*L. Grüter*, H. Huthmann*, and A. Cornec†*

# Transferability of Laboratory Specimen Crack Growth Characteristics to Circumferentially Cracked Pipes

**REFERENCE** Grüter, L., Huthmann, H., and Cornec, A., **Transferability of laboratory specimen crack growth characteristics to circumferentially cracked pipes**, *Defect Assessment in Components – Fundamentals and Applications*, ESIS/EGF9 (Edited by J. G. Blauel and K.-H. Schwalbe) 1991, Mechanical Engineering Publications, London, pp. 723–737.

**ABSTRACT** Results are presented on $R$ curve characterisation by crack tip parameters such as $J$, $J_M$, $\delta_5$ and CTOA for cracked CT specimens with 25 and 50 mm width and pipes with a nominal diameter of 700 mm and a nominal wall-thickness of 11 mm of the austenitic stainless steel 316L mod. The data transfer from small specimens to pipes is discussed with respect to crack initiation and stable crack extension. Application of the $\delta_5$ crack tip parameter by using the Engineering Treatment Model (ETM) is summarised.

## Notation

| | |
|---|---|
| $A$ | Crack area |
| $a$ | Crack length |
| d$a$, $\Delta a$ | Crack extension |
| $B$ | Specimen thickness |
| CTOA | Crack tip opening angle |
| $E$ | Young's modulus |
| $F$ | Load |
| $F_y$ | $F$ at incipient net section yielding |
| G | Linear elastic energy release rate |
| $J$ | $J$ integral |
| $J_M$ | Modified $J$ integral |
| $J_{pl}$ | Plastic part of $J$ ($J_{pl} = J - G$) |
| $K$ | Stress intensity factor |
| $n$ | Strain hardening exponent |
| $W$ | Width |
| $\delta$ | Load point displacement (see equations (1)–(4)) |
| $\delta_5$ | Crack tip opening displacement at fatigue pre-crack tip |
| $\delta_y$ | $\delta_5$ at incipient net section yielding |

## Introduction

A knowledge of the crack resistance properties of structures is essential for safety analyses. In order to characterise crack resistance properties of the base material condition of the austenitic stainless steel 316L mod. (316L mod.

---

* Interatom GmbH, D-5060 Bergisch Gladbach 1, FRG.
† GKSS-Forschungzentrum, D-20504 Geesthacht, FRG.

means a type 316 stainless steel with a low carbon content between 0.015 and 0.03 percent and a high nitrogen content between 0.06 and 0.08 percent) experimental investigations on small specimens and large pipes are in progress. The tests are accompanied by analytical studies. The main topics are:

- $R$ curve characterisation;
- transferability from specimen to structure;
- qualification of an easy to apply method for component evaluation.

The work is still in progress, and the present paper reports some preliminary results. Thus, the conclusions drawn at the end of the paper are rather provisional than representing final solutions to the problems raised.

Further information is given elsewhere in the proceedings of this conference **(1)**.

## Test programme

The following tests have been performed at room temperature.

- For characterisation of the $R$ curve:
  - CT specimens with two widths (6 specimens of 25 mm width and 8 specimens of 50 mm width) and a thickness of about 10.5 mm, corresponding to the wall-thickness of the pipes **(2)**;
  - three circumferentially through-wall cracked straight pipes with initial crack angles between 60 and 120 degrees, a diameter of 700 mm and a wall-thickness of 11 mm (nominal data), tested under bending **(2)**–**(4)**.
- For characterisation of the load–displacement correlation:
  - notched (non-precracked) CT specimens specimens (two specimens of $a/W = 0.5$ and 0.6 with a width of 50 and 100 mm respectively) and CCT specimens (two specimens of $a/W = 0.5$ and 0.6 with $2W = 100$ mm) with a thickness of about 10 mm.

The experimental part is supported by analytical studies concerning the applicability of the engineering treatment model (ETM) **(1)**.

## Results and discussion

The $R$ curves are characterised by the crack tip parameters $J$ ($J$ integral), $J_M$ (modified $J$ integral), $\delta_5$ (crack tip opening displacement as defined in **(1)**) and CTOA (crack tip opening angle):

### J *integral and modified* J, $J_M$

For the small specimens standard test procedures after DVM **(5)**, EGF **(6)** and ASTM **(7)** have been used. In case of the pipes $J$ and $J_M$ are calculated by using the definitions of $J$ and $J_M$ respectively

$$J = \int_0^F \left(\frac{\partial \delta}{\partial A}\right)_{F=\mathrm{const}} \cdot \mathrm{d}F \tag{1}$$

$$= -\int_0^\delta \left(\frac{\partial F}{\partial A}\right)_{\delta=\mathrm{const}} \cdot \mathrm{d}\delta \tag{2}$$

$$J_M = J - \int_{a_0}^a \left(\frac{\partial (J-G)}{\partial a}\right)_{\delta_{\mathrm{pl}}=\mathrm{const}} \cdot \mathrm{d}a \tag{3}$$

$$= J - \int_{a_0}^a \left(\frac{\partial J_{\mathrm{pl}}}{\partial a}\right)_{\delta_{\mathrm{pl}}=\mathrm{const}} \cdot \mathrm{d}a \tag{4}$$

where

$J$ = current value of the $J$ integral
$G$ = linear elastic energy release rate ($G = K^2/E$)
$J_{\mathrm{pl}}$ = plastic part of $J$ ($J_{\mathrm{pl}} = J - G$)
$\delta_{\mathrm{pl}}$ = plastic part of the load point displacement; or the total minus the elastic one, ($\delta_{\mathrm{pl}} = \delta - \delta_{\mathrm{el}}$)
$a_0$, $a$ = initial and current values of the crack length

The partial unloading technique has been used; loads, displacements and crack extensions have been measured.

### *Crack tip opening displacement, $\delta_5$*

With two special clip gauges measuring the crack tip opening displacement at the original fatigue pre-crack tip over a gauge span of 5 mm (a schematic drawing is shown in Fig. 13 of **(8)**) the data for the CT specimens have been obtained. In case of the pipes a transmission light microscope has been used to measure the crack tip opening displacements of the crack edges on the photos taken during the pipe tests.

