Dynamic crack growth and arrest, simulated by Cohesive Zone Models. Application to a subclad in a RPV.

G. Debruyne

Acoustic and Mechanical Analysis Department, Research and Development Division, EDF, Clamart, France, e-mail: gilles.debruyne@edf.fr

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1. ABSTRACT

The paper deals with the fast crack growth and arrest simulated by CZM (Cohesive Zone Models) based on energy principles. After some details about our CZM developments, validations of this model are carried out on a DCB specimen involving fast growth and arrest. In particular, the effect of cohesive parameters and stress waves round trips on crack kinematics are investigated. Then, the dynamic propagation of a subclad flaw in a PWR vessel is considered. A 6mm radial crack is embedded into the ferritic steel, under the austenitic cladding. To simulate the potential crack growth, a set of CZM elements is dispatched on a straight line on both sides of the flaw (crack kinking is not considered here). The vessel is submitted to a hypothetical loading involving a high inner pressure to start up a running crack growth. Furthermore, heterogeneous fracture properties are capable of enhancing the running process or in contrary to cause the arrest crack. The main results are the following: The crack onset predicted with CZM is in good accordance with a Griffith criterion associated to classical J integral. It always occurs towards the base metal owing to the cladding ductility. The crack kinematics, including velocity and arrest length, is very few sensitive to the CZM critical tensile strength (in the range considered for steels) and to the cohesive law. Plastic behaviour tends to more crack growth stability than elasticity.

2. INTRODUCTION

Service life extension of Pressure Water Reactor (PWR) vessels is an important issue for a number of nuclear operators. This aim is partially subjected to improvement of safety margins. These margins may be enhanced by the acceptance of a limited amount of crack growth, starting from the initial flaw, under the most severe accidental loadings. It is therefore necessary to predict not only the crack onset but also the crack arrest (Burdekin (1999)). For some accidental transient loading, the possible suddenness of the propagation and arrest, due to the toughness variation of a part of the vessel by neutron irradiation and collapse of temperatures may involve important dynamic effects. Furthermore, some local brittle zones may enhanced these phenomena.

3. COHESIVE ZONE MODELS DERIVED FROM ENERGY CONCEPT

The first cohesive models were introduced by Dugdale (1959) and Barenblatt (1960) at the beginning of the sixties. In the seventies Hillerborg et al. (1976) introduce the concept of fracture energy and propose a cohesive force versus crack opening relationship for concrete. Since, a large number of cohesive model were developed with important range of applications. Needleman (1987) may be quoted for interface debonding modeling concerning composite materials with metal matrix.
Our approach is following the thread of these author ideas, but the most original feature of our study is based on the least energy principle, derived from the latter developments of the Francfort-Marigo theory (Francfort et al. (1998), Charlotte et al. (2000)) for mode I or mode II crack opening (in the next sections, only applications with mode I will be considered). Two interface cohesive laws are suggested here, the first law deals with an exponential expression for the force opening displacement relationship and the second one with a polynomial expression.

Let’s denote by $\Gamma$ some surfaces in the body subjected to displacement jumps $\delta = (\delta, n, \delta t)$ with $(n, t)$ the crack normal and tangential unit vectors (cf. fig. 1), and $\Psi$ the surface energy activated during crack lips motion. The dissipative process is governed by the threshold variable $\kappa$ which gives the maximum norm of the jumps ever reached all along the crack history. Following the value of $\| \delta \|$−$\kappa$, the surface energy displays either a dissipative mode ($\| \delta \| > \kappa$) or a non dissipative mode ($\| \delta \| < \kappa$) and will be designed by $\Psi_{\text{dis}}(\| \delta \|)$ or $\Psi_{\text{lin}}(\| \delta \| \kappa)$. Furthermore, an indicator function prohibiting the lips interpenetration is numerically estimated by a continuous penalty function denoted $\Psi_{\text{pen}}$.

The cohesive stress vector denoted $\sigma$ corresponds to the energy derivative with respect to the norm of the displacement jump $\delta$. Its depends both on the cohesive law and the energy mode (fig. 2). The general expression of the stress vector is:

$$\sigma = H (\| \dd \| - \kappa) \sigma_{\text{dis}} + [1 - H (\| \dd \| - \kappa)] \sigma_{\text{lin}} + \sigma_{\text{pen}}$$

where $H$ is the Heaviside function.

