

Damage behavior of a composite film based on cassava starch reinforced with coconut mesocarp fibers

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Abstract :

We have developed a composite material based on cassava starch reinforced with coconut mesocarp fibers which has given convincing mechanical, physical and chemical properties. The objective of this work is to analyze its elastic damageable behavior. For this, we made an analytical study followed by simulations under the Cast3M calculation code. It appears that before displacements in the vicinity of 0.51 mm, the composite, although presenting cracks, does not reach a state of total rupture. In addition, local fractures are observed from 0.52 mm in displacement. The comparison of the two methods shows a very high agreement of the values obtained. This thus confirms the results on the behavior of this material in our previous work. This composite can be used in certain areas such as packaging.

Keywords: Starch, cassava, fibers, coco, cracks, elastic, damage

1.Introduction

Materials, during their life cycle since their development, are subject to anomalies that lead to their degradation. In the absence of cracks or more precisely if their behavior conforms to that of materials produced under the best possible conditions, they will be considered sound. Otherwise, it is referred to as a damaged state. The analysis of the damage concerns the evolution of the degradation from the initial state until the appearance of a state characterized by the presence of cracks of representative sizes compared to the volume of the material. Most often, this term of damage is associated with the mechanical properties and more particularly with the deterioration of the Young's modulus by the creation of cavities or discontinuities (Robert Schirrer, Christophe Fond, 2008).

The purpose of this study is to analyze the damage of a cassava starch-based composite reinforced with coconut mesocarp fibers developed in the body of our previous work (Ahmed Doumbia, 2020; Ahmed Doumbia, Pierre J.-M. R. Dable, Edja F. Assanvo, 2018). To do this, initially, the damage D is determined analytically. The second phase consisted in making calculations by simulations by finite elements under the calculation code Cast3M. A comparison is then made between the two methods. It appears that the composite is more and more damaged as the displacement increases. In both cases, the damage is almost zero up to around 0.2 mm. There are microcracks between 0.3 mm and 0.51 mm. Around 0.52 mm, local fractures appear. Finally, the density of the mesh of the finite elements brings more precision on the dispersion of the damage of the material.

2. General hypotheses of the study

The elaborated composite is a film whose photo of a sample is shown in Photo 1.



Photo 1. Composite film based on cassava starch reinforced with coconut fibers (Ahmed Doumbia, 2020)

In view of the findings during our previous work (Ahmed Doumbia, 2020) we accept the following general hypotheses:

- the material has an isotropic damaging elastic behavior
- there is no manifestation of plasticity and viscosity
- charging time is short
- the main stress is unidirectional

3. Analytical study of the damage

3.1. Elements of theory

The analysis of the elastic behavior of a material from its loading to its damaged state reveals the appearance of two different successive states: an almost linear phase and another where the modulus of elasticity drops considerably. In the first case, the damage is practically non-existent; while at the second stage, microcracks suddenly develop (Batoz J.L. Dhatt G., 1990; Mazars J., 1984; Lemaitre J., chabochej.L., 1998).

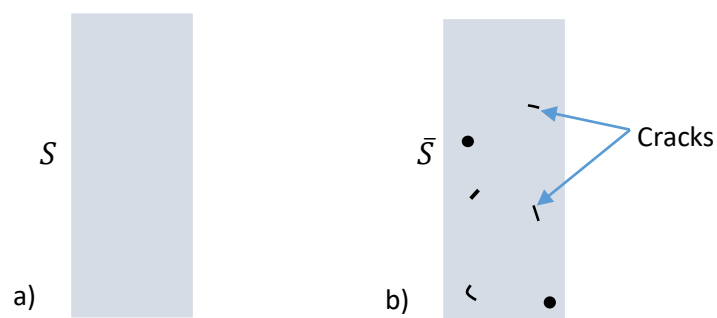


Figure 1 a) Healthy surface; b) Damaged surface

The stresses in the healthy material and in the damaged material are respectively:

$$\sigma = \frac{F}{S} \quad (\text{MPa}) \quad (1)$$

$$\bar{\sigma} = \frac{F}{\bar{S}} \quad (\text{MPa}) \quad (2)$$

With S: healthy surface area (m^2) ; \bar{S} : effective area of the damaged surface (m^2) and F: force applied to the surface (N).

