Finite Element Analysis of Dynamic Crack Propagation

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Abstract

In accidental situations, nuclear pressure vessels can be subjected to severe thermal shocks, eventually leading to dynamic fracture propagation. From a safety point of view, it is necessary to analyse such crack propagations, and to understand the crack arrest phenomenon.

The simple case of a laboratory specimen was considered, in order to investigate the feasibility of a numerical approach using the PLEXUS code of the CEASEMT Finite Element System. It was shown that PLEXUS is a suitable numerical frame, in order to investigate such problems. Additional work is needed in order to implement more realistic models, to represent the fracture processes.

Comparison between numerical results and experimental data from reference laboratory experiments will also be carried out in the near future.

I. INTRODUCTION

In accidental situations, nuclear pressure vessels can be subjected to severe thermal shocks, eventueally leading to dynamic fracture propagation. From a safety point of view, it is necessary to analyse such crack propagations and to understand the crack arrest phenomenon.

Fracture of structural steels can occur under different conditions :

- Without important plastic deformations during propagation : cleavage.
- After an important plastic deformation around the crack tip : ductile fracture.

On the other hand, the stress state during dynamic propagation of a crack is extremely complex. For example, the interaction between the crack tip, and the waves reflected from the boundaries of the structure have to be taken into account, since it might influence significantly the propagation phenomenon.

The complexity of the problem implies a numerical approach. Developements within the explicit PLEXUS code of the CEASEMT Finite Element System have been performed, in order to handle dynamic crack propagation problems. The simple case of a laboratory specimen was considered, in order to investigate the feasibility of the numerical approach.

II. FINITE ELEMENT APPROACH

The PLEXUS Code [1] is a finite element programm specially formulated for fast dynamic analysis : An explicit time integration procedure is used.

Elastic and plastic behaviour can be taken into account, as well as large displacements, with large strains.

Two specific fracture criteria were implemented, in order to perform a first feasibility study :

- **Brittle fracture** : In order to keep the approach as simple as possible, a local stress criterion [2] is used, to account for cleavage :

  $\mathrm{Max}_i \; \sigma_i = \sigma_c$

  where σ_i are the principal stresses and σ_c is the cleavage stress, at a given distance from the crack front. When the criterion is met within a finite element, the stresses corresponding to the cleavage direction are set to zero ; on the other hand, a compressive wave is generated back towards the structure, in order to restitute the strain energy previously stored within the element.

  When the material is purely elastic the cleavage criterion is identical to : $K_1 = K_{1_D} = C^{te}$. However, if plastic strains occur in the vicinity of the crack tip, the K_{1_D} and σ_c criteria are not equivalent anymore.

- **Ductile fracture** : Ductile fracture is described using a local criterion similar to the one suggested by d'ESCATHA [3]. This criterion is formulated in terms of a fracture damage function related to the history of stresses and strains averaged over a characteristic volume ahead of the crack tip. Previous numerical studies have shown that the characteristic value can be assimilated to a square 0,1 mm x 0,1 mm finite element.

  The ductile fracture criterion then becomes :

$$\int_0^{\varepsilon^*} 0{,}283 \; \mathrm{Exp.} \left(1{,}5 \frac{\sigma_m}{\sigma_{eq}}\right) d\,\varepsilon^* < 1{,}5$$

  with :

$$\sigma_m = \frac{1}{3} I_1 = \frac{1}{3} (\sigma_{11} + \sigma_{22} + \sigma_{33})$$

$$\sigma_{eq} = \sqrt{3 J_2} = \frac{1}{2}(\sigma_{11} - \sigma_{22})^2 + \frac{1}{2}(\sigma_{22} - \sigma_{33})^2 + \frac{1}{2}(\sigma_{33} - \sigma_{11})^2 + 3\sigma_{12}^2 + 3\sigma_{23}^2 + 3\sigma_{31}^2$$

$$d\varepsilon^* = \sqrt{\frac{2}{3} d\varepsilon_{ij}^{pl} \; d\varepsilon_{ij}^{pl}}$$

  When the criterion is met, the corresponding finite element is broken in all directions ; it is assumed that the fracture process consumes all the energy previously stored within the element.

III. SPECIMEN FINITE ELEMENT MODEL

The geometry of the specimen is identical to the one used by HAHN and HOGLAND [4]. However, a single material was considered for the computations.

