A NUMERICAL METHOD TO SIMULATE DUCTILE CRACK GROWTH

S. MARIE[*] and S. CHAPULIOT[*]

To model ductile tearing crack growth, a term homogeneous to an energy release rate and relevant of the dissipated energy in the fracture process is proposed. This parameter, G_{fr}, associated to the crack growth increment λ used in the calculations leads to a critical value of the local energy release rate calculated near the crack tip G_l. This method allows to simulate large crack growth in the case of CT specimens of different sizes made in a japanese STS 49 steel and of CT and SENT specimens made in a A106 Grade B steel. All these specimens are side grooved. The parameter G_{fr} appears to be independent to the geometry and loading conditions.

NOMENCLATURE :

a	Crack length.	**G_l**	Local energy release.
a_0	Initial crack length.	**G_{fr}**	Energy release rate relevant of the fracture process.
B	Specimen thickness.		
B_n	Specimen net thickness.	**J**	Rice's integral.
E	Young modulus.	**J_i**	Critical value for the initiation
F	load.	**LLD**	Load Line Displacement.
G	Energy release rate.	**LLD_{ini}**	LLD value at initiation.
G_c	Critical energy release rate.	λ	Crack increment length.

INTRODUCTION

Predicting the behaviour of a cracked structure is of a great importance to insure its integrity. Method based on a parameter like the J-Δa curve are confronted to the transferability problem of characterisation test results to real components.

[*] Commissariat à l'Energie Atomique, DRN/DMT/SEMT/LISN, 91191 Gif-sur-Yvette Cedex, France.

Recently, a method was proposed (1) to simulate large crack growth using an energy release rate calculated near the crack tip, relevant of the energy dissipated in the fracture process. The simplicity of this method lies on the fact that it aims to estimate the dissipated energy during the crack growth but don't interest in the manner how this energy is spent.

This article intends to validate this method, and, in particular, interests to the transferability of the parameter G_{fr}, which represents the energy dissipated by the fracture.

PRESENTATION OF THE METHOD

This method use two parameters : The first one describe the crack initiation. It is given by a characteristic value of the J integral related to the stretch zone width. This term is a material property (2). The second is assimilate to an energy release rate, named G_{fr}, although it is relevant of a dissipated energy and not of a restored energy. It represents the energy spent in the fracture process.

To calculate the energy release rate, the approach use the method introduced by Destuynder (3), named $G(\theta)$. G is expressed by :

$$G = \int_{\Omega} Tr(\sigma \nabla U \nabla \theta) d\Omega - \int_{\Omega} W_{tot} \, div\theta d\Omega \tag{1}$$

where Ω is the disturbed domain and W_{tot} the total strain energy ($W_{el}+W_{pl}$).

This relation is identical to Rice J integral when the integration path is taken remote from the crack tip. Proportional loading conditions must be satisfied to insure G validity.

For a non stationary crack, it is proposed to calculate a local energy release rate close to the crack tip. The originality of the method consists in calculating G, named G_l, with an integration path smaller in size than the discrete crack extension increment. This means that crack extension concerns only a few number of elements surrounding the crack tips and that the integration paths are included between the previous and the current crack tips. A fine mesh is therefore needed to allow the calculation of a relevant number of integration paths mourned the crack tip. This presents the advantage of providing a good description of the fields around the crack tip. To calculate the energy dissipated in the fracture process, the following assumptions are made :

- The fracture process is controlled by dissipated energy. Only the plastic part of the local energy release rate is accounted in the criteria. Indeed, the ductile fracture mechanisms essentially consists in voids growth, controlled by plastic deformations (4).
- This energy is translated in a critical energy release rate G_c, function of a parameter intrinsic to the material, G_{fr}.
- The energy needed by the fracture is proportional to the crack extension increment λ.

These assumptions lead to the relationship:

$$G_c = \bar{\lambda}.G_{fr} \tag{2}$$

where $\bar{\lambda}$ is the dimensionless value of the crack increment λ. During the calculation, the calculated local energy release rate must be separate into its elastic and plastic components. The elastic term G_{el} is estimate from the compliance variation.

APPLICATION

To illustrate the method possibility, the influence of geometry is investigated from experimental results available in the IPIRG database (5), for CT specimens of different sizes made in a japanese STS 49 steel and for SENT and CT specimens made in a A106 Grade B steel. All these specimens are side grooved. The Young modulus and the yield stress of the Japanese STS-49 steel are respectively 150 GPa and 244 GPa. In the case of the A106 Grade B steel, they equal to, respectively, 240 GPa and 258 MPa. Specimens description is given in table 1.

