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Problematic of composite materials with woven reinforcement

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Since the beginning of the production of composites, one of the most common forms of reinforcement is woven structure, i.e., fabric. Although accepted for general use without reservation, this form of reinforcement is shown to have its limits in certain areas of application. During the development of deformation members for the automotive industry, we encountered a problem where fibers that seemed very suitable for this purpose lost half of their ability to absorb energy due to weaving in. This led us to a more detailed analysis of the behavior of the fiber structure in the form of a plain weave.

We tried to explain the differences in the behavior of the material in the form of the yarn itself and in the form of a woven structure by the process itself of weaving-in the yarn. So to a certain extent we chose a mezzo scale approach, thus. The first thing we encounter when trying to describe a fabric is determining its geometry. It is of course possible to proceed experimentally, but this approach requires a former knowledge of the specific fabric, either in the form of a laminated composite or in another form. Since viscose fabric is not a common article, we

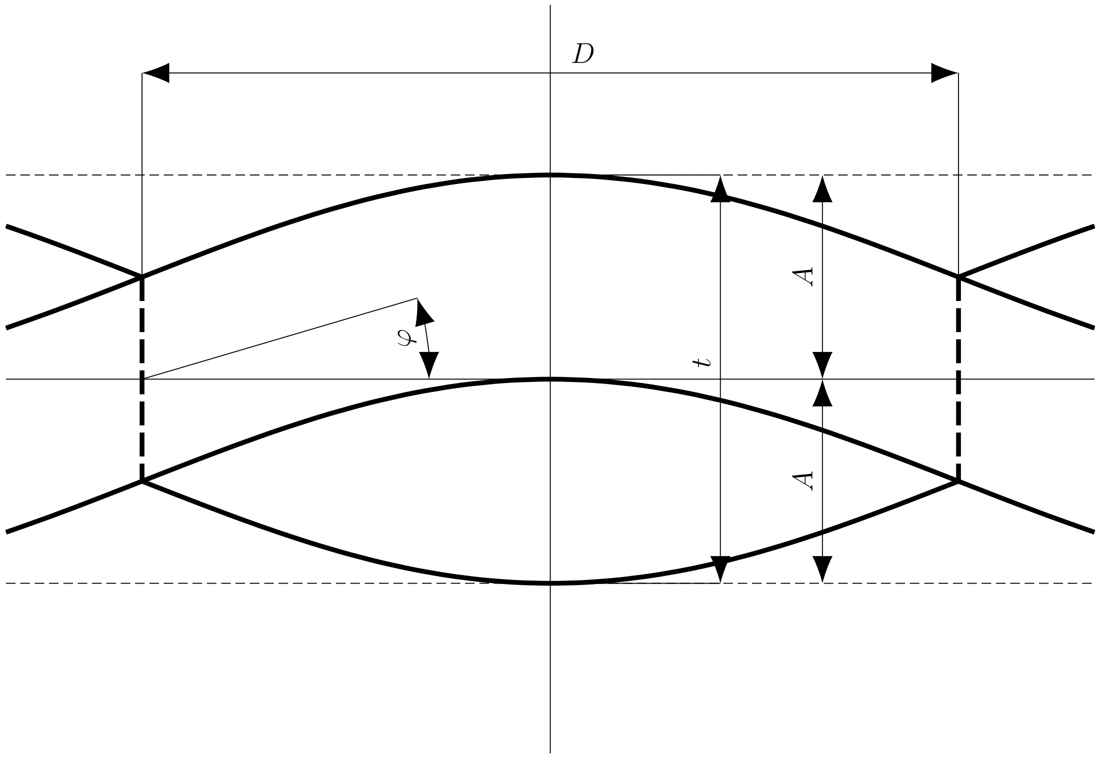

Fig. 1. Description of a plain weave fabric geometry at mezzo scale

did not have this knowledge available, so we proceeded using geometric notions. We modeled the fabric using sine waves with a sinusoidal cross-section, see Fig. 1. This idea is used in the so-called lens model of fabric, however, in general it is not used either to determine the thickness of the fabric neither to determine other parameters that have an effect on the mechanical properties and properties affecting the resulting composite, for example the volumetric ratio of reinforcement.

