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COMPRESSION STRENGTH OF CONTINOUS STEEL FIBER REINFORCED POLYMERS

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1 General Introduction

The compression behavior of unidirectional steel fiber composites has been studied as a part of a larger study exploring possible applications of steel fiber reinforced polymers. In contradiction to glass and carbon fibers, the mechanical properties of steel fibers are rather ductile and after the yielding point highly non-linear. An important compression failure mode in unidirectional composites is kink-band formation. For conventional unidirectional fiber composite the fiber misalignment and plastic deformation of the matrix material plays the important roles in the kink-band formation [1,2]. Taken into account the weak elastic non-linearity of carbon fibers, only a negligible influence on the kink-band formation has been identified [3]. On the other hand, general structural buckling is known to be influenced significantly on material non-linearity's where the buckling load depends on the instantaneous stiffness of the material. Steel fibers optimized with respect to the tensile strength may do to the Bauschinger effect show a low yield stress in compression, see e.g. [4]. This may influence the compression failure of the composite significantly [5].

2 Numerical model

Based on the individual non-linear elastic-plastic behavior of the fiber and matrix material, the compression failure is predicted using a plane strain 2-D smeared-out incremental composite material model formulated for finite strains and rotations by Christoffersen and Jensen [6-7] and implemented in the commercial finite element code Abaqus by Sørensen, Mikkelsen and Jensen [8] as a user defined material using the UMat user interface.

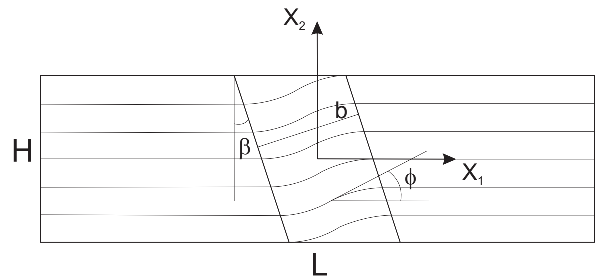

Fig.1. Initial horizontal fiber misalignments.

The finite element model has been used to predict the kink-band formation in a block of material under compression. In order to facilitate the kink-band failure mode, a small imperfection has been introduced in the initial aligned fibers as a small fiber waviness as shown in Fig. 1. The waviness has a maximal miss-alignment angle, ϕ_m, along a band width in the center of the material block. The band has the width b and is inclined with an angle, β, with respect the vertical direction of the block of material [8].

Both the steel fibers and the polymer matrix material are modeled using a standard isotropic power law hardening elastic-plastic material law following a J_2-flow theory. From this, we have that both the fiber and the matrix material in the composites are given by individual Young's modulus, E, Poisson's ratio, ν, initial yield stress, σ_y, and a hardening exponent, n. Together with the fiber volume fraction of the composite, c_f, this sums up to 9 material parameters in total for the composite.

The two incremental given material laws are combined into a smeared-out incremental composite law by using the Voigt and Reuss classical model, respectively, working along and transverse to the instantaneous fiber-directions in the composite [6].

3 Material behaviour

Based on non-linear steel fiber tensile curves, the non-linear composite tensile curve and the non-linear composite compression curve, the compressive non-linearity of the steel fiber has been extracted. In principle it should also be possible to extract the non-linear behavior of the matrix material from the tensile and compression test before failure, but do to the low matrix stiffness compared with the fiber stiffness, the polyester matrix properties has been taken from the literature. Assuming a power-law hardening behavior of the following form

$$\varepsilon = \begin{cases} \dfrac{\sigma}{E} & ,\sigma \le \sigma_y \\ \dfrac{\sigma_y}{E}\left[\dfrac{1}{n}\left(\dfrac{\sigma}{\sigma_y}\right)^n - \dfrac{1}{n} + 1\right] & ,\sigma > \sigma_y \end{cases} \tag{1}$$

the set of representative material parameters for compression used in the study is shown in Table 1. For all cases analyzed, the fiber volume fraction is taken to be $c_f = 0.4$. Do to the fact that the steel fiber material has been optimized in tension with a rather high yield stress and tensile strength on approximately 2GPa and 3GPa respectively with a hardening exponent on $n = 10$, the corresponding compression yield strength is found to be significant lower but with a significant steeper hardening curve

	E	ν	σ_y	n
Fiber	200GPa	0.3	700MPa	2
Matrix	3GPa	0.4	35MPa	5

Table 1. Elastic-plastic compressive power-law hardening material parameters for the constituents

Fig. 2 show the material response of a block of material when compressed in the horizontal direction. The initial fiber mis-orientation with respect to the horizontal direction is in the range $\phi \in [1^\circ;5^\circ]$. The simulations are performed using one 4-noded element why a homogenous deformation state is obtained. In Fig. 2, it can be seen that for small initial fiber mis-orientations, the yielding of the fibers will occurs before matrix material which are also indicated by the fact that $\sigma_y^f / E^f << \sigma_y^m / E^m$ in the specific case. The fiber yielding will be followed by a non-linear loading curve, which after yield in the matrix material will follow a strongly non-linear loading shortening path including extensive shearing of the matrix material, load-drop and snap-back behavior giving a very imperfection sensitive behavior on the material level. If the plastic yielding of the matrix material is suppressed, only a monotonic increasing load are predicted. A observation also found using other material parameters [9]. In the case of larger initial fiber misalignments, only matrix yielding is observed.

