A BIPHASIC MODEL TO PREDICT THE COMPRESSION STRENGTH OF MISALIGNED THERMOPLASTIC COMPOSITE

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Abstract
A bi-phasic micro-mechanical model has been used to evaluate compression strength of continuous fiber thermoplastic composite. Fibers are supposed purely elastic, and their architecture is defined by a simple geometrical model where the misalignment angle is the main parameter. The matrix material is described through a complex viscoplastic model. The strain state in the matrix due to the misalignment is computed, and the fiber angle and matrix stresses are therefore updated with an explicit time-integration method. Simulating a compression test, a maximum stress appears when the misalignement angle grows suddenly due to the plastification of the surrounding matrix, which can be interpretated as kinking.
Numerical results are compared to experimental data on glass/PP and carbon/PA66. Good correlations are obtained for the first material. Same tendancies are observed for the second, but with an over-estimation of the strength at low angle of misalignement.

1. Introduction

To answer the needs of low cost industries, new materials and new processes are developed by the composite material industry. As a promising solution, the forming of pre-impregnated thermoplastic composite sheet is currently intensively studied [1]. Several automotive demonstrator parts already exist.
In this type of material, the compression strength is one of the most critical design values. Compare to an aeronautic grade composite material, a formed thermoplastic composite sheet presents lower compression strength [2] due to:

- the use of less stiff matrices
- the waviness of fibers resulting from coarse fabrics or forming process (up to 30°!)

2. Biphasic Kinking Model

Through two PhD thesis [3][4], GeM laboratory has developed a bi-phasic micro-mechanical model. The representative volume of the material is schemed in figure 1. The material parameters are :

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- The elastic modulus and the failure strain of the fiber (which may be found in supplier datasheet)
- The stress/strain curve in uniaxial tension of the matrix (possibly simplified in intial modulus, yield stress/strain and ultimate stress/strain, whichmay be found in supplier datasheet)
- The fiber volume fraction, the warp/weft ratio, and the geometric description of the fiber (as in **Figure 1.** , representing for example half of a fabric elementary cell) : Initial misalignement angle θ_i, length of misaligned fiber l_θ and length of well-aligned fiber l_d.

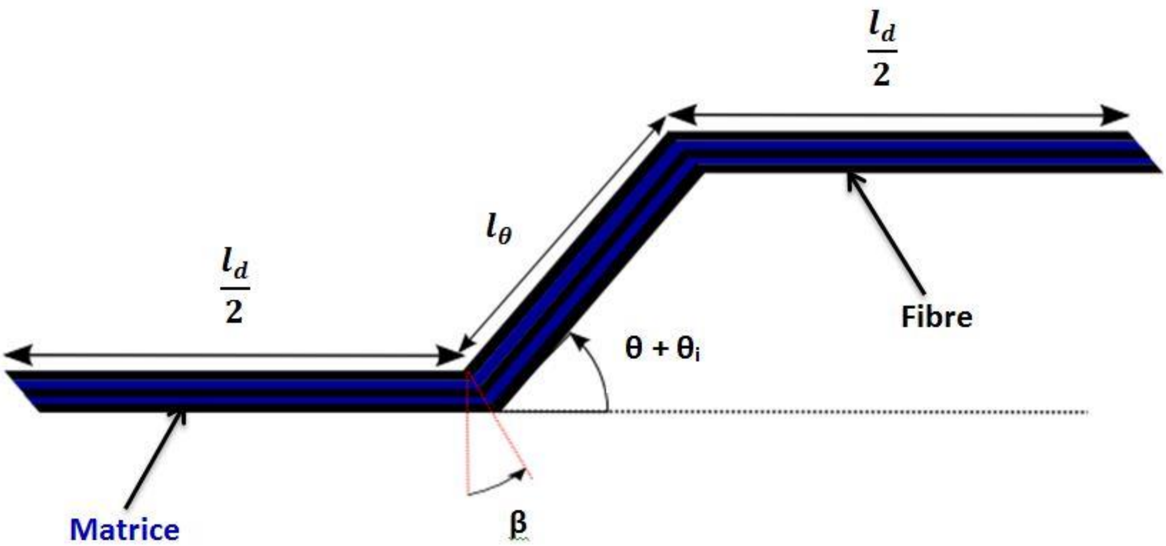

Figure 1. schematic view of fiber misalignment.