Let us assume to be known all the characteristic parameters of the fabric in plain balanced weave, i.e., two of following three parameters are given: either the area density γ ($[\gamma] = \frac{\mathrm{kg}}{\mathrm{m}^2}$) or density of weft yarns d_1 ($[d_i] = \frac{1}{\mathrm{m}}$) and that of warp $d_2 = d_1$ or fineness $\lambda_1 = \lambda_2$ ($[\lambda] = \frac{\mathrm{kg}}{\mathrm{m}}$) of both yarns. Let us assume the circular cross section of individual filaments, too; this assumption is well respected for glass or carbon. As the helix angle of the filaments in a yarn is very flat the filaments can *freely* reposition and thus, their most compact layout is in hexagonal mesh, see detail in Fig. 2. Maximum volumetric ratio of filaments in a yarn is then given by geometry of this hexagonal cell

$$v_{f,yarn} = \frac{\pi}{2 \cdot \sqrt{3}} \doteq 0.9. \tag{1}$$

Volume of yarns in the cell bounded by the boundaries of one binding point is (see Fig. 1)

$$V_f = \frac{4}{\pi} \cdot A \cdot D^2.$$

As the thickness is $t = 2 \cdot A$, the volumetric ratio of yarns in the cell then is

$$v_{f,cell} = \frac{V_f}{2 \cdot A \cdot D^2} = \frac{2}{\pi}. \tag{2}$$

Taking into account the relation (1), we get the final formula for the maximal volumetric ratio

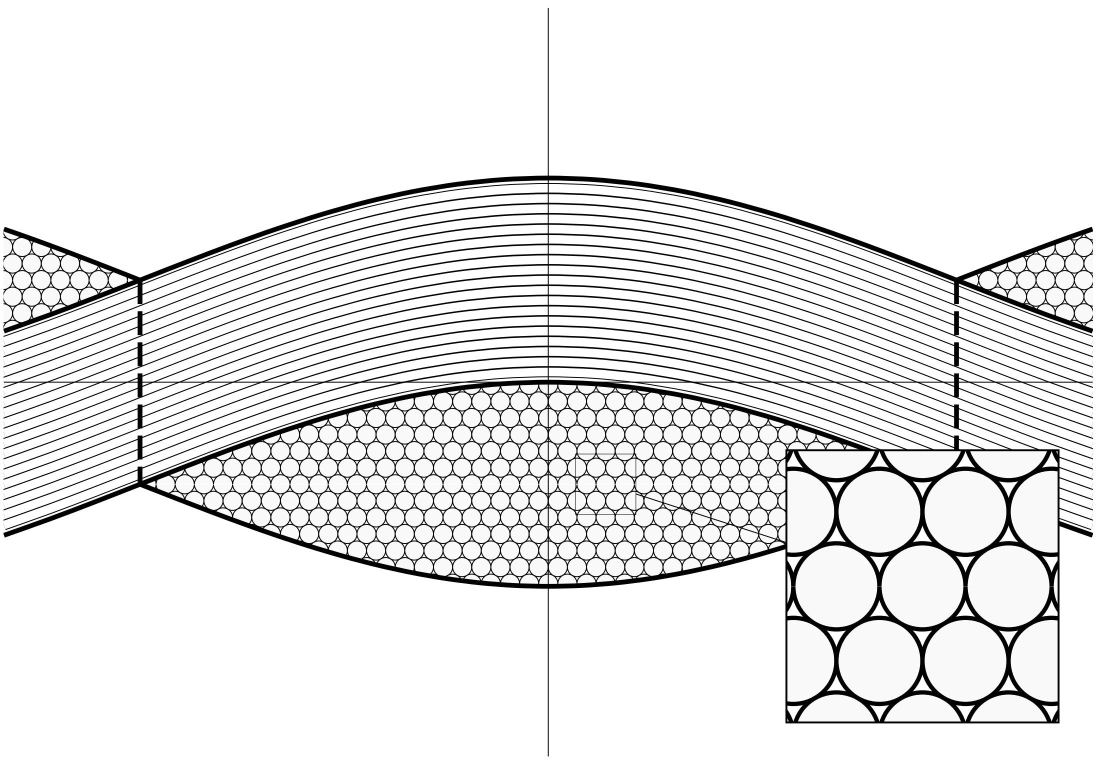

Fig. 2. Description of a plain weave fabric geometry at micro scale

of reinforcement in a plain weave fabric

$$v_{f,max} = v_{f,yarn} \cdot v_{f,cell} = \frac{1}{\sqrt{3}} \doteq 0.58. \tag{3}$$

A few additional notes:

1. This value is valid for fabrics with high density of yarns d_i. It may be higher for very flat yarns (tapes, narrow rovings) in the specially designed fabrics.