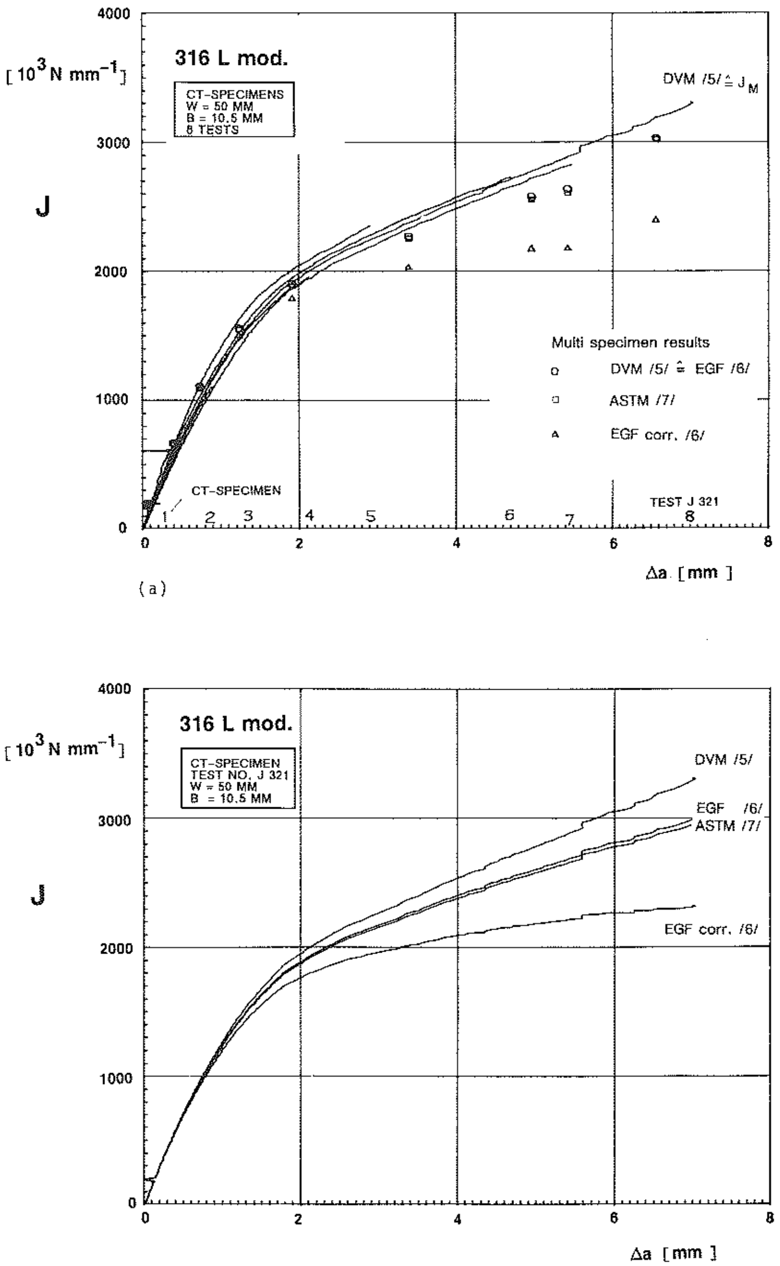
### *Crack tip opening angle, CTOA*

The crack tip opening angles have been measured on the pipes at a position 4 mm behind the actual crack tip. For the CT specimens CTOA is estimated by using the data of the $\delta_{5,\mathrm{R}}$ curve for crack extensions between 0.5 and 5.8 mm. Thus, only in case of $\Delta a = 4$ mm the data of the pipes and the CT specimens are directly comparable.

## Crack resistance properties

### *Calculations*

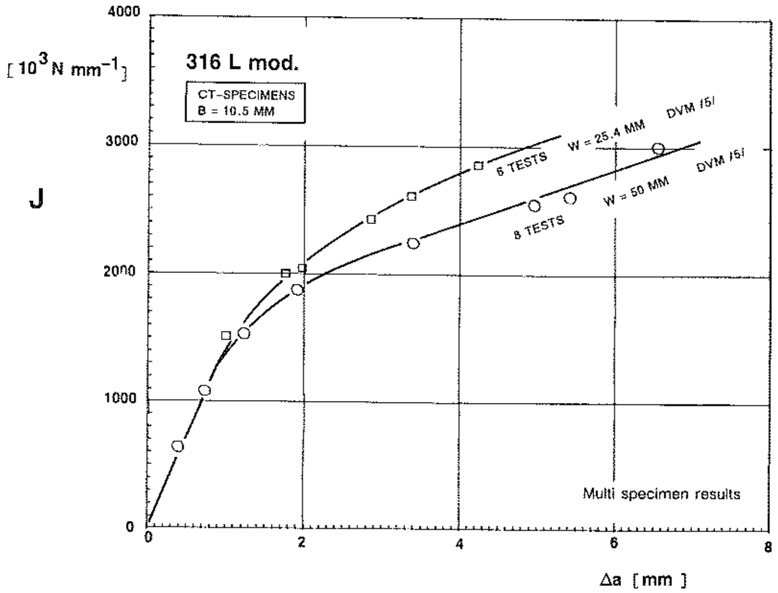
Results of $J$ calculations are affected by the calculation procedure (e.g., for small specimens after DVM, EGF or ASTM **(5)**–**(7)**), i.e., comparative studies are limited to cases with identical calculation procedures. In Figs 1(a) and 1(b)



(a)

(b)

**Fig 1** **$J_R$ curves for CT specimens: (a) $J_R$ curves for single specimen evaluation according to DVM (≙ $J_M$) (5) and $J$ values from multi-specimen evaluations (6)(7); (b) $J_R$ curves for test no. 321 determined from different single specimen test methods (5)–(7); (c) influence of width of CT specimens on $J_R$ curves; procedure after (5)**



(c)

the strong effect of the calculation procedures on the $J_R$ curve of CT specimens with $W = 50$ mm can be seen. A similar effect may be found if the specimen geometry is slightly changed. This is demonstrated in Fig. 1(c) for the $J_R$ curves of CT specimens of 25 and 50 mm width. The $J$ and $dJ/da$ values of the second geometry are lower than of the first geometry. The results presented in Fig. 1 prove that a reliable extrapolation of the $J_R$ curves, obtained from the small specimen tests, to structures with larger crack extensions – such as the pipes – is not possible presently.

