Numerical Evaluation of Cracked Pipes Under Dynamic Loadings Using a Special Finite Element

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ABSTRACT

In order to apply the leak before break concept to piping systems, the behavior of cracked pipes under dynamic, and especially seismic, loading must be studied. A simple finite element model of a cracked pipe has been developed and implemented in the general purpose computer code CASTEM 2000.

This model has been used for the design of dynamic tests to be conducted on shaking tables. The influence of the frequency of excitation was studied.

Finally, evaluation of margin, due to plasticity, in comparison with the standard design procedure is made.

1. INTRODUCTION

For leak before break appplications, a special finite element that represents the behavior of a cracked pipe section has been developed and implemented in the general purpose computer code CASTEM 2000 (Brochard, 1988).

In this paper, we present its application in dynamics for the design of seismic tests.

2. PRINCIPLE OF THE TESTS

The aim of the tests is to have a cracked pipe subjected to an inertial load such as a dynamic bending moment. This goal is reached by adding inertial masses at each end of a straight pipe. The whole test set up is given a vertical acceleration by a shaking table. A schematic of the test set up is shown on figure 1.

For this system, the parameters that determine the dynamic response are the eigenfrequency and the frequency of excitation.

3. STRUCTURE CHARACTERIZATION

Static four point bending tests have already been performed on cracked straight pipes (Moulin, 1989). For dynamic tests, it was chosen to have the same material (stainless steel) and the same geometry (figure 2). These data determine the model for elastic behavior.

A calculation was made to determine the first eigenmode of the structure, including stiffness due to crack. Figure 3 shows the value of the eigenfrequency as a function of crack length, ranging from 0 to 200°. One can see a decrease of the value which is due to the increasing flexibility. For an angle of 120°, which will be the case in dynamic tests, the value is f_o = 6.5 Hz, that is to say a 7% reduction compared to pipe with no crack.

4. IMPOSED ACCELERATION

The signal roughly represents a real seismic excitation which typically has an increasing part ($t \leqslant t_c$) followed by a strong part ($t > t_c$).

The imposed acceleration of the shaking table was chosen of the following form:

$$\gamma(t) = \gamma_o (t/t_c)^2 \sin \omega_e t \qquad \text{for } t \leqslant t_c$$

$$\gamma(t) = \gamma_o \sin \omega_e t \qquad \text{for } t \geqslant t_c$$

with $\omega_e = 2\pi f_e$.

For each calculation, t_c is adjusted so that the increasing part of the signal lasts 5 cycles (e.g. $t_c = 5/f_e$). A representation of the imposed acceleration versus time is shown on figure 4.

5. TYPICAL TIME-HISTORY RESULTS

In order to achieve the design of dynamic tests, non linear time history calculations were performed. An implicit, unconditionally stable algorithm was used. The material behavior was supposed elastic perfectly plastic. The flow stress was adjusted so that the maximum moment calculated is equal to the experimental one. Figures 5 to 7 show typical time-history results for $f_e = f_o$ and γ_o = 0.2 g. The presented results are displacement of end masses, moment in the crack section and rotation due to crack. Weight has been taken into account, so the crack is already open at t = 0. Some observations can be made:

- the bending moment in the crack section reaches a limit value which is consistent with the elastic perfectly plastic model used,
- though the imposed acceleration is limited to a constant maximum value after 5 cycles, the plastic deformation always increases. This can be seen on displacement-time and rotation-time curves. This phenomenon is due to the mass weight and ensures that failure will be reached.

6. INFLUENCE OF THE FREQUENCY OF EXCITATION

One of the goals of the dynamic tests is to study the excitation frequency influence on the cracked pipe response. For various values of f_e, we determined the value of γ_o that leads to failure at 15 cycles.

Instability (and then failure) is supposed to appear when rotation due to crack reaches a critical value φ_c. φ_c is determined on the real moment-rotation curve (from static test) and is defined as the rotation after which moment decreases (see figure 8).

