KINETIC OF FIBER RUPTURES IN A UNIDIRECTIONAL COMPOSITE WITH A VISCOELASTIC MATRIX

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Abstract
Structural applications of fiber reinforced polymers are strongly dependent on long-term durability studies. Subject to sustained loading, the material undergoes several phenomena reducing its mechanical performances and potentially leading to its failure. To understand the creep rupture mechanisms and identify relevant mechanical parameters that will need to be adjusted during the composition of the material, modeling at the fibers scale seems adequate. In this article a shear-lag model will be presented. This 2D model integrates a viscoelastic behavior of the matrix and a stochastic distribution of fibers strength. Results showing the main phenomena occurring in the stress redistribution in the composite material will also be presented.

1 Introduction
Composite materials present numerous advantages, combining mechanical performances, lightweight and low thermal conductivity (a considerable asset in sustainable construction). In civil engineering, where service time is counted in decades, they are mainly used in combination with more traditional construction materials such as wood, concrete and steel as reinforcement. In order to use composites as main structural material, efforts are still needed in experimental studies and modeling of their long-term behavior [1].
The development of the pultrusion technique allows the production of composite profiles at high rates and low costs, while controlling their quality. The use of glass fibers in combination with this technique makes composite materials affordable for large-scale civil engineering and construction applications. In order to make the most of the mechanical properties of composite materials, new innovative structures, specifically designed for them need to be developed. An example of such structures using glass fiber pultruded composites, the gridshells [2,3], profit from material's flexibility and strength to reach important bending deformations and therefore use structural stiffness of double curved shells. In such structures, the material is under sustained loading. It was experimentally observed that in conditions of permanent loading, composite materials creep and may undergo creep rupture [4-6]. Studies presented in this article concentrate on the second aspect: creep rupture. The aim is to understand the basic mechanisms of creep rupture and the role played by different

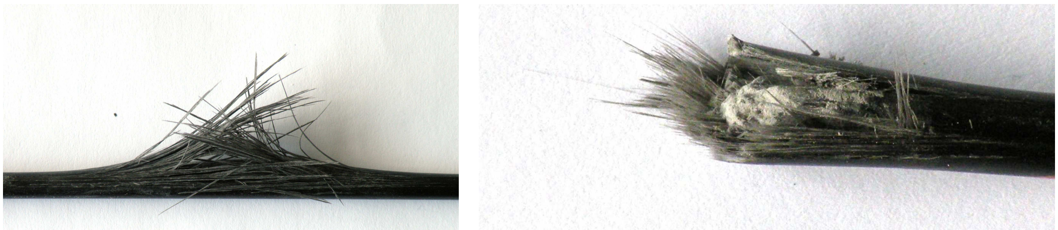
constituents, fibers, matrix and interface in this phenomenon. In order to do so, a model at the fibers scale taking into account individual properties of the constituents was built.

2. Phenomenology

Creep rupture phenomenon is relatively well-known. Its main mechanisms can be summarized as follows:

- When a loading is applied to the material, certain fibers break instantaneously as numerous flaws are distributed on their surface [7].
- Broken fibers locally cannot support the load applied to them, it is redistributed to the neighboring intact fibers through shear loading of the polymer matrix.
- The additional stress on the neighboring fibers can cause new fiber breaks.
- The matrix under shear stress can undergo plasticity and the interface between fibers and matrix can be damaged (debonding).
- The polymer matrix's behavior is viscoelastc, its stress relaxes in time. As a consequence, the overstress profiles of the intact fibers broaden, this in return can cause the interaction of initially independent break sites: the overstress profiles can come to overlap increasing even more the stress of the intact fiber. This phenomenon is time-dependent; therefore the fibers' overstress is progressive and new fiber ruptures can appear in time.

Experimental study led in the frame of the research presented in this paper, allowed the observation of different creep rupture modes of the material. The samples used are pultruded GFRP thin rods (5mm diameter) with a vinylester matrix. Creep tests were performed. In these conditions, 4-point bending tests revealed a progressive rupture mode through fiber-matrix bundles tearing off as shown in the figure 1a below. Other tests involved combined bending-torsion loading. Under these loading conditions, the matrix is directly stressed as torsion causes its shear. The rupture occurs brutally through a localized fracture of the specimen, as shown on the figure 1b. A considerable decrease of the composite's lifespan compared to that of the pure bending tests was observed.



a. b.

