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EXPERIMENTAL DETERMINATION OF J VALUE ON CIRCUMFERENCIALLY CRACKED STAINLESS STEEL PIPES UNDER BENDING

MOULIN D.- LEBEY J.- ACKER D.
CEA Centre d'Etudes Nucleaires de Saclay, 91 - Gif-sur-Yvette (FR).
Dept. d'Etudes Mecaniques et Thermiques

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D. MOULIN, J. LEBEY, D. ACKER

Development of leak before break methodology in nuclear industry requires determination of conditions of crack stability in piping products. Due to tough and strain-hardening materials involved, a promising parameter to characterize such a behaviour seems to be the driving force J.

An experimental program is carrying on in CEA at Saclay in order to establish and to verify analytical and experimental methods to predict conditions of crack stability.

It concerns circumferencially cracked tubes (outside diameter = 106 mm, inside diameter 90 mm, subjected to 4 points bending, inside span length = 1050 mm). The through wall crack center angles range from 30° to 150°. Blunt end notchs are considered, as well as fatigue precracked notchs. Loading is imposed monotonically in displacement controlled conditions until maximal load is reached.

The paper will present experimental procedure and first results obtained. Instrumentation and typical recordings (load, rotations at different distances from crack section, crack opening displacement, electric potential drop, ovalization) will be described.

Experimental results are interpreted in terms of limit analysis and J estimation to predict crack initiation and maximal loads as a function of crack length.

Results obtained permit the adjustment of experimental scaling functions usually employed for J evaluation with one single specimen. These functions are compared with analytical ones based on theoretical considerations of a simple limit state of the pipe cracked section.

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D. MOULIN, J. LEBEY, D. ACKER
C.E.A. - D.E.M.T.
Centre d'Etudes Nucléaires de Saclay

Experimental determination of J value on circumferencially cracked stainless steel pipes under bending

SYNOPSIS The driving force J and limit analysis are applied to experimental results concerning crack initiation of pipes subjected to bending. The validity domain of some simplified methods of evaluation is verified.

NOTATION

J	Driving force
σ_N	Net section stress
M	Bending moment
R	Mean radius of the pipe
t	thickness
θ	Total center angle of the initial crack.
S_y	yield stress
S_u	ultimate tensile stress
E	Young's modulus
φ_1, φ_2	Angle of rotation of tube sections.
δ	crack opening displacement
S_f	Flow stress
g	Scale function on bending moment
η	Factor for the single specimen determination of J.

1 INTRODUCTION

Development of a leak-before-break methodology in nuclear industry requires evaluation of conditions of crack stability in piping products. Due to tough and strain-hardening materials generally involved, attention is focused on the driving force J. This parameter seems to be a promizing one to perform fracture mechanics analysis in situations where plasticity plays an important part.

2 GENERAL DESCRIPTION OF THE PROBLEM - AIM OF THE STUDY

During the past few years, important work was performed for development of non linear techniques to assess degraded nuclear piping. In this context a reference study was made at Battelle's Laboratories [1] ; practical experimental procedures are available ([2], [3]) to treat the particular problem of circumferencially cracked pipe in bending. To predict conditions of crack initiation it is proposed to use a simplified limit analysis in terms of a net section stress σ_N or J estimation.

The first criterion, in bending situation, is simply given by the formula : (see figure 1 for notation signification).

$$\sigma_N = \frac{M}{4\,R^2 t}\;\frac{1}{\cos\frac{\theta}{4} - \frac{1}{2}\sin\frac{\theta}{2}} \qquad (1)$$

