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Crack Analysis in Fully Ductile Regime — the Critical Stress Criterion

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Abstract

The required toughness in terms of Charpy-V energy for the application of a certain plastic limit load concept has been extracted from more than 250 fracture mechanics experiments. Reduction in area measured in tension tests has been investigated as an alternative index of toughness. This property, however, does not suit the purpose to define a lower bound toughness. The concept is based on lower bound limit load formulae in plane stress and does not account for strain hardening. The method is able to yield conservative information on the integrity of nuclear pressure retaining components.

1 Introduction

In many stages of construction and operation the primary components of nuclear power plants with postulated flaws or NDE indications require their integrity to be manifested. To comply with this task a method of assessment is necessary which accounts for the ductile state of the material and whose results can be relied upon to be on the safe side. At Kraftwerk Union a method has been developed which centers on a critical stress criterion.

2 Principles of Plastic Limit Load Theory

Plasticity theory furnishes two theorems to construct upper and lower bounds of plastic limit loads. Approximate as they are these solutions imply an ideally plastic material behavior. Plastic hardening may be accounted for by using a flow stress σ^* which replaces the yield strength in simple tension (σ_y) and is commonly defined as

$$\sigma^* = \frac{\sigma_y + \sigma_{ult}}{\alpha} \qquad (2.0 \leq \alpha \leq 2.5)$$

For completeness the two bounding theorems are given below although for safety analysis only the lower bound solutions should be regarded. (For mathematical treatment see Kachanov /1/, Hill /2/ or Hencky /3/.)

Lower Bound Theorem

A structure does not collapse if a stress distribution can be constructed which equilibrates the external load and nowhere exceeds the yield strength of the material.

Upper Bound Theorem

A structure does collapse if a kinematic mechanism can be constructed whose rate of plastic dissipation is equal to the rate of external work.

Many problems suitable to twodimensional reduction (assuming plane stress or plane strain) have been solved mathematically on these theorems. Plastic limit loads of threedimensional structures can be established either by finite element simulation or by experiments.

It is obvious that the nature of these approximate solutions and their premises result in considerable differences in the calculated loads (Fig. 1). A proof of nuclear component integrity will certainly have to be based on lower bound solutions.

3 Marginal Ductility for Net Section Yielding

Limit load analysis is appropriate for ductile materials. Charpy-V energy (C_v) is a material property widely used to indicate the state of ductility. A marginal value of C_v-energy (C_{vPL} - plastic limit) has to be established whence this concept can be applied. Figure 2 shows the results of an evaluation of more than 250 experiments on specimen and component geometries covering the whole regime of ductility. P_{max} is the ultimate load (moment, pressure) reached and P_L the theoretical limit load. The materials involved comprise pipeline and pressure vessel steels such as ASTM A508 and A533 specified nuclear grade types as well as some intentionally degraded melts and a 0.15 % carbon/0.3 % molybdenum alloyed pipeline steel. Austenitic pipeline materials have also been included.

Certain guidelines have been observed for this evaluation:

a) To calculate the theoretical limit load P_L use a lower bound formula of plane stress state.

b) Use the yield strength in simple tension σ_y instead of a flow stress σ^*.

c) Consider only very well documented experiments and do not select in any other respect.

By assuming plane stress all kinds of crack geoemtries such as sharp cracks, notches with various tip radii etc. are covered conservatively. The use of the yield strength overcomes the difficulty to define a flow stress for such different materials as ferritic and austenitic steels.

The essence of Figure 2 expresses:

A structure made of material with 45 J or more C_v-energy does sustain at least the load predicted by a lower bound limit load formula in plane stress using the yield strength instead of a flow stress.

Figure 3 illustrates the evaluation procedure with tests on CT-specimens. The curves represent eleven limit load formulae collected from literature. All experiments below the lowest curve (CT.1) have been performed on material with less than 45 J.

Point c) of the guidelines reveals that a huge variety of structural geometries, materials and limit load formulae have been introduced into this program. The resulting C_{vPL} is the more general and better supported. Especially no difference has been recognized with materials of transitional or upper shelf ductility. On the other hand there is evidence that not necessarily does a structure of very tough material improve in terms of P_{max}/P_L.