If S_f is the total surface of the cracks, the parameter of damage is defined by:

$$D = \frac{S_f}{S} \quad (3)$$

That to say :

$$D = 1 - \frac{\bar{S}}{S} \quad (4)$$

From (1), (2) and (4), the effective stress can also be expressed by the relation:

$$\bar{\sigma} = \frac{\sigma}{1-D} \quad (5)$$

The hypotheses of equivalence in deformation supposes that the behavior with the deformation of the matter is affected by the damage only under the only form of the effective stress. The constitutive law of the damaged material is the same as that of the healthy material. Hooke's law of the damaged material is therefore written:

$$\varepsilon = \frac{\bar{\sigma}}{E} \quad (6)$$

With ε : the deformation and E: the modulus of elasticity of the material in MPa.

From (5) and (6), we have the elastic constitutive law that can be damaged:

$$\sigma = E\varepsilon(1-D) \quad (7)$$

In addition, the purely elastic constitutive law is written:

$$\sigma = E\varepsilon \quad (8)$$

From relations (7) and (8), we have:

$$D = 1 - \frac{\bar{E}}{E} \quad (9)$$

E: modulus of elasticity of the healthy material (MPa); \bar{E} : modulus of elasticity in the damaged state (MPa)

D is such that:

- If $D = 0$, we have a virgin material; undamaged;
- If $0 < D < 1$, there is the presence of microcracks which generate an effective resistant section where the drop in the modulus of elasticity is significant, This is the phase of the elasto-damageable behavior;

- If $D = 1$, one speaks of critical damage which corresponds to the rupture of the voluminal element.

3.2.Measurement of damage

The measurement of the damage is made from the evolution of the effective modulus of elasticity obtained by the tensile test (Ahmed Doumbia, 2020; Ahmed Doumbia, Pierre J.-M. R. Dable, Edja F. Assanvo, 2018) . The instantaneous value of the Young's modulus therefore makes it possible to determine the evolution of the damage. The results are given in Table 1 below.

Table 1. Modulus and damage values as a function of displacement

| Displacement Y (mm) | 0.1 | 0.2 | 0.3 | 0.4 | 0.51 | 0.6 | 0.7 | 0.8 |
|---|-------|-------|-------|-------|-------|------|------|------|
| Effective elastic modulus \bar{E} (MPa) | 49.33 | 49.33 | 30.55 | 18.81 | 10.36 | 9.87 | 8.39 | 6.22 |
| Damage D | 0 | 0 | 0.38 | 0.61 | 0.78 | 0.80 | 0.82 | 0.89 |

We notice that the effective elastic modulus decreases when the displacement increases. This means that the composite loses rigidity. As a result, it increasingly suffers local and then global destruction in the worst case. This explains the increase in damage. The values measured here are those of the overall behavior. Indeed, up to around the displacement $Y = 0.8$ mm, there is no total rupture of the composite film. However, at the local level, we have the appearance of microcracks. This phenomenon will be clarified in the second part devoted to the simulation of the elasto-damageable behavior.

4.Simulation of composite damage

4.1.Additional data and hypotheses

The discretization of structures by the finite element method makes it possible to locate the damage (Batoz J.L. Dhatt G., 1990; Mazars J., 1984). For the simulation, we used the finite element calculation code Cast3M. In addition to the general assumptions quoted previously, we will use the plane constraint mode with the quadratic elements with eight nodes QUA8. The damage is evaluated according to the displacement under a monotonous tensile stress. This is more practical thanks to the linearity between displacement and deformation. The properties of the composite obtained from our previous work are listed in Table 2.

Table 2.: Mechanical properties of the composite (Ahmed Doumbia, 2020)

| E[MPa] | ϵ_B [%] | $R_e(\sigma_B)$ [MPa] | ϵ_C [%] | $R_m(\sigma_C)$ [MPa] | A [%] | σ_E [MPa] |
|--------|------------------|-----------------------|------------------|-----------------------|-------|------------------|
| 49.33 | 7.5 | 3.7 | 14 | 5.2 | 22 | 3.5 |

4.2.Results of numerical calculations

In the following simulations, the damage was calculated according to each value of displacement Y taken from 0.1 to 0.8 mm. Initially, we used a single mesh density which corresponds to 100 elements for 341 nodes in order to take into account only the influence of displacement (Figure 2).