The mesh is presented by Figure 1. Point A corresponds to the initial location of the crack tip. The following boundary conditions are imposed :

$U_y = 0$ along for AD

$U_x = 0$ for point D

The uniaxial behaviour of the material is reported on table 1 :

σ(MPa)	ε(%)
402	0,2
530	1,5
562	2,3
584	3,1
604	3,9
614	4,7
631	5,6
643	6,7
650	7,7
657	8,7
667	9,9
672	11

TABLE 1 : Uniaxial behaviour of the material

A Von Mises yield criterion with isotropic hardening is used.
A uniform displacement U_y is first imposed along BC in order to simulate the static loading before crack proagation. Although an explicit time scheme is used in PLEXUS, the static stress state can be computed by use of a damping coefficient, close to the critical value corresponding to the lowest eigenfrequency of the structure. Then, the element ahead of point A is relaesed externally. Subsequent crack propagation is the result of the step by step computation. During the dynamic phase, the displacement along BC is kept constant.
For the computations, the cleavage stress is 680 MPa. Although, the finite element size in the crack propagation area is 1 mm × 1 mm, the numerical values for the ductile fracture criterion are left unchanged.

IV. NUMERICAL RESULTS

IV.1/ Static loading

For static loading, a uniform displacement of 1,27 mm is imposed along segment BC. The deformed shape of the specimen after the kinetic energy became negligible, is shown by Figure 2.

Figure 3 shows the stresses at the crack tip. Using the displacement of the crack lips, K_1 could be determined. The obtained value was chercked using an analytical expression applicable to the specimen [5]. The numerical and analytical values coincided within a few percent.

IV.2/ Dynamic crack propagation

After static loading, the dynamic fracture criteria where applied and the crack started to propagate. Figure 4 shows the crack length and crack speed versus time. After an initial jump of about 30 mm, the crack speed continuously decreases. The final crack length at arrest is about 200 mm. During the propagation the cleavage criterion was the only one activated.

This result is due to the values of the numerical constants chosen for this study.

IV.3/ Dynamic crack propagation without wave reflection at the boundary of the specimen

When the crack progresses a compressive wave is generated from the newly created discontinuity. This wave propagates, reflects into a tensile wave, and propagates back towards the crack front, where additional tensile stresses are then created. In order to investigate the influence of this phenomenon, a second computation was carried out. The outer boundary of the finite element model was provided with special elements which prevent reflection of waves, without having any other contribution to the mechanical behaviour of the structure. No significant effect could be observed concerning the crack speed and the crack length versus time. This result is quite surprising and somewhat contradictory with available experimental results [6]. More work is needed to investigate this problem.

V. CONCLUSION

A preliminary study was undertaken, in order to investigate the capability of PLEXUS Code, in the domain of dynamic fracture mechanics. The geometry of a simple laboratory specimen was considered. The following conclusions could be drawn :

- the static stress state prior to crack propagation can be accurately computed with the PLEXUS Code, although an explicit time integration scheme is used.
- PLEXUS is a suitable code to handle crack propagation problems, in the dynamic range : it is possible to determine the stresses and strains at the tip of the crack, and to use criteria corresponding to cleavage and ductile fracture.
- more work is needed to implement realistic fracture models and to describe adequately the physics of dynamic crack propagation.

In the near future, comparison will be performed between numerical results and precise data corresponding to reference laboratory experiments.

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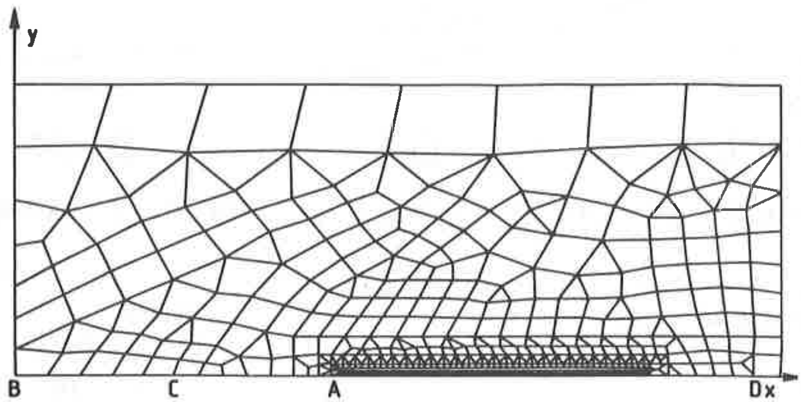