Reduction in area Z /%/ as measured in conventional tension tests is another index of ductility. However this material property does not suit the purpose to define a lower bound ductility. Figure 4 indicates that many a test at $Z < Z_{PL}$ has been terminated under fully ductile conditions and would be excluded by a Z_{PL}.

4 Ductile Tearing and Leak-Before-Break

The phenomenon of ductile tearing cannot be handled by a net section yield procedure. In general however the net section of a structure has completely plastified before the crack starts to propagate upon increasing load. Besides, the safety analyst's everyday problem is to calculate critical crack geometries for a given loading. As the loading is bounded critical crack geometries differ from existing or postulated flaws so widely that safety factors were scarcely altered if stable crack growth would be accounted for.

The plastic limit load concept offers a leak-before-break capability by comparing the final crack length of a fatigue crack growth analysis with the critical through wall crack length of a conservatively accumulated load case.

5 Summary

Statements of structural integrity of pressure vessels and pipelines can well be based on a critical stress criterion provided the material has 45 J Charpy-V energy the minimum. This marginal energy denoted as C_{vPL} has been extracted from more than 250 experiments. Reduction in area as an alternative material property is not suitable to define this margin.

The plastic limit loads have been calculated neglecting any strain hardening effects. The state of stress has been assumed to be plane as within fully plastic domain this always yields results on the safe side. The concept is easy to apply, for only geometrical data of the structure and two material properties are required: C_v-energy and the yield strength of simple tension.

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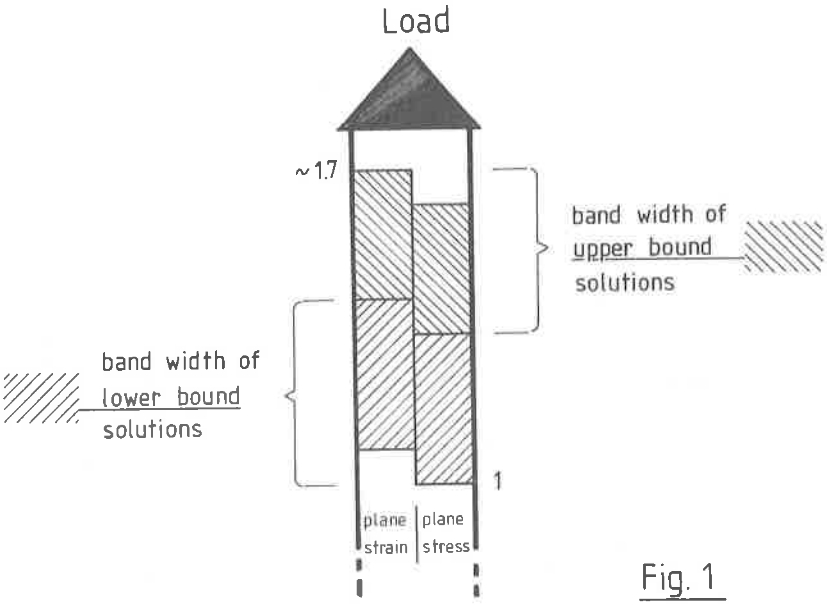
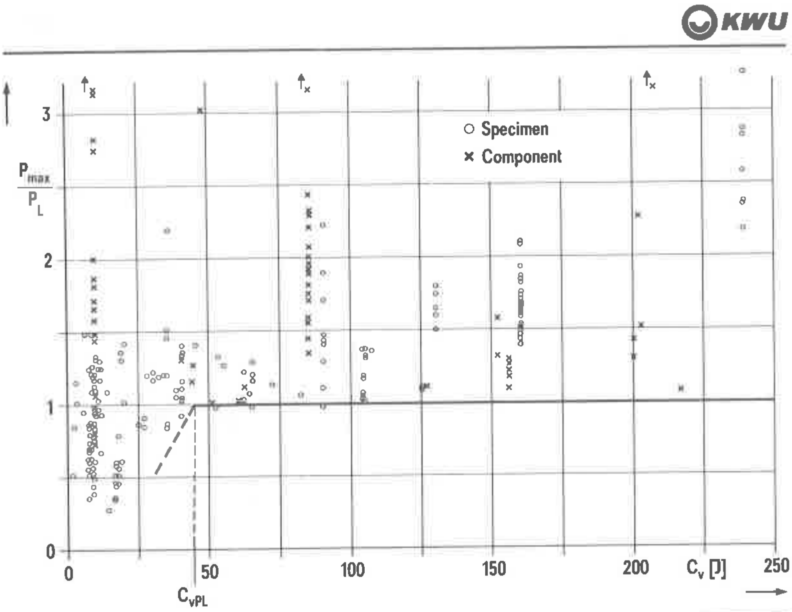


