EVALUATION OF COMPONENTS TESTS WITH ANALYTICAL FRACTURE MECHANICS METHODS (DUCTILE FAILURE CRITERIA)

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To evaluate the fracture mechanics methods used for the safety analysis of components (especially leak-before-break analysis assuming ductile failure) the relevant fracture mechanics tests on components have been analysed since 15 years. A database has been established including own and other tests on components as piping and pressure vessels.

All the tests have been analysed with the methods usually used by Siemens for the calculation of critical crack dimensions and checked with respect to the conservatism of the prediction and / or interpretation of the tests.
As an example an evaluation of the tests is given for circumferential through-wall cracks in ferritic and austenitic piping.

INTRODUCTION

To evaluate the fracture mechanics methods used for the safety analysis of components (especially leak-before-break analysis assuming ductile failure) the relevant fracture mechanics tests on components have been analysed since 15 years. A database has been established including own and other tests on components as piping and pressure vessels.

At the moment 1300 tests are included, 800 with longitudinal cracks and 500 with circumferential cracks. Regarding the circumferential cracks, 300 are with part-through cracks and 200 with through-wall cracks (100 with austenitic and 100 with ferritic material).
All the tests have been analysed with the methods usually used by Siemens for the calculation of critical crack dimensions and checked with respect to the conservatism of the prediction and / or interpretation of the tests. The tests have been evaluated with the following parameters:

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Source of tests, material type, material data (toughness, yield and ultimate strength at test temperature), component dimensions (diameter, wall thickness), crack dimensions (depth, length, location, orientation), experimental result (internal pressure, external moment, nature of failure as stable, leak, break), theoretical prediction with the Siemens methods, comparison of theory and experiment.

This database allows an evaluation of the fracture mechanics methods used with respect to
- scatter band (realistic prediction)
- conservatism of prediction (safety analysis),

meeting the requirements of fracture mechanics concerning stress, material and defect analysis.
As an example an evaluation of the tests is given for circumferential through-wall cracks in ferritic and austenitic piping.

MODELS FOR DUCTILE FAILURE

For the safety analysis of components especially leak-before-break analysis of nuclear piping systems, for more details see Bartholomé and Wellein (1), the ductile failure mode is relevant.

The following analytical fracture mechanics approaches (simplified elastic-plastic fracture mechanics concepts) for circumferential cracks
- FSC (Flow Stress Criterion) according to Bartholomé et al. (2)
- PLL (Plastic Limit Load) according to Roos et al. (3)

and for axial cracks
- BMI (Battelle Memorial Institute) according to (3)
- RUIZ according to Ruiz (4)

are used by Siemens for the evaluation of ductile failure of components. In Fig. 1 the models FSC and PLL are described in more detail (circumferential through-wall cracks, only bending moment). Only these models are considered in this paper. To verify these approaches a comprehensive literature review has been done to get as many as possible informations on tests of real components. All available data have been evaluated with respect to the influence of material properties, loading conditions, geometry of components and cracks on the calculated values for the failure stress. Up to now approximately 1300 experiments have been analysed.

PREREQUISITES FOR THE APPLICATION OF FSC / PLL

The prerequisites for the application of FSC / PLL concerning material properties are as follows:
- impact energy > 45 Joule (ductility criterion)
- use of material properties of the base material (instead of weld material or heat affected zone properties).

The material parameter flow stress (being a value between the yield strength $R_{p0,2}$ and the ultimate tensile strength R_m) is chosen as follows for circumferential through-wall cracks:

For FSC:

flow stress = R_m*) ferritic material
flow stress = $(R_{p0.2} + R_m)/2$ austenitic material

For PLL:

flow stress = $R_{p0,2}$ ferritic + austenitic material

*) instead of $(R_{p0,2} + R_m) / 2.4$ - as used in (1), (2), (3) and (5) - to be more realistic

PRINCIPLES FOR THE EVALUATION OF EXPERIMENTS

For circumferential through-wall cracks in straight pipings (ductile failure) the following parameters are analysed:

Dimensions:
actual, measured values at begin of experiment for diameter, wall-thickness of piping and for through-wall crack length.

