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RESEARCH ARTICLE

MIXED-MODE CRACK PROPAGATION USING THE EXTENDED FINITE ELEMENT METHOD (XFEM) IN A CASSAVA STARCH-BASED COMPOSITE REINFORCED WITH COCONUT FIBERS

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Abstract

In our previous work, we studied the damage of a composite based on cassava starch reinforced by coconut fibers. This study showed its limits with the presence of macro-cracks and their propagation. The objective of this article is to analyze the propagation of cracks using fracture mechanics. To do this, we will use the Extended Finite Element method (XFEM) to determine the resistant behavior of the film by calculating the stress intensity factor (FIC). Two approaches were used: simulation by XFEM and analytical XFEM. A parametric analysis was carried out to elucidate the influences of crack size and position; and the intensity of the applied load. Finally, the comparison of the results from the two approaches confirms the precision and effectiveness of the XFEM in describing the behavior of the composite object of our study.

Introduction:-

The appearance of cracks can modify the behavior of materials, thus having disastrous consequences on their performance and monitoring in service [1]. The study of this problem cannot be carried out on a standard Finite Element Model (FEM) with the presence of macro-cracks and because of poorly controlled crack tip stress problems [1,2, 3]. The objective of this work is to analyze the resistant behavior of a composite film based on cassava starch reinforced by coconut fibers [4, 5] to crack propagation. The determining quantity is the stress intensity factor (FIC) which accounts for this behavior. To do this, we carried out simulations with the Cast3M calculation code followed by analytical calculations using the XFEM method of the FIC in mixed mode. Then, the influences of crack size and angular position, and loading were studied. The results obtained are consistent and convincing.

Description of the problem

The material subject of our study [4, 5] was characterized in our previous work [4]. The data useful for this study are given in Table 1. We chose a sample of square film of dimensions 1x1 presenting a crack centered and inclined at an angle θ relative to the perpendicular to the direction of traction as illustrated in Figure 1.

Table 1:- Mechanical characteristics of cassava starch-based films reinforced with coconut fibers [4].

Module of Young E[MPa]	Elastic limit $R_e(\sigma_e)$[MPa]	Maximum stress σ_{max} [MPa]	Stress at ruture σ_r[MPa]
49.33	3.7	5.2	3.5

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(a) Infinte plate (b) Crack centered and inclined at an angle θ

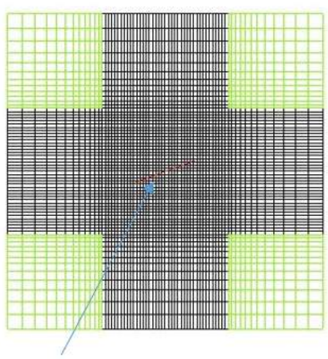
Fig. 1:- Mixed-mode simulation sample.

In all that follows, we assume the following hypotheses:
- The film is of infinite dimension compared to the size of the crack.
- The composite is homogeneous and isotropic
- The load is main unidirectional
- The loading duration is short enough to consider uniform deformation
- We adopt a plane strain study.

Mixed-mode digital XFEM analysis

Boundary conditions and discretization

As the results are intended for an analysis of fracture mechanics, we pay particular attention to the mesh at the crack tip in the immediate vicinity of the crack tip.



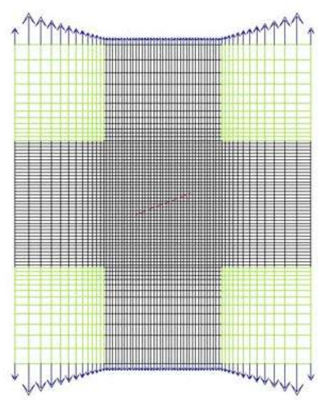


Fig. 2:- Discretization of the sample **Fig. 3**:- Loading the film.

For this we use a very fine mesh. The crack and the film are meshed separately. The mesh density in the vicinity of the crack is higher than that of the film sample [6, 7, 8] (Figure 2). In order to avoid any parasitic bending, we block the movements of the meshes along the axis orthogonal to the study plane. Thus, we apply displacements along the vertical. (Fig. 3).