The stress vector in dissipative mode is defined as:

- Polynomial law $\sigma_{\text{dis}} = \frac{\partial \Psi_{\text{dis}}}{\partial \dd} = \sigma_c \dd \left( \frac{1}{\| \dd \|} - \frac{\sigma_c}{2G_c} \right)$
- Exponential law $\sigma_{\text{dis}} = \frac{\partial \Psi_{\text{dis}}}{\partial \dd} = \sigma_c \dd \exp \left( - \frac{\sigma_c}{G_c} \| \dd \| \right)$

while the stress vector in linear mode is:

$$\sigma_{\text{lin}} = \frac{\partial \Psi_{\text{lin}}}{\partial \dd} = P(\kappa) \dd$$

where $P$ expression depends on the cohesive law:

- Polynomial law $P(\kappa) = \sigma_c \left( \frac{1}{\kappa} - \frac{\sigma_c}{2G_c} \right)$
- Exponential law $P(\kappa) = \frac{\sigma_c}{\kappa} \exp \left( - \frac{\sigma_c}{G_c} \kappa \right)$

Figure 1 Crack surface and cohesive zone.
At last, the penalization Stress vector may be written as the derivative of the penalty function:

\[ \Psi_{pen} = \frac{1}{2} P(\kappa_0) (\delta n)^2 + \text{cons} \]

\[ \delta_{pen} = \frac{\partial \Psi_{pen}}{\partial \ddot{a}} = P(\kappa_0) \left( \begin{array}{c} \ddot{a} n \\ 0 \end{array} \right) \]

The material parameters are the critical stress \( \sigma_c \) and the fracture energy \( G_c \).

\[ \text{Figure 2.a Polynomial interface law} \quad \text{Figure 2.b Exponential interface law.} \]

### 4. CZM VALIDATION FOR CRACK ARREST IN A DCB SPECIMEN

In order to check the validity of our cohesive model in a dynamic frame, a bimaterial DCB of length \( L \) and height \( 2h \), with an initial crack length \( a \), is considered here. The elastic properties are the same for both materials but these latter differ from each other by their respective surface energy density \( G_1 \) and \( G_2 \), with the ratio \( \eta = G_1 / G_2 > 1 \), on the interface located at \( x = x_0 \) (Fig. 3). A displacement \( \pm U_y \) is slowly prescribed at each end-arm of the specimen, so that the crack is quasi-statically growing, until it reaches the interface at \( x = x_0 \). At this stage, the loading is stopped so that \( G = G_1 \). The energy surface jump at the interface \( x = x_0 \) involves inertial effects and the crack should run throughout the first interface in the weakest material with possible stop and go or definitive crack arrest. Our attention is focused here on the conditions of crack velocity and arrest along the \( x \) direction, versus the ratio \( \eta \). And others cohesive parameters. The analysis is performed with plane strain conditions.

The potential crack path along \( x \)-axis is discretized by 4000 interface elements uniformly dispatched ahead the initial crack (each element length is fixed to 25\( \mu \)m so that the estimated cohesive zone suggested by Rice J.R. (1980) for a linear cohesive law is covered by at least 4 elements if \( \eta > 20 \)).

#### 4.1 Comparison of CZM and release node method.

An alternative method to CZM, based on released node techniques and Griffith criterion is compared to the cohesive energy approach. The regular released node method is associated here to an iterative procedure involving, for each crack growth step, the dynamic energy release rate estimate for a range of virtual crack velocity. The actual velocity is found by dichotomy, fulfilling the condition
\( G = G^2_c \) in the weakest material, and the crack length is updated by releasing nodes to reach the next crack growth step. This process is very time consuming, and is only compared to CZM for a relatively short time interval, with the aim of assessing CZM relevance for dynamic crack growth and to estimate the influence of the cohesive zone length (governed by the cohesive strength) on the crack behaviour against a pure Griffith criterion. and the cohesive zone growth is computed with a dynamic procedure within the interval \([0, 15 \times 10^{-4} \text{ s}]\) divided in uniform time steps \(\Delta t = 2.10^{-7} \text{ s}\) and using a classical non dissipative Newmark scheme \((\alpha = 0.5, \beta = 0.25)\) for the time step integration.

Figure 4 displays the comparative crack velocity, derived from a Griffith criterion associated to the releasing nodes iterative process, and from the polynomial CZM investigation (with a cohesive strength \(\sigma^2_c = 1200 \text{ MPa}\)) for \(\eta = 3\).

![Figure 3. DCB geometry and loading](image)

![Figure 4. Comparative crack velocities for the CZM and the release node procedure(\(\eta = 3\))](image)
The results are in a good accordance, except for the first point where the releasing node procedure exhibits an irrelevant velocity beyond the Rayleigh wave speed ($C_R = 3460 \text{ m/s}$). Moreover, the CZM pick up crack tip stop and go, unlike the released node model.

4.2 Comparison of the polynomial and the exponential interface laws.

Figure 5. Comparative crack growth along time for a polynomial and an exponential law ($\eta = 2$)

The figure 5 sketches the crack growth simulation with both of the two interface laws. Only few differences appear between the two laws, so that following investigations will use the most classical polynomial law. It may be noted that the crack growth is generated with many stop and go resulting from waves return.