Elasto-damageable state as a function of displacement

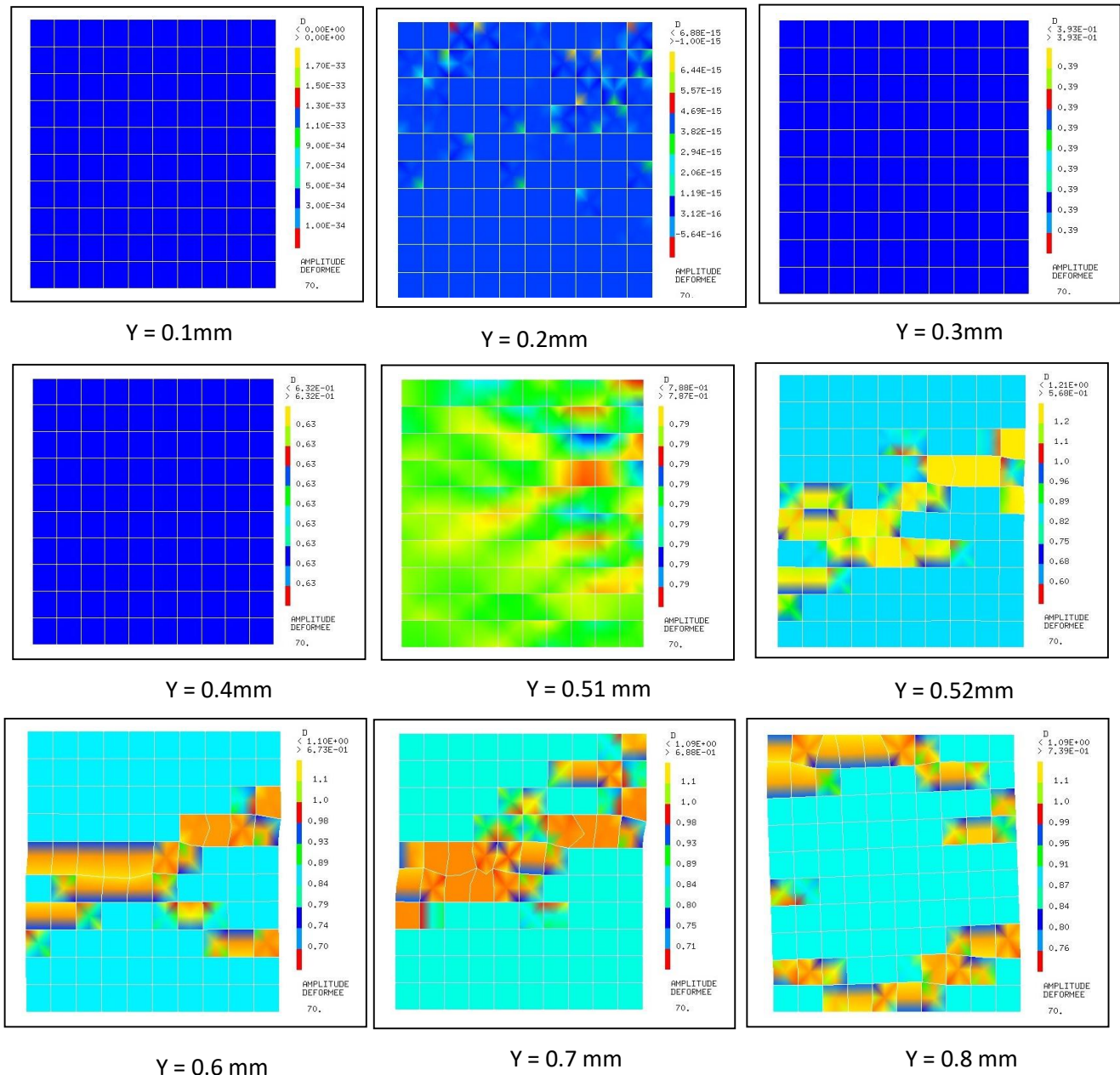


Figure 2: States of damage to the composite as a function of displacement

Then the density of the mesh is made varied from 1 to 30 elements on each side. This is equivalent to meshes of 1 and 900 elements respectively for the entire volume of the sample (8 and 2821 knots respectively) (Figure 3.). Beyond these values, the maximum number of sub-steps is reached taking into account the calculation hypotheses imposed.

5. Analysis and interpretation of numerical results

The discussion focuses on the data in Figures 2. and 3. Figure 2. describes the state of elastic damageable behavior of the film under tensile stresses. We observe three main behaviors as displacement evolves. The first starts from Y = 0.1 to 0.2 mm, the second from Y = 0.3 to 0.51