Japanese steel STS 49				
Specimen	**W (mm)**	**B (mm)**	**B_n (mm)**	**a_0 (mm)**
CT 20%SG 1.5T	76.15	35.38	28.6	41.2
CT 20%SG 3T	152.4	25.4	20.42	81
A106 Grade B steel				
SENT 10%SG	14.48	45.75	41.2	7.0
CT 20%SG	40.64	17.8	14.22	21.1

TABLE 1 : Specimens description.

As no experimental values for J_i were available, the crack initiation was obtained from examination of the load line displacement versus Δa curve. The parameter G_{fr} has been determined with the 20%SG CT 1.5T specimen in the case of the japanese STS 49 steel, and with the SENT specimen in the case of the A106 Grade B steel. It is chosen to have a good agreement between the numerical and the experimental displacement versus Δa curves. Once this parameter determined, it is used to simulate the behaviour of the other specimens. Table 2 summarises the parameters used in the calculation. To illustrate the crack increment length λ independence of the method, the 20%SG CT 1.5T specimen calculation is realised with two different λ.

Material	**G_{fr} (kJ/m^2)**	**Specimen**	**LLD$_{\cdot ini}$ (mm)**	**λ (mm)**	**G_c (kJ/m^2)**
STS 49	143	CT 20%SG 1.5T	2.8	1.5	215
			2.8	3.	430
		CT 20%SG 3T	4	3.	430
A106 Grade B	120	SENT 10%SG	0.4	0.6	72
		CT 20%SG	0.9	0.8	96

TABLE 2 : Parameters used in the calculations.

Figure 1 compare the numerical load versus displacement curve with the experimental one, successfully. A good agreement is also find in the case of the displacement versus Δa curves in figure 2.

DISCUSSION OF THE RESULTS

Figure 3 shows the Von Mises stress variation during the crack growth obtained for each specimen studied. This stress is determined at the intersection between the ligament in front of the crack tip and the integration path used in the G_I calculation. After a short transient period, the equivalent stress remains constant with the crack length.
In figure 4, the same behavior is obtained for the CTOA. The CTOA is calculated from the ratio between the opening displacement of the previous crack tip to the crack increment length λ. This result show the coherence of the approach with this well known physical phenomena during propagation.
This confirms that a relation between the G_{fr} parameter and the local terms exists. G_{fr} represents the energy dissipated locally in the fracture process.

CONCLUSION

A numerical method is proposed to simulate ductile tearing large crack growth based on a local energy rate calculation. It use a critical parameter G_{fr} relevant of the dissipated energy in the fracture process itself. This method don't interest in how this energy is spent near the crack tip, which explains its simplicity compared to the local approach.
Large crack growth were modelled for different type of specimen, which prove the capability of the method to represent the geometry effect. Locally, parameters like equivalent stress and CTOA remain constant during the crack growth. This last result shows the coherence of the method with well known physical phenomena which occurs during ductile propagation.

REFERENCES

(1) Marie, S.and Chapuliot, S., Fat. & Fract. of Engng Mat. & Struct., Vol. .21, 1998, pp. 215-227.
(2) Eisele, U. and Roos, E., Nucl. Engng & Design, Vol.130, 1991, pp.237-247.
(3) Destuynder, Ph., Djaoua, M. and Lescure, S., Journal de Mécanique Théorique et Appliquée, Vol.2, N°1, 1983, pp.113-135.
(4) Rice, J.R. and Tracey, D.M., J. of Mech. & Phys. of Solids, Vol.17,1969, pp.201-217.
(5) Wilkowski, G.M., et al., 'Degraded Piping Program Phase II', experiment numbers 4.3-6 and 4112-7, NUREG/CR-4082.

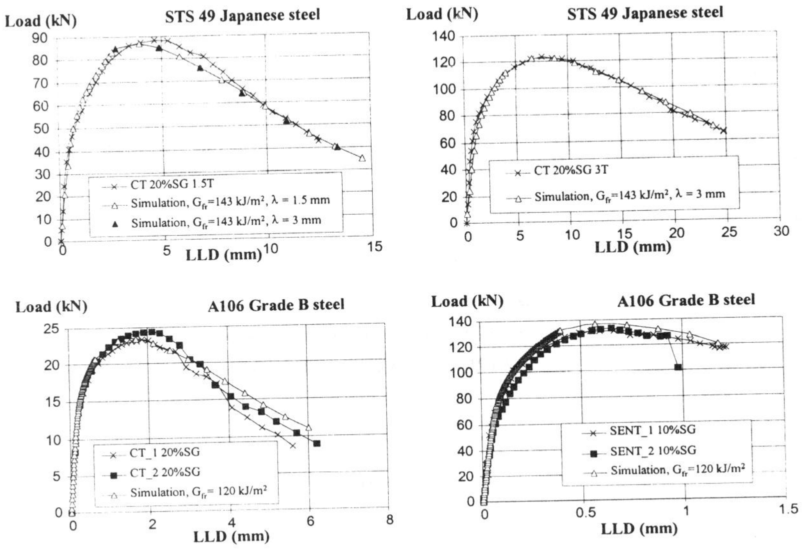

Figure 1 : Calculation results : load versus load line displacement curves.