Figure 1. Two different creep rupture modes. a: 4-point bending test. b: combined torsion and bending

This indicates that matrix has an important role in the creep rupture of the composite material and that several damage mechanisms may be involved. The aim of the model proposed in this paper is to highlight these different damage mechanisms and identify the main properties of the constituents that drive the creep rupture of the whole composite.

3. Model description

In the current model version, the considered loading is traction, applied in the same direction as the fibers. The model is of the shear-lag type, as one considers that the fibers bear the full loading and the matrix only mechanical function is the load transfer via its shearing. This approximation is correct for glass fibers and polymer matrix composite materials, as the Young modulus ratio is high: about 70GPa to 4GPa.

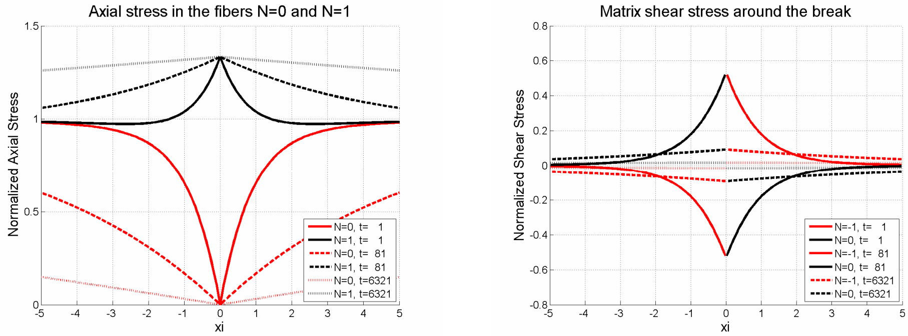
The fibers have an elastic fragile behavior. A random distribution of flaws is considered along their length. The distribution follows Weibull's law with 2 parameters. The matrix has a linear viscoelastic behavior, and its relaxation function is defined by a phenomenological power law, commonly used for the description of the polymer matrix of composite materials.
The material is seen as 2 dimensional, and is represented by an infinite stacking of 1D elements - the fibers - linked together by the matrix, being described as a cohesive zone. The resolution is done in an analytical way for 1D, for an infinite number of fibers, and then the material is subdivided in order to calculate the stress and displacement fields in a finite area of the material, and thus compute the location of fiber ruptures. The analytical solution of successive fibers ruptures can be found in the article of Beyerlein and al. 1998 [8]. The solution to the elastic case of the influence of debonding can be found in Beyerlein and al. 1995 [9]. Viscoelastic case was derived in the present study. With these solutions in hand, one can calculate the stress fields in a material with several rupture sites using the superposing of influences of each damage site.
For initialization, for each fiber's element (in the subdivided material) a resistance value is set independently following the Weibull’s law. Then, for each time step and corresponding damage state, one must calculate the stress field in the fibers and the associated shear deformations in the matrix. From this, one can deduce if new ruptures need to occur in the material. For each iteration a single new rupture or debonding element appears, the one which experiences the greatest overload to its strength. The process is repeated integrating this new rupture/debonding until, for the given time step, the updated damage to the fibers and associated stress/strain fields do not lead to new ruptures. The time increases then by one step. One can thus follow the damage evolution in time.