Influence of mesh density on damage

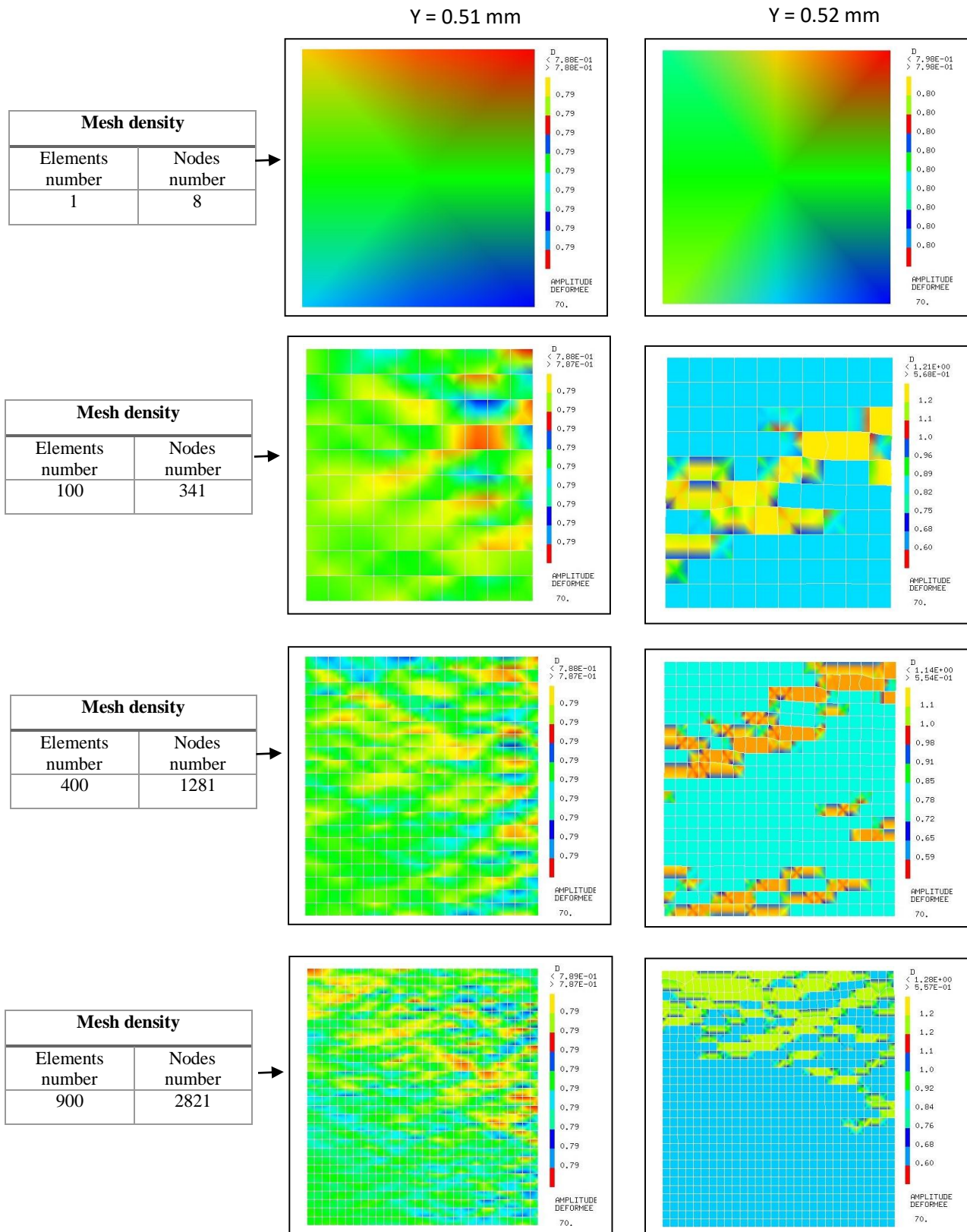


Figure 3: Dispersion of damage as a function of mesh density

mm and the last from 0.52 mm. At the first stage, the damage is uniform and practically null, $D=0$. The behavior is similar to that of a healthy material. However, for $Y = 0.2$ mm, we observe a slight dispersion of the texture. Indeed, when the composite undergoes a weak loading, it develops a resistance during the time of a modification of its structure. This is due to a reorientation of the polymer chains in the direction of loading, a homogenization of the discontinuities of the fiber/polymer chain interfaces (Ahmed Doumbia, 2020). This state allows the composite to withstand low stresses transiently. In the second phase, the damage increases abruptly from 0 to 39 to reach 79. This is due to a drop in interface forces and the propagation of microcracks which essentially come from the elaboration of the material. However, at this level, the relay for the resistance is given to the fibers. Indeed, these take the direction of the loading and with an elastic modulus of 175 MPa (Ahmed Doumbia, 2020; Ahmed Doumbia, Pierre J.-M. R. Dable, Edja F. Assanvo, 2018) opposes a rigidity to the destruction. For $Y = 0.3$ to $Y = 0.4$ mm, the uniformity of the texture explains the mechanical homogeneity of the composite and the good dispersion of the material with damage equal to 0.39 and 0.79 respectively. Microcracks appear. This degradation is more remarkable around $Y = 0.51$ mm for $D = 0.79$. This loss of strength of the composite is due to two phenomena which can coexist. The first is the destruction of the fibre/starch interface. And the second cause is the progressive breaking of the polymer chains. At this stage, these are phenomena that only have a local impact. There is therefore no break at the global level. At the last phase, from $Y = 0.52$ mm, we observe damage values $D = 1$. This means that there is a partial dislocation of the material. By following the isovaleurs of $Y = 0.6$ to 0.8 mm, one notices that the damage becomes increasingly large. This reveals the progressive breaking of fibers. The overall accumulation of these local damages could lead to the total rupture of the film.

