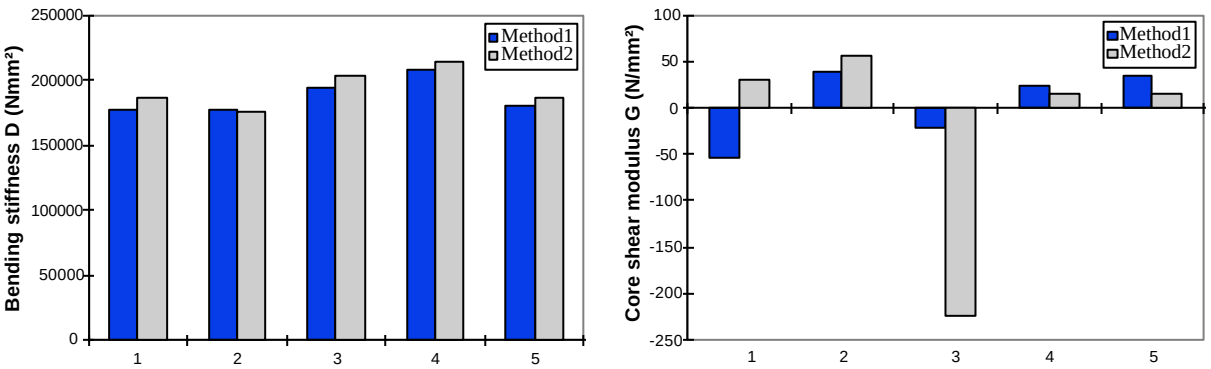


*Fig. 4: Comparison of the two methods for calculating the bending stiffness D (**left**) and the core shear modulus G (**right**) for one batch of 3D-knitted composite test samples. The values for D look OK but those for G are not correct. (k20 warp; 63 w% resin; **c** =21°).*

The previous procedure has been carried out for all bending tests. Unfortunately the results were not so good. Fig. 4 shows the results for one batch of test samples. The values of D and G were calculated using two data reduction schemes. Both methods yield exactly the same results for D and

the spread between the results was very small. On the other hand, the calculation of G seems less convincing. The two calculation methods give quite different results. What is worse, sometimes negative values for G are obtained and these are physically not possible at all. For this reason, it was decided to test these properties separately. The results of tensile tests on the skins will be presented in the next paragraph. The shear tests will not be discussed in this paper.

SKIN STIFFNESS OBTAINED FROM TENSILE TESTS

The stiffness of the skins of 3D-knitted sandwich structures was measured by doing tensile tests. The bending samples are used as a hole. They are not cut, only at the ends, the core is filled with additional resin which is cured. This is needed to clamp the samples with the hydraulic grips of the INSTRON machine. The sample will not have out-of-plane deformations because the two skins compensate for each other. A big advantage is that the samples can be reused for doing shear tests when the ends are cut off. Of course this is only allowed if the sample has only been deformed elastically.

