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Application of the Engineering Treatment Model (ETM) to the Prediction of the Behaviour of a Circumferentially Cracked Pipe

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ABSTRACT Two pipes out of a series of six tests performed at room temperature were selected for a first application of the Engineering Treatment Model (ETM) to a large structural component. In the pipe tests, crack growth, the crack tip opening displacement, the applied load, and some other quantities, were measured. Calculations were performed to derive best estimates of the maximum applied moment and the amount of crack growth at that point. The results are in good agreement with the experimental findings.

Notation

a Crack length
a_{eff} Plasticity corrected crack length
E Young's modulus
F Applied force
F_Y F at incipient net section yielding
K Linear elastic stress intensity factor
K_{eff} Plasticity corrected K
$\bar{K}$ Average of K and K_{eff}
M Applied moment
M_Y M at incipient net section yielding
n Strain hardening exponent
t Wall thickness
Y Calibration function for K
δ_5 Crack tip opening displacement at fatigue pre-crack tip
δ_Y δ_5 at incipient net section yielding
ε Strain
σ Applied stress
σ_Y Yield stress
Φ Crack angle

Introduction

The necessity for making quick assessments of the severity of a crack-like flaw in a structure led to the development of a number of failure assessment

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methods **(1)** which are relatively easy to apply, provided that the relevant input information is available. Among these, the Engineering Treatment Model (ETM) is aimed at estimating the mechanical behaviour of a cracked member by closed form solutions. Formulae have been developed for predicting the crack tip opening displacement (CTOD) in the form of δ_5, the load line displacement, s, and the J integral. The main emphasis is put on the CTOD part, as it seems that the use of CTOD is less restrictive than that of the J integral. Details are given in references **(2)–(4)**.

In order to make the present paper self-explanatory, those relationships which will be needed for the analysis are repeated in the following.

The ETM distinguishes between the load ranges $F \leqslant F_Y$ and $F > F_Y$, where F_Y is the yield load which is related to the attainment of net section yielding. In the load range $F \leqslant F_Y$ the CTOD is given by the plasticity-corrected small-scale yielding solution.

Tension configurations

$$\delta_5 = \frac{K_{eff}^2}{E\sigma_Y} \tag{1}$$

Bending configurations

$$\delta_5 = \frac{\bar{K}^2}{E\sigma_Y} \tag{2}$$

with

$$K_{eff} = \sigma\sqrt{(\pi a_{eff})}Y(a_{eff}/W) \tag{3}$$

$$a_{eff} = \frac{K^2}{2\pi\sigma_Y^2(1+n)} + a$$

$$K = \sigma\sqrt{(\pi a)}Y(a/W)$$

Y = calibration function for stress intensity factor, K

and

$$\bar{K} = 0.5(K_{eff} + K) \tag{4}$$

In the net section yielding regime, i.e., for $F > F_Y$, δ_5 is given by

$$\delta_5 = \delta_Y\left(\frac{F}{F_Y}\right)^{1/n} \tag{5}$$

where δ_Y designates the value of δ_5 at $F = F_Y$ as calculated by equation (1) or equation (2); n is the strain hardening exponent of a piece-wise power law representing the material's engineering stress–strain curve

$$\varepsilon = \varepsilon_Y\left(\frac{\sigma}{\sigma_Y}\right)^{1/n} \tag{6}$$

As these formulations have already been successfully applied to laboratory specimens **(2)–(4)**, it was intended to use ETM for predicting the behaviour of a large scale structural part.

Such an occasion was given by tests which were carried out by Interatom on cracked pipes made of an austenitic steel. Some details of these tests will be given in the following section.

Pipe tests

Six bend tests have already been carried out on 2 m long pipes made of the austenitic steel 316Lmod. Two pipes were selected for the work described in the present paper. The pipes were circumferentially through-cracked by fatigue with crack details as follows, Fig. 1.

Pipe No. 1: crack in base material;
crack angle $\phi = 61.6$ degrees;
crack length $2a = 377$ mm;
wall thickness $t = 12.19$ mm.