Loadings:
actual, measured values for max. internal pressure and max. bending moment

Type of failure:
differentiation between rupture - leakage - stability

Material properties
min. measured (min. specified) values at the real temperature of the experiment for yield strength $R_{p0.2}$, tensile strength R_m, and impact energy A_v.

RESULTS

The influences of the following parameters
- material type (austenitic, ferritic)
- dimensions (diameter, wall-thickness)
- through-wall crack length etc.

on the ratio of experimental to theoretical stress are investigated, see also Bartholomé et al. (5).

The influence of material type (austenitic, ferritic) and toughness using FSC is shown in Fig. 2 and using PLL in Fig. 3. The experimental value of the failure stress (sum of the stresses due to measured internal pressure and maximum bending moment at failure) is compared to the theoretical prediction. The ratio is always larger than 1, this means the procedures FSC and PLL give conservative results.

Especially for austenitic material the influence of the following parameters is investigated:
- ratio of yield strength to ultimate strength, Fig. 4 and 5
- crack length, Fig. 6 and 7
- ratio of diameter to wall thickness, Fig. 8 and 9.

There is no significant influence of one of these parameters on the ratio of experimental to theoretical stress. The scatter as well as the conservatism of the prediction are almost independent of these parameters.

CONCLUSIONS

The analytical fracture mechanics methods used by Siemens for the evaluation of ductile failure of nuclear piping (especially for the evaluation of circumferential through-wall cracks):

Flow Stress Criterion (FSC)
Plastic Limit Load (PLL)

give conservative results. This is demonstrated by a comparison to 200 experiments on real components as piping and pressure vessels. The scatter as well as the conservatism of the prediction are almost independent of the various experimental parameters.

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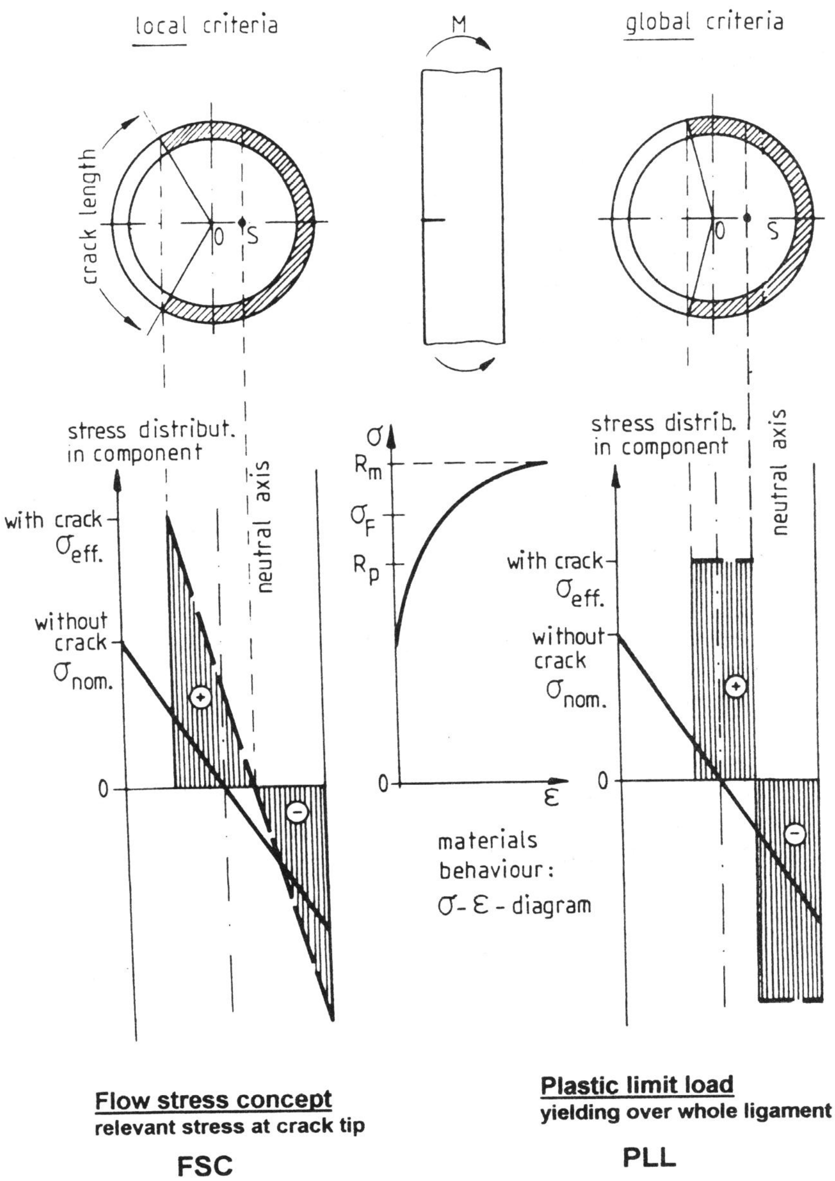