Results:-

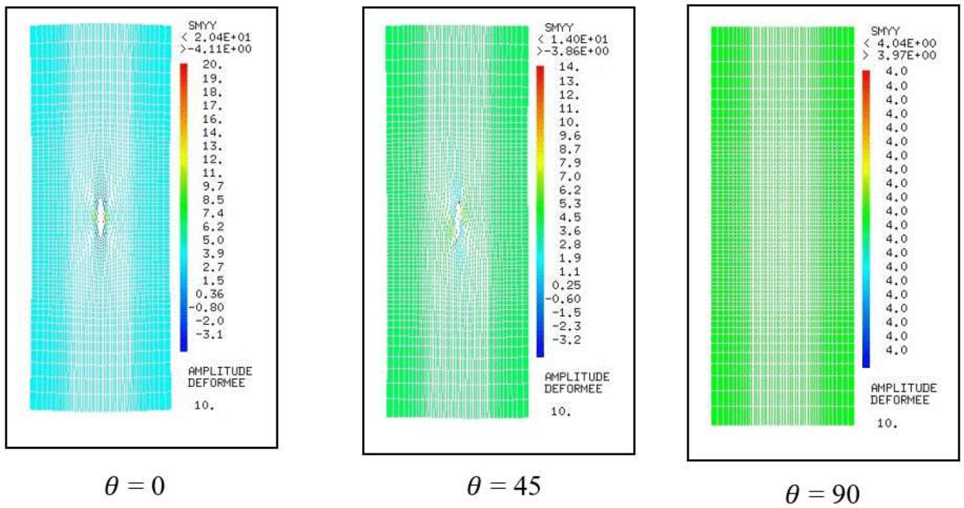
In the following, for the analysis of crack propagation, the results will focus on the stress distribution and the calculation of the stress intensity factor (FIC). The load applied to the film, the half-length and the angular position of the crack are named σ, L and θ respectively.

Stress distributions

Influence of the angular position of the crack (σ = 4 MPa, L = 0.05 m)

Figure 4. illustrates the influence of crack inclination on the stress distribution in the cracked composite.

Fig. 4:- Stress distribution σyy following the direction of loading as a function of the angular position θ.



We notice an increase in the stress density when θ goes from 0o to 90^{o} passing through 45o. This is manifested by a higher value near the crack tip. In particular, for an angle equal to 90^{o}, the stress is distributed homogeneously and equal to 4 MPa which corresponds to the applied load.

Influence of crack size (σ = 4 MPa, θ = 30^{o} and 60^{o})

Figure 5. illustrates the influence of the crack size on the stress distribution in the cracked composite.

We note that for θ = 45^{o}, the material adopts the same behavior in both modes I and II. This is what justifies the choice of angles 30 and 60^{o} on either side of this value. An increase in stress is observed when the size of the crack increases from 0.01 to 0.1m in both cases. However, for an inclination of 60^{o}, it is lower at L=0.1m.