Pipe No. 4: crack in heat affected zone of a circumferential weld;
crack angle $\phi = 124.2$ degrees;
crack length $2a = 756.6$ mm;
wall thickness $t = 11.47$ mm.

In these experiments, the applied moment, M, the crack angle, ϕ, the crack length, $2a$, the CTOD in terms of δ_5 (except pipe 1), and some other quantities

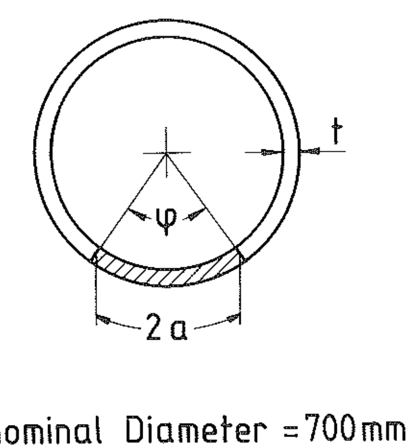

Fig 1 Cracked cross section of the pipes

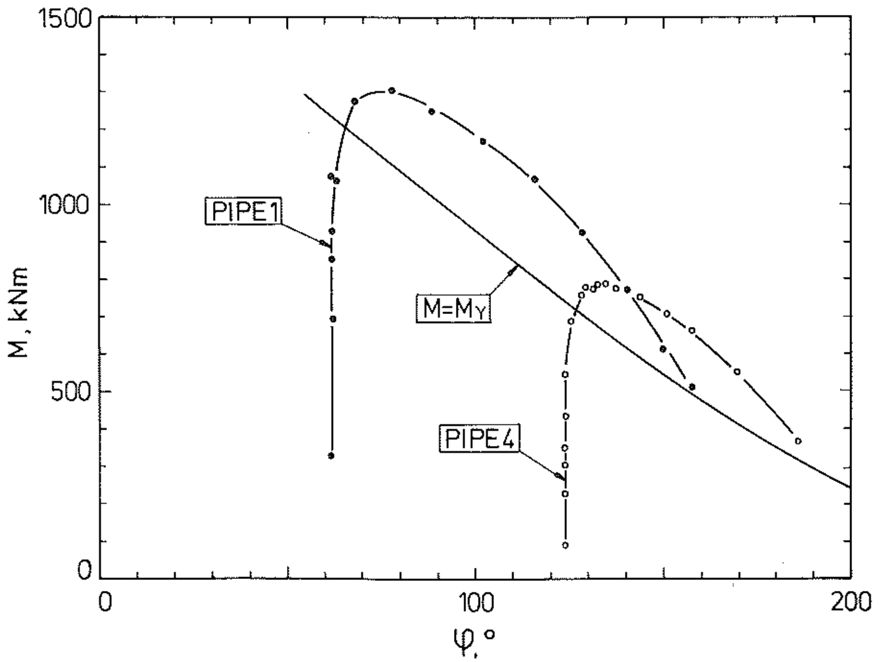

Fig 2 **Applied moment for both pipes as a function of the crack angle, Φ. The yield moment, M_Y, was calculated for base material conditions**

were measured. Figure 2 shows the applied moment as a function of the crack angle for both pipes. On pipe 4 the δ_5–R curve was determined (HAZ); it is shown in Fig. 3. A further pipe (not considered here) delivered the base material δ_5–R curve which is also plotted in Fig. 3.

Predictions

Input data

Material properties

The σ–ε diagram of the base material steel 316Lmod is plotted in Fig. 4. It consists of two linear sections in double logarithmic scales. According to the rules of ETM set out in reference **(5)** an average slope was determined by a straight line going through $R_{p0.2}/\varepsilon_{0.2}$ and touching the σ–ε curve at its upper end as a tangent. The tensile data are listed in Table 1.

