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► **To cite this version:**

Xi Chen, Nathalie Godin, Aurélien Doitrand, Claudio Fusco. Influence of the node release methods on the acoustic emission signals due to crack initiation. CSMA 2024, CNRS, CSMA, ENS Paris-Saclay, Centrale Supélec, May 2024, Giens, France. hal-04822989

HAL Id: hal-04822989

<https://hal.science/hal-04822989v1>

Submitted on 6 Dec 2024

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Influence of the node release methods on the acoustic emission signals due to crack initiation

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Résumé — The direct node release method is proposed to simulate dynamic crack initiation, as an acoustic emission (AE) source model, from a circular hole on a PMMA plate under tension loading. This method avoids considering the velocity profile during the crack initiation, which has a non-negligible influence on the critical loading and crack length. We evaluate under which hypothesis this method seems applicable to accurately model crack initiation. Then, the influence of the node release methods on the AE signals is investigated to figure out their influence on the AE source modeling.

Mots clefs — Direct node release method, crack initiation, source modeling.

1. Introduction

Acoustic emission (AE) refers to the emission of transient elastic waves due to stress accumulation within or on the surface of the material [1]. These elastic waves propagate in the material and they are recorded by the piezoelectric sensors on the surface of the material. Simulating this AE process requires considering two aspects: on the one hand, the modeling of the source; on the other hand, the acquisition chain including the sensor effect. Sause et al. [2] described three sequential modeling steps, including the static step, the crack propagation step, and the wave propagation step. At the beginning, the model starts to be loaded. With increasing time and loading, the crack starts to propagate, which generates, an acoustic wave propagating in the studied medium. The AE source can be modeled as a change in the geometry based on the fracture mechanism. The fracture mechanisms of the crack initiation and propagation in composite materials, for instance, the fiber breakage, the fiber pull-out, and the matrix crack [3, 4], are simulated by releasing the nodes successively step by step.

To achieve a simulation of crack initiation, the Coupled Criterion (CC), proposed by Leguillon [5], is implemented to predict the mechanical results, for instance, the critical crack length and the critical loading. It is based on the simultaneous fulfillment of two separate conditions: on the one hand, the stress over a finite length must be larger than the material tensile strength; on the other hand, the incremental energy release rate (IERR) must be larger than the crack surface creation energy. Up to now, many studies used the quasi-static coupled criterion approach to predict the crack initiation from a circular hole in plates [6-9]. Leite et al. [9] used the quasi-static coupled criterion to study the crack initiation from a circular hole on the PMMA plate and compared the predicted fracture stress with the stress measured by tensile experiments. The quasi-static CC was used to predict the crack initiation of two symmetric cracks at a circular hole of a stretched PMMA plate. It is found that there is an underestimation between the fracture stress predicted by CC and the one measured experimentally. For the same model, the dynamic CC approach taking into account the kinetic energy has proved to allow retrieving a variation of the fracture stress corresponding to the experimental results with different crack velocities for different hole diameters [10]. The nodes over a finite crack length are released successively with a certain crack velocity over a finite crack length. It is found that under the assumption of a constant crack velocity during the crack initiation, the larger the hole diameter, the larger the predicted crack velocity. There is a non-negligible influence of the velocity profile on the prediction of the critical crack length and the critical loading. Thus, to reduce the influence of the velocity profile on the simulation of the crack initiation, a direct node release method is proposed. At variance with the successive node release method, to simulate the crack initiation, all nodes over the

critical crack length are released directly instead of successively. Thus, it is not necessary to consider the crack velocity profile, but it is only required to set a constant mean crack velocity during the crack initiation. We thus study the influence of the direct node release method on the crack dynamic aspect compared to that obtained for the successive node release method.

The objective of this work is to study the influence of the successive node release method and the direct node release method on the prediction of crack initiation and AE source modeling. The different node release methods are defined in Section 2. The computational set-up of the AE simulation is presented in Section 3. Then, the dynamic CC approach is applied to assess the crack initiation using these two node release methods to illustrate the influence of the methods on the mechanical simulation.

2. Different node release methods

2.1. Successive node release method

To simulate the crack initiation driven by the dynamic function, the nodes over a finite crack length are released. At first, for the successive node release method, all nodes are released in one calculation, as shown in Figure 1. Starting from the initial state in the first step, the stress variation before initiation $\sigma(U)$ is obtained before releasing the nodes. Then, for each crack length l_{c1} , l_{c2} , and l_{c3} , the corresponding nodes are released step by step. After releasing all nodes, the potential energy W_p and the kinetic energy W_k as a function of the crack length are obtained so that the IERR $G_{inc}^{dyn}(l(t), U) = \frac{-\Delta W_p(l) - \Delta W_k(l)}{l}$ can be computed. Note that, the duration of each step, for the defined crack length l_c can be determined by the velocity profile function $v_{crack} = dl(t)/dt$. For example, assuming a constant crack velocity v_{crack} during the crack initiation, the duration of each step is calculated as l_c/v_{crack} . Thus, using the successive node release method, a crack velocity profile needs to be considered.