Two additional properties, more difficult to find, are needed :

- The bulk modulus of the matrix, which may be found in literature [5]
- The kink band angle β, that can be seen on a compression test sample, or choose between 25° and 40° according to [3]

The matrix behavior is derived from Drozdov'smodel [6]. Details for detailed model implementation as explicit FEA material law can be found in [3]. Time step for theses calculations has been checked to be small enough to give stable results (1% precision) compared to smallest time step. The hydrostatic part of the matrix behavior is supposed elastic:

$$\bar{\bar{\sigma}}_{m,hydro} = K_m 3Tr(\bar{\bar{\varepsilon}}_m)\bar{I} \tag{1}$$

$\bar{\bar{\sigma}}_{m,hydro}$: matrix hydrostatic stress tensor; K_m : matrix bulk modulus ; $\bar{\bar{\varepsilon}}_m$: matrix strain tensor

The plastic part of the strain is defined as a part of the total strain, defined by a function updated at each time step, when the initial or already reached elastic maximum strain is reached.

$$\frac{d\bar{\bar{\varepsilon}}_{m,pl'}}{dt}(t+dt) = \Phi(t+dt)\,\frac{d\bar{\bar{\varepsilon}}_{m'}}{dt}(t) \tag{2}$$

$\bar{\bar{\varepsilon}}_{m,pl'}$: matrix plastic deviatoric strain tensor ; Φ : Drozdov function (see eq. 3); $\bar{\bar{\varepsilon}}_{m'}$: matrix deviatoric strain tensor

This Drozdov function is defined by a differential equation, whose coefficient are calibrated to match the strain-stress curve of the matrix.

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$$\frac{d\Phi(t)}{d} = A\dot{\varepsilon}_m(1-\Phi(t))B \quad (3)$$

A, B : drozdov law coefficient ; $\dot{\varepsilon}m$: Frobenius norm of the matrix deviatoric strain increment

Finally, the matrix stress is calculated thanks to the bulk and deviatric modulus of the matrix. Then the composite stress is calculated by homogeneization of matrix and purely elastic fiber.

$$\bar{\bar{\sigma}}_m = 2\mu_m(1-\phi)\bar{\bar{\varepsilon}}'_{m,el} + \bar{\bar{\sigma}}_{m,hydro} \quad (4)$$

$\bar{\bar{\sigma}}_m$: matriw stress tensor ; μ_m : deviatoric modulus; $\bar{\bar{\varepsilon}}'_{m,el}$: matrix elastic deviatoric strain tensor

3. Experimental correlation

3.1. Glass/PP composite

Experimental data are available on Twintex material in [3] and [7]. This two authors use two different fabrics : balanced and fine (745g/m²) for [3], unbalanced 4:1 and coarse (1815g/m²) for [7].

- The fibre volume fraction , the elastic modulus and the failure strain of the fiber are calculated from [8] :
  - fraction = 35%
  - Failure module = Composite Modulus / (Fibre volume fraction * warp fibre ratio) E_f = 14 GPa / 35% * 50% =80 GPa
  - Failure strain = failure stress / modulus = 300MPa / 14GPa = 2,14%
- The stress/strain curve in uniaxial tension of the matrix are found (figure 3.12) in [7]. The material model is used to find :
  - μ_m = matrix modulus/2 = 700MPa
  - Initial elastic maximum strain = 0,1%
  - A = 20 ; B = 3