Fig. 1 - MESH USED FOR THE COMPUTATIONS

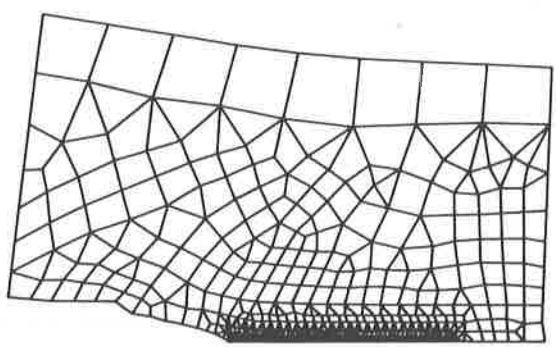

Fig. 2 - DEFORMED SHAPE OF THE SPECIMEN AFTER STATIC LOADING

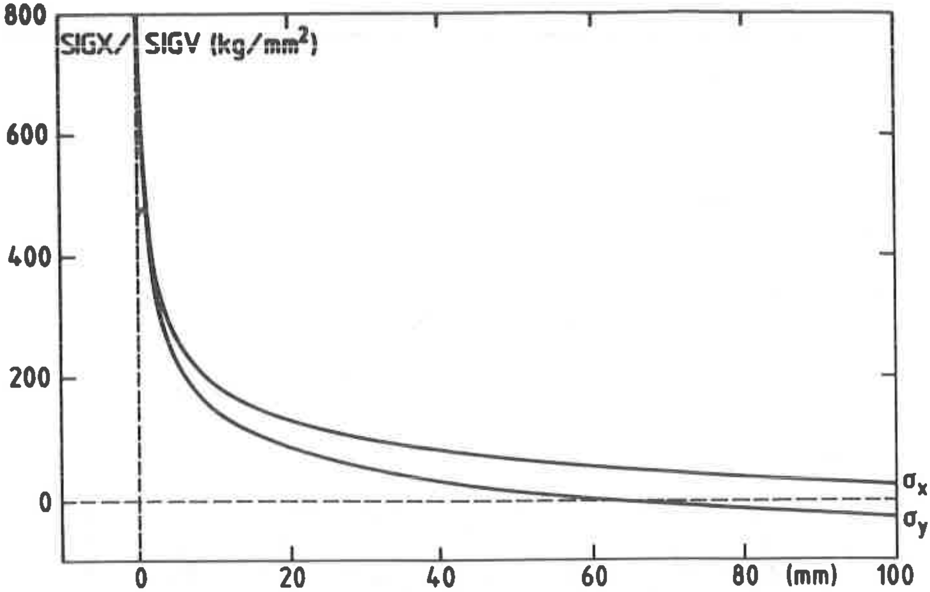

Fig. 3 - STRESSES AT THE CRACK TIP AFTER STATIC LOADING

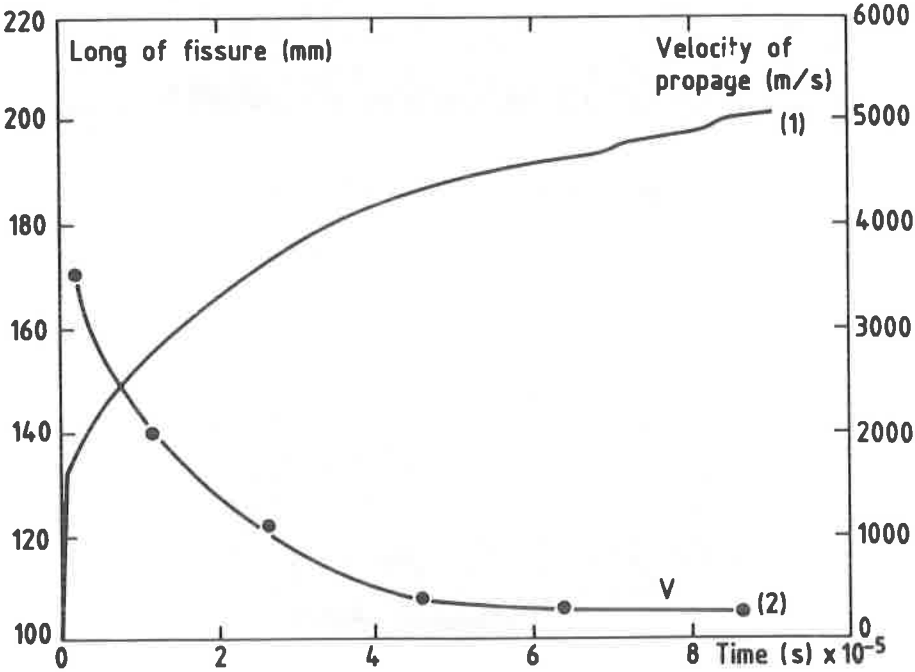

Fig. 4 - CRACK LENGTH AND CRACK SPEED VERSUS TIME