4.3 Crack arrest simulation with polynomial CZM and energy considerations.

Figure 6. Crack growth and kinetic energy along time ($\eta = 3$)
Starting from the figure 5, it is somewhat difficult to detect a definitive arrest, because of the great number of wave round trips involving short arrest. The figure 6 enlightens this point, sketching the kinetic energy vanishing at the definitive arrest (with a further bouncing corresponding to beam vibration).

4.4 Influence of wave round trips on the crack kinematics.

To check the influence of wave returns on the crack kinematics, absorbing conditions are prescribed all along the beam edges (Engquist (1977)). The figure 7 displays the two crack kinematics related to each boundary conditions. Until the pressure waves have reflected from boundaries to the crack tip, there is no difference then, the crack slows down in the case of setting an artificial absorbing condition. Taking account of stress waves is of primary importance to simulate fast crack growth, in the case of thin bodies as a DCB.

![Figure 7. Crack growth comparison between actual and absorbing boundary conditions](image)

5. SUBCLAD CRACK GROWTH AND ARREST IN A RPV.

This section is devoted to investigations about crack growth and arrest in a Pressure Water Reactor Vessel under some particular geometry and loading conditions, which do not involve actual transient loadings. The vessel base metal is a ferritic steel and the inner cladding of 7.5 mm width is an austenitic steel, known as more ductile. A 6 mm deep radial flaw takes place in the base metal, under the cladding. The vessel is submitted to an inner pressure loading increasing up to the crack onset. Contrary to the DCB case explored in the previous section, this loading and this geometry involve more unstable crack growth while the crack tip runs inside the vessel wall. But, for actual Reactor Vessel, the deeper within the ring wall, the tougher the base metal, because of the decrease of irradiation (and also the rise in temperature inside the wall, which is disregarded here). Thus, a crack arrest is expected inside the wall. Two situations are considered here: 1) an homogeneous base metal with an uniform fracture energy is considered, so that no arrest is expected, but the influence of the medium behavior (elastic or elastoplastic) on stability is analyzed; 2) a thin elastic and brittle inclusion is embedded in the base metal, ahead of the initial flaw, which could enhance the crack velocity. Beyond this zone, the metal exhibits a strong toughness again, and the crack arrest conditions versus this toughness value are explored.

To take into account the close end effect, the vessel shell ring geometry is considered here as an axisymmetric tore with a large curvature radius (cf. Figure 8), which involves that the initial flaw is assumed to be axisymmetric too. This latter assumption should lead to a crack growth overestimation (real flaws are rather of elliptical shape with a finite circumferential width). Each material behavior is considered either as the one of an elastic medium or as the one of an elastoplastic medium.
Isoparametric linear triangular and rectangular elements are used to mesh the vessel (cf. fig. 9). A set of interface elements supporting polynomial CZM as introduced in the third section, is spread out on both sides of the initial crack, along the expected rectilinear crack path. To lighten the F.E. model, CZM elements are set along only the half of the wall width, and the length of each element is in the range [0.05 mm, 0.2 mm] which is sufficient, compared to previous DCB experiments exhibiting similar materials.

5.1 Flaw onset.

Our first study is devoted to the crack onset, which only involves a quasi-static analysis since the pressure loading is slowly prescribed. Both behaviors (elastic and plastic) are considered for the base metal and the cladding, and compared with a classical analysis based on Griffith criterion. Besides the actual short flaw of 6mm, another deep crack with a 16mm length has been considered. Tables 1 and
2, respectively for elastic materials and elastoplastic ones, sketch the comparative results for both methods and both cracks. For CZM, the critical inner pressure $P^*$ is associated to the rupture of the first Gauss point, ahead of the crack tip in the base metal. This pressure value is then used to assess the energy release rate, within a classical Griffith crack model (the cohesive elements around the initial are then deactivated to make way for a Griffith crack ligament). This energy release rate is estimated by a theta method (Destuynder (1981)), so that $G\theta(P^*)$ for the critical pressure is expected to be close to $G_C$. For the elastic behavior, the critical pressure leads to an apparent toughness close to the actual one in the base metal ($K_{lc} = 40 \text{ MPa}\sqrt{m}$) and which gets closer as the crack length increases (because the cohesive length becomes relatively smaller).