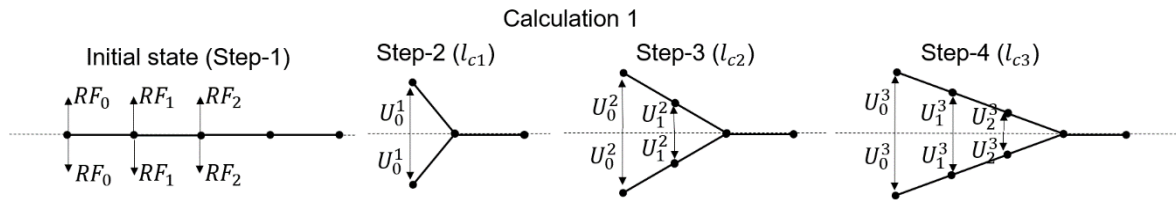


Figure 1 – Nodes released successively in one calculation

2.2. Direct node release method

To reduce the influence of the crack velocity profile on the CC and the AE signal characteristics, the direct node release method is proposed. This section will define the direct node release method. Using this method, stress condition is also obtained from the initial state, where there is no node to be released, as shown in Figure 2. Thus, the stress along the crack path before initiation is the same as using the successive node release method. In the following, for the crack length l_{c1} , the corresponding nodes are released in the first calculation. Then, for the second crack length l_{c2} , another calculation is made where the corresponding nodes are released. After releasing all the nodes in several calculations, the IERR $G_{inc}^{dyn}(l(t), U)$ can be obtained as a function of the crack length using the potential energy W_p and the kinetic energy W_k . Because the nodes are released directly for a finite crack length in one calculation, there is no need to consider a velocity profile during crack initiation, but the mean velocity should be taken into account to calculate the step duration.

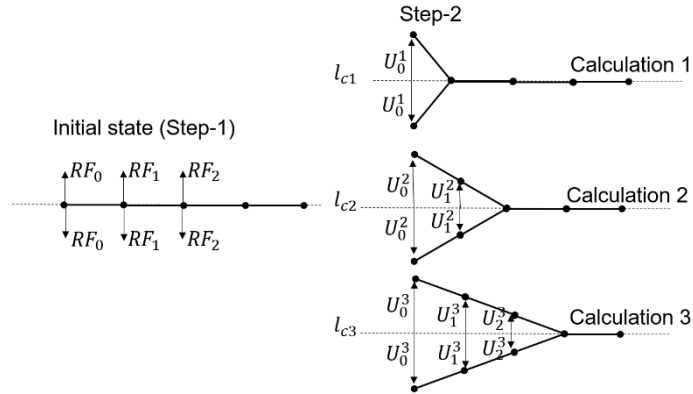


Figure 2 – Nodes released directly in different calculations

3. Numerical Implementation

3.1. Geometry and material property

A schematic representation of the geometry and loading under investigation in uncracked and cracked specimens is shown in Figure 3. The length L and the width W of the holed plate are 300 mm and 40 mm respectively. The hole diameter ϕ varies from 0.5 mm to 10 mm. The study is done on an amorphous thermoplastic polymer, Polymethyl Methacrylate (PPMA). The material properties determined in [9] are given in Table 1.

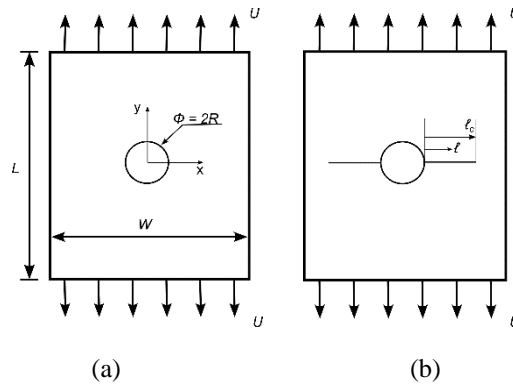


Figure 3 – Geometry and loading of the plate (a) before crack initiation, (b) after symmetrical crack initiation

Table 1 – Material properties of PMMA [9]

E (MPa)	ν	ρ (kg/m ³)	σ_c (MPa)	G_c (J/m ²)
3000	0.34	1100	63.4	496

3.2. Dynamic Coupled Criterion

For the dynamic CC, we assumed that the crack initiation is a non-instantaneous process. A crack velocity profile is thus considered. At first, we start from the general concept of the CC. Applying the CC, there are two requirements, the stress requirement and the energy requirement, which should be

satisfied simultaneously. The stress requirement of the CC states that the stress is larger than the tensile strength σ_c all along the crack path before crack initiation, which is written as:

$$\sigma(x, U) \geq \sigma_c \quad \forall 0 \leq x \leq l_c, \quad (1)$$

where x is the position along the crack path before initiation. U , the imposed loading or the displacement, and l_c , the initiation crack length, are the two problem unknowns.