2. This value does not depend on the weave (i.e., theoretically it is the same for twill or satin weave), its prove lies outside of the scope of the presented work. However, the weaves other than plain are prone to become more easily flat when under pressure which affects the real value of v_f.

3. In practice it is possible to exceed slightly this limit value by using for example very high pressure to compact the plies in a laminated composite.

4. Higher values of v_f reported by experimenters are not to be necessarily wrong, the measured values depend strongly on the experimental procedure.

The fabric thickness is the key value when modeling a fabric ply, e.g., using FEM. With respect to (3) and using parameters of the fabric, we get

$$t = \frac{\gamma}{\rho} \cdot \sqrt{3}, \tag{4}$$

where γ is the area density of fabric and ρ is density of the yarn material. It is certainly interesting that the value determined following (4) tends to be much closer to the real thickness of the fabric ply in a laminated composite than the value determined experimentally following the ASTM D1777 – 96 (2019) standard [1].

Another phenomenon that relates closely to the woven composite reinforcement is the waveness of the yarn. In fact it was this effect of yarn undulation that has brought us to the problems of the woven reinforcements. Once the geometry based on fabric parameters is known we can easily calculate the real length of the corresponding section of yarn as well as the crossing angle φ of yarns. As the fabrics are relatively flat (the report between t and D is of order 0.1), corresponding elongation of yarn is around 1%. This seems to be very low but in reality it *consumes* non negligible part of available yarn strength. This is all the more important the stiffer the fibers are. Thus the final strength of the fabric is significantly lower than the sum of the strength of individual yarns comprised in the corresponding fabric width.

Even with known (calculated or measured) strength values of a fabric reinforced composite the calculations are complicated by drawbacks of used failure criteria. In a general-use FEM software such bidirectional reinforcement is usually modeled by superposing two unidirectional plies. This is often done internally during preprocessing using classical theory of composites and the resulting values of moduli and strength are used for FEM computations. The most used failure criterion of composites in postprocessing then is that of Tsai-Hill (or its variant Tsai-Wu) which, however, are derived for unidirectional cross isotropic materials [2]. So for a fabric ply it should be used either the full Hill criterion either some of its variations for appropriate material properties. It has to be said that there are dedicated FEM software that offer to take this difference into account. For example, for the balanced fabric working under in-plane stresses and with the same behavior in traction and compression, we have $R_l = R_t$ in-plane strengths, a different value for normal-to-ply direction R_n and of course values for shear strength R_{lt} and $R_{ln} = R_{tn}$. We get the criterion in the following form:

$$\kappa = \frac{(\sigma_l - \sigma_t)^2}{R_l^2} + \frac{\sigma_l \cdot \sigma_t}{R_n^2} + \frac{\tau_{lt}^2}{R_{lt}^2}.$$

As can be seen, the value of such a criterion depends strongly on the out-of-plane *intralaminar* strength R_n (not to be confused with interlaminar strength). This value is unfortunately difficult to measure. One possible way to determine it theoretically could be by using known fabric geometry at mezzo scale with given strengths of yarns and matrix, but this approach has not been explored yet.

While working on the rayon fabric, we faced quite surprising, albeit simple, challenges; just to describe the fabric geometry without time-consuming experiments is not completely obvious. On the other hand, it turned out that the mechanical properties of woven reinforcements are in principle limited and the fabric cannot fully utilize the quality of the yarns. The use of woven reinforcement in composite materials must therefore be strictly justified. In many cases, especially in the one where a pseudo-isotropic stacking is to be used, there is an alternative to using reinforcement fibers in the form of a much cheaper mat.

References

[1] ASTM D1777-96(2019) Standard test method for thickness of textile materials, 2019.

[2] Gay, D., Composite materials, Éditions HERMES, Paris, 1991. (in French)