A SIMPLIFIED KEY-CURVE PROCEDURE FOR J-R-CURVE TESTING OF CT-SPECIMENS

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A novel key-curve based procedure for crack length measurement on CT-specimens is presented. The procedure is compared with other testing methods for three different pressure vessel steels. The new procedure is shown to yield accurate enough results for normal J-R-curve testing. Different causes affecting the accuracy of the method are discussed.

INTRODUCTION

Reliability of J-R-curve testing depends, from a testing point of view, on how accurately the load, displacement and crack growth are measured. Most problems rises from the crack growth measurement during the test. Several methods to measure the crack growth have accordingly been developed. The methods can be divided into multiple specimen and single specimen techniques.

The simplest and most reliable but at the same time most expensive and laborous method to determine the crack growth is the so called multispecimen technique. With this method several specimens are loaded to different loading levels so as to produce different amounts of crack growth in each specimen. The crack growth for each specimen is then measured after the test directly from the fracture surface. In this way each specimen yields one point on the J-R-curve. This kind of testing needs much material, many tests and the result is strongly dependent of the materials homogeneity.

The most used single specimen test technique to determine crack growth is based on the so called partial elastic unloading compliance technique. In this method several small elastic unloadings are performed during the test in order to measure the specimens elastic

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compliance. By using a specimen geometry dependent calibration function it is then possible to calculate the crack length at the moment of unloading. In order to get reliable results with this method the testing system must be rather sophisticated and the friction in the test must be extremely small. Also the need to perform a large number of partial unloadings makes the test quite slow and thus expensive.

In this work a single specimen method based on a simplified key-curve analysis for CT-specimens has been developed. Many of the assumptions made in the analysis are already commonly applied, but some of them must be regarded as novel. These novel assumptions makes it possible to use a very simple treatment and yet to get reliable enough J-R-curve results. The analysis method is verified for three different pressure vessel steels. The verification is performed by comparing the key-curve results with results based on both partial elastic unloading compliance as well as the multi-specimen technique.

THE KEY-CURVE ANALYSIS METHOD

The method is based on the assumption that the load displacement curve expression for a CT-specimen can be presented as

$$\frac{P}{\alpha \cdot b} = A \cdot \Delta^c \quad \text{(1)}$$

where A is a material and specimen size dependent constant
c is a material constant
Δ is the total displacement
and α is the Merkle and Corten expression

Theoretically it would be more correct to use only the plastic part of the displacement (Δ_{pl}) but it was found that the analysis method yielded more reliable results when using the total displacement Δ.

Equation 1 can be written as

$$\frac{P}{\alpha \cdot b} = \frac{P_f}{\alpha_f \cdot b_f} \cdot \left(\frac{\Delta}{\Delta_f}\right)^c \quad \text{(2)}$$

where sub-f corresponds to the test end values and/or final crack length. The procedure for obtaining the slope (c) is presented in Figure 1. First the load-displacement data normalized with the initial crack length a_0 is plotted in log-log coordinates. The slope is obtained from

$$c = \log\left(\frac{P \cdot \alpha_f \cdot b_f}{\alpha_0 \cdot b_0 \cdot P_f}\right) / \log\left(\Delta/\Delta_f\right) \quad \text{(3)}$$

All the data is checked in order to find a point $i(x_i, y_i)$ yielding a minimum value for c. An additional requirement is that the second derivative of the measured curve at the point must be negative. The crack length at point $i(x_i, y_i)$ is set as a_o+ blunting. Next the procedure is repeated using this new estimate of a_o, until the point $i(x_i, y_i)$ remains unchanged. The crack growth between points i and f is obtained by rewriting equation (2)

$$\alpha \cdot b = \frac{P \cdot \alpha_f \cdot b_f}{P_f \cdot (\Delta / \Delta_f)^c} = A \quad \text{.......(4)}$$

Making use of the Merkle and Corten expression, a is obtained as

$$a = W + A - \sqrt{2 \cdot A^2 + 4 \cdot W \cdot A} \quad \text{.......(5)}$$

and

$$\Delta a = a - a_o \quad \text{.......(6)}$$

At point i the value of Δa is set equal to the blunting value of Δa. Presently the method applies the ASTM E813-81 version of blunting, but a physically better defined expression can of course be used as well.