In Fig. 2 the $J_R$ curves from the pipe tests are plotted for crack extensions up to 300 mm. All curves increase monotonically. The shape of the curves is non-linear. Some theoretical considerations on this phenomenon are given in reference **(9)**. Nevertheless, the data in Figs 1 and 2 indicate that crack initiation seems to be independent of geometry changes. In the early crack extension phase, values of $dJ/da$ – the slope of the $J_R$ curve – are well above 200 $N \cdot mm^{-2}$, while for large crack extensions lower values of about 60 $N \cdot mm^{-2}$ are observed (see Fig. 3). Above about 50 mm of crack extension the $dJ/da$ data are nearly constant. This result is known also from other tests on circumferential cracks **(10)(11)**. Because of this non-linear shape of the crack resistance curve any extrapolation from small specimens to large structures is impeded. Support is given by the comparison of CT specimen and pipe data shown in Fig. 4. Although the correlation of both structure's data is reasonable, it is immediately clear that any extrapolation from small specimen data will be difficult due to the small crack extension of only a few mm in these specimens.

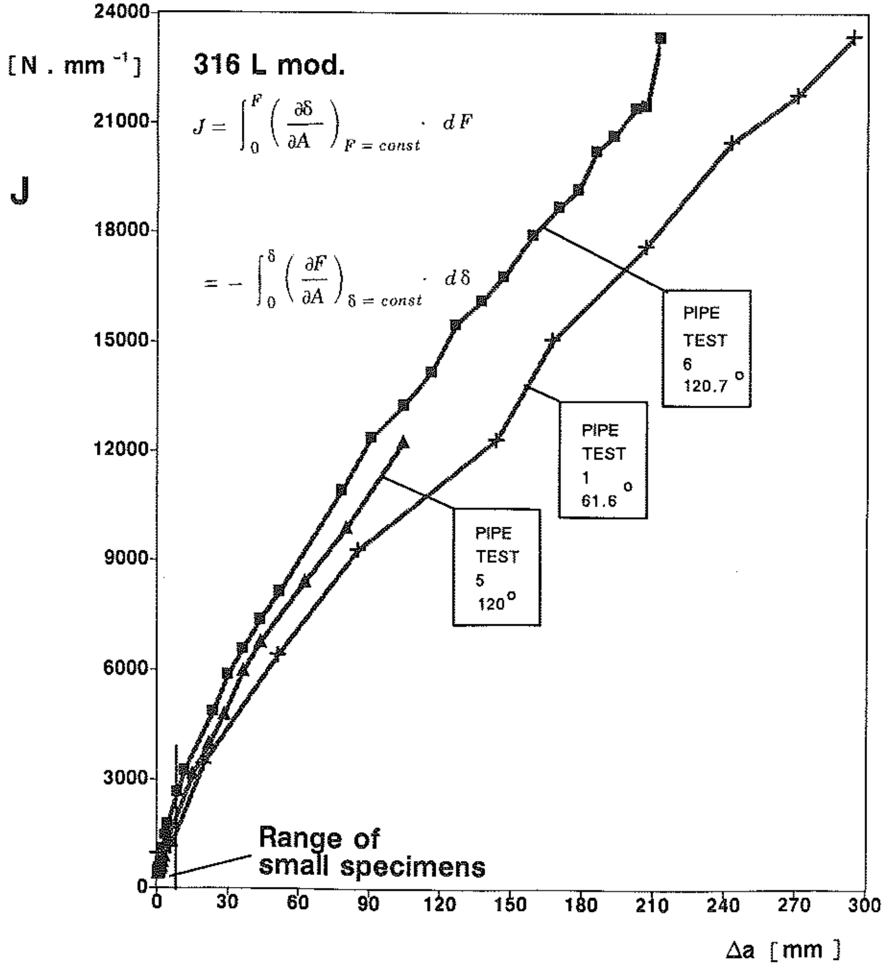


**Fig 2** $J_R$ **curves for the pipes with crack extensions up to 300 mm**

To develop a geometry independent *R* curve Ernst (**12**) suggested a modified *J* integral, $J_M$. In Fig. 5 the $J_R$ and $J_{M,R}$ curves of the three pipes tested are plotted. In the initial phase of crack extension the curves are identical; this is also found for the CT specimens as can be seen in Fig. 1. For larger crack extensions the $J_{M,R}$ curves are slightly higher than the $J_R$ curves. This behaviour is found in the CT specimens for $\Delta a \geqslant 1.5$ mm while in the pipes $\Delta a \geqslant 10$ mm is given. In the latter case the $J_{M,R}$ curve is non-linear.