The second criterion J is evaluated from the bending moment M - angle of rotation φ plot obtained from experiments. Figure 1 shows a circumferencially cracked pipe in circular bending and a cracked pipe section. The angle of rotation φ is the total angle of rotation between two sections where the bending moment M is assumed constant. In such situations J can be evaluated by the following formula:

$$J = \eta \int_0^{\varphi} M \, d\varphi \qquad (2)$$

where the integral value is obtained from the area under the M-φ curve and η is a parameter depending only on the crack angle θ. The value of η is constant for a test configuration (specimen dimensions and material). The η term can be evaluated from a simple limit analysis that gives the equation:

$$\eta = -\frac{1}{Rt}\;\frac{-\frac{1}{4}\sin\frac{\theta}{4} - \frac{1}{4}\cos\frac{\theta}{2}}{\cos\frac{\theta}{4} - \frac{1}{2}\sin\frac{\theta}{2}} \qquad (3)$$

In order to check the validity of these proposed criteria, an analytical and experimental study, supported in France by EDF, FRA, and CEA, is being carried out at Saclay. The basic aim of this work is to verify experimentally the existence of the σ_N and η parameters, to determine their values and to compare them with those obtained from simplified analyses presented above.

The study concerned straight pipes specimens (presented in this paper) and elbows specimens (presented in [4]).

3 DESCRIPTION OF EXPERIMENTS

3.1 General description

The study is based on a four points bending experimental device (see figure 1). The specimen is a straight tube containing a through thickness circumferencial crack in the middle section. The influence of crack length is studied by varying the crack angle from one specimen to the other. Tests are performed under displacement (central deflexion) controlled conditions until a maximal force is reached.

3.2 Specimens

The specimens are machined from tubular products made of a 316 L type austenitic steel. Mean dimensions values are calculated from measurements performed on all concerned specimens:

$R = 0.0485$ m
$t = 0.00836$ m

Two types of defects were experimented:

- blunted mechanical notches, in order to avoid crack propagation and to get $M-\varphi$ plots at constant crack angle θ up to maximal loading.
- fatigue precracked defects liable to propagation during loading.

The initial crack angle values, before the test under monotonic loading, ranged from 0 to 150 degrees.

The austenitic steel material of each specimen is characterized by a tensile stress-strain curve, of which representative mean values are given by:

- $S_y = 222$ MPa
- $S_u = 487$ MPa

3.3 Instrumentation

During one experimental test, the following parameters are recorded:

- Total rotation angles φ_1 measured between two sections located at 550 mm distance from the middle of the specimen.
- Total rotation angle φ_2 measured between two sections located at 85 mm distance from the middle of the specimen.
- Horizontal and vertical ovalizations on a section located at 180 mm distance from the middle of the specimen.
- Crack opening displacement δ, measured at mid length of the defect, on the external radius.
- Electric potential drop between the two lips of the crack.

3.4 Some results

Figure 2 represents $M-\varphi_2$ plots obtained for precracked tubes. The uncracked tube, labelled $\theta = 0$, is considered in this set of curves. It is worth noting that maximal bending moments are obtained earlier with precracked tubes than blunted cracked ones. The difference between φ_2 and φ_1 recordings decreases when crack angle increases. This behavior indicates that the larger the crack the more rotation concentrates near the section of the crack.

Beginning of crack propagation (on precracked pipes) is determined on plots giving the evolution of electric potential drop as a function of rotation angles. The initial portion of such a curve is almost linear, then there is a rapid increase of the slope. The first point where the slope rapidly changes is taken as the instant of crack initiation. The corresponding φ_2 values are given in table 1. Worth noting are the almost constant φ_2 values at initiation. Bending moments at initiation are very close (98%) to the maximal bending moment obtained experimentally. These points of initiation are indicated on the curves in figure 2. Initiation occurs when plastic behavior is important.

Table 1. Theoretical and experimental values

$\theta°$	$\varphi_2°$ at initiation	g(exp.) at initiation	g (theory)	J MN/m	J* MN/m
30	5.4	0.88	0.862	1.39	1.17
60	4.9	0.83	0.716	1.61	1.08
90	4.85	0.70	0.570	1.54	0.95
120	5.1	0.60	0.433	1.46	1.08
150	6.0	0.44	0.310	1.49	1.68

4 COMPARISONS - LIMIT ANALYSIS AND J ESTIMATION

Comparisons between theoretical and experimental results concern the prediction of initiation of crack in precracked tubes.