Figure 9 shows the variation of γ_o as a function of the normalized frequency f_e/f_o. One can see that this curve has a minimum for $0.9 \leqslant f_e/f_o \leqslant 1.0$. This means that failure can be reached with a minimum energy input if f_e is equal to roughly 95% of f_o. We can also note that the required value of γ_o is about 2.5 times bigger for f_e/f_o = 0.5 and 3.5 times for f_e/f_o = 1.5.

7. MARGIN EVALUATION

To evaluate the margin resulting from a standard design procedure, the preceding results of non linear calculations have to be compared to those of linear computations.

If M_L is the maximum moment in non linear calculation, we determine the value γ_{oL} which gives a maximum moment equal to M_L for 15 cycles in a linear analysis. Then, the margin is defined as:

$$m = \frac{\gamma_o}{\gamma_{oL}}$$

Two kinds of linear calculation were performed taking into account or not the presence of the crack (stiffness reduction). Figure 10 shows the evolution of margin as a function of the normalized frequency f_e/f_o. The main points are that:

- there exists a significant discrepancy in the evaluation of the margin depending on whether or not the crack is accounted for in the linear calculation;
- comparing to a calculation with crack leads to a margin ranging from 2 to 3 for $0.5\ f_o \leqslant f_e \leqslant 1.5\ f_o$;
- comparing to a calculation without crack gives a margin between 1.5 and 4 for the same variation of f_e.

Of course, these results are only valid for our particular case, and a generalization would require more studies. For examples, calculations with other ratios of static loading over dynamic loading should be made.

8. CONCLUSION

A special cracked pipe finite element has been developed and its application in dynamics has been shown. It is an helpful tool for the design of dynamic tests on cracked pipes. It was also demonstrated that it gives the opportunity to evaluate the margin resulting from the standard design procedures.

After its validation on dynamic tests, it will become an industrial tool for leak before break applications.

REFERENCES

Brochard, J., Petit, M., Jamet, P. "A Special Cracked Pipe Element for Leak before Break Applications". IAEA specialist's meeting on Fracture Mechanics Verification by Large Scale Testing, 25-27 May, 1988.

Moulin, D., Lebey, J., Acker, D. "Experimental Determination of J Value on Circumferencially Cracked Stainless Steel Pipes under Bending". Second conference on pipework and operation, London, 21-22 February, 1989.