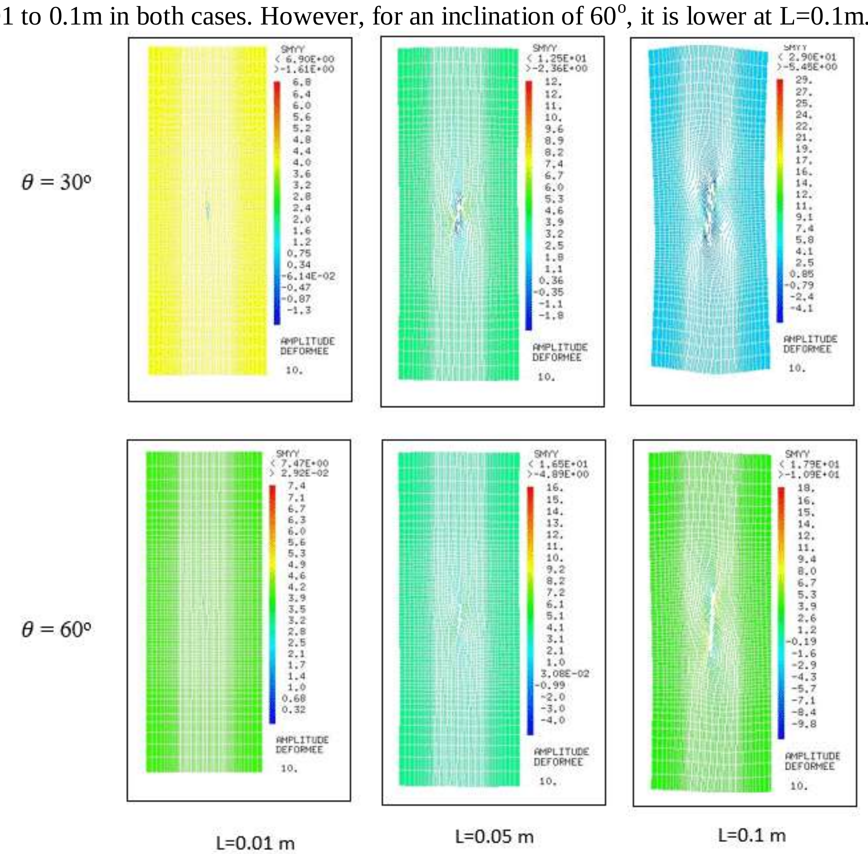


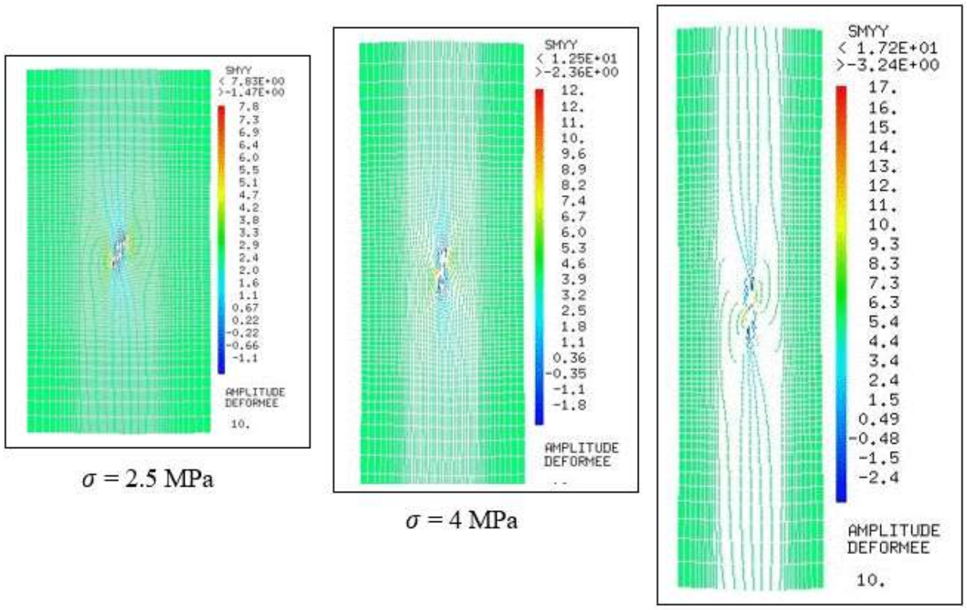
Fig. 5.:- Stress distribution σ_{yy} following the direction of loading as a function of the size of the crack.

Influence of the applied load ($\theta = 30^o$, L = 0.05 m)

Figure 6. illustrates the influence of loading on the stress distribution in the cracked composite.

We observe an elongation of the test piece. This is accompanied by an increase in stress and higher dispersio. Negative values are also present. The stress is denser near the crack tip.

Fig. 6.:- Stress distribution σ_{yy} following the direction of loading as a function of loading.



σ = 2.5 MPa σ = 4 MPa σ = 5.5 MPa

Stress Intensity Factors (FIC) in mixed mode: K_{IN} and K_{IIN}

The FIC K_I and K_{II} are calculated according to the different parameters such as the angle and size of the crack, and the applied load. The values are given in Tables 2.

Table 2.:- FIC as a function of A) the angular position of the crack, B) the size of the crack and C) the applied load.