4.1 Net Section stress

Figure 3 gives the experimental points representing bending moment at initiation as a function of crack angle θ for each precracked tubes. The curve drawn in this diagram represents bending moment calculated with a net section stress (formula 1) equal to the material flow stress S_f given by:

$$S_f = \frac{S_y + S_u}{2}$$

The agreement between the theoretical curve and experimental points is good for all values of angles but the 30 degrees one. It seems that for small angles the limit analysis performed is not correct. This remark is reinforced by considering the smooth tube ($\theta=0$). In this case the maximal bending moment value reaches 2200 daN.m.

4.2 J estimation

The verification of the method used to estimate J by experimental investigation consists in calculating a scale factor g, depending only on crack angle, that permits to deduce all the M-curves from a reference one (for example corresponding to $\theta=0$). The value of this factor for two curves (θ and $\theta=0$) is calculated for each tube by the ratio:

$$g(\theta) = \frac{M(\varphi,\theta)}{M(\varphi,\theta=0)}$$

It is calculated on constant crack curves (i.e. with curves corresponding to tubes containing blunted crack). The results are presented graphically in figure 4 with φ_2 rotation. It reveals that when φ_2 values are high enough to produce non linear behaviour due to plasticity, the g values became almost constant. This remark is however less true for the largest cracks ($\theta>30°$). The particular g values found for $_2$ values corresponding to initiation on precracked tubes are given in table 1 (experimental values).

It is easy to show that η function used in formula 3 corresponds to a limit analysis that calculates the scale factor $g(\theta)$ by the expression:

$$g(\theta) = \cos\frac{\theta}{4} - \frac{1}{2}\sin\frac{\theta}{2}$$

The corresponding theoretical values are given in table 1. In this analysis η is then deduced from the following equation:

$$\eta = -\frac{1}{Rt}\;\frac{g'(\theta)}{g(\theta)}$$

where $g'(\theta)$ is the derivative of $g(\theta)$ versus θ. It is then possible to calculate J values from the M-φ_2 plots.

Comparison between theoretical and experimental results is given in figure 5. Results are presented in a diagram where the ordinate axis represents $-\text{Log}\,[g(\theta)]$ and the abscissa axis the crack angle θ. This presentation is chosen because J is proportional to $\frac{g'(\theta}{g(\theta)}$ which is equal to the derivative of $\text{Log}[g(\theta)]$. It means that, in the graphical presentation, the slopes of the experimental and theoretical curves are to be compared between themselves. This comparison indicates that a satisfactory correlation is obtained but between 30° and 60° where the slopes diverge by a factor equal to 3 at most.

For completion J values were calculated for precracked tubes at the instant of initiation by the formula 2 by considering M-φ_2 plots and η theoretical value. The results are presented in table 1. This table gives also J values (labelled J^*) calculated according to the multi specimen technique [9] with M-φ_2 plots determinated on tubes containing blunted cracks and φ_2 at initiation determinated on precracked ones. In this later case the basic formula to calculate J is

$$J = -\int_0^{\varphi} \left(\frac{\partial M}{\partial \theta}\right)_{\varphi} d\varphi$$

The integration and derivation are made numerically from M.φ_2 data.

Figure 6 gives the evolution of J calculated according to this technique as a function of rotation φ_2 for blunted cracked tubes.

The J values in table 1 are in the same range. The discrepancy is however smaller by the single specimen technique relying on formula 2.

5 CONCLUSIONS

An experimental study is performed to verify calculation methods used to predict crack initiation in austenitic pipes in bending.

A four points bending test device is used to perform the experiments.

Specimens tubes are circumferencially cracked in the mid section. Blunted cracks that do not initiate during loading are considered. Fatigue precracked tubes are used to define initiation by electrical potential drop technique.

Criteria checked in this study are the net section stress σ_N and the driving force J.