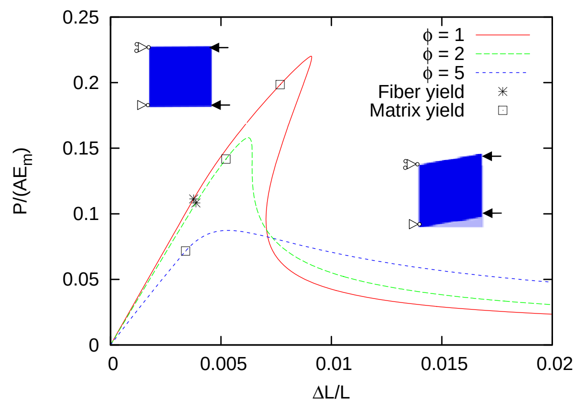

Fig.2. Compressive elastic-plastic material response of one linear element.

4 Kink-band predictions

In order to include the possibility of strain localization in the finite element model, a rectangular block of material with a height over length ratio on $H/L = 3/10$ under axial compression has been simulated using 30×100 4-noded linear elements. The unidirectional fiber orientation includes a small fiber misalignment with a smooth variation as shown earlier in Fig. 1. In the specific case, the imperfections parameters has been chosen to $\phi_m = 5^\circ$, $\beta = 5^\circ$ and $b/L = 2$ resulting in a fiber misalignment variation as shown in Fig. 3 where the contours shows the angle levels $\phi = 1^\circ, 2^\circ, 3^\circ, 4^\circ$ and 5°. Earlier simulations [8], shows only a weak influence of the β angle and the b value on the kink band formation. On the other hand there is a strong influence of the maximum misalignment angle ϕ_m on the kink-band formation and the load carrying capacity.

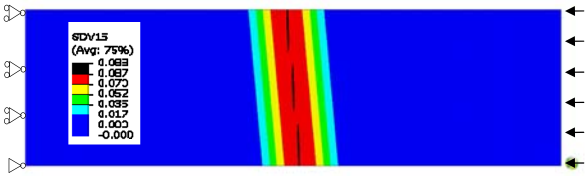

Fig.3. Initial horizontal fiber misalignment angles , ϕ , in the case with $\phi_m = 5^\circ$, $\beta = 5^\circ$ and $b/L = 2/10$.

The solid red curve in Fig. 4 show the load versus shortening curve for the steel fiber, polyester matrix case from Table 1. Corresponding to the case $\phi = 5^\circ$ from Fig. 2, the matrix material is yielding first, but now followed by a snap-back load versus shortening curve when the kink-band is forming. A local yielding of the fiber material inside the kink band occurs later in this process. The corresponding deformed structure are shown in Fig. 5 where the contours show the effective plastic strain of the matrix material. A plastic deformation which are only develop in the kink-band region. In [9] it was found that if the yielding behavior of the matrix material is suppressed, no kink-band will form and the block of material will then form a Euler column buckling mode.

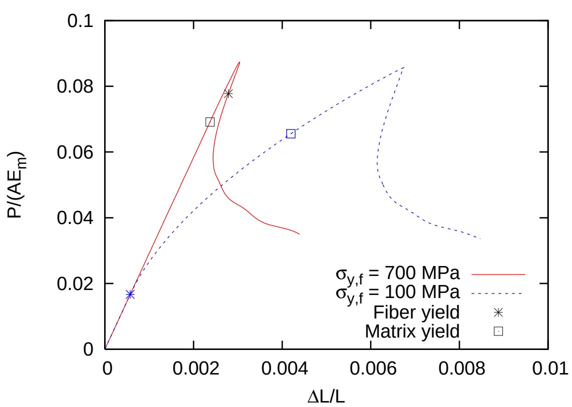

Fig.4. Load versus shortening curve for a block of material under compression.

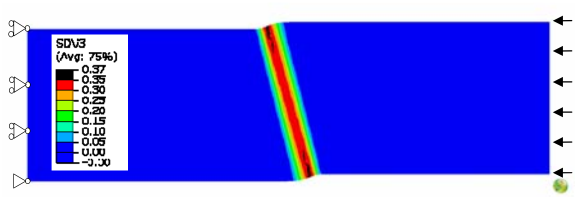

Fig.5. The contours of the effective plastic strain in the matrix material shown on the deformed structure.

The blue dashed curve in Fig. 4 show the corresponding case where the steel fiber material has been work harden even more in tension resulting in a lower compression yield stress. All other parameters are assumed to be unchanged. In this case, the fiber yielding occurs early in the loading story resulting in a strongly non-linear composite behavior. Nevertheless, it is first after the yielding of the matrix material that a kink-band can begin to form in the material block. In the specific case, the load carrying capacity is found to be unaffected of the much lower yield stress of the fiber material, but the softer overall composite response may lead to buckling failure of the composite structure, and the composite has a overall more flexible response.

5 Conclusion

A smeared out non-linear material model has been implemented in the commercial finite element code Abaqus using the UMat user interface. Using this, it has been possible to simulate kink-band formation in a block of material under compression. Predictions, which otherwise would require a full micromechanical model [3]. A micromechanical model, which will be completely unrealistic to perform for realistic composite structures such as simulating wind turbine blade. In addition, such a micromechanical model will reveal unnecessary details. The smeared out model is found to give rather similar results to the micromechanical model. Nevertheless, the smeared out composite material law has no intrinsic length scale and consequently the width of the kink band is weakly mesh dependent as shown in [8].

The numerical predictions will be compared with simple analytical models [10] and experimental measurements using compression test fixture [11]. The compressive elastic-plastic material response of the steel fibers will be extracted from the compression test of the composite.

Acknowledgements

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