Fig. 1



Experiments on Specimen and Component Geometries

Fig. 2

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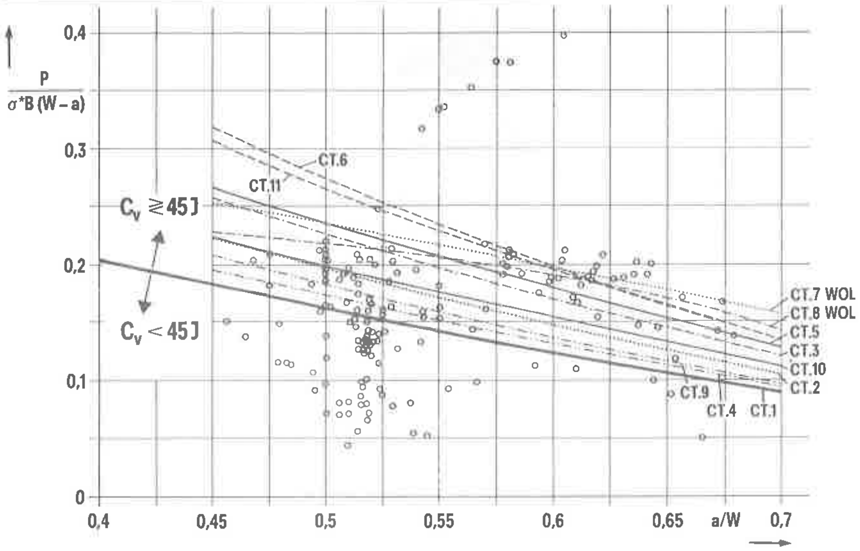

Plastic Limit Loads of CT Specimens

Fig. 3

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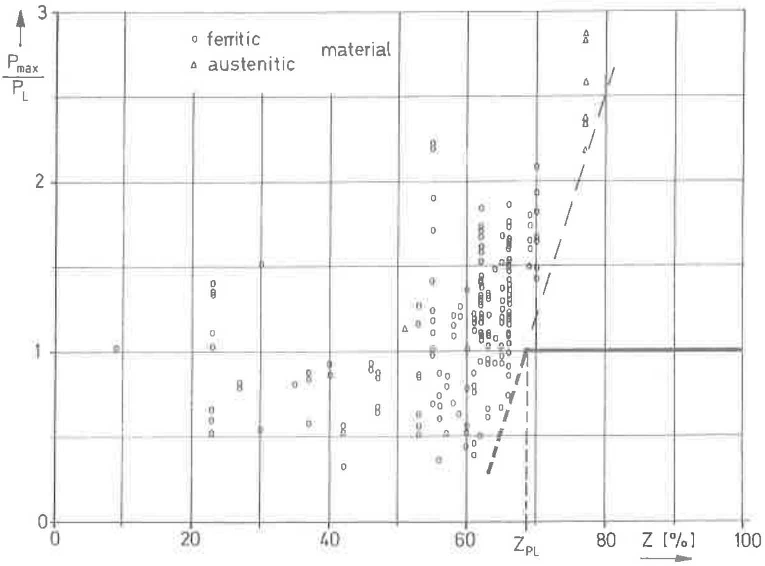

Reduction in Area

Fig. 4