Both draws satisfactory predictions of initiation but for the smallest (θ = 30 degrees) crack angle in the case of limit analysis.

It seems that for small cracks some developments are still necessary.

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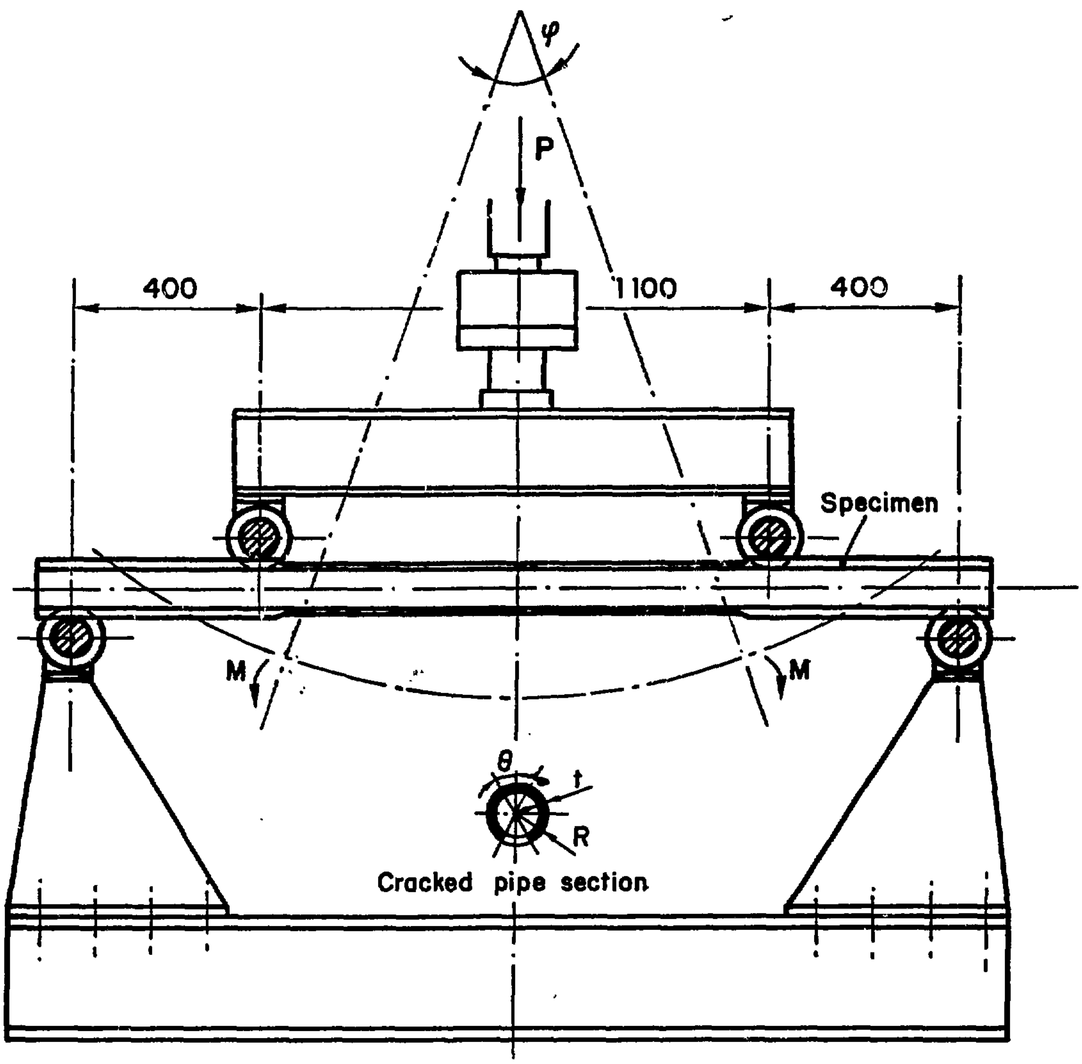

Figure 1 _ Experimental device _ Specimen.