Figure 3. presents the influence of mesh density on damage. For displacements of $Y = 0.51$ and $Y = 0.52$, the number of elements (respectively of nodes) was varied: 1; 10; 400 and 900 elements (respectively 8, 341, 1281 and 2821 nodes). We made two observations. The first observation is that before the appearance of local fractures, in the vicinity of $Y = 0.51$ mm, the damage exists, but remains homogeneous and isotropic. Second, from $Y = 0.52$ mm, it becomes larger and larger ($D = 1$ locally in places). At this level, we observe the effect of the mesh density. Indeed, the larger it is, we obtain a better dispersion of the damage thus revealing the initiating points of cracks.

6. Comparison of analytical and numerical results

For the simulation, we used a one-element mesh because it gives the best overall behavior state (Annex). The values obtained are given in Table 3. We note that the values of the damage found by the analytical study and those of the numerical simulation by the computer code Cast3M are of very close agreement (Figure 4). This makes it possible to validate these simulations. We have also drawn the curves representative of these analytical quantities and those obtained by the simulation.

Table 3.: Comparative table of the analytical and numerical results of the damage D

| | | | | | | | | | |
|-------------------------|-----|-----|------|------|------|------|------|------|------|
| Displacement Y (mm) | 0.1 | 0.2 | 0.3 | 0.4 | 0.51 | 0.52 | 0.6 | 0.7 | 0.8 |
| Numerical results of D | ~ 0 | ~ 0 | 0.39 | 0.63 | 0.79 | 0.80 | 0.83 | 0.86 | 0.88 |
| Analytical results of D | 0 | 0 | 0.38 | 0.61 | 0.78 | 0.80 | 0.82 | 0.87 | 0.89 |

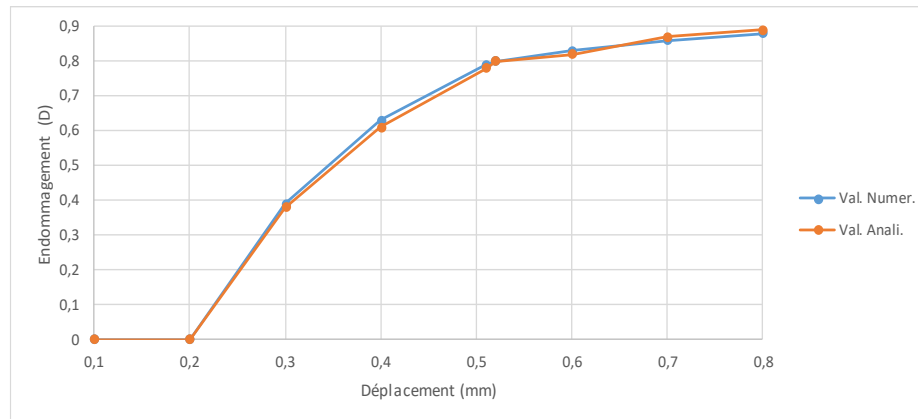


Figure 4 : Graphical comparison of the values of the numerical and analytical damage

Conclusion

This work aimed to analyze the damage behavior of a cassava starch-based composite reinforced with coconut mesocarp fibers. To do this, we made an analytical study followed by numerical simulations under the Cast3M calculation code. The results obtained for the two methods are very consistent with a difference of one hundredth. They explain the behavior of the composite well. For example, for displacements in the vicinity of 0.52 mm, local fractures appear. However, for the simulations, the density of the mesh allows a very good local dispersion of the damage. All this allows the validation and the use of these simulations and shows the exploitation of this software in the field of mechanics.

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Annex: States of damage of the composite according to displacement Y for the density of mesh [1 element, 8 nodes]