	A)**σ** = 4 MPa et L=0.05m									
θ (°)	0	10	20	30	40	45	60	70	80	90
K_{IN}	1005.1	970.27	881.83	749.12	588.62	499.48	249.13	116.83	30.21	0
K_{IIN}	0	171.2	319.17	432.26	490.82	498.43	431.01	319.47	169.88	0

		B) **σ** = 4 MPa									
L (m)		0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1
K_{IN}	θ =30°	281.53	478.54	574.43	664.8	749.12	825.27	904.78	979.33	1037.1	1098.9
	θ =60°	186.89	128.44	190.63	222.74	249.13	275.74	303.69	326.75	342.29	365.4
K_{IIN}	θ =30°	232.62	335.27	337.61	387.22	432.26	476.39	522.25	564.66	592.79	631.08
	θ =60°	130.13	318.91	340.55	385.24	431.01	475.24	520.08	562.25	589.63	626.46

		C) L = 0.05m									
σ (MPa)		1	1.5	2	2.5	3	3.5	4	4.5	5	5.5
K_{IN}	θ=30°	299.65	449.47	599.3	749.12	898.95	1048.8	1198.6	1348.4	1498.2	1648.1
	θ=60°	99.6	149.48	199.31	249.13	298.96	348.79	398.62	448.44	498.27	548.1
K_{IIN}	θ=30°	172.9	259.35	345.81	432.26	518.71	605.16	691.61	778.06	864.52	950.97
	θ=60°	172.41	268.61	344.81	431.01	517.22	603.42	689.62	775.82	862.03	948.23

For an inclination of 45°, the FICs in Mode I and Mode II are equal. In addition, for both modes, and for angles equal to 30 and 60°, the composite has an increasingly higher resistance. However, with $\theta = 30^o$, the values are larger at L=0.1m. In all cases for the three parameters, the observations made previously for the stress distribution remain valid.

Comparison of numerical and analytical (exact) FIC values in mixed mode by XFEM analysis
To verify the validity of the mixed-mode FIC simulation method that we have chosen, it is necessary to take the exact solution values as a reference. Then we make the comparison with the values of the simulated XFEM. The comparison is shown in Figure 7.

Calculation of the exact (analytical) value of the FIC in mixed mode by the XFEM: K_{IE} and K_{IIE}
The specimen comprising a crack inclined at an angle θ is stressed in tension as indicated in Figure 3. In mixed mode, the stress intensity factors in mode I and II depend on the inclination and the size of the crack. crack, and the applied load. [7]. The expressions are given by equations 1. and 2.:

$$K_{IE} = \sigma\sqrt{\pi L}\,(\cos\theta)^2 \quad (1)$$

$$K_{IIE} = \sigma\sqrt{\pi L}\cos\theta\sin\theta \quad (2)$$

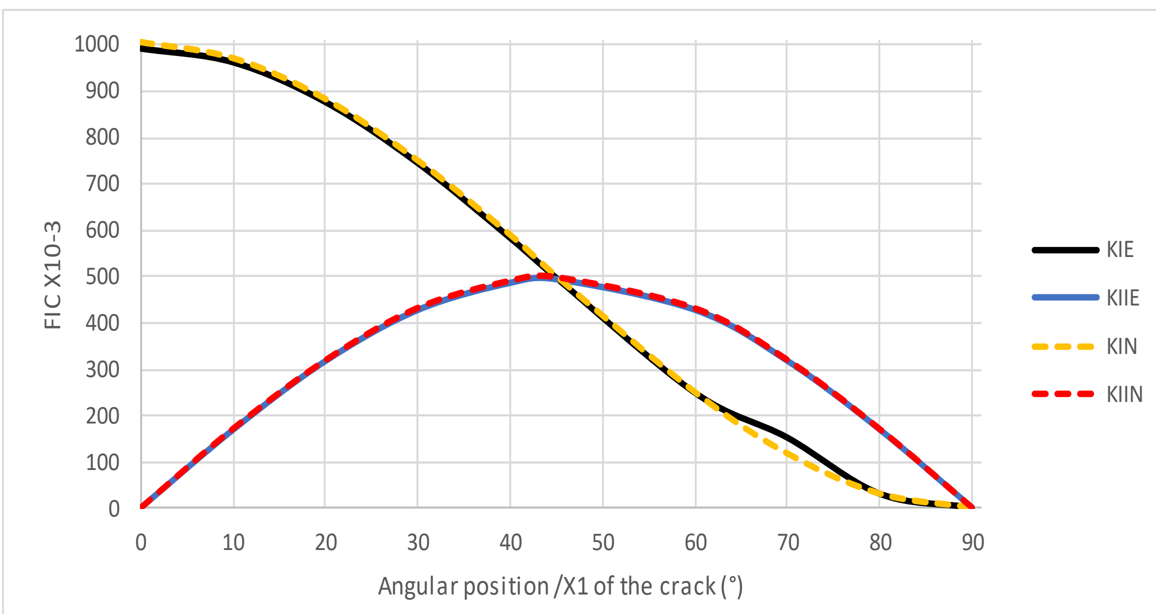
In order to have the effect of one parameter, we vary it while keeping the other two constant. We use the same uniform mesh of the simulation with quadrangular elements following all sides [6, 7, 8]. The results are compared to those of the simulation. They are represented graphically in Figure 7.