In order to get reliable results with the method one must perform an additional task prior to the key-curve analysis. One must perform a geometric rotation correction on both the load and displacement.

ROTATION CORRECTION

A rotation correction of the displacement comes simply from the fact that when the crack opens, i.e. the specimen rotates, the measured load line displacement no longer corresponds to the effective load line displacement, because the effective load line moves towards the centre of the specimen. A rotation correction of the load is in reality a correction of the moment and the reason for this is the same as for the displacement. The rotation correction used here is presented in Figure 2.

EXPERIMENTAL

The key curve analysis method was applied to three different pressure vessel steels. The major part of the work was performed on a 2 1/4 Cr 1 Mo steel taken from a hydrogenating vessel that had been in service for more than20 years. The two other steels were A533B Cl.1 reactor pressure vessel steel and an A542 type steel, which was used in the European Group of Fracture J_{Ic} test round robin. The room temperature tensile properties of the steels are presented in Table 1.

TABLE 1 - Room temperature tensile properties of test materials

Material	$\sigma_{0.2}$[MPa]	σ_u [MPa]
2 1/4 Cr 1 Mo	300	532
A533B Cl.1	468	624
A542	560	670

All tests were performed on 25 mm (1T) CT-specimens with 20 % deep sidegrooves. This specimen geometry is a standard geometry commonly used in J-R-curve testing. The tests were performed with a computerized testing system, which has been described in detail elsewhere (Wallin et al. (2)).

RESULTS

2 1/4 Cr 1 Mo steel

The resulting key-curve, for this material at +50^{0}C, based on multiple specimen results is presented in Figure 3. The loads and displacements are marked as effective because of the rotation correction. At least for this material equation 1 is quite adequate to describe the key-curve. The resulting J-R-curves for the three specimens showing the largest amount of crack growth is presented in Figure 4 together with the multiple specimen results. It is seen that the key-curve method yields essentially identical results with the multiple specimen method for this material.

The material was also examined by using the partial elastic unloading compliance method. The results of ten separate specimens are presented in Figure 5. The same data were also analysed with the key-curve method and the corresponding J-R-curves are presented in Figure 6. The scatter bands from the partial elastic unloading compliance method are also plotted in Figure 6. The reproducibility of the key-curve method is seen to be at least equal to the compliance method. The key-curve results are located slightly lower than the unloading compliance results. This may be because the unloading compliance results somewhat underestimate the true crack growth in most specimens whereas the key-curve is constructed based on the actual crack growth.

A 542 steel

The key-curve method results for this material were compared with both multispecimen and unloading compliance results. The results of the comparison are presented in Figures 7 and 8. This was the only material where the key-curve method and the unloading compliance method yielded clearly different results. It is not, however, evident that the key-curve results would be in error, because they are consistent with the multi-specimen results. Unfortunately the material was quite inhomogenious so that it cannot be conclusively stated which method is better. It can of course always be argued that the single specimen method, yielding the same result as the multispecimen method, is the better one. In this case it would be the key-curve method.

A 533 B Cl.1 steel

The key-curve method results for this material were compared with results based on unloading compliance at room temperature, +150^{0}C and +270^{0}C. At room temperature one specimen was used whereas at +150^{0}C and +270^{0}C two specimens were compared at each temperature. The comparison is presented in Figures 9 - 11. Out of the five specimens there is a discrepancy in the J-R-curves only in one specimen tested at +270^{0}C. In this case it seems, however, that it is the unloading compliance result that is in error. In this specimen, unloading compliance underestimates the true crack growth considerably.

DISCUSSION

The simplified key-curve method for crack length estimation is not claimed to be a method yielding "exact" results. This is impossible because it is based on a simplified description of the load-displacement curve. Based on the results of this study it is, however, claimed that the method yields accurate enough results for normal J-R-curve testing. The method has been applied on three different types of pressure wessel steels. In only one case the method yields clearly different results than what is obtained with the partial elastic unloading technique and even in this case the key-curve results are comparable with the multispecimen results.

