FATIGUE CRACK-INITIATION FROM NOTCHES IN FERRITIC-PEARLITIC STEELS.

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A fatigue criterion was established to predict crack-initiation at the tip of a notch in ferritic-pearlitic steels. This criterion was used to predict the residual lifetime of pipes damaged by idealized defects of the "notch only" or "notch in dent" type and subjected to cycles of internal pressure.

INTRODUCTION

Gas transmission pipelines are subject to external mechanical damage of various origins (excavation machinery, etc...). The resulting defects are often gouges, dents or gouge in dent combinations. In this context, the nocivity of notches to the residual lifetimes of pipes is studied. This paper includes two parts:

- the determination of a crack-initiation criterion for ferritic-pearlitic steels used in manufacturing piping.
- a criterion applicable to the prediction of the minimal residual lifetime of notched pipes loaded by internal pressure cycles.

DETERMINATION OF THE CRACK-INITIATION CRITERION

A local elastic analysis was chosen for the following two reasons:

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- It gives an easy-to-use criterion which has already been applied with success for instance by Masson (1) in the nuclear industry to predict fatigue crack-initiation in stainless steel sleeves subjected to repeated thermal shock.
- This criterion provides a good description of the entire range of pipeline operation from a few to a moderate number of fatigue cycles (10^5 cycles) and, as shown previously (2), (3), it is relatively insensitive to initial residual stresses at such numbers of cycles. In stainless steels, Devaux et al. (4) have linked the number of crack-initiation cycles Na to the stress variation $\Delta\sigma\theta\theta$ computed in elasticity at a characteristic distance d from the tip of the defect. The characteristic distance d is the distance at which, for a given number of crack-initiation cycles, Na, the stress variation $\Delta\sigma\theta\theta$ is the same whatever the notch geometry.

To establish the crack-initiation criterion, four heats of low carbon ferritic-pearlitic steels were selected. The lowest and highest grades delimit the range of steels commonly used by Gaz de France in piping. The mechanical properties of these materials are given in Table 1.

TABLE 1 - Mechanical properties of steels

Grade	A42	X65 N°1	X65 N°2	X70
$R_{p0.2}$ (MPa)	325	499	500	581
UTS (MPa)	476	608	595	671
A%	37	22	30	24

$R_{p0.2}$: Yield Strength, UTS: Ultimate Tensile Strength, A%: Elongation at rupture

Charpy V type specimens were taken from gas transmission pipes and the notch radii accurately machined at values of 0.1 mm, 0.2 mm, 0.5 mm, 1.0 mm ou 2.0 mm. The specimens were loaded in 4-point bending fatigue with a load ratio of 0.1 (figure 1). The number of crack-initiation cycles was conventionally defined as corresponding to a 0.1-mm crack detected by a potential drop technique.

The stress variations $\Delta\sigma\theta\theta$ were computed in elasticity at several different distances from the notch tip using the Creager formula (5) and 2D finite elements for the 2-mm notch radius assuming plane strain conditions.

All the test results were compiled to determine the law $\Delta\sigma\theta\theta = f(Na)$ at a confidence interval of 95%. The minimum scattering in the graph ($\Delta\sigma\theta\theta$,Na) was obtained for the calculation of $\Delta\sigma\theta\theta$ at a characteristic distance of 44 μm from the notch root (figure 2). To give a laboratory estimate of the minimal residual lifetime of damaged pipes, the lower limit of the confidence interval for crack-initiation criterion was chosen:

$$\Delta\sigma\theta\theta \text{ (MPa)} = 17050 \ Na^{-0.294}$$

This expression is valid for a range of cycles included between 5 10^3 and 10^5 cycles.

PREDICTION OF THE RESIDUAL LIFETIME OF DAMAGED PIPES.

Defects of a "notch only" or "notch in dent" type, parallel to the longitudinal axis of the pipes and sufficiently long (> 100 mm), were made in pipes of two different geometries: 457 mm in diameter and 6 mm thick (grade X60); 762 mm in diameter with 13 mm thick (grade X42).