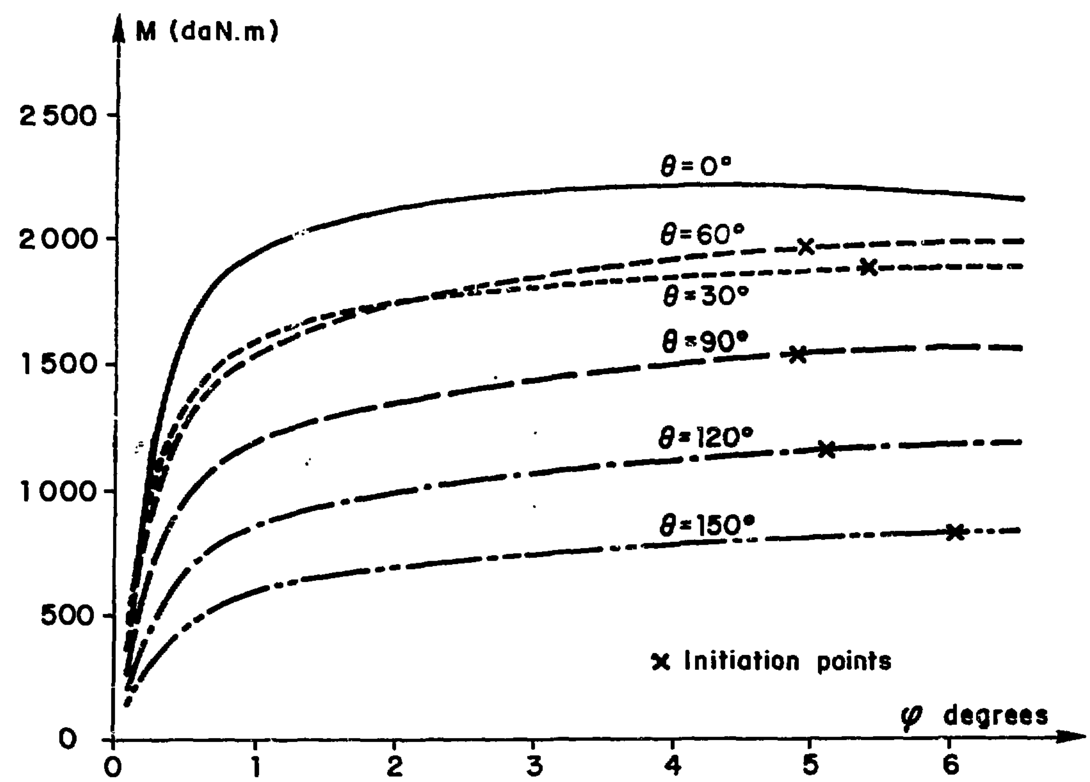

Figure 2 _ M-φ_2 plots for precracked tubes.