Stress intensity factor

If the applied bending moment, M, is converted into a nominal stress, σ, by

$$\sigma = \frac{M}{\pi t R^2} \tag{7}$$

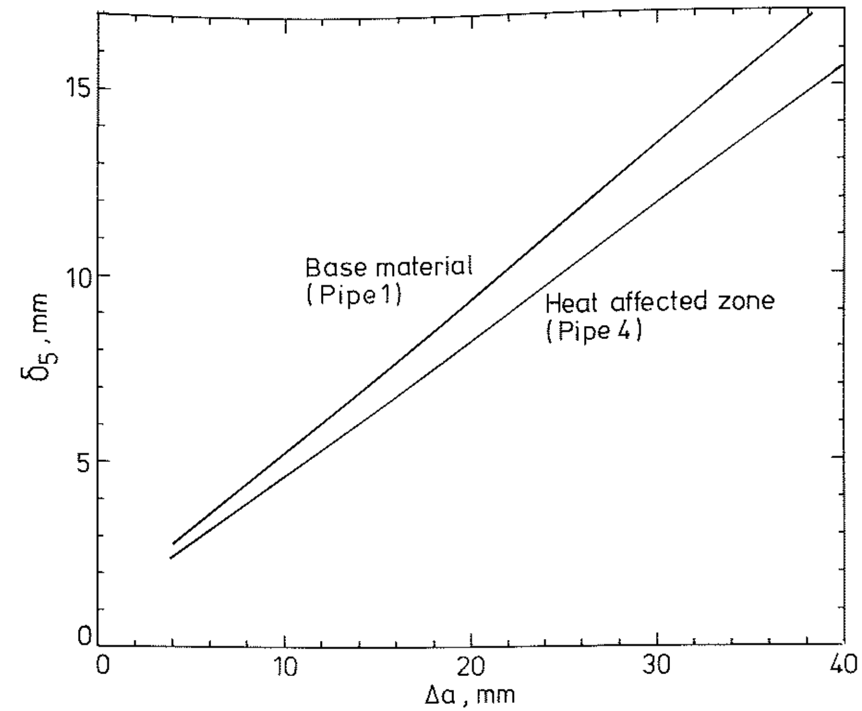

Fig 3 **CTOD R curves measured on both pipes**

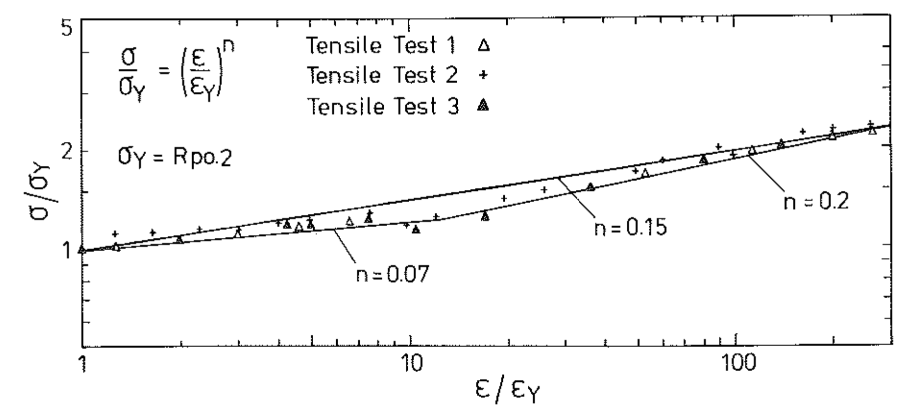

Fig 4 **Stress–strain curve of the steel 316Lmod**

Table 1 **Tensile properties of steel 316Lmod**

Yield strength $\sigma_Y = R_{p0.2}$ *(MPa)*	*Tensile strength* R_m *(MPa)*	*Young's modulus* *(MPa)*	*Strain hardening exponent*, n
297	613	192 300	0.15

where t denotes the wall thickness and R denotes the radius of the pipe, the stress intensity factor can be expressed as

$$K = \sigma\sqrt{(\pi a)}\,Y(a/W) \tag{8}$$

The calibration function $Y(a/W)$ was determined experimentally on all pipes tested. The data thus obtained were approximated by the following equation

$$Y = a_0 + a_1\left(\frac{\phi}{2\pi}\right) + a_2\left(\frac{\phi}{2\pi}\right)^2 + a_3\left(\frac{\phi}{2\pi}\right)^3 + a_4\left(\frac{\phi}{2\pi}\right)^4 \tag{9}$$

with

$a_0 = 1$

$a_1 = 2.98661526$

$a_2 = 52.0816052$

$a_3 = 176.3015325$

$a_4 = 199.8495663$

Yield moment

A further quantity needed is the moment, M_Y, for incipient net section yielding

$$M_Y = 4\sigma_Y R^2 t\left(\cos\frac{\phi}{4} - \tfrac{1}{2}\sin\frac{\phi}{2}\right) \tag{10}$$

where the general symbol for the yield stress, σ_Y, is understood as $R_{p0.2}$.