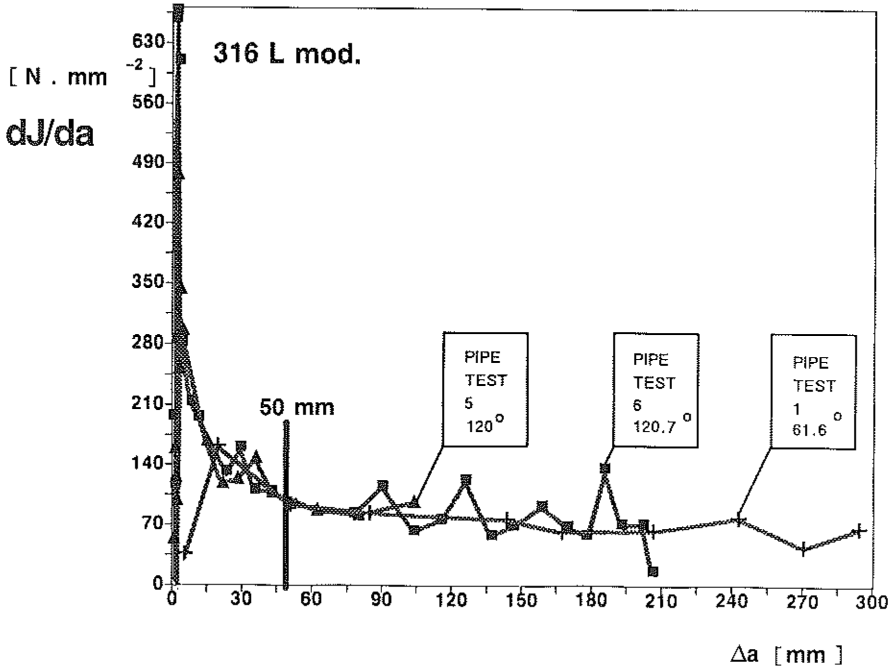


**Fig 3 Slope d*J*/d*a* of the** $J_R$ **curves for the pipes with crack extensions up to 300 mm**

*Measurements*

The crack tip opening displacement $\delta$ is not imposed by such strong limitations for the allowable ligament and crack extension (**8**). In Fig. 6 the $\delta_{5,R}$ curves measured on 8 CT specimens ($W = 50$ mm) are shown. The scatter of the measurements is very small. Data are available for crack extensions up to 5.8 mm. In this range the $\delta_R$ curves of the pipe experiments tend to change over to a linear behaviour which is followed up to the end of the experiments (Fig. 7). The CT specimen data are at the upper bound of the pipe data (see comparison shown in Fig. 8), following the non-linear trend curve up to the maximum observed crack extension. The later linear $\delta_{5,R}$ curves measured on the pipes are within the range of possible extrapolations from the small specimen measurements. Further tests on specimens with crack extensions up to about 30 mm are recommended.

In case of CTOA, measured data for CT specimens are not available; thus only an approximation for the crack tip opening angle by using the $\delta_5$ measurements is possible for crack extensions up to 5.8 mm. The results are given in Fig. 9. The trend of the CT data – i.e., the transition regime of CTOA up to a crack extension of about 25 to 50 mm which is the starting point in the base material for a constant CTOA of about 13 degrees – is in correspondence to the pipe results. But for an acceptable prediction of the pipe behaviour, crack extensions above at least 30 mm (see above) have to be measured in CT specimens (for the base material condition).

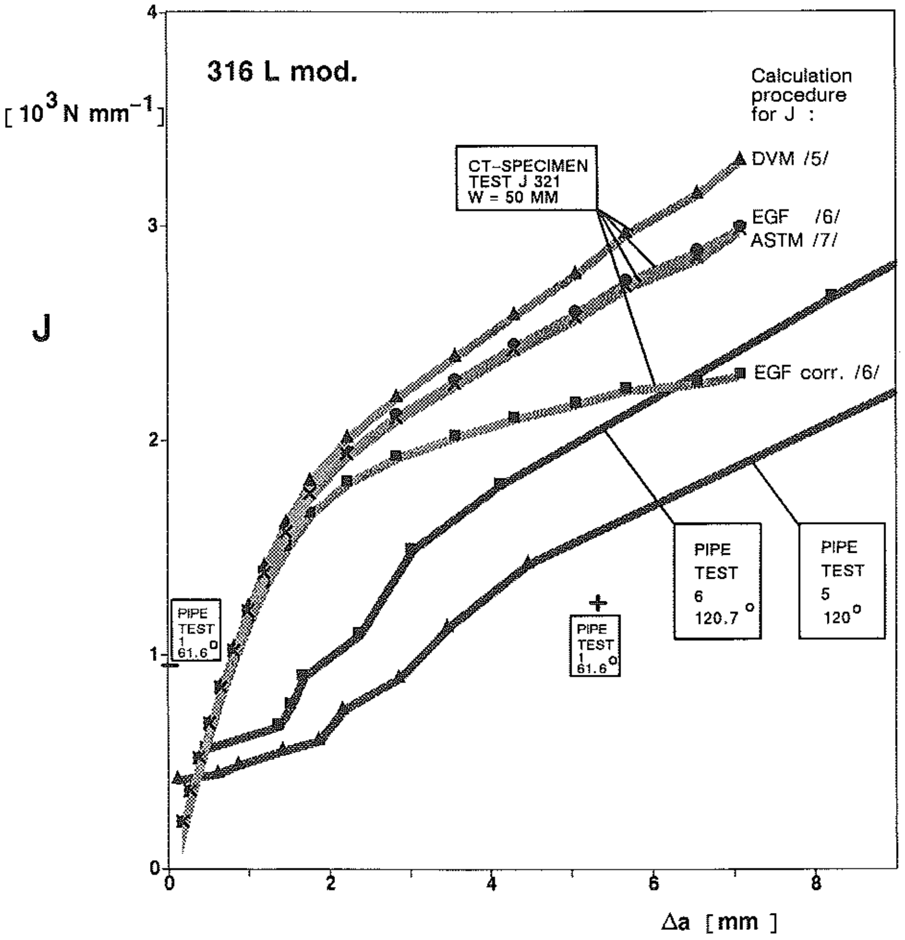


Fig 4 Comparison of the $J_R$ curves obtained for the CT specimens and the pipes

## Transferability

The width of standard CT specimens is relatively small. Therefore, stable crack extension is limited to some mm. The $J_R$ curves measured on the pipes and the CT specimens are in acceptable agreement. However, due to the non-linear $J_R$ curves found for large crack extensions on the pipes the extrapolation from the CT specimen data by using a linear procedure, which is the usual procedure at this moment, is non-conservative by overestimating the slope of the $J_R$ curves. The arguments concerning the non-linear $R$ curve behaviour are also still valid in case of $J_M$. Thus both crack tip parameters may be recommended for structural analyses only, if the non-linear resistance curves are considered conservatively.