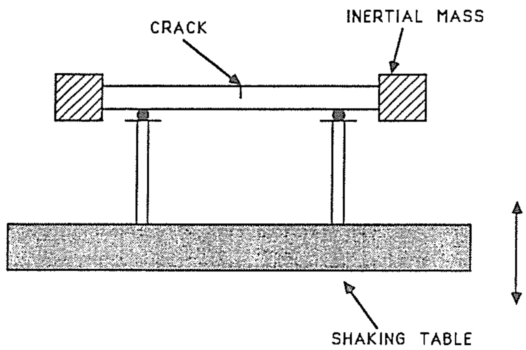

Fig. 1 - Schematic of the test set up

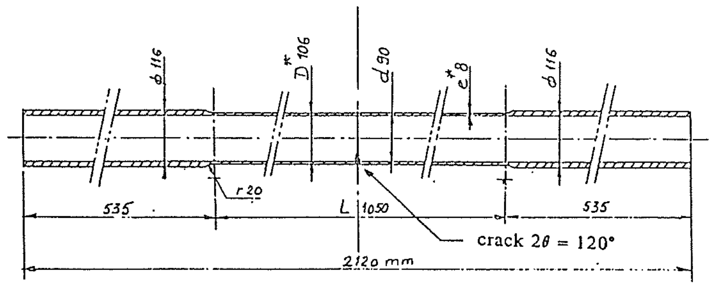

Fig. 2 - Pipe geometry

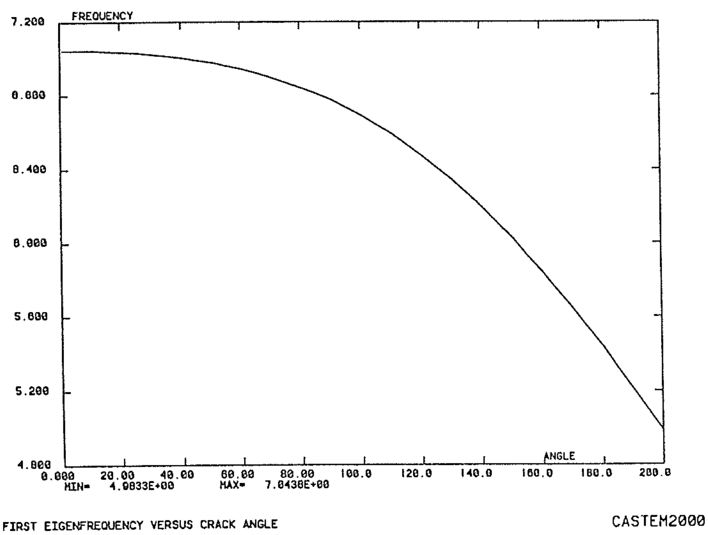

Fig. 3 - Influence of crack length on eigenfrequency

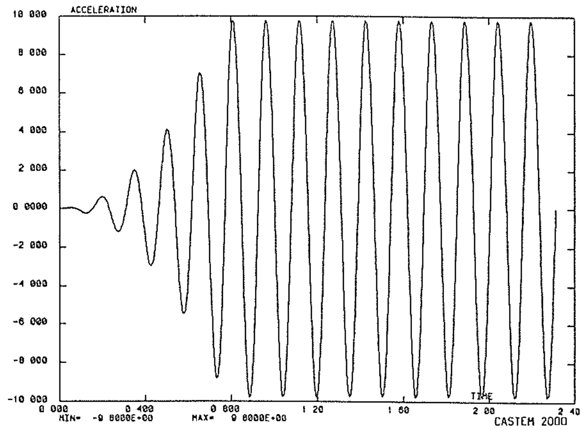

Fig. 4 - Acceleration of shaking table versus time

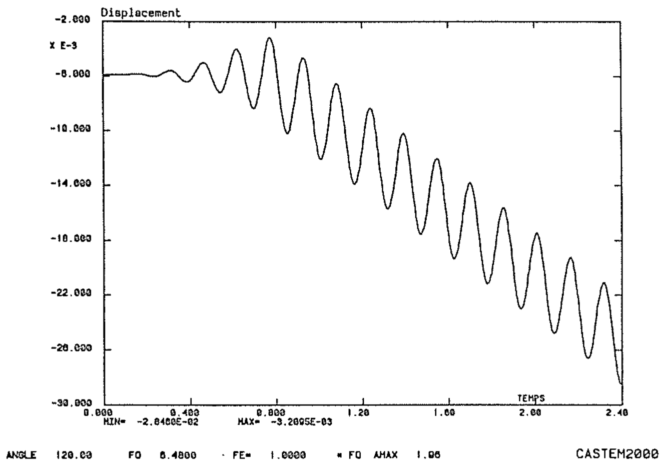

Fig. 5 - Displacement of end masses versus time