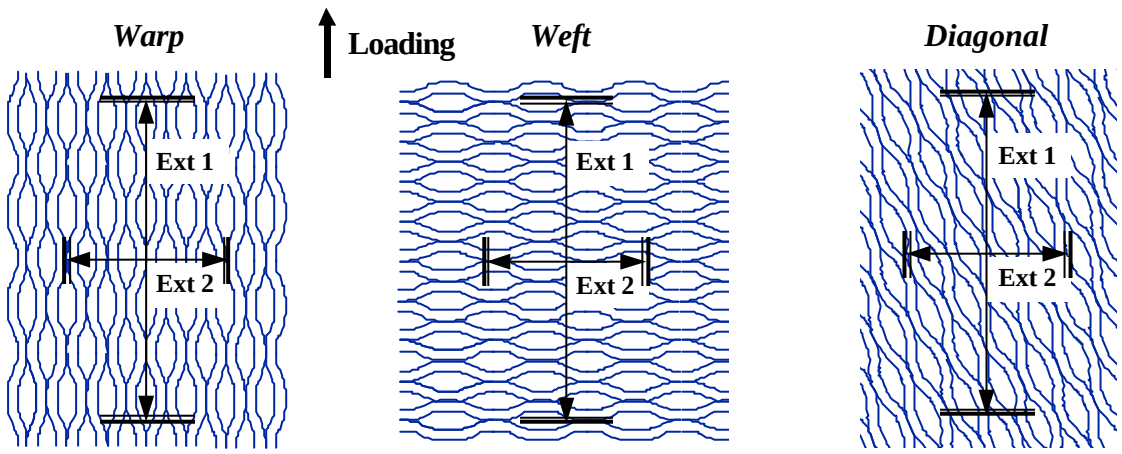


Fig. 5: Three types of tensile samples were used: warp, weft and diagonal direction. Each time, two extensometers were applied to be able to calculate the Poisson's coefficient too.

The tensile tests were carried out on an INSTRON 4045 machine with a constant cross-head speed of 2mm/min and hydraulic grips were mounted to clamp the specimen. Because of the expected inhomogeneous deformation it was decided to mount extensometers onto the test specimen instead of using the cross-head displacement (Fig. 5). An extensometer with a gauge length of 50mm was placed in the length direction of the specimen. The other extensometer had a gauge length of 25mm and was positioned in the transverse direction.

Table 1: Description of the test samples for bending and tensile tests.

Knit	***Thickness (mm)***	***Resin content (w%)***	***Glass content (m/m)***
k20	5.5	56-63	1.2
k19	7	50-52	4.6
k21	8	45-49	4.3

Table 1 describes the test samples which are used for the mechanical tests. Fig. 6 presents the stiffness of the skins for three types of composites (k19, k20, k21) for both warp and weft direction. For the ***warp direction***, the stiffness decreases rapidly when the degree of expansion increases. When the rhombic angle χ varies from 20° to 30° the stiffness is already reduced by a factor of two. To have a better comparison it is worth noting that the stiffness of 2D-knitted composites is typically between 10-15GPa. The values for 2D-woven composites are situated somewhat higher between 20-30GPa. The reason for this big difference is of course due to the large holes in the 3D-knitted skins. Another aspect that can be noticed in Fig. 6 is that all curves show the same profile in the investigated interval.

It is also nice to see that the glass content of the skins does have an influence after all. So far, this influence could not be seen clearly in the results for bending tests because there was a lot of interference with other parameters. Knit k19 has the highest stiffness because it has 4.6m of glass per meter of beam element. Knit k21 has 4.3m while k20 only has 1.2m of glass yarn in the skins.

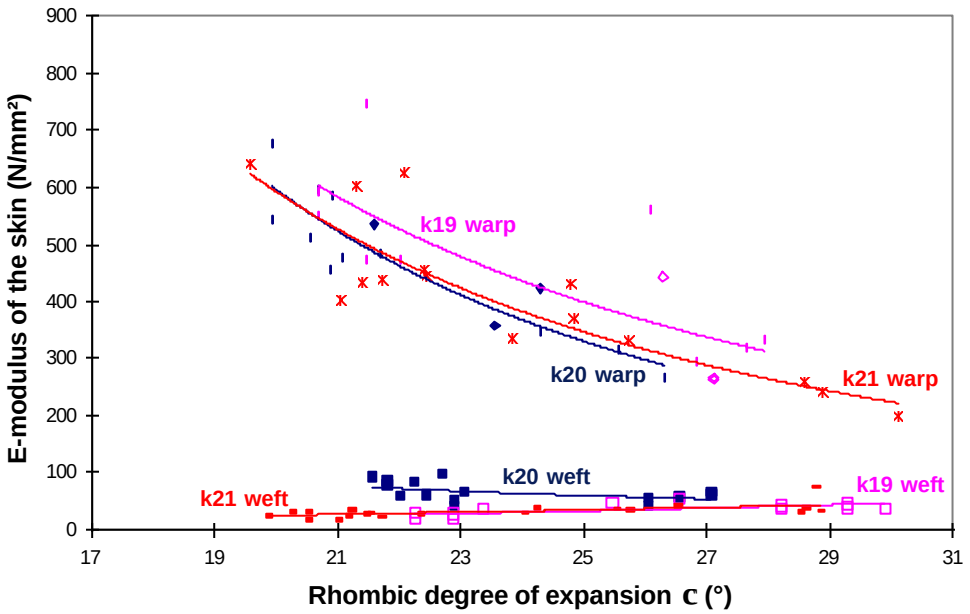


Fig. 6: E-modulus of warp and weft skins plotted versus the degree of expansion c(°).