- The "notch only" defect was machined into the wall thickness to relative depth of 30% to 40%.

- The combined "notch in dent" defect was machined in two stages. First, a pipe at an internal pressure of 70 bar or with no pressure was dented parallel to the pipe's longitudinal axis using a cylindrical denting tool. After withdrawal of the denting tool, the highest values for the residual displacements of the dents were 1% of the diameter for pipes with a pressure of 70 bar and 5% for pipes with no internal pressure. Second, notches were machined in dents of a relative depth of 16% to 42% of the thickness. The damaged pipes were then loaded by varying the internal water pressure from 40 bar to 70 bar. A calibration curve of the potential drop versus the depth of the defect was used to detect the initiation of a crack 0.1mm deep. A fit of the curves recordering the potential and the number of cycles by polynomial functions made it possible to calculate Na for each test.

To deduce Na from the criterion, a 2D calculation in elasticity of $\Delta\sigma\theta\theta$ at 44 μm from the notch tip was sufficient for the "notch only" defect. In all cases, it was assumed that the notch tip radius was equal to 0.1-mm. The "notch in dent" defect required two further stages:

- a global approach consisting in a simulation of pipe denting by a numerical calculation in 3D elastoplasticity to determine the macroscopic forces to generating the stress profiles under the dent. The contact of the denting tool with the pipe was simulated by spring elements. The simulation was validated by a comparison of experimental and calculated curves of load versus displacement of the denting tool.

- The second stage was a local approach by which the macroscopic forces associated with the stress profile under the dent were decomposed into bending moment and tensile load and applied to a notched bar specimen to calculate $\Delta\sigma\theta\theta$ at 44 μm from the notch root. Then, Na was directly deduced from the law $\Delta\sigma\theta\theta = f(Na)$.

To compare the total number of observed and calculated cycles Nt, the number of propagation cycles Np detemined by means of Paris law was added to Na predicted by the criterion. The materials parameters of the Paris law were (C=2.33 10^{-12}, m=2.94) and (C=3.38 10^{-12}, m=3.24) for pipes 457mm and 762mm in diameter respectively. These values were determined from conventional crack propagation tests on 4-point bend fracture mechanics specimens.

The test and calculation results are presented in Table 2.

TABLE 2: Results of tests and calculations on damaged pipes

Defect type	Test number	Na detected (cycles)	Nt observed (cycles)	$\Delta\sigma\theta\theta$ (MPa)	Na predicted (cycles)	Np calculated (cycles)
	ENF0.1	697	3430	1985	1502	9906
	ENF0.2	1213	10046	1292	6470	37834
Notch in dent	ENF0.3	11034	29458	1096	11320	58413
	ENF0.4	2222	8885	1723	2430	15517
machined	ENF0.5	12161	30000 *	937	19300	78630
	ENF0.6	8368	17071	1392	5021	22977
with no pressure	ENF0.7	304	7556	3302	266	458
	ENF0.8	1048	10266	2652	561	1404
	ENF0.9	2837	17195	2265	959	2172
Notch in dent	ENF70.1	2912	16143	1420	4692	29192
machined	ENF70.2	10140	27675	1601	3120	18041
at a pressure	ENF70.3	510	4953	1678	2659	18559
of 70 bar	ENF70.4	139	1268	2491	697	5604
Notch only	E1	5693	14786	1442	4453	19679
	E2	33215	33215 *	865	25330	0

* these pipes did not break

Predicting initiation with the proposed criterion is in good agreement generally with the detected number of crack-initiation cycles (figure 3). Nevertheless, the agreement is less satisfactory for very low numbers of cycles because:

- the crack-initiation criterion was deduced from an elastic approach which ceases no longer valid once plasticity extends beyond the immediate vicinity of the defect. This occurs in the range of low number of cycles for which the criterion was not validated by tests and had therefore to be extrapolated.
- for the notch in dent, the modification of the stress profile under the dent when the notch is machined in the dent was not taken into account in the calculation.