4. Results

4.1 Main mechanisms for stress redistribution

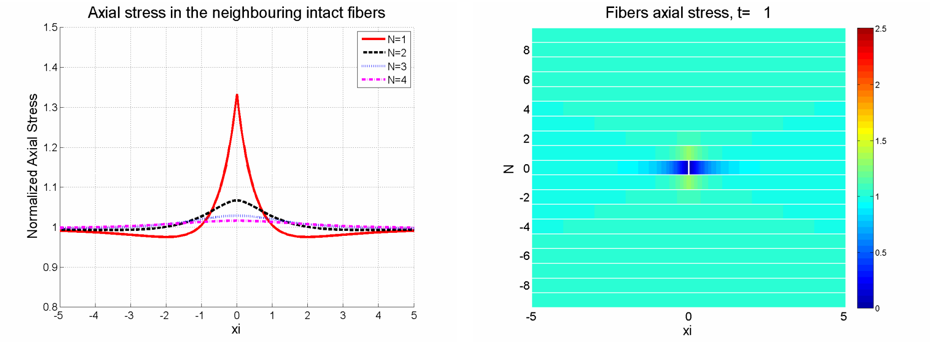
4.1.1 One broken fiber

The stress of the broken fiber is null at the break location, and gradually increases when moving away from the break until the stress level imposed at the far field is reached (all the parameters are normalized, the far field stress is taken equal to 1). On figure 2a (continuous lines represent the elastic response), one can observe that the first neighboring fiber is severely overloaded directly in the vicinity of the break, then its overload decreases as one moves away from the rupture until the stress level is equal to the one imposed at the far field. For the matrix shear stress (figure 2b), a stress peak can be seen close to the break location.
In time the overload profiles on the intact fibers widen, and the matrix experiences relaxation (see figure 2, dotted lines). One can also note that the maximum overload of the neighboring fibers remains constant through time: there is no stress decrease with time.



a. **b.**

Figure 2. a: stress in the broken fiber and its first intact neighbor. b: shear stress in the matrix surrounding the broken fiber.



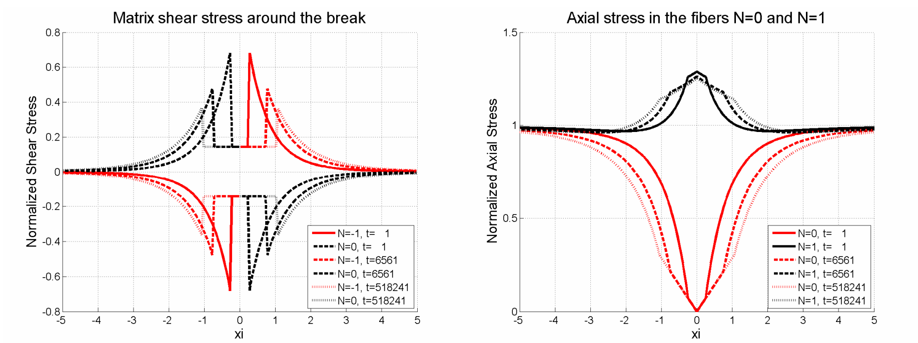
a. **b.**

Figure 3. Elastic response a: axial stress in the intact neighbors of the broken fiber. b: axial stress in the material

The overload of the neighboring intact fibers remains localized, as the induced overload quickly decreases, and from the 4th fiber on, the rupture has almost no impact (see figure 3a). On figure 3b, each horizontal strip represents one fiber. The warmer the color, the higher the fiber stress is. The colder the color, the lower the fiber stress is, trending towards zero.

4.1.2 Debonding influence

In this case, one fiber rupture is present around which a debonding zone progresses in time. A constant shear stress is imposed in the debonded region to account for friction. The shear stress profile modification due to progressive debonding has consequences on the stress transfer between the broken and intact fibers. The overload profile on the first neighboring fiber is broadening in time as the debonding region progresses (figure 4b, black curves), at the same time the broken fiber regains more slowly the stress it is subjected to (4b red curves).



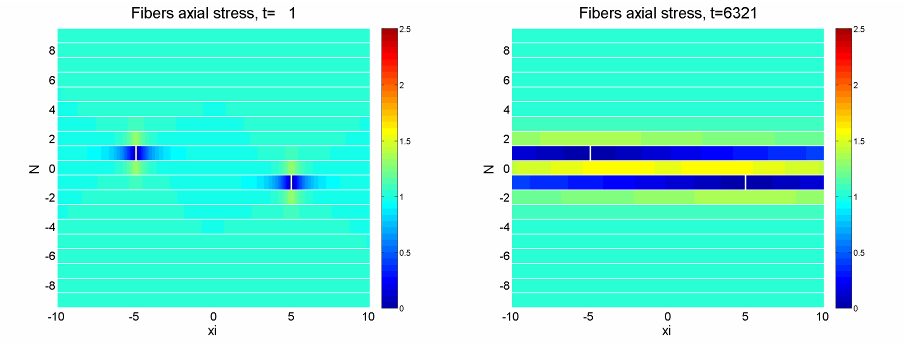
a. **b.**

Figure 4. a: matrix shear stress near the broken fiber. b: axial stress in the broken fiber and its first neighbor.