On the other hand, knit k21 seems to have a low performance. One would expect the curve of k21 to be situated closer to that of k19 because they have a similar glass content. The resin content is on average lower for k21 (47w%) than for k19 (51w%). Although this difference is not that big, visual observations show that knit k21 has not been impregnated enough. Also, the loop structure in k21 is not so nice as in k19. In k19 the loops have a regular structure and they are denser while the loops in k21 are more like those of k20. k21 has a lot of holes in the knitted beams that are not filled because of the low resin content hence reducing the stiffness.

Another reason is that for those three knits, the glass has been knitted in a different ways. In k21 the glass is curved more than in k19 and of course much more than k20 where the glass is more or less "straight". Furthermore, the cells in k21 are larger because h and l are bigger. This will lower the relative areal density of the material and hence also the mechanical properties.

For the ***weft direction***, the skin stiffness increases slightly when the reinforcing textile has been expanded. In fact when χ changes from 20° to 30° the stiffness increases by a factor of two (k19 & k21). It is the inverse situation compared to the warp direction, but anyway the stiffness remains very low. Samples k19 and k21 seem to behave exactly the same while k20 performs better in this direction. The stiffness of k20 is higher but it decreases as χ goes up. This is not really expected because it looks like the glass does not have an influence in this direction. Probably this difference is due to the resin content or the resin distribution.

From visual inspections, it can be seen that the resin in k19 and k21 has been absorbed inbetween the fibers and this is why these samples are not so shiny. For k20 the resin is present on top of the fibers as well, so that these samples reflect more light. Some of the resin is present in the hinges between the beams (Fig. 7). It is probably this resin that is responsible for the "increased" stiffness of the weft direction for k20.

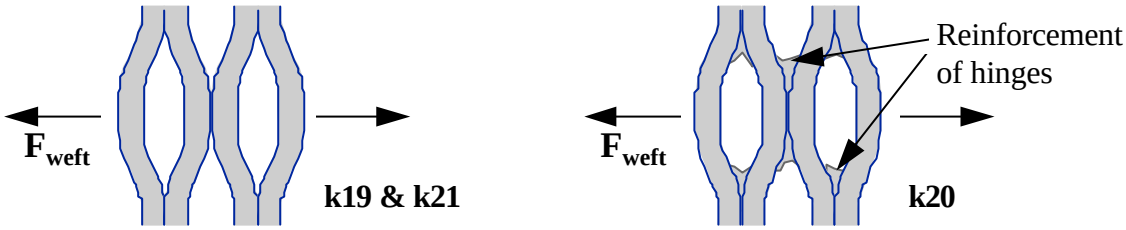


Fig. 7: E-modulus of warp and weft skins plotted versus the degree of expansion c(°).

The results for the ***diagonal direction*** are more difficult to interpret (Fig. 8). For two types of composites (k20 and k21) there does not seem to be any dependence of the stiffness on the degree of expansion χ in the range 20-30°. For the other material (k19) there is a clear dependence on the angle.