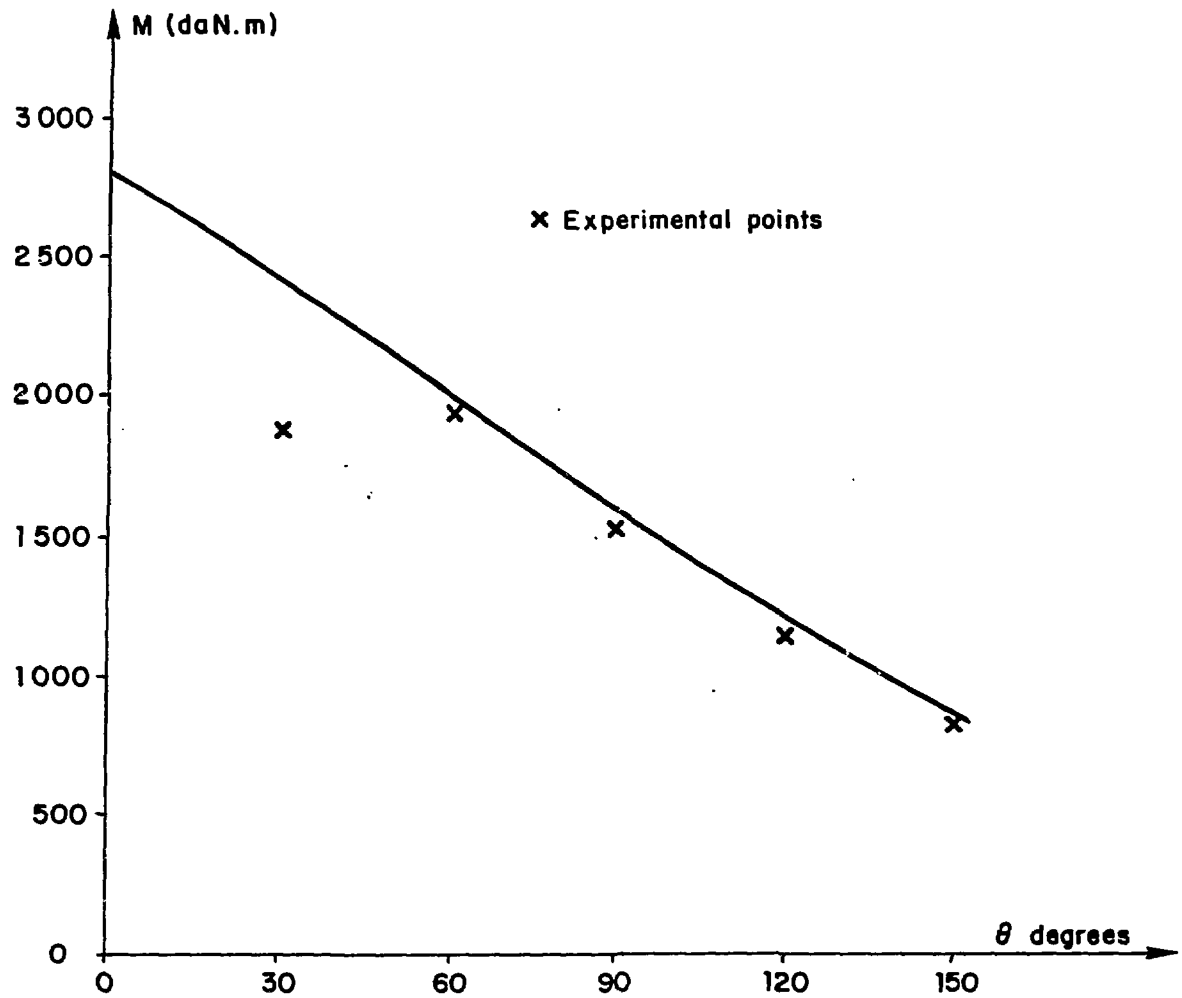

Figure 3 _ Verification of net section stress criterion at initiation.