4.1.3 Interaction of break sites, viscoelastic case

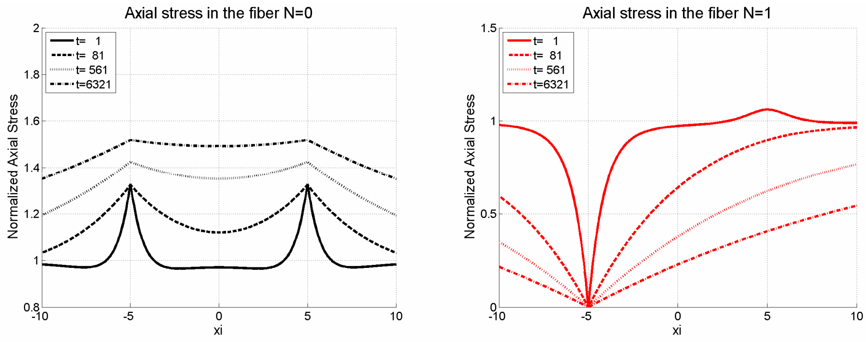
One considers a material with two broken fibers, sufficiently apart so there is no interaction at the initial stage (elastic response). Of particular interest is the intact fiber between the two broken fibers. The next two figures (figure 5) show the initial stress and the stress after matrix relaxation in the material. Initially, two localized and separated zones where the broken fibers have an influence can be observed. Then, the two zones evolve with time and eventually overlap to form only one zone. There is interaction between the two rupture sites.

The two figures 6a and b show the axial stress in the intact fiber (figure 6a) and in the broken fiber located above the intact fiber (figure 6b). The central fiber stress analysis shows a complete initial independence of the two rupture sites. Then the overload profiles broaden: first, the overload peak intensity (maximal overload stress) remains the same as in the elastic case, whereas the stress level in the middle of the central fiber increases with time. Then, a true interaction between the two sites occurs as the overload peak significantly increases from about 1.33 (single rupture) to 1.46. This is paired with a progressive discharge of the broken fiber that can be observed on the figure 6b (the profiles are similar for the broken fiber below the central one).



a. **b.**

Figure 5. Time evolution of the stress state in the material due to two broken fibers. a: elastic response. b: after matrix relaxation



a. **b.**

Figure 6. a: evolution of the axial stress in the central intact fiber. b: evolution of the axial stress in the broken fiber above the intact one

As shown, the constructed model permits a clear reproduction of the essential stress transfer mechanisms that occur during the progressive damage of a material: progressive recovery of the stress in the broken fiber; overload of the neighboring fibers; matrix relaxation; overload profile widening and interaction between the rupture sites as time advances.

4.2 Study of a macro-defect formation

Study of the progressive damage in a sample was carried out. In this part, debonding was not modelled. The sample studied is an infinite unscathed lamina, where 71 fibers can break. Each fiber has 991 elements in the longitudinal direction.

4.2.1 Static tests

First, the sample is subject to increasing loads in order to determine the corresponding static damage. The figure 7 below shows the evolution of the number of fiber breaks versus the applied load. The curve presents an area of rapidly changing slope (circled in red) for an applied load to the fibers between 460MPa and 500MPa.

The graphics in the figure 8 present the evolution of the damage in this area (460MPa, 470MPa, 490MPa, 500MPa). One can see that initially fiber ruptures are dispersed. Then, as the applied load increases, ruptures tend to group together, align to form a macro-defect, a crack, clearly visible on the last image.