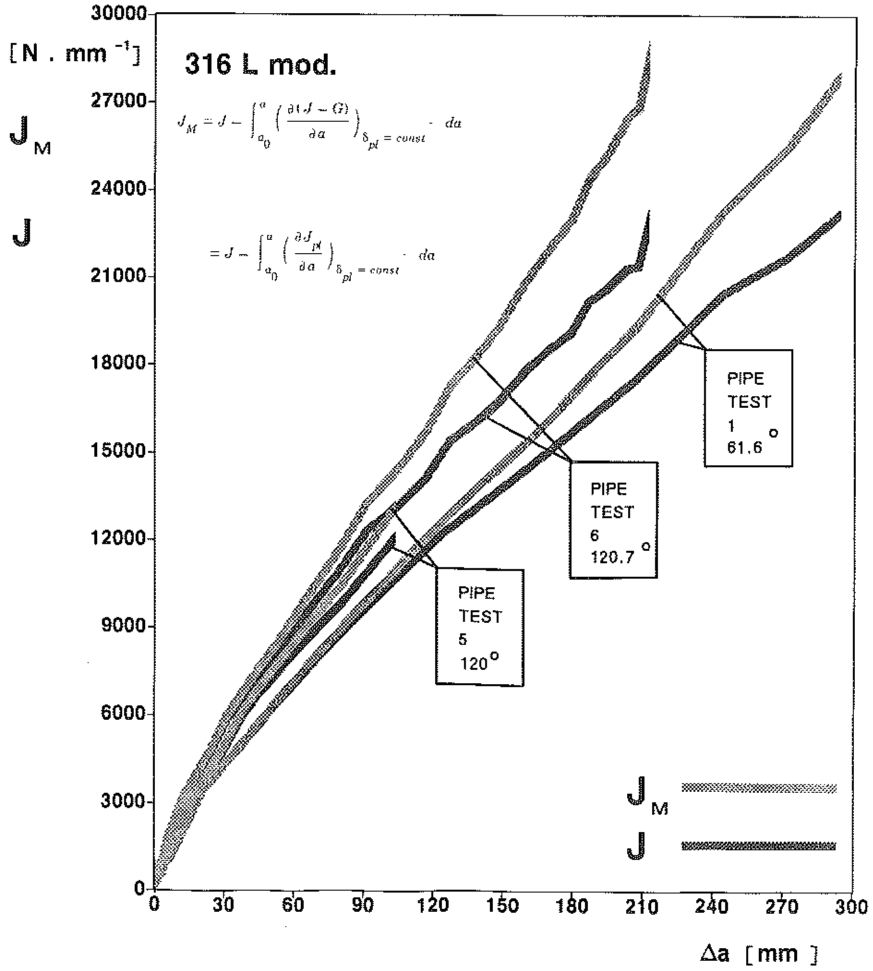


Fig 5 $J_R$ and $J_{M,R}$ curves for the pipes with crack extensions up to 300 mm; for comparison with the CT specimens (see Fig. 1)

The correlation of the $\delta_5$ $R$ curves from CT specimens with those from the pipes is substantially better than that of the $J_R$ curves, compare Figs 4 and 8.

In the case of $\delta_5$ the linear $R$ curves measured for crack extensions $\geqslant 10$ mm on the pipes will favour the use of a linear extrapolation procedure. Further tests on specimens with crack extension up to about 30 mm are recommended.

Constant CTOA values, desired for component evaluation, are found for the base material condition only above a crack extension of 25 to 50 mm. This parameter needs further investigations to be qualified for structural analyses.

Crack growth data need careful handling if they are to be used for analyses of large structures, in particular with respect to extrapolation from small specimen data to larger structures with potentially much larger crack extension.

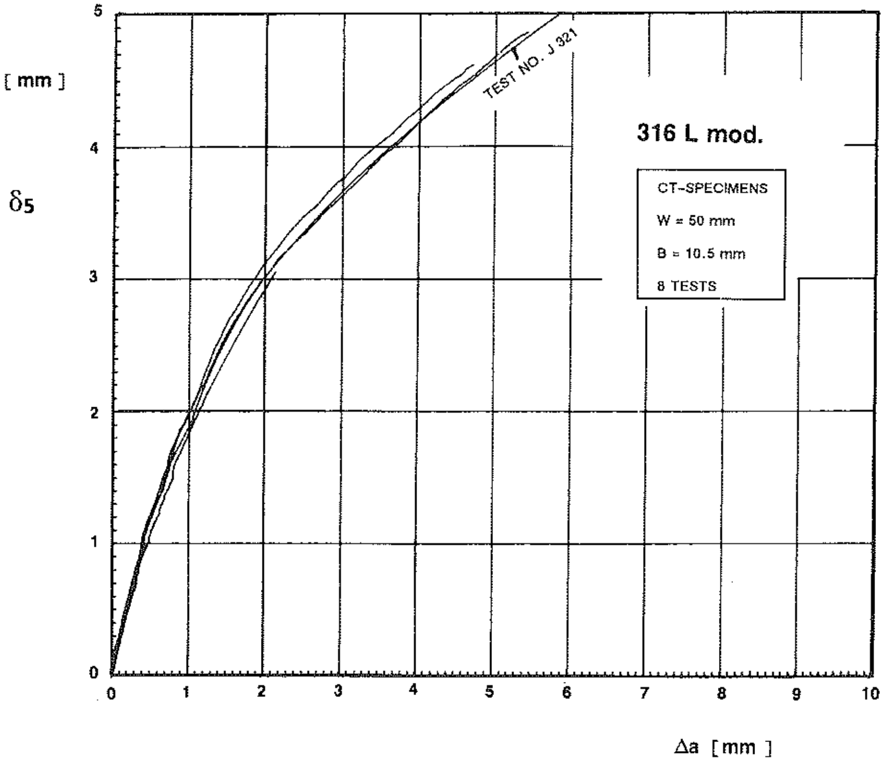


**Fig 6** $\delta_{5,R}$ curves measured on CT specimens of 316L mod. base material

## Applicability of the ETM

In order to apply methods of component evaluation, the properties measured on laboratory specimens must be transferable to the component under consideration. This requires fracture mechanics properties of the structure which are similar to if not identical with those of the specimen and the ability to predict or to estimate the crack driving force in the component. Whereas the former problem was considered in the previous sections, in the following some points referring to the latter topic will be raised. Within the research programme this paper is based upon, the Engineering Treatment Model (ETM) is being verified as an easy to apply, approximate method for component assessment (1). Within the framework of the ETM the material is supposed to strain harden in a power law fashion. Since structural materials do not follow an ideal power law it is necessary to define a representative strain hardening exponent, $n$. Therefore, deformation studies on notched (but not fatigue cracked in order to avoid crack growth) CT specimens with widths of $W = 50$ and $W = 100$ mm – representing the bending case – and on notched CCT specimens with a width of $2W = 100$ mm – representing the tension case – were carried out.