In figure 4, the total numbers of observed and calculated cycles Nt are compared. A less satisfactory agreement is also observed for the very low cycle numbers, for the second reason mentioned above. Furthermore, the possible presence of residual stresses not taken into account in the calculations may also profoundly modify the rate of crack propagation, as shown elsewhere (2).

On examination of Table 2, the Na predicted by the criterion is always lower than the observed Nt, whereas Np is often higher than Nt. Hence, to predict the minimal residual lifetime of a damaged pipe at cycle numbers of less than 10^5, it is preferable to use the crack-initiation criterion alone rather than those of an approach to calculating propagation cycle numbers based on Paris law, because the results of the former are more conservative.

CONCLUSION

A fatigue crack-initiation criterion at notch root for ferritic-pearlitic steels, which is both easy-to-use and relatively insensitive to residual stresses, showed the advantage in gas applications, of adaptability to the steel grades for pipes and the operating ranges for pipelines. This criterion gives a satisfactory and conservative prediction of the residual lifetime of pipes damaged by idealized defects. This is a particularly encouraging result as it can be used conversely to define the critical dimensions of natural notch type defects versus prescribed residual lifetimes.

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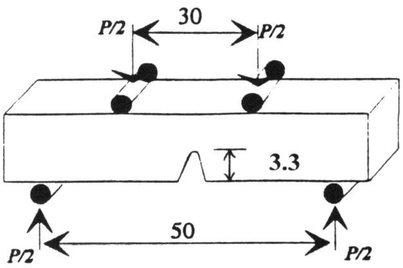

Figure 1 4-point bending fatigue on Charpy V specimen (dimensions in mm)

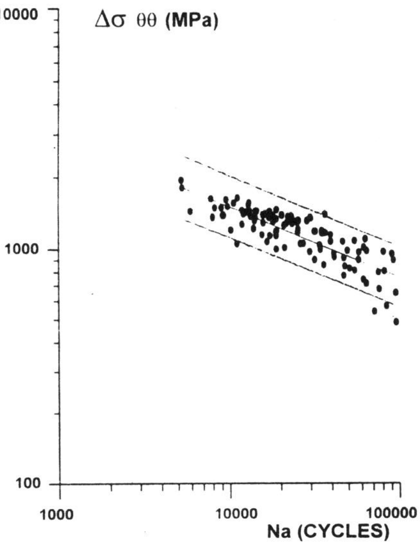

Figure 2 Crack-initiation criterion

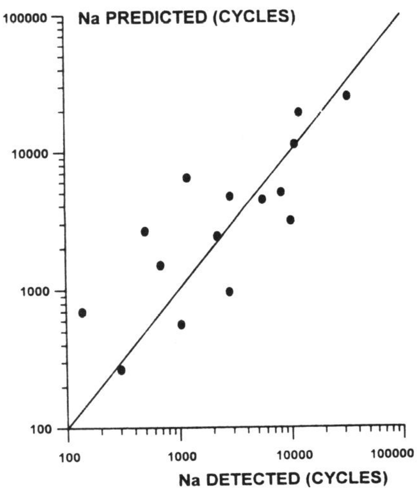

Figure 3 Comparison of predicted and detected cycles number Na

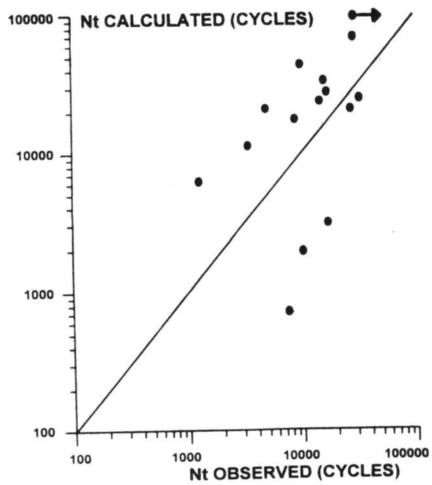

Figure 4 Comparison of calculated and observed cycles number Nt