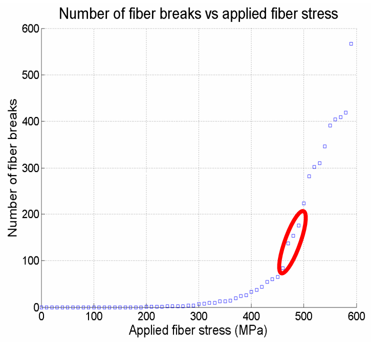


Figure 7. Evolution of the fiber breaks versus applied static load

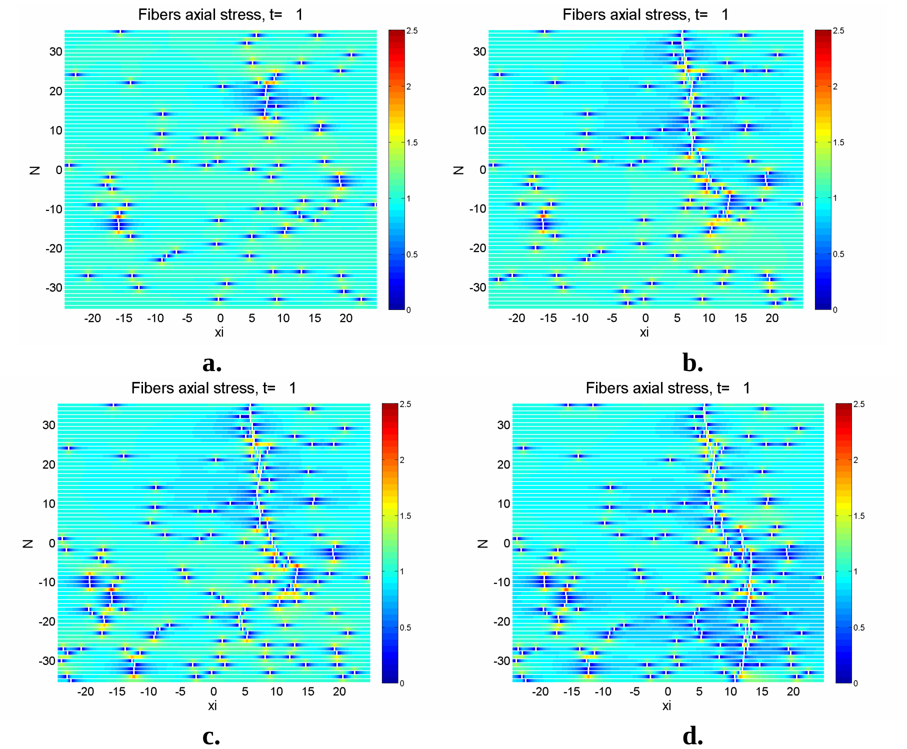


Figure 8. Evolution of the damage pattern in the changing slope area. a: 460 MPa. b: 470MPa. c: 490MPa. d: 500MPa

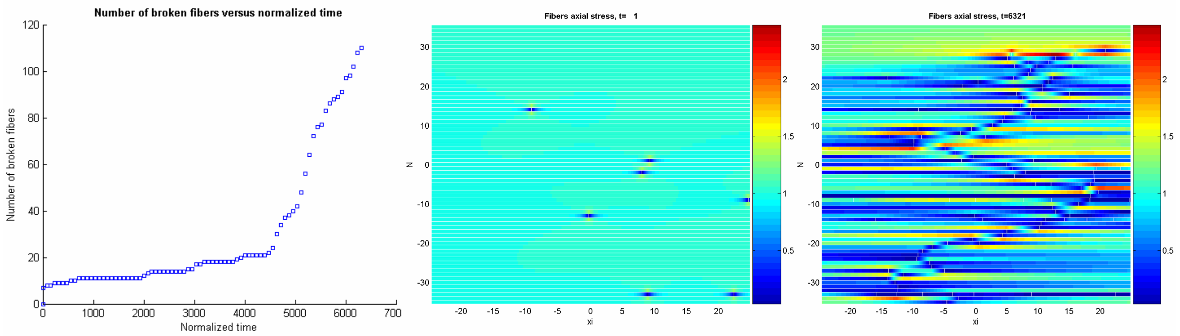
4.2.2 Long-term study

In this part, a sample with the same distribution of strengths as previously is subject to a constant load and the time evolution of the damage (fibers ruptures exclusively) is assessed. Two different load levels were studied. Loads were chosen low enough, far from the changing slope area observed previously: 280MPa and 300MPa.