<table>
<thead>
<tr>
<th>Elasticity</th>
<th>6mm subclad flaw</th>
<th>16mm subclad flaw</th>
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<tbody>
<tr>
<td>Critical pressure $P^*$ at the crack onset with CZM</td>
<td>$P^*$=38.2 MPa</td>
<td>$P^*$=23.4 MPa</td>
</tr>
<tr>
<td>Apparent toughness for a Griffith crack with $P^*$</td>
<td>$K_{lc} = 37.4\text{MPa}\sqrt{m}$</td>
<td>$K_{lc} = 40.8\text{MPa}\sqrt{m}$</td>
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Table 1 Crack onset comparative predictions with a classical Griffith criterion and with CZM for a linear elastic material.

The elastoplastic behavior leads to poorer agreement between the two methods as shown in table 2. It is well known that the energy release rate in elastoplastic media considered as non linear elastic may lead to underestimating the crack resistance.

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<th>16mm subclad flaw</th>
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<tbody>
<tr>
<td>Critical pressure $P^*$ at the crack onset with CZM</td>
<td>$P^*$=37.4 MPa</td>
<td>$P^*$=24.7 MPa</td>
</tr>
<tr>
<td>Apparent toughness for a Griffith crack with $P^*$</td>
<td>$K_{lc} = 45.4\text{MPa}\sqrt{m}$</td>
<td>$K_{lc} = 44.5\text{MPa}\sqrt{m}$</td>
</tr>
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Table 2. Crack onset comparative predictions with a classical Griffith criterion and with CZM for an elastoplastic material.

5.2 Flaw propagation in an homogeneous material.

A quasi-static simulation is achieved, up to the critical loading $P^*$ (which is different for an elastic or an elastoplastic material, as mentioned in tables 1 and 2.). At this stage, the dynamic algorithm is engaged. As expected, according to the quasi-static observations summarized in fig. 9, we did not notice any propagation at all in the frame of an homogeneous plastic material, while, for an elastic one, a fast crack growth without arrest and with an increasing velocity is observed, as depicted by the red curve of fig. 9.

To promote a propagation even with plasticity, an elastic inclusion of 2 mm width and 20 mm high, embedded into the base metal ahead of the initial crack tip, is now considered (fig. 8). This inclusion is elastic but keeps the same fracture properties as the base metal one, and the surrounding material keeps its plastic properties. Under these conditions, the crack quickly runs into the inclusion and stops abruptly in the middle of inclusion ($\Delta a = 1.2\text{mm}$), see blue curve of fig. 9). This configuration shows the importance of the bulk material properties on the crack growth, and specially the stabilizing properties of plasticity.
5.3 Flaw propagation and arrest in an heterogeneous material.

The elastic inclusion is now embrittled. Its toughness is half the one of the regular base metal ($K_{\text{incl}}^{\text{inc}} = K_I^1 / 2 = 20 \text{MPa} \sqrt{\text{m}}$), which enhances the growth instability. Beyond this brittle defect, the media is tougher than the initial base. The crack front velocity through the inclusion and beyond is depicted in fig. 10.a. For $G_C^2 > 1.6 G_C^1$, a crack arrest occurs on the interface. For a slightly smaller energy surface, there is no arrest and the crack accelerates. For an elasto-plastic behavior of each section of the base metal (except the inclusion which remains elastic), the same parametric analysis is performed. When $G_C^2 > G_C^1$, an arrest always occurs at the interface inclusion-tough metal. To enhance instability, a new parametric analysis is performed with $G_C^2 < G_C^1$. The crack only runs beyond the inclusion (without arrest) for $G_C^2 < 0.86 G_C^1$ (fig. 10.b), which confirms the strong stabilizing part of plasticity, and the importance to take into account that feature for crack arrest investigation.

**CONCLUSION**

In this paper, some dynamic phenomena, due to material toughness jumps, are exhibited. Numerical results derived from the CZM developed here are in good accordance with some traditional methods such as the release node technique associated to the energy release rate concept.
Concerning the PWR vessel analysis, affected by a subclad crack, a virtual high inner pressure loading is prescribed, to start up the crack growth. The main feature investigated here, is the role of plasticity on the crack kinematics. The study shows two situations. The first one deals with growth inside a vessel wall with an uniform toughness, and in this case two extreme situations take place according to the material behavior:

If the material is elastic, the kinematics is fully unstable, without any crack arrest. If the material is elastoplastic, the kinematics is stable.

The second situation deals with a small brittle elastic defect embedded in a tougher base metal, and located on the crack path. Once again, two situations take place according to the material behavior:

If the material is elastic, the crack is pushed forward throughout the defect, and the arrest takes place just at the end of the brittle defect, only if the material beyond this interface is sufficiently tough with respect of the initial base metal. Otherwise, no arrest is detected.

If the base metal is elastoplastic (the defect keeping its elastic properties), the arrest occurs at the same point as in the previous case, even if the metal downstream the defect is slightly less tough than the initial metal upstream the inclusion. A next step in further investigations should be 3D and viscosity effect analyses.

REFERENCES