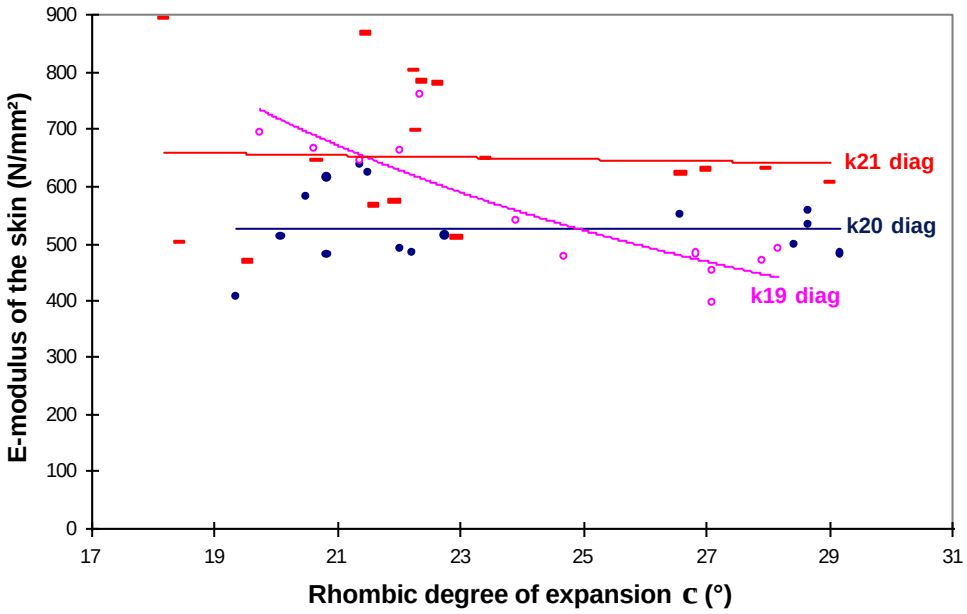


Fig. 8: E-modulus of diagonal skins plotted versus the degree of expansion c(°).

To explain this, one should look at the type of loads that are present during the tensile tests in diagonal direction. In principle there are mainly tensile forces in the beams that are oriented parallel to the loading direction. Beams that are inclined to this axis will mainly be subjected to bending moments. For the warp samples, most deformation will occur due to bending of the single beams which are inclined. For the diagonal samples those single beams are more parallel to the loading axis and will hence be subjected to tensile forces. For these samples the double beams are inclined to the loading axis so that they will be subjected to bending. However, these double beams are twice as wide as the single ones and this means that their moment of inertia is eight times bigger. The same is true for their bending stiffness.

The conclusion here is that the tensile stiffness of the single beams will play a more dominant role while doing tests in the diagonal direction. With this in mind one could explain the larger difference between k20 and k21 as follows. Sample k21 has three times more glass in the beam elements than k20 has. Of course in k20 this glass is straighter and for this it should be more effective. However, there simply is much less present to make a difference.

COMPARISON OF BENDING AND TENSILE RESULTS

So far, the stiffness of the skins was calculated in two ways. The first was to use the sandwich theory to estimate the skin stiffness. Two calculation methods were used and both gave the same results. However, there was still some uncertainty about the correctness of these results. For this it was decided to measure the skin stiffness in an other way, namely with tensile tests. In this paragraph, both methods will be compared.