The energy requirement is based on the principle of energy conservation between the state before and after the crack initiation. It is obtained by a balance of the variation in the external force work (W_{ext}), elastic strain energy (W_p), kinetic energy (W_k), and crack surface creation energy ($G_c l$, where G_c is the material fracture toughness and l is the crack length):

$$\Delta W_{ext}(l, U) - \Delta W_p(l, U) - \Delta W_k(l, U) = G_c l \quad (2)$$

The crack initiation occurs if the two requirements in Eqs (1) and (2) as functions of l and U are simultaneously fulfilled. Then, the solution of the CC reverts to determining the minimum imposed displacement and crack length satisfying both Eqs (1) and (2).

Based on the dynamic approach, under the quasi-static loading condition, the stress requirement is the same as in the quasi-static approach due to the fact that the stress depends only on the loading condition. Here, we only consider the quasi-static loading condition. Compared with the quasi-static approach, we assumed that the crack initiation is a non-instantaneous process. A crack velocity profile $v_{crack} = dl(t)/dt$ is considered, where the crack length jumps from 0 to the initiation crack length l_c in a given time. Thus, the IERR taking into account the kinetic energy can be written as follows:

$$G_{inc}^{dyn}(l(t), U) = \frac{\Delta W_{ext}(l(t), U) - \Delta W_p(l(t), U) - \Delta W_k(l(t), U)}{l(t)} \quad (3)$$

Thus, due to the consideration of the kinetic energy, the energy criterion Eq. (2) can be written as an equality: $G_{in}^{dyn}(l(t), U) = G_c$. Note that, in the case of the prescribed displacement, $\Delta W_{ext} = 0$. More details about the dynamic CC approach can be seen in the paper [10]. For these two cases, the function of the stress $\sigma(l(t), U)$ and the IERR $G_{inc}^{dyn}(l(t), U)$ are two nonlinear functions for the former case of U and U^2 .

3.3. Numerical implementation

These different node release methods are implemented for crack initiation and propagation from a circular hole on the PMMA plate. Due to the geometry and loading symmetry, only one-quarter of the plate is modeled as shown in Figure 4. The imposed loading is a prescribed displacement U along x direction, imposed to all nodes of the right edge. Symmetry conditions are imposed on the bottom and the left edges. To simulate the crack initiation and propagation, the symmetry condition of all nodes along the crack path is released. Here, we assume a constant crack velocity during the crack initiation and propagation. For the process of the crack initiation, the crack velocity is determined by the dynamic CC to correspond to the fracture stress measured experimentally using both node release methods. For the process of crack propagation, the crack velocity remains the same value using these different methods, and the crack propagation distance is chosen as 5 mm, which is a relatively small distance to the width (20 mm). To capture accurately the AE signal, a fully controllable square mesh is generated. The mesh is refined along the crack path with a uniform mesh size l_m [10].

To capture the out-of-plane velocity, as AE signals, we select three positions as the sensors, as shown in Figure 5. One sensor (sensor 1) is chosen at one node on the circular hole, where $x = 0.1$ mm. The other two sensors (sensor 2 and sensor 3) are located on the upper edge, where $x = 20$ mm and $x = 100$ mm. The sensor-source distance varies from a small distance (sensor 1) to a large distance (sensor 3) to investigate the influence of the wave propagation on the AE signal.