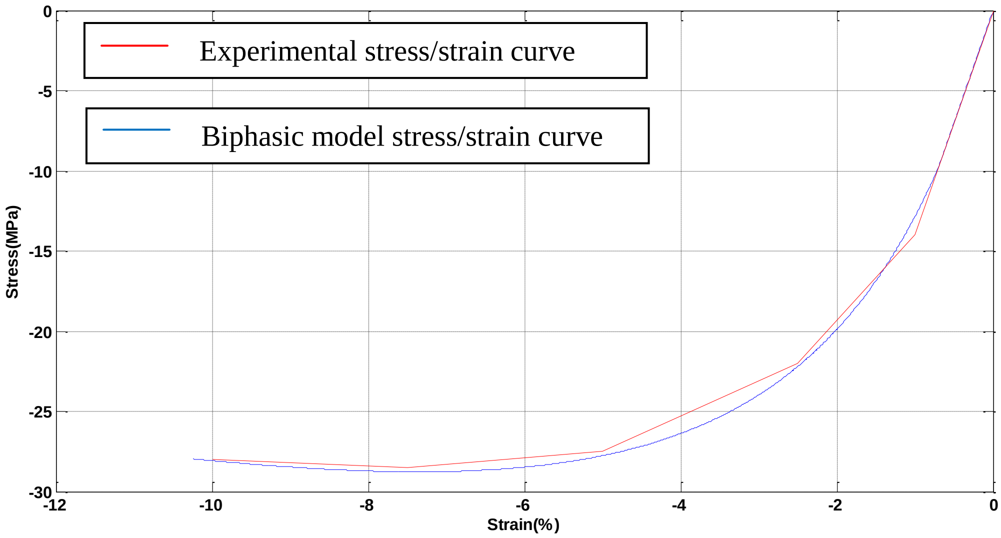

Figure 2. PP Matrix stress/strain curve

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Note that the behavior of the matrix far away the yield point is of weak interest as the kinking appears in the composite near this point.

- The geometric description of the fiber is derived from the fabric definition. We propose simple rules for this evaluation :
  - Misalignement amplitude is half of the ply thickness
  - Misalignement length is equal to the thread gap of perpendicular fibre
  - Length of well-aligned fiber depend of the fibre architecture, and may be estimated with simple scheme like **Figure 3.**

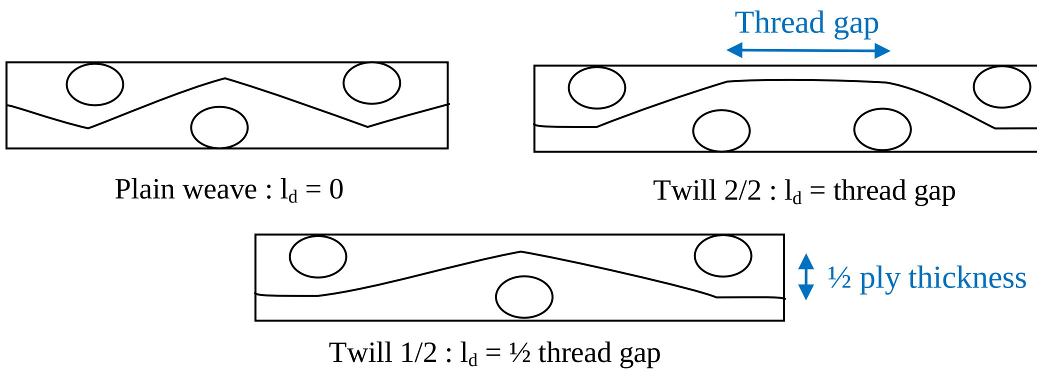

Figure 3. Geometric description of a fabric

Theses rules give the following results :

Table 1. geometric parameter of the evaluated Twintex fabrics

Warp and weft in [3]	**Theoric Warp in [7]**	**Corrected warp in [7]**	**Weft in [7]**
Ratio = 50%	Ratio = 80%	Ratio = 80%	Ratio = 20%
θ_i = arctan (0,25/2,5) θ_i = 0,10 rad	θ_i = arctan (0,6/13,3) θ_i = 0,045 rad	θ_i = arctan (0,6/4) θ_i = 0,15 rad	θ_i = arctan (0,6/3,3) θ_i = 0,18
l_θ = 2,5 mm	l_θ = 13,3 mm	l_θ = 4 mm	l_θ = 3,3 mm
l_d= 2,5 mm	l_d= 6,5 mm	l_d= 16 mm	l_d= 1,65 mm

Parameters are corrected for warp direction in [7] as it is obvious regarding the picture of the fabric (figure 2.11 in [7], **Figure 4.** Below) that, due to the high thread gap in weft direction, the misalignement of warp fibre is concentrated on 8mm around a weft thread, and not smoothed on 26,6mm. Note that in [3], the author measure on micrographic view θ_i = 0,08 rad and l_θ = 1,8 mm, close of our basic evaluation.