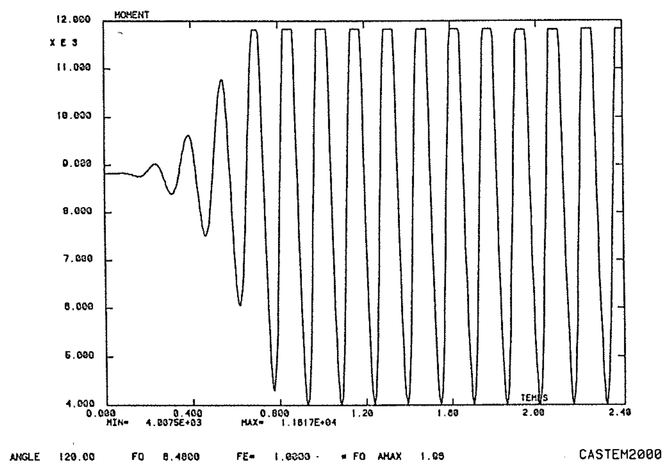

Fig. 6 - Moment in the crack section versus time

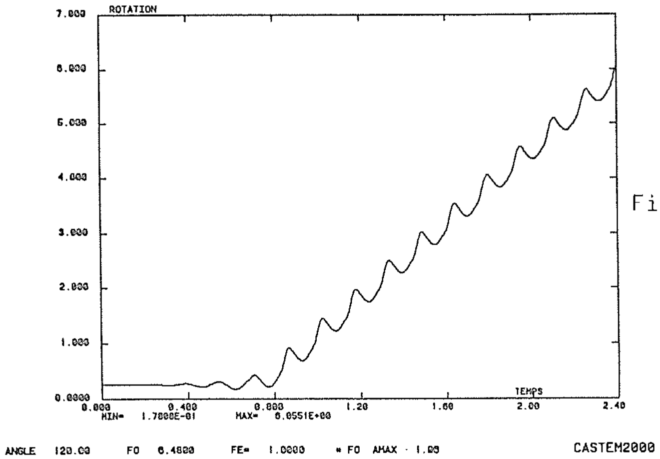

Fig. 7 - Rotation due to crack versus time

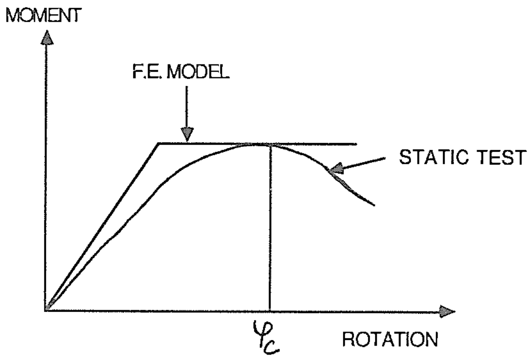

Fig. 8 - Moment-rotation curve

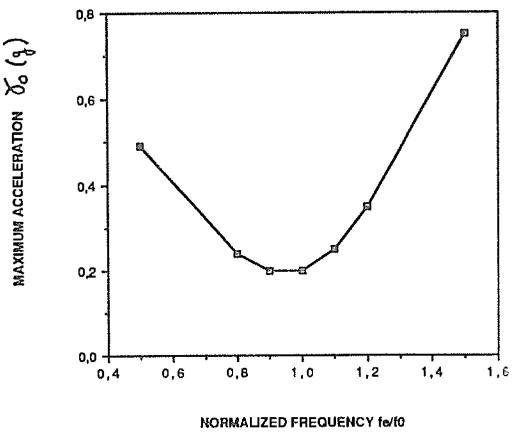

Fig. 9 - Required acceleration for instability at 15 cycles

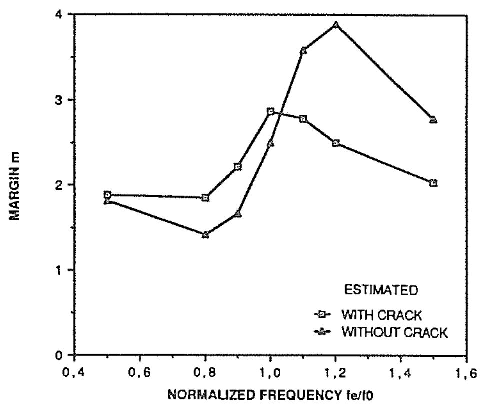

Fig. 10 - Margin due to plasticity