The key-curve technique is extremely simple to use. It does not require any additional instrumentation above what is needed to measure the J-integral. Furthermore, the whole test can be performed in one stage, like in a simple K_{Ic} test. Also, based on the results of a Nordic J-R curve round robin (Wallin (3)), the key-curve method seems less dependent on possible friction effects than unloading compliance.

SUMMARY AND CONCLUSIONS

A new simplified key-curve method for CT-specimens has been developed. Based on a comparison of the method with other J-R-curve testing methods, the following can be concluded:

- The key-curve method yields accurate enough estimates of the crack growth for normal J-R-curve testing.

- The reliability of the method is mainly dependent on the accuracy of the crack length measurements from the fracture surface.

ACKNOWLEDGEMENTS

This work is a part of the Structural Materials in Nuclear Power Plants program performed at the Technical Research Centre of Finland (VTT) and financed by the Ministry of Trade and Industry in Finland.

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33K

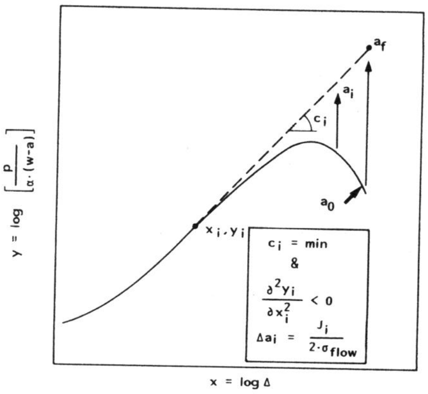

Figure 1 Simplified key-curve procedure

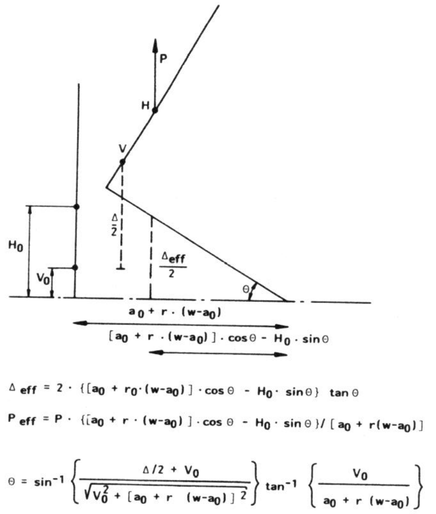

Figure 2 Rotation correction for CT-specimen

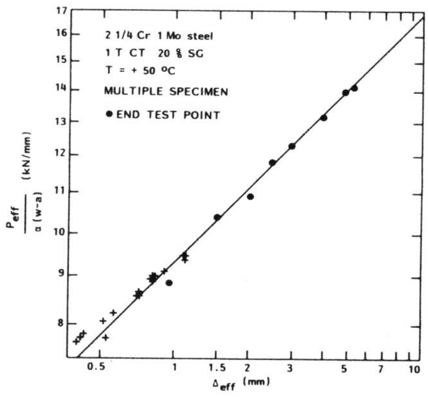

Figure 3 Multiple specimen based key-curve

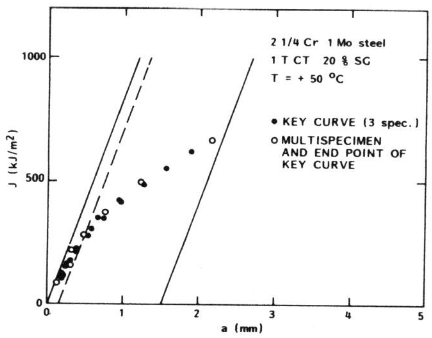

Figure 4 J-R-curve comparison (Key-curve vs. multiple specimen)