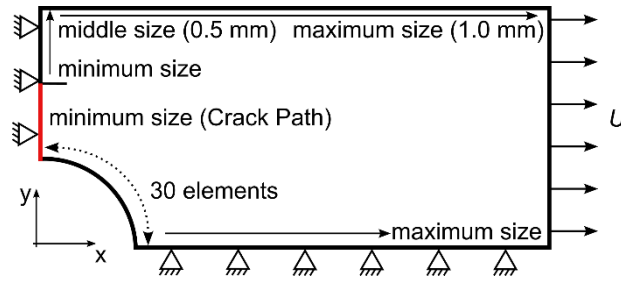


Figure 4 – Schematic view of mesh size distribution

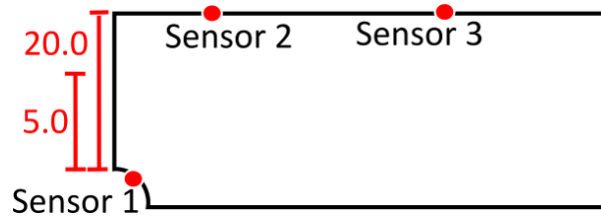


Figure 5 – Schematic view of sensor position

4. Influence of the node release methods on the mechanical simulation

At first, two node release methods are applied to the dynamic CC, so that the critical crack length and the crack velocity can be determined to reproduce the experimental results. Here, we assume that the crack velocity during the crack initiation is a constant value for the implementation of the successive node release method. To reproduce the fracture stress measured experimentally, we calculate the crack velocities for different hole diameters as we have done in [10].

Figure 7 shows the crack velocities to reproduce the experimental results, predicted by the dynamic CC, using (a) the successive node release method and (b) the direct node release method. It's found that there is the same increasing trend of the crack velocity with an increasing hole diameter. However, for the large diameter (10 mm), the crack velocity obtained using the direct node release method is too high and non-physical. Comparing these two figures, the velocity range using the direct node release method is significantly larger than that using the successive node release method. Thus, the critical crack length, the loading, and the crack velocity will be different using these two node release methods.

To compare the influence of the node release methods on the AE signals, we set three different cases, where the dynamic CC is satisfied, as shown in Table 2. The 1 mm hole diameter is set as a reference to the study. At first, using the successive node release method, the crack velocity, the crack length, the initiation duration, and the prescribed displacement are determined by the dynamic CC to correspond to the experimental results. Then, using the direct node release method, the first case 'Direct A' is set with the same crack velocity as using the successive node release method. The CC should satisfy the dynamic CC with the other three parameters, the crack length, the initiation duration, and the loading. The second case 'Direct B' is set with the same loading, and the other three parameters are derived from a satisfaction of the dynamic CC.

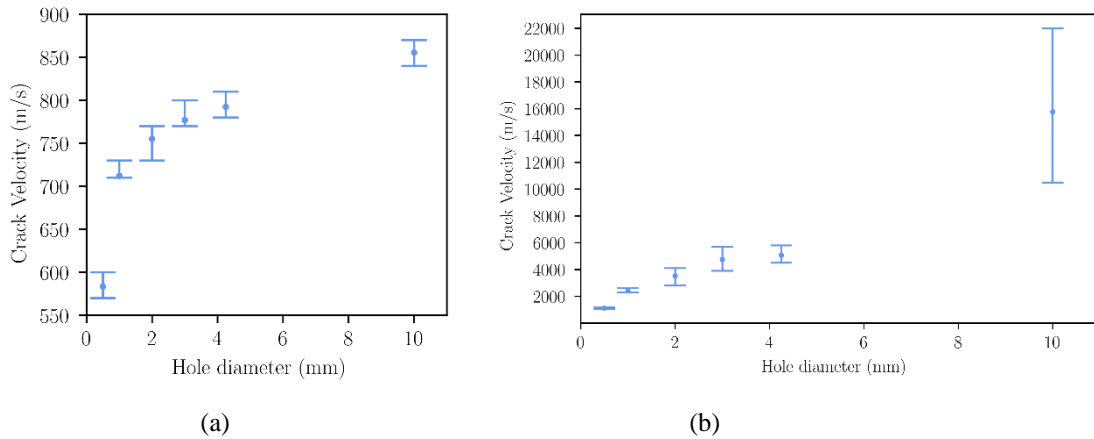


Figure 7 – Range of crack velocities to reproduce the experimental results using (a) the successive node release method and (b) the direct node release method.

Table 2 –Parameters setting using different node release methods

	Crack velocity (m/s)	Crack length (mm)	Initiation duration (μ s)	Displacement (mm)
Successive	750	1.120	1.495	2.650
Direct A	750	0.331	0.441	1.800
Direct B	3200	1.053	0.329	2.650

5. Conclusion

The direct node release method is proposed to reduce the influence of the crack velocity profile on the crack initiation, predicted by the dynamic CC. Compared with the successive node release method, there is a large difference in the critical crack length, the critical loading, and the crack velocity on the mechanical simulation. Then, the influence of the node release methods on the AE signal characteristic will be investigated by a parametric study first and a comparison of the AE signal under three cases in Table 2. According to the AE signals during the crack initiation and the crack propagation, on the one hand, we can conclude on the feasibility of the implementation of the direct node release method on the AE simulation; on the other hand, we can figure out the role of the simulation of the crack initiation during the whole AE simulation.

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