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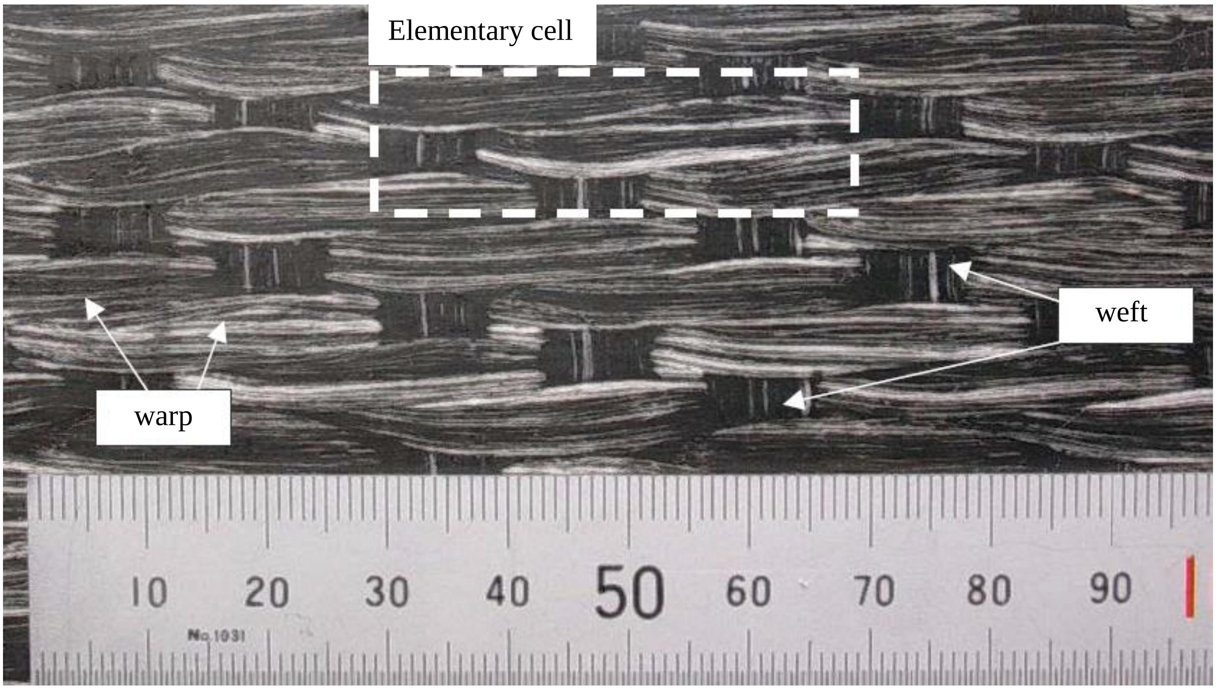

Figure 4. Picture of the twintex fabric from [7]

- The bulk modulus of the polypropylene is the same in [3] and [5] : K_m = 3,5 GPa
- The kink band angle β for this quasi-static test is found in [4] : β = 0,64 rad

The model is applied to the 3 types of composite defined **Table 1.** A stress/strain curve (**Figure 5.)** is obtained, and the maximum stress Xc is compared to the available experimental results. Note that the "post kinking" behavior is perturbed in the model by numerical "fiber vibration" that have not be treated yet.