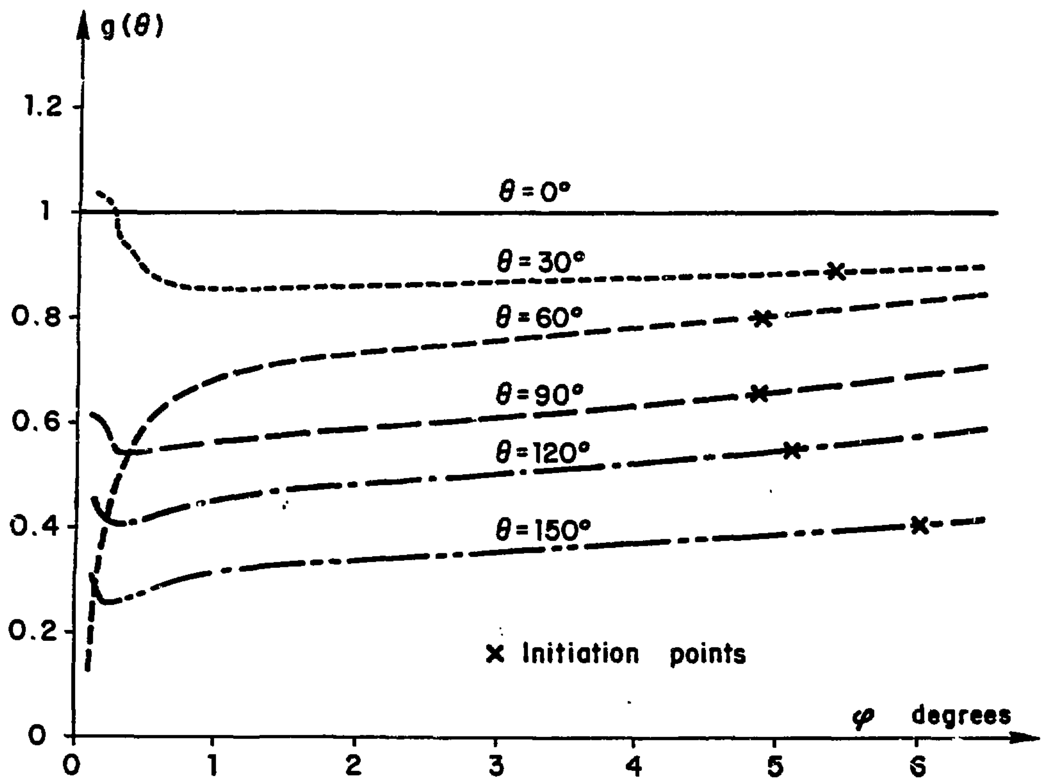

Figure 4 _ Verification of scale factor on bending moment.