Crack growth resistance curve

Ideally, data from small scale laboratory specimens should be used to predict the behaviour of full scale structural parts. However, from the CT specimens tested so far only very short R curves could be derived. Therefore it was decided to use the R curves directly obtained on the pipes for the purpose of ETM predictions, see Fig. 3.

Results

For both pipes the maximum moment, M_c, and the related crack extension, Δa_c, were predicted using equation (5) translated into moment

$$\delta_5 = \delta_Y\left(\frac{M}{M_Y}\right)^{1/n} \tag{11}$$

as the driving force expression for the R curve analysis. The maximum moment was determined by interpolation between those points where the two driving force curves immediately adjacent to the R curve are parallel to the R curve as shown in Figs 5 and 6.

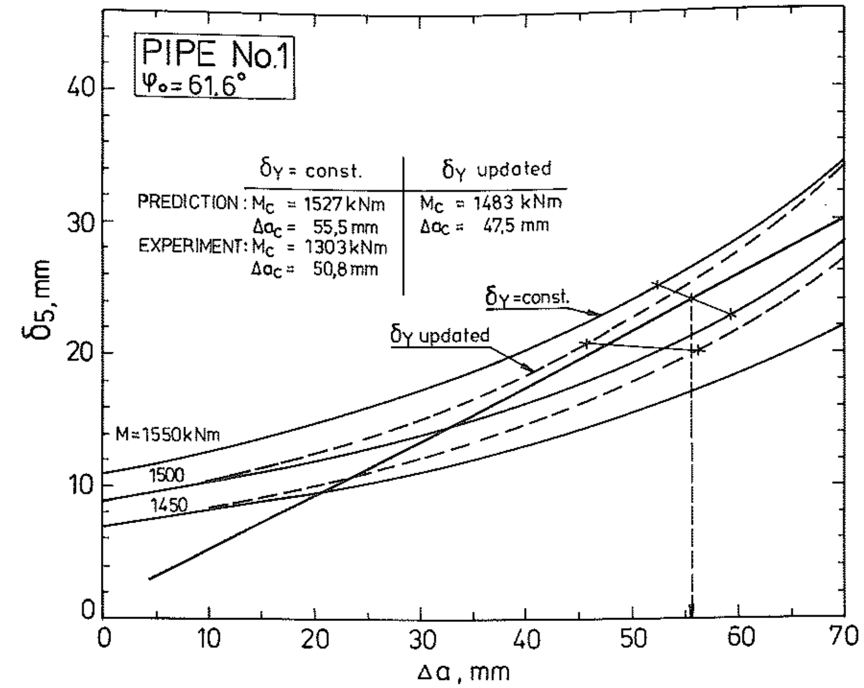

Fig 5 *R* curve construction for pipe 1

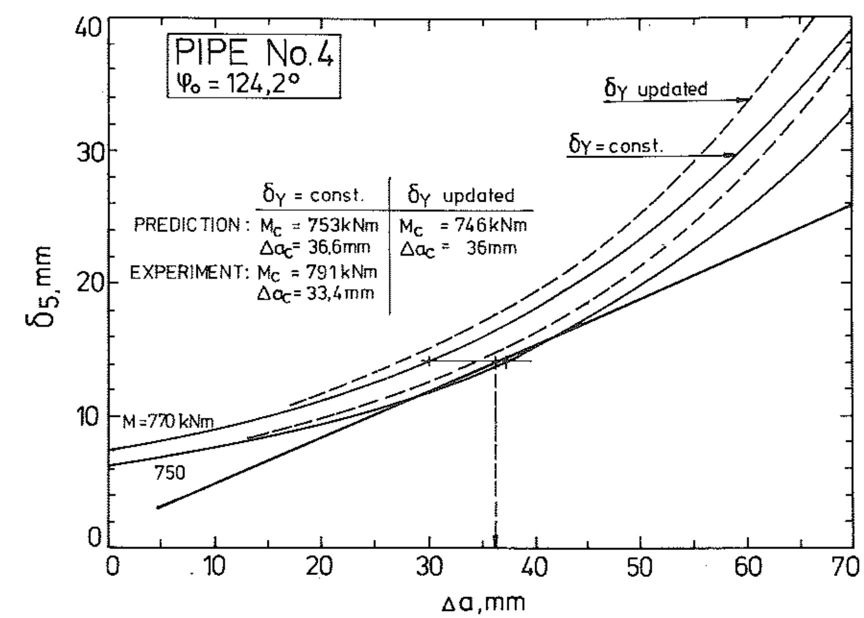

Fig 6 *R* curve construction for pipe 4

Table 2 Predicted and measured maximum applied bending moment, M_c, and crack extension at maximum moment, Δa_c

	Experiment		*Prediction*			
			$\delta_Y = const.$		δ_Y *updated*	
Pipe No.	M_c *(kNm)*	Δa_c *(mm)*	M_c *(kNm)*	Δa_c *(mm)*	M_c *(kNm)*	Δa_c *(mm)*
1	1303	50.8	1527	55.5	1485	47.5
4	791	33.4	*R* curve from base material			
			767	37		
			R curve from heat affected zone			
			753	36.5	746	36

The predictions were done by considering the following parameters.

- Pipe 4 was treated using both the *R* curves from the heat affected zone and the base material to account for the possibility that the crack leaves its original position in the HAZ.
- The quantity δ_Y – representing δ_5 at net section yielding – varies with crack length according to the variation of K at $M = M_Y$. In one set of calculations δ_Y was thus updated with crack growth, in a second one it was kept constant for $a = a_0$, in order to have a much simpler evaluation of equation (11).

Table 2 compiles the results of the predictions and of the experiments.

Discussion and conclusions

The ETM formalisms are based on simplifying assumptions as discussed at length in references **(1)**–**(4)**, the most important one being the simple power law representation of the CTOD by equation (5). One may be concerned that these simplifications may oversimplify the real behaviour of a flawed part. However, numerous analyses of laboratory specimens of different size, geometry, and material both in the form of experiments and finite element calculations have shown that the ETM provides quite reasonable estimates.