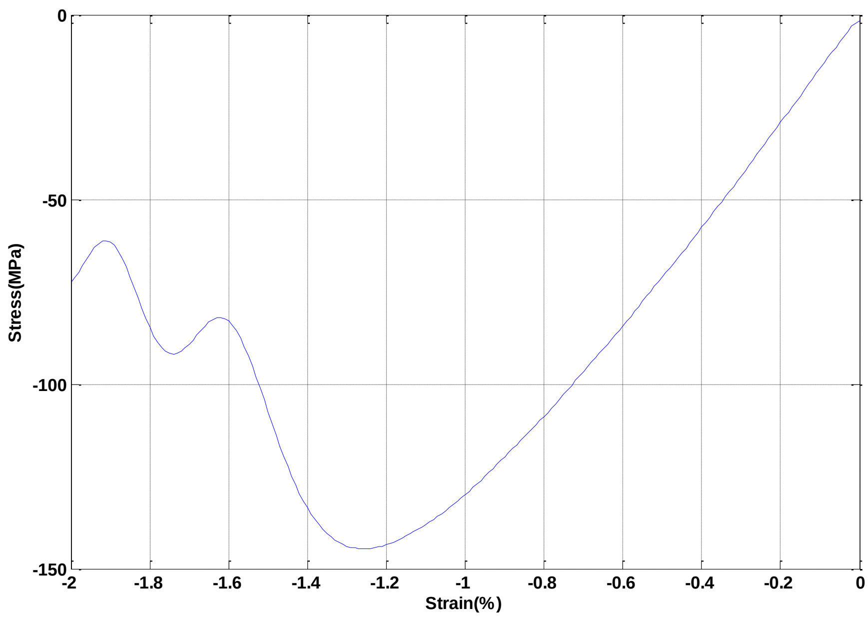

Figure 5. Stress/strain curve for Twintex fabric in [3]

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Experimental and numerical results are compared **Table 2.** below.

Table 2. geometric parameter of the evaluated Twintex fabrics

	Warp in [3]	**warp in [7]**	**Weft in [7]**
Numerical results	Xc = 145 MPa	Xc = 186 MPa	Xc = 37 MPa
Experimental results	Xc = 160 MPa +/-15%	Xc = 117 MPa +/-11%	Xc = 51 MPa +/-5%

Results are in fair agreement for warp in [3] and weft in [7]. Strength is overestimated for warp in [7]. That may be due premature failure of test coupons, as the author write that failure " is accompanied by the buckling of the fibers but also of the specimen.".

3.2. Carbon/PA66 composite

Working on effect on misalignement on mechanical characteristic, CETIM has used CELSTRAN CFR6TO PA66 CF60 from Celanese UD Carbon/PA6 to manufacture UD plate of thickness 2mm. Sample have been tested according ASTM D6641 standard. Fiber misalignement has been willingly created and measured, allowing to build a curve of composite compression strength versus misalignement angle (**Figure 6,** misalignement angle reported in abscissa is the maximum observed in the sample).

The Biphasic kinking model has been used to predict results. The material characteristic has been derived from provider datasheet for the fiber, and from a typical PA66 stress/strain curve (50% HR equilibrium) found in [9]. The material parameter are **Table 3.**

Table 3. Carbon/PA66 material parameter

Fiber	**Matrix**	**geometry**
Fibre volume fraction = 49%	μ_m = 750MPa	Warp Ratio = 100%
Failure module = 230 GPa	Initial elastic maximum strain = 0,1%	θ_i = 0,05 → 0,5
Failure strain = 2,1%	A = 14,5 ; B = 4	l_θ = 5 mm
Kink band angle β = 0,64 rad	K_m = 5050 MPa	l_d= 5 mm