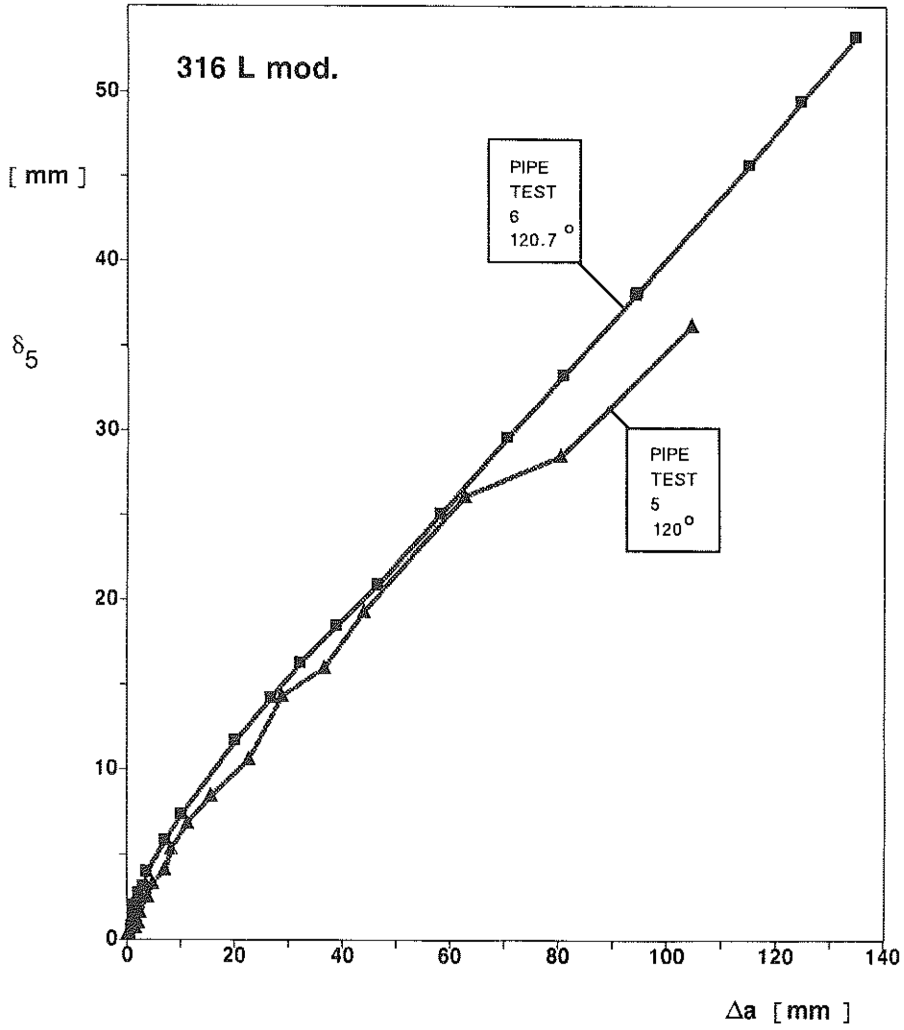


**Fig 7** $\delta_{5,R}$ curves measured in the pipe experiments for crack extensions up to 140 mm

The deformation characteristics of the CCT specimens duplicates exactly the bilinear power law behaviour of the stainless steel 316L mod., Fig. 10(a). The diagram also shows that a single, average hardening exponent of $n = 0.15$ gives a very good approximation in the total deformation range. In contrast to this, the second hardening exponent of the material ($n = 0.2$) dominates the CT specimens; the same finding can be applied to a fatigue cracked CT specimen, Fig. 10(b). On the other hand, the pipes are subjected to much less defor-

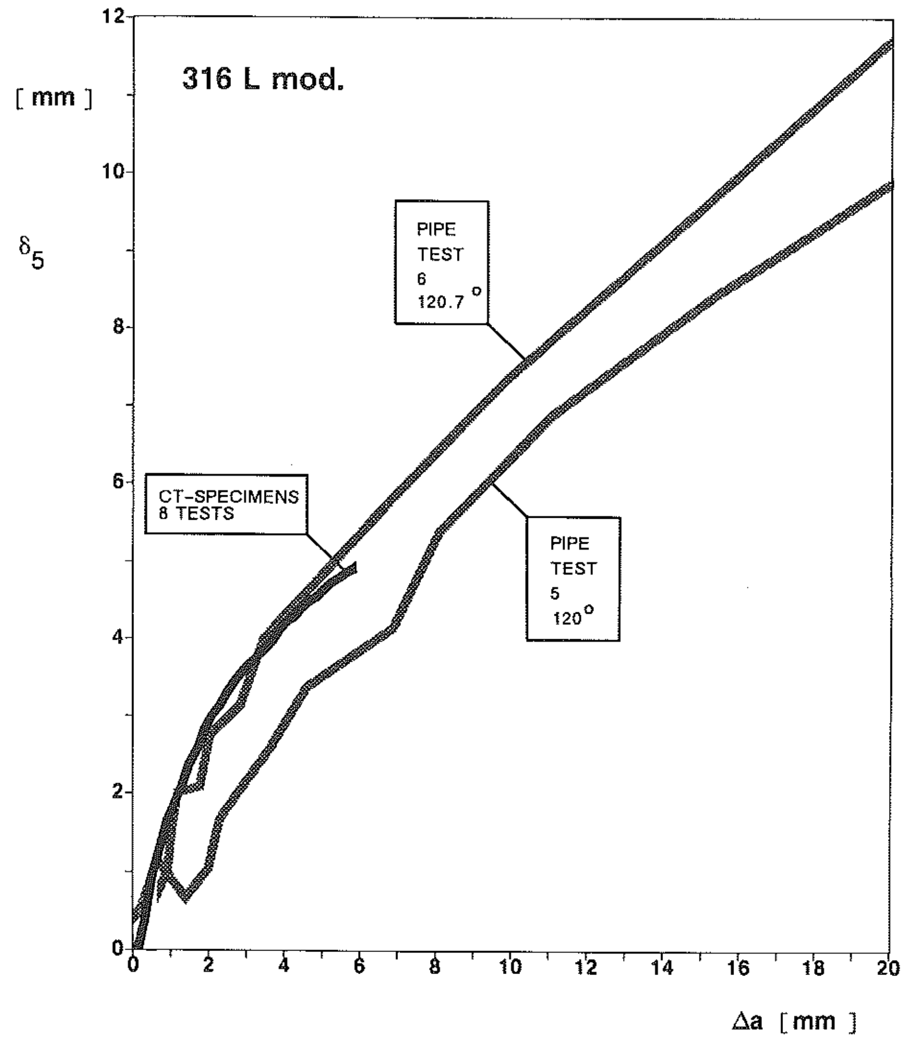


**Fig 8** Scale-up of Fig. 8 for crack extensions up to 20 mm and comparison of $\delta_{5,R}$ curves of the pipe and CT specimen tests