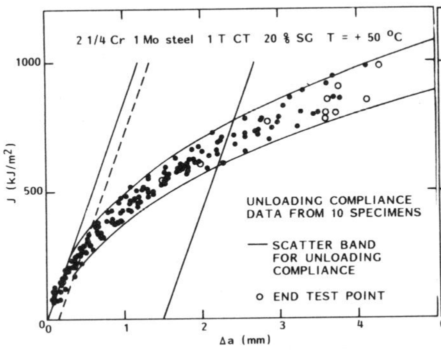

Figure 5 Unloading compliance data from 10 specimens

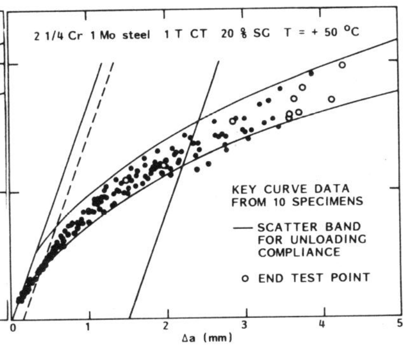

Figure 6 Key-curve from 10 specimens

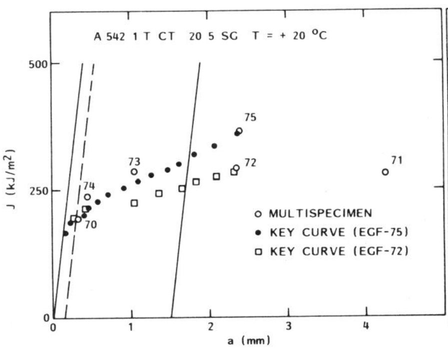

Figure 7 J-curve comparison A542, T = +20^{0}C

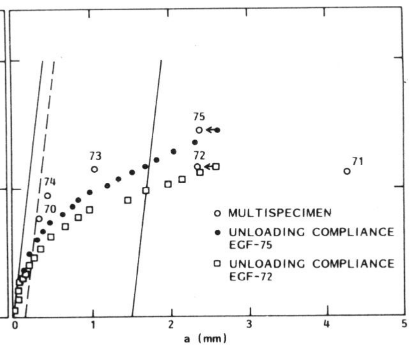

Figure 8 J-curve comparison A542, T = +20^{0}C

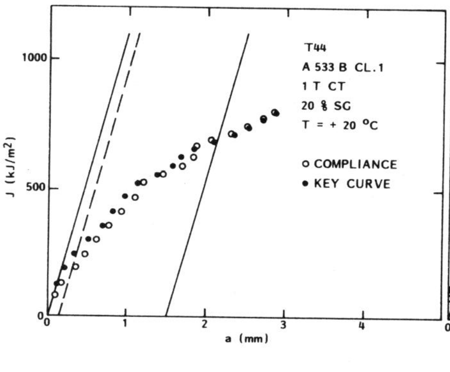

Figure 9 J-R-curve comparison
A533B Cl.1, T = +20^{0}C

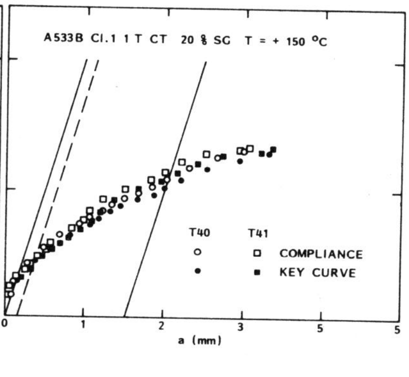

Figure 10 J-R-curve comparison
A533B Cl.1, T = +150^{0}C

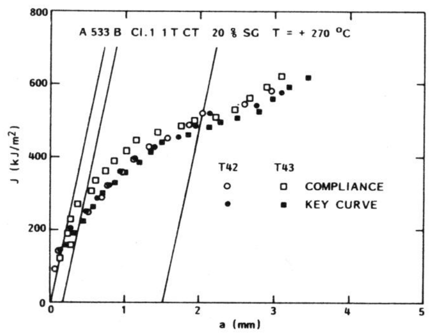

Figure 11 J-R-curve comparison
A533B Cl.1, T = +270^{0}C