Graphical comparison
The curves representative of the evolution of the FIC as a function of the different parameters are given in Figure 7.

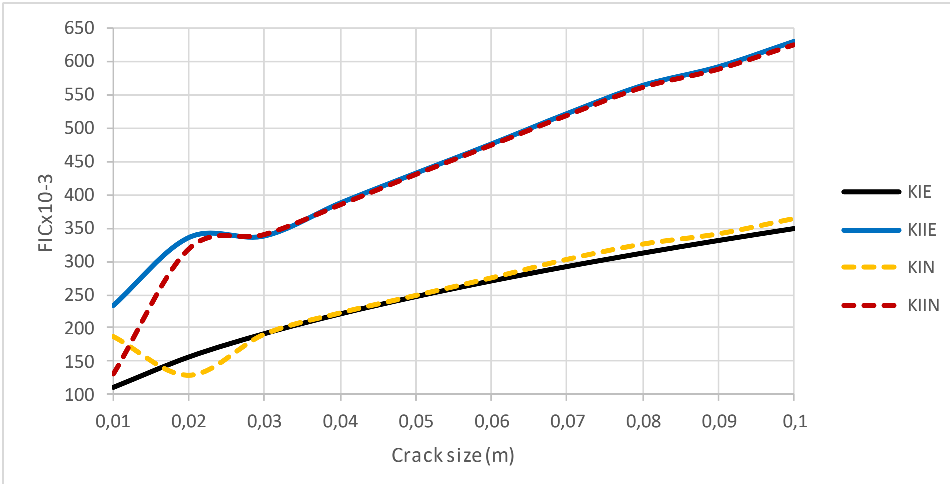
For all parameters, the simulated and analytically calculated FIC curves are practically superimposable. However, when the size of the crack is small, close to 0.015m, instabilities appear whatever the calculation approach and the failure mode.

Discussion:-

The observations made previously lead us to reflect on the behavior of the composite object of our study in resisting crack propagation. Indeed, the maximum value of the stress observed for $\theta = 0^o$ (Fig. 4.) is due to the fact that the crack is orthogonal to the loading direction. At this level we are in pure I mode. It is this mode which occupies an important part in the rupture of materials. At $\theta = 90^o$, we are in pure mode II; the crack is parallel to the loading. The shearing effect becomes preponderant. The stress has a homogeneous distribution. The local breaks observed from $\theta = 0^o$ disappear with an inclination of 90^o. The composite is stronger in mode I than in mode II.