Tertiary creep

At 300MPa, initial damage is rather low (see figure 9): a few fiber breaks are scattered around the material. But at the end of a certain period of time, fiber ruptures form a macro-defect. Time used in these experiences does not have a physical meaning as the matrix has been taken more viscous than a real matrix would be, the aim of this phase of investigation being to show the phenomena, not to quantify them.

The graphic figure 9a represents the time evolution of fiber breaks. One can clearly see a slope changing area indicating a secondary creep stage followed by tertiary creep. Two major observations can be made on this experience. First, a load level relatively low compared to the static critical load level can lead over time to a macro-damage forming in the material. Second, the morphology of the macro-damage is not the same in the elastic and viscoelastic cases. Although in the first case, in order to form a crack, fiber breaks need to be almost aligned (figure 8d), as overstress profiles broaden in the viscoelastic case, fiber breaks located further apart still form a cluster (figure 9c).

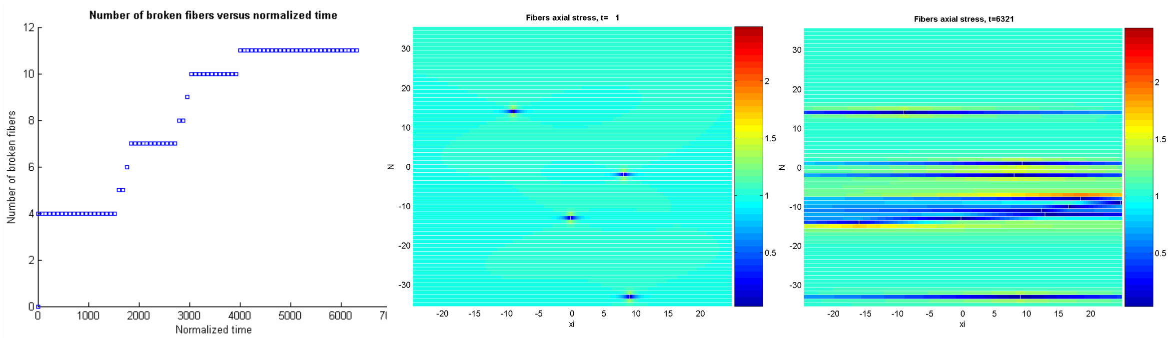


a. b. c.

Figure 9. a: time evolution of fiber ruptures of a sample subjected to 300MPa. b: initial damage pattern. c: final damage pattern

Secondary creep and stabilization

Similar simulations were carried out with a lower load level: 280MPa. Analysis of the curve presenting the number of fiber breaks in time (figure 10a) shows the presence of a plateau: a stabilization of the number of fiber ruptures is reached and tertiary creep does not occur.



a. b. c.

Figure 10. a: time evolution of fiber breaks for a sample subject to 280 MPa. b: Initial damage pattern. c: final damage pattern

Initial damage is low and comparable to that observed for 300MPa (see figures 10b and 9b). But at the end of the same period of time as previously, instead of forming a macro-defect, the damage propagation has stabilized and final ruptures form only a micro-cluster, or even isolated ruptures.

5. Conclusions and future work

Static and long-term studies allowed observing the main phenomena of the progressive damage of a unidirectional composite material with a viscoelastic matrix subjected to longitudinal traction. This model enables the observation of a macro-damage forming in the material. These macro-defects are to be linked to the rupture of the whole composite structure studied. In order to do so, results from the present model need to be included into multi-scale models.

Several developments and future results are considered: a sensitivity analysis to different material parameters (matrix properties, volume fraction of fibers…) will be carried out; debonding will also be taken into account in cases of complex damage studies.

Experimental results in the part 2 showed two distinct rupture modes. In particular application of torque to the material leads to a brutal rupture of the composite. Future developments of the model, particularly the integration of debonding in the viscoelastic simulations, should allow explaining the modification of the rupture modes. For this a new loading type will be included: combined traction and shear. Shear, representing torsion in the experimental study, will superimpose to the local shear stress due to fiber breaks.

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