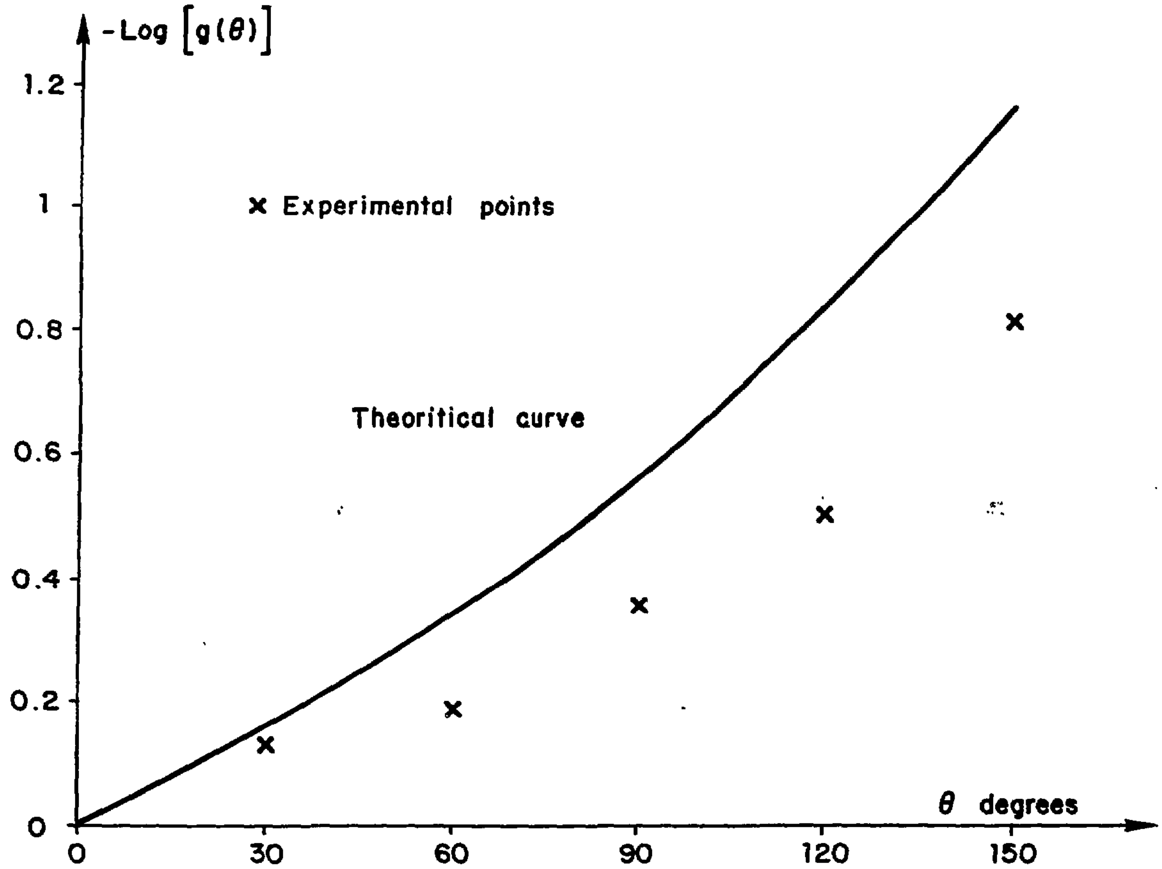

Figure 5 _ Comparison between experimental and theoritical g scale functions.

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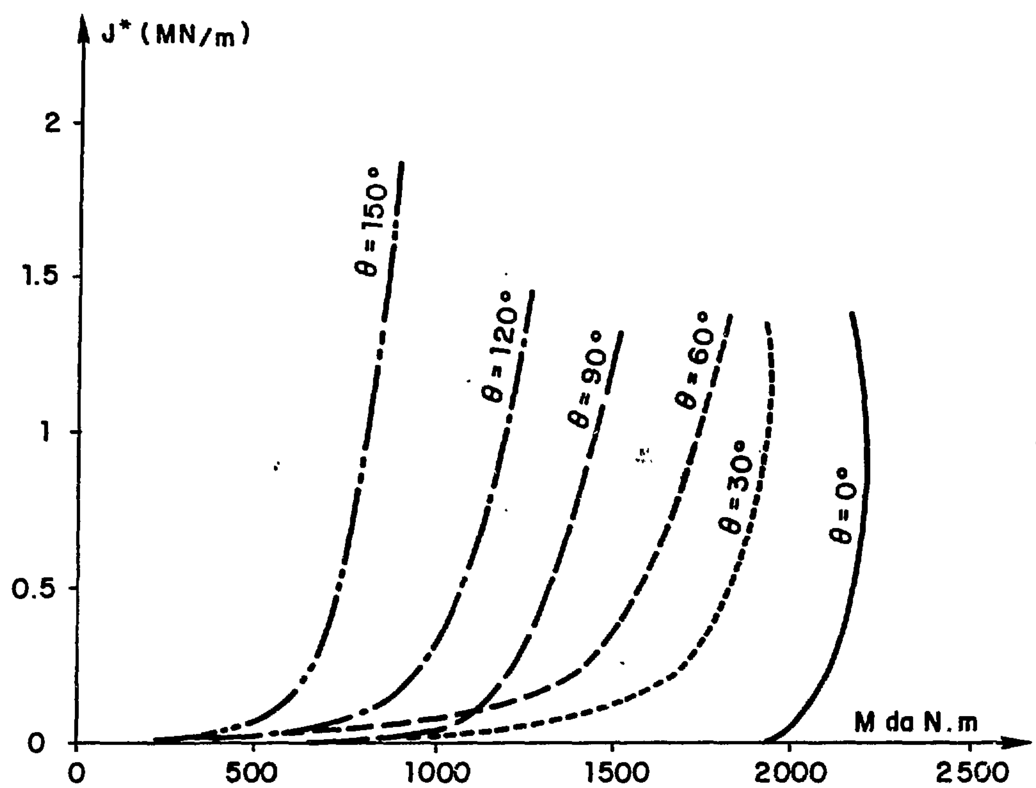

Figure 6 _ J* estimations for blunted cracked tubes.