The pipe experiments discussed in the present paper provided a chance to check the ETM on a structural member. Table 2 shows that the maximum moment of pipe 1 is overpredicted whereas the crack growth up to the maximum moment is in good coincidence with the experiment. In the case of this pipe, the actual, experimentally determined K calibration values were substantially higher than the curve fit, equation (9), a finding which may explain the overestimation of the critical moment. A detailed analysis of this will be done in a follow-up paper providing predictions for further pipes and a sensitivity study.

The predictions for pipe 4 are very close to the experimental data, both for load and crack growth. They are quite insensitive in the choice of the *R* curve,

which is understandable if one notes the small difference in the *R* curves, see Fig. 3. It should also be noted, that for this pipe equation (9) fits the experimental *K* calibration values much better than in the case of pipe 1.

Table 2 also shows that it does not matter much if the quantity δ_Y is kept constant at the first attainment of net section yielding or if it is updated during crack growth. Thus, for the sake of simplicity, at least up to maximum load δ_Y can be kept constant.

The exercise described in this paper represents the first step in an extensive analysis of pipe bending experiments using the ETM, and the following conclusions emerge.

- Even in a 'first run assessment' the maximum load conditions of two precracked structural parts being well beyond net section yielding conditions were reasonably well modelled with the ETM.
- During this work it became evident that variability in input data – like *K* calibration function, nominal versus actual data for material properties and pipe dimensions – had in some cases only minor effects on the results, but it is likely that in other cases these effects can be substantial.
- Following from this, a further study will be undertaken comprising the analysis of the four further pipes tested and a sensitivity study with respect to input information.

  Due to the closed form solutions of the ETM such a sensitivity study can be performed with limited effort.

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