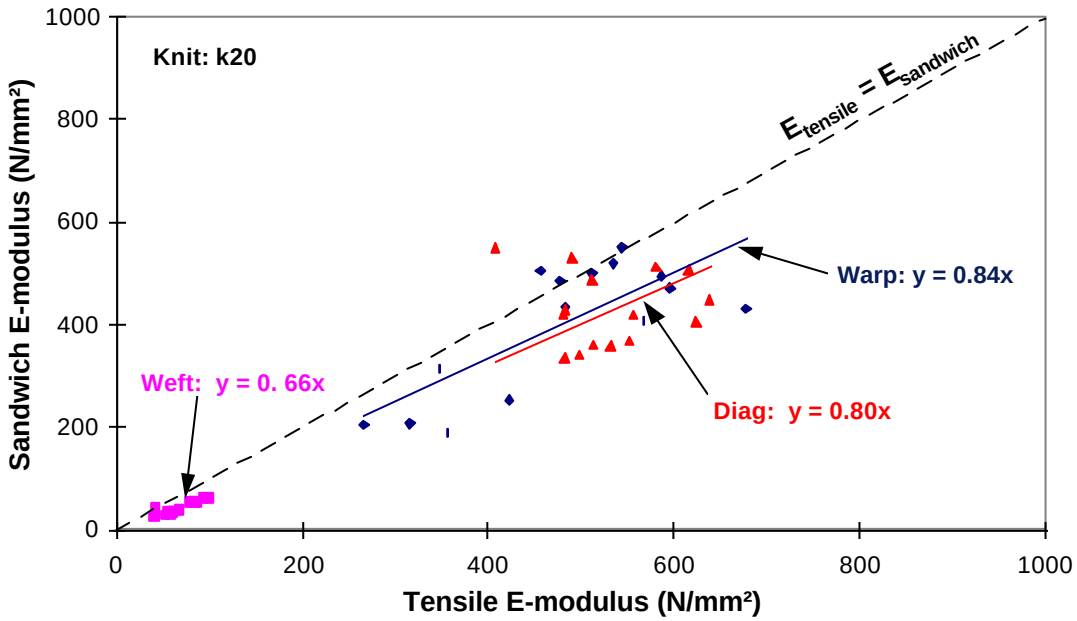


Fig. 9: Comparison of the skin stiffness measured with tensile tests and calculated with the sandwich theory from bending tests. The results are plotted separately for the three directions and this is done for one type of material (k20).

Fig. 9 presents the stiffness calculated with the sandwich theory and this was plotted versus the corresponding value obtained with tensile tests. For each direction a linear regression line was calculated and the slope of these lines was indicated. In theory both methods should yield the same result which means that all data points should be positioned on the diagonal of the figure. In practice the E-modulus as calculated from the sandwich theory is a bit too low. In the present case, the values are 20% too low for the warp and diagonal directions. For the weft this is even more than 30%.

For the other materials a similar picture could be shown. However, since there was not a lot of difference between the warp and diagonal direction for one material, it was decided to group all the data from warp, weft and diagonal direction. A regression line was calculated for each type of material. This can be seen in Fig. 10.

Some interesting conclusions can be drawn from this figure. Material k19 seems to be the closest to the theoretical value. This means that this material behaves the most like a sandwich structure if only the skin properties are considered. On the other hand, material k20 already deviates 20%. The reason for this is probably that there is quite a lot of interaction between the core and the skins because of the presence of resin feet. Besides, the material is quite thin so the sandwich effect is not so pronounced. For material k21 the deviation is even bigger (30%).

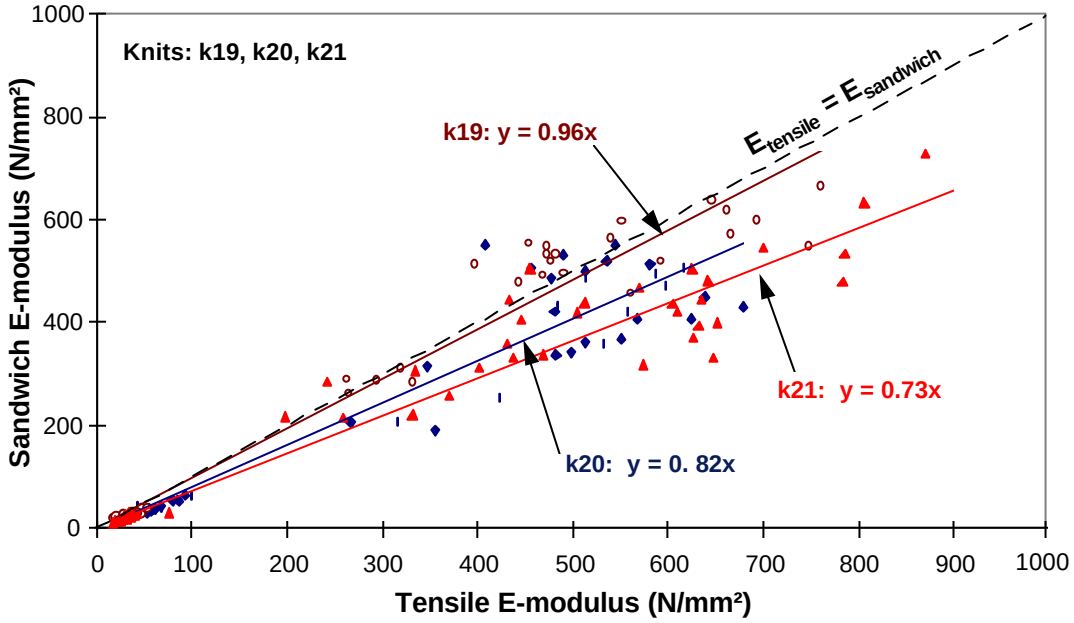


Fig. 10: Comparison of the skin stiffness measured with tensile tests and calculated with the sandwich theory from bending tests. The results are plotted for three types of material (k19, k20, 21). No distinction was made between the directions.