A) σ= 2.5 MPa et L = 0.05 m



B2) σ= 2.5 MPa et θ=60^o

C2) θ=30^{o}et L = 0.05 m

B1) σ= 2.5 MPa et θ=30^o

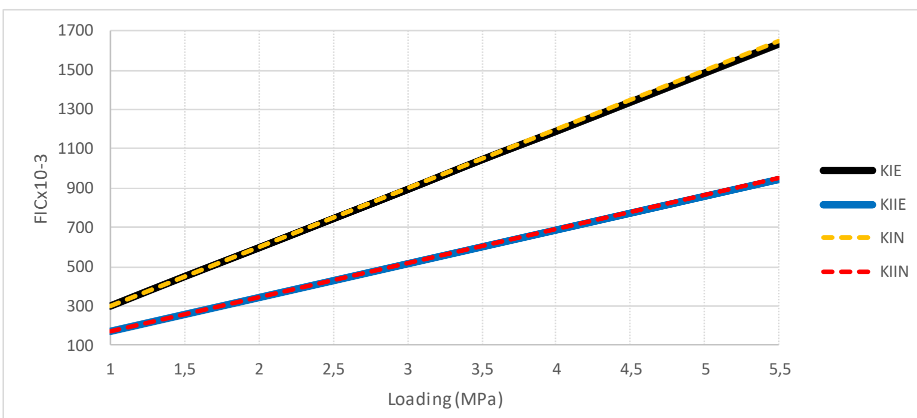
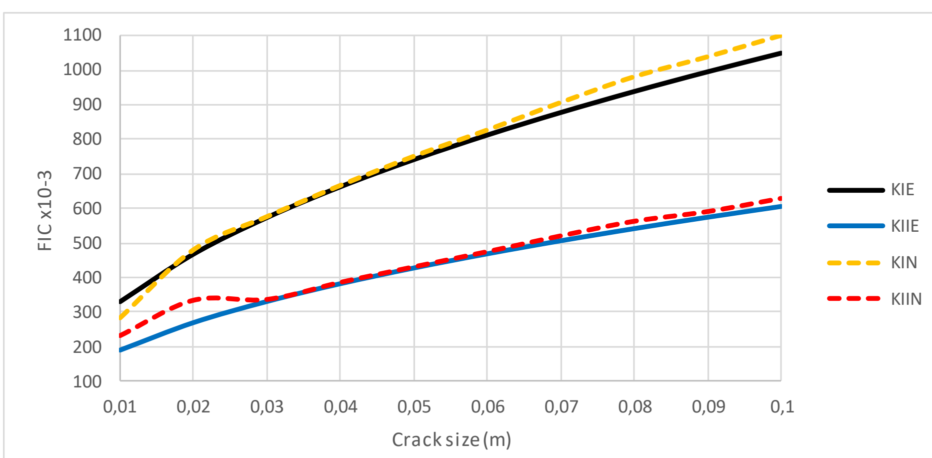


Fig. 7.: Comparative curves of the evolution of the numerical and analytical FICs as a function of (A) the angular position of the crack, (B1,B2) the size of the crack and (C1 and C2) the applied load.

C1) θ=30^{o}et L = 0.05 m



In addition, when the half-length L of the crack increases from 0.01m to 0.1m, the stress increases (Fig. 5.). This increase is accompanied by observed local breaks. For $\theta = 30^o$ and $\theta = 60^o$, we are respectively closer to mode I and mode II of rupture. This is what justifies the lower constraint at L=0.1m for $\theta = 60^o$.

The elongation observed in Figure 6 explains the behavior of the specimen when destroyed under load. Firstly, it is made possible thanks to the elasticity of the composite with a Young's modulus equal to 49.33 MPa on the one hand. This amounts to a rearrangement of the structure of the polymer chains. Secondly, we observe a somewhat plastic behavior due to the sliding of the polymer chains relative to each other. We notice that for a loading of 5.5 MPa, there is total rupture of the film. At this level, all values near the vertical center line are greater than the composite breaking stress equal to 3.5 MPa.

The comparison with the exact values of the FIC (Fig. 7.) confirms the reliability of these results.

Conclusion:-

The aim of our study is to analyze the crack propagation behavior of a composite based on cassava starch reinforced with coconut fibers. To do this, we carried out a parametric study to highlight the influence of the size and position of the crack, and the applied load. In particular, we determined the stress intensity factors (FIC) by the X-FEM. This work is followed by a comparison with the exact values resulting from analytical expressions. The very strong agreement between the two approaches confirms the reliability of the results obtained.

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Conflicts of Interest :

The authors declare that there are no conflicts of interest that could inappropriately influence, or be perceived to influence, the work reported in this manuscript.

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