mation ($\delta_5/\delta_y \approx 10$, as compared with $\delta_5/\delta_y \approx 100$) than the specimens, Fig. 10(c). Within this range a single $n$ value of 0.15 is still close to a CT specimen's characteristics, see the data points in Fig. 10(a).

Further work with systematic variation of the relevant parameters is needed to check whether the use of a single hardening exponent can be justified if the stress–strain curve exhibits a bi-linear power law type. Finite element studies with this aim are underway.

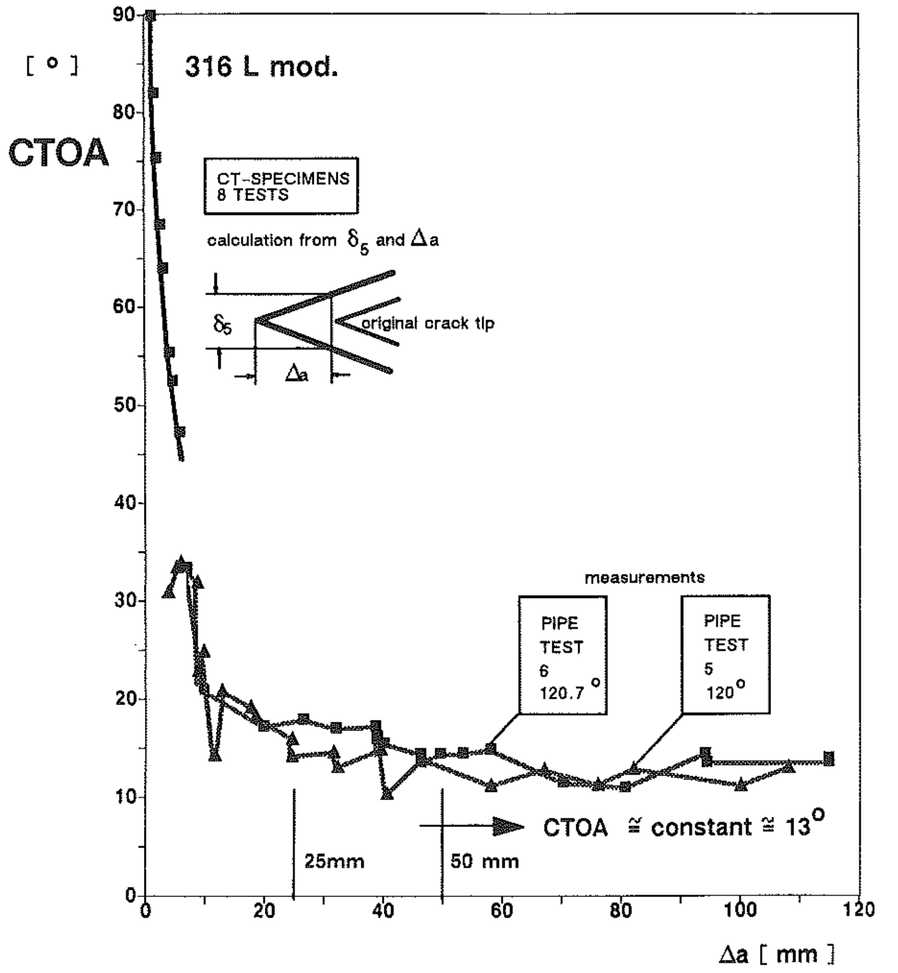


**Fig 9** Comparison of CTOA data: for the pipes: measured data; for the CT specimens: calculated data by using $\delta_5$ measurements

## Conclusions

The results of the research in progress demonstrate exemplarily on the base material of the austenitic stainless steel 316L mod., that the fracture mechanics concept for a reliable transfer of crack resistance data from small specimen geometries to large structures is still to be qualified for high toughness materials. The use of the $J$ integrals and the constant CTOA are regarded as problematic, the main disadvantages of $J$ are the effects of geometry and calculation procedure together with the non-linear $R$ curve. The necessary crack extension for a constant CTOA is larger than the geometrical dimensions for