MODELLING OF THE SKIN STIFFNESS

Fig. 11 shows the influence of the double and single beam length h and l on the stiffness of the skins in the warp direction as a function of the degree of expansion (β). The beam thickness t was kept constant because only the ratios h/t and l/t are important. One type of sample has been used as a reference and its geometrical data can be found in the graph.

From the graph, several conclusions can be drawn. First of all, the stiffness decreases extremely fast when the fabric has been expanded more. At an angle of 20° the stiffness of the referenced sample is 1.5GPa. When β reaches 90°, the stiffness is already ten times lower. It must be mentioned that in practice, 3D-knitted composites will have an angle β typically between 25° and 60°. Even then, the stiffness is still very low when compared to other composites. E.g. comparable composites like those based on 2D-knits typically have a stiffness in the range of 10-15 GPa, while the epoxy resin itself has a stiffness of around 2.7 GPa. The reason why the stiffness is so low is due to the large holes in the skins which make up more than half of the surface area. The maximum stiffness that can ever be reached in the warp direction is the stiffness of the beam elements (3.2GPa). This was shown earlier.

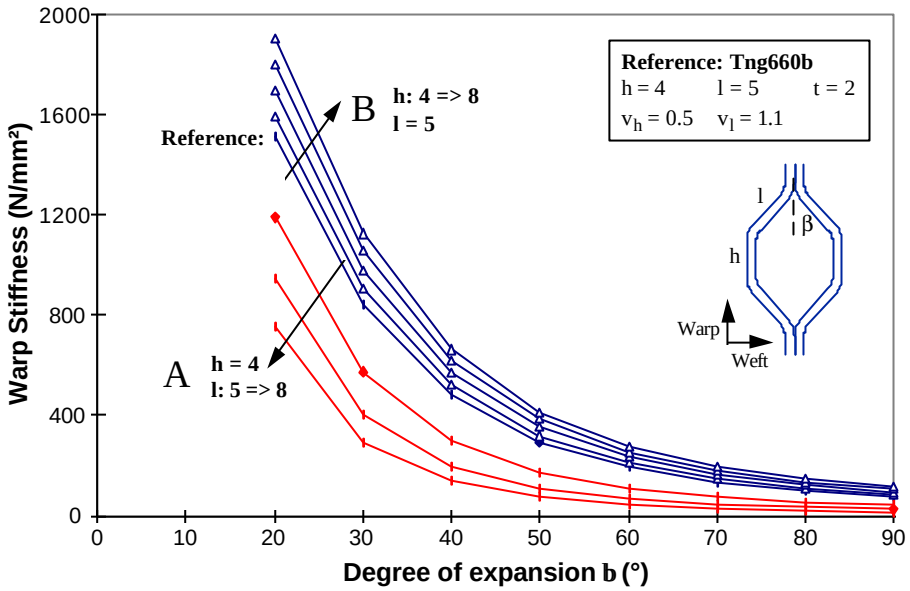


Fig. 11: Influence of the basic dimensions of the unit cell (h, l, t) on the stiffness of the 3D-knitted composite skins in the warp direction. The parameter t is fixed.

The curves in the graph can be divided in two groups: in group A the parameter l has been varied while group B looks at variations in the parameter h. The easiest way to understand these results is to look at the corresponding unit cells plotted in Fig. 12. Each time l is increased, the corresponding skin stiffness is going down drastically (A). The parameter l is in fact the length of those beams that are subjected to bending loads and the bending resistance is proportional to $1/l^3$. The longer the beam, the lower the resistance. On the other hand when h is increased (B), the skin stiffness goes up steadily. The reason for this can once again be seen from the unit cell. When h increases, relatively more beams are oriented in the tensile direction (warp) and hence most beams are subjected to tensile loads. In other words, less beams are subjected to bending which is a more severe case of loading.