Results of kinking model are **Figure 6.**

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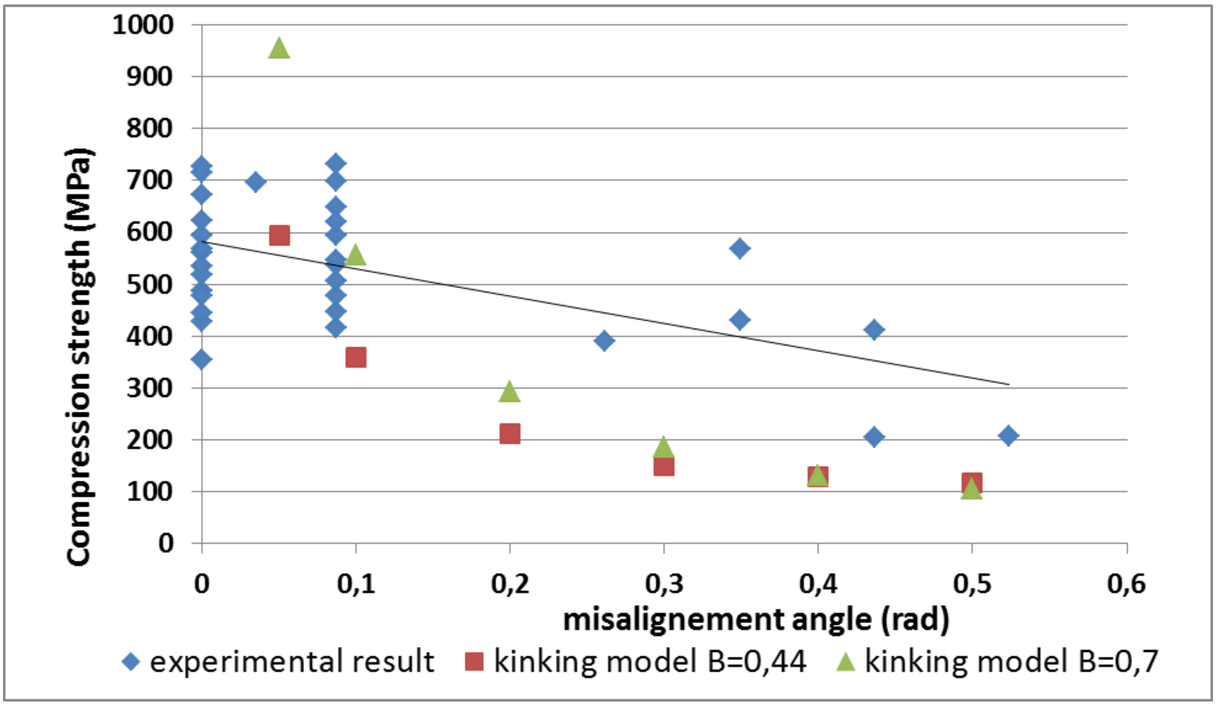

Figure 6. Compressive strength Xc of carbon/PA66

Experimentals results are highly variable beween 0 and 0,1 radian (6°) . This highlight the fact that fiber alignement is a key factor of performance, and hard to master and control for “low cost” forming process. Numerical results show good tendency but underestimated strength for high angle.
Main “uncertain” parameter influence has been checked (**Table 4**). Note that when μ_m is changed, A and B are adapted to to keep same yield point in the material curve.

Table 4. Influences on compressive strength Xc of some material parameters

	μ_m	β	l_d
μ_m = 750MPa And β = 0,44 rad And l_d= 5 mm	Xc = 360 Mpa	Xc = 360 Mpa	Xc = 360 Mpa
μ_m = 1250MPa Or β = 0,57 rad Or l_d= 50 mm	Xc = 403 Mpa	Xc = 439 Mpa	Xc = 585 Mpa
μ_m = 1750MPa Or β = 0,7 rad Or l_d= 135 mm	Xc = 406 Mpa	Xc = 556 Mpa	Xc = 930 Mpa

l_d has a strong influences on the results that isn’t physical. It comes from dynamical effects in the misalignement angle updated that are not relevant for this study. We recommend then to use l_d= 0mm. μ_m has a weaker influence on the results. β is therefore the main unknown parameter that

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can impact significantly the results. We note that with β=0,64 rad, as it was determined for polypropylene, we obtain Xc = 485MPa, in line with the experimental results.
Concerning the underestimation of the Compressive strength for high misalignement angle, it can be explained by the fact that the numerical model consider the defect on all the material, whereas a local maximum angle is reported. In the experience, the best-aligned fibers unload which are not, leading to higher compressive strength. Studying the modulus of the sample allow to correct results. The two weakest sample (Xc=~200MPa) have a mean modulus of ~38GPa. Such a modulus in the numerical model is obtain with θ_i = 0,22 rad, leading to a coherent compressive strength of 229MPa (with β=0,64 rad and l_d= 0mm)

Conclusion

The model developed by A. Martin and C. Priem allows to estimate the compressive strength of thermoplastic composite with mainly widely available material parameters. Tendancies and results level are globally coherent. But uncertain parameters (essentialy the kink band angle β and the fiber alignement geometry) remain. Additionnal works are then needed to develop a material estimator giving reliable results. At this stage, we recommend to use β=0,64 and θ_i = 0,1 if there no reliable date on the initial misalignement. The tensile modulus may be used to calibrate the deviation angle if the misalignement is significant and homogeneous on the tested volume. Otherwise, as the model predicts that strongly misaligned fiber produce very low compression strength, subtracting the defect area to the section of the sample may be the better way to estimate the residual strength of a structure.

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