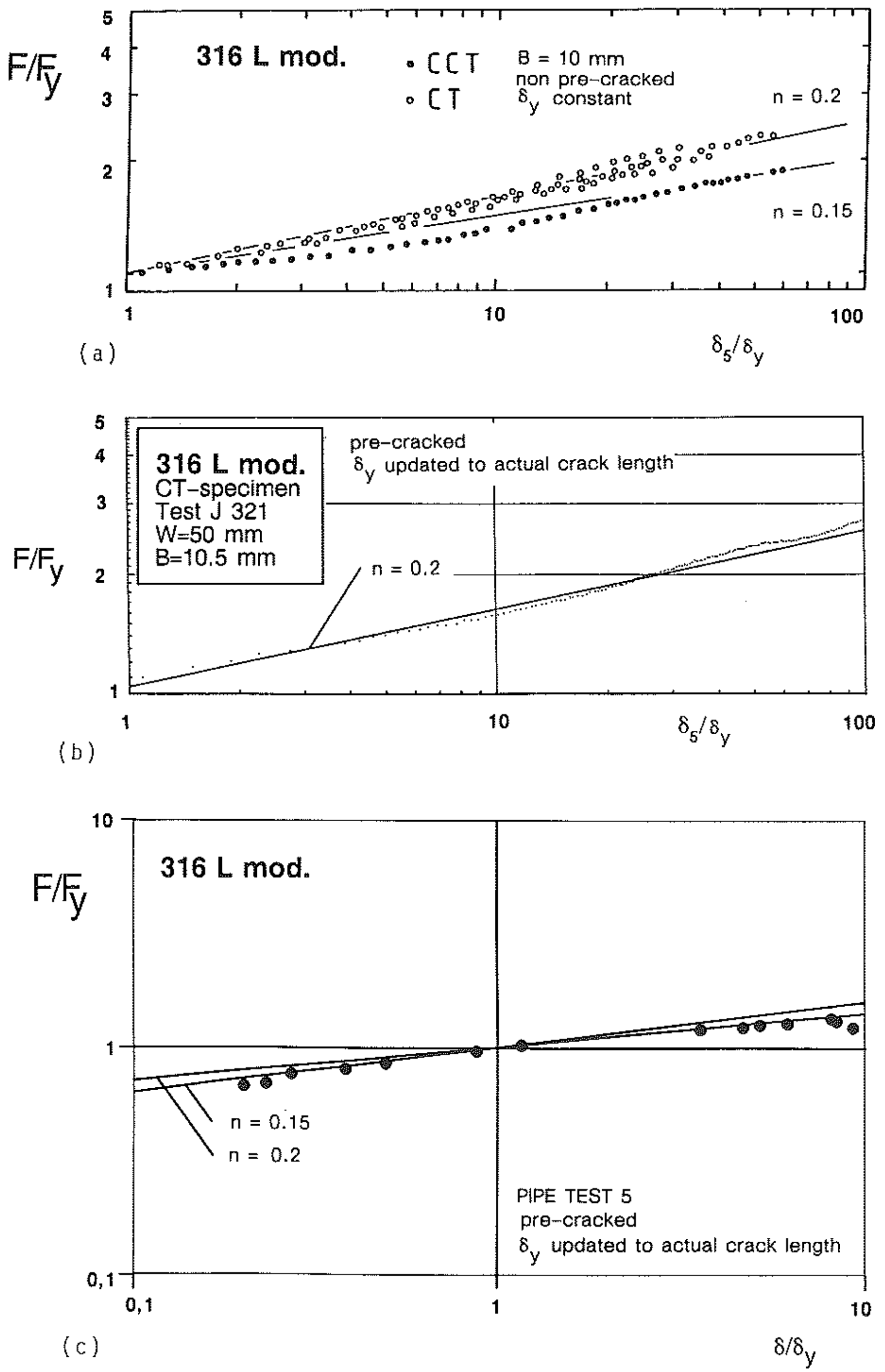


**Fig 10** **Comparison of the $\delta_5$ data obtained for the non-precracked CT and CCT specimens (a) and the cracked pipes and CT specimens (b, c)**

the usual CT specimens. The crack tip opening displacement in the form of $\delta_5$ shows a better agreement between the *R* curves measured on CT specimens and pipes than *J*. $\delta_5$ presents the following advantages:

- a direct measurement;
- a linear behaviour for crack extensions larger than 10 mm;
- a good estimation by the ETM using a mean strain hardening exponent.

This has to be confirmed by investigations on possible geometry effects on the $\delta_{5,R}$ curve and for crack extensions above 10 mm in small specimen geometries.

## References

(1) SCHWALBE, K.-H. and GRÜTER, L. Application of the engineering treatment model (ETM) to the prediction of the behaviour of a circumferentially cracked pipe; this volume, pp. 1125–1133.

(2) HUTHMANN, H., GOSSMANN, O., GRÜTER, L., FORTMANN, M., BHANDARI, S. and FAIDY, C. (1987) Messung von $J_R$-Kurven an CT-Proben und Rohren aus dem Stahl 316L, Vorträge der der **19.** Sitzung des DVM–Arbeits–kreises Bruchvorgänge, DVM, pp. 453–477.

(3) GRÜTER, L., FORTMANN, M., BHANDARI, S., and FAIDY, C. (1988) Crack resistance properties of through-cracks in austenitic straight pipes DN 700 under bending, *Nucl. Engng Des.*, **108**, 447–456.

(4) BHANDARI, S., NESA, D., FAIDY, C., and GRÜTER, L. (1990) Initiation and instability behaviour of cracked LMFBR piping: Comparison of different theoretical approaches and experiments, *Nucl. Engng Des.*, pp. 337–345.

(5) DVM-Merkblatt DVM002 (1987) Ermittlung von Rißinitiierungswerten und Rißwiderstandskurven bei Anwendung des *J* integrals.

(6) ASTM E 813-87 (1987) *Standard test method for* $J_{Ic}$, *a measure for fracture toughness*, ASTM, Philadelphia.

(7) EGF Recommendations for determining the fracture resistance of ductile materials (1987) 1st Draft.

(8) SCHWALBE, K.-H. (1983) Überlegungen zur Anwendung der Bruchmechanik, Möglichkeiten und derzeitige Grenzen, Vorträge der 15, Sitzung des Arbeitskreises Bruchvorgänge, DVM, pp. 41–43.

(9) WILL, P., MICHEL, B., and ZERBST, U. (1987) Kritische Analyse von Bruchzähigkeitsprufüngen und Vorschläge für eine Änderung, *Mat.-Prüfung.*, **29**, 273–276

(10) SHIBATA, K., OHBA, T., KAWAMURA, T., MIYAZONO, S., KANEKO, T. and YOKOHAMA, N. (1986) Ductile fracture behaviour of 6-inch diameter type 304 stainless steel and STS42 carbon steel piping containing a through-wall and part-through crack, JAERI-M 86-078.

(11) SHIBATA, K., KANEKO, T., YOKOHAMA, N., OHBA, T., KAWAMURA, T., and MIYAZONO, S. (1986) Ductile fracture behaviour and LBB evaluation of circumferentially cracked type 304 stainless steel under bending load, *Atsuryoku Gijutsu*, **24**, 236–244.

(12) ERNST, H. A. (1983) Material resistance and instability beyond *J* controlled crack growth; *ASTM STP 803*, ASTM, Philadelphia, I-191–I-213.