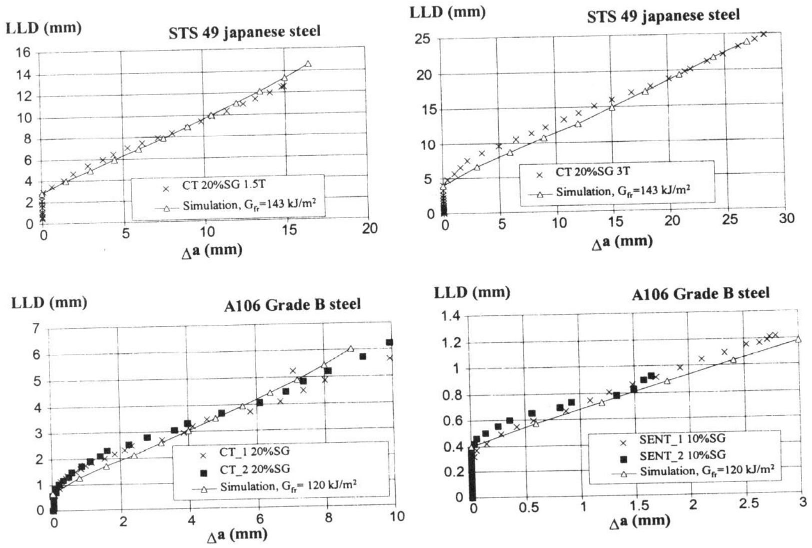

Figure 2 : Calculation results : load line displacement versus Δa curves.

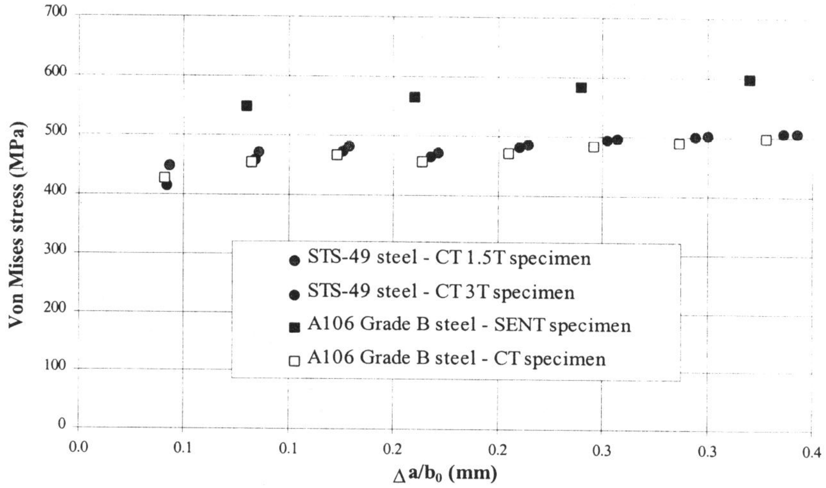

Figure 3 : Von Mises stress variation during crack growth.

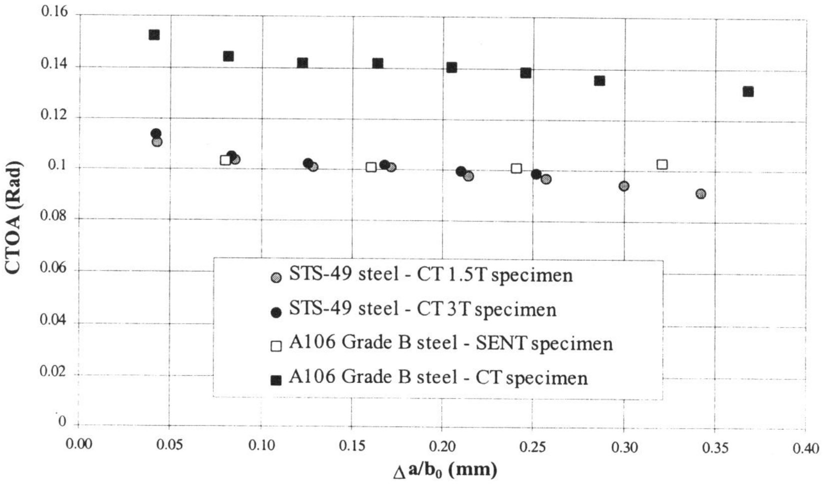

Figure 4 : CTOA evolution during crack growth.