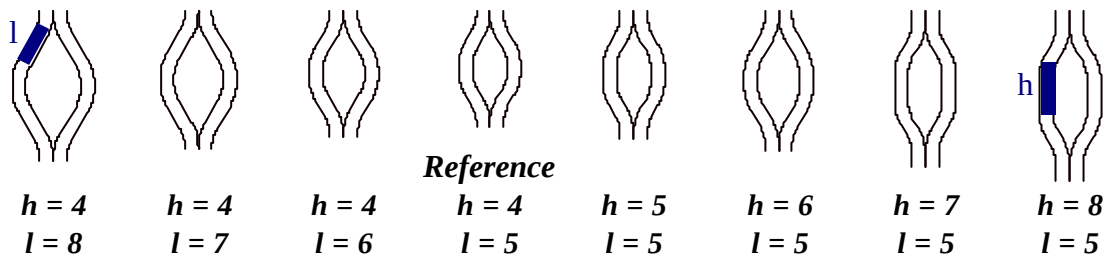


Fig. 12: View of the cell geometry of the samples used in the previous graph.

So far, all data was plot versus the degree of expansion β. However, this β is not a really practical parameter, it is more of theoretical use. In fact, it more interesting to plot the data versus the rhombic angle χ as was done in the experimental part. These results are not shown here since the graphs are very similar because the relation between β and χ is almost linear. A more interesting and practical way to present the data is to plot it as a function of the areal density. Here, the relative areal density ρ_{rel} (%), is preferred. This relative areal density is proportional with the real areal density in g/m² for the composite.

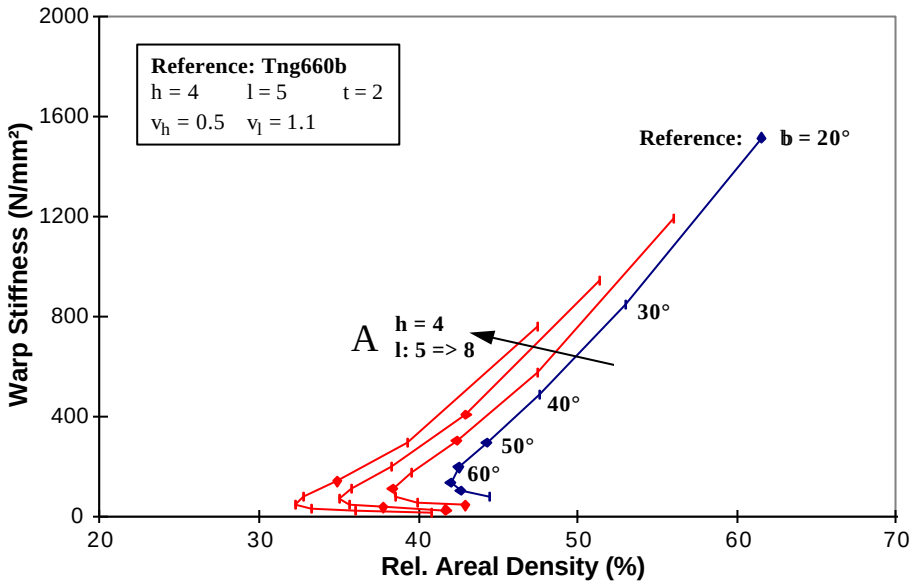


Fig. 13: Influence of the parameter l on the warp stiffness of the 3D-knitted composite skins plotted as a function of the relative areal density.

Some very interesting results can be seen in Fig. 13. The relation between the warp skin stiffness and the relative areal density is almost linear. Only at high degrees of expansion (70° or more) the dependence is not linear anymore. For real 3D-knitted composites, β varies between 25° and 60° which is exactly the region where the curves are linear. Once again one can see a difference between groups A and B. For group A (Fig. 13), the curves for different values of l have a similar shape, but they have been deformed. For group B, similar curves can be drawn.

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