Figure 1 Models for ductile failure (only bending moment)

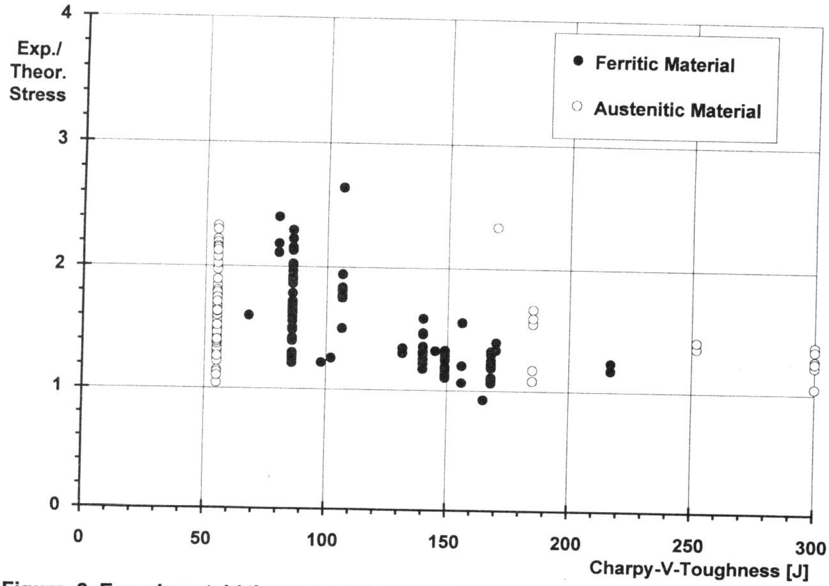

Figure 2 Experimental / theoretical stress using FSC in dependance of toughness of material (circumferential through-wall cracks)

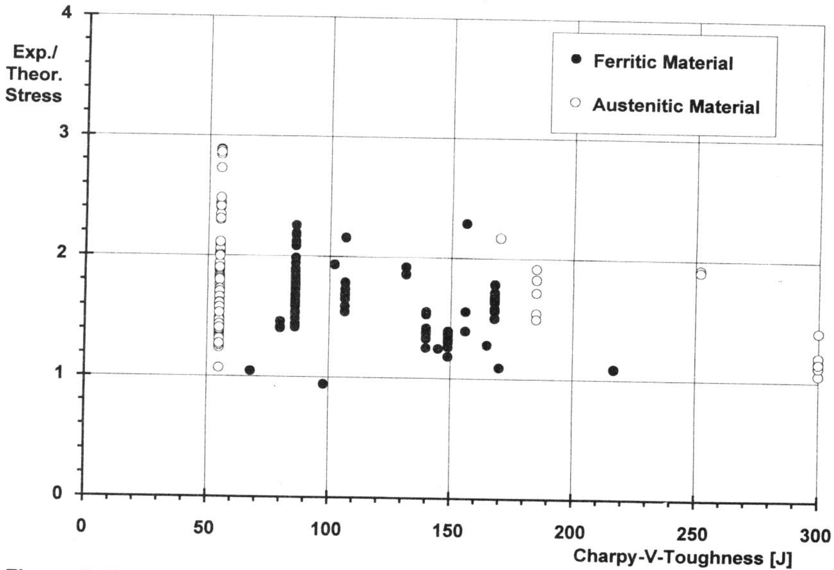

Figure 3 Experimental / theoretical stress using PLL in dependance of toughness of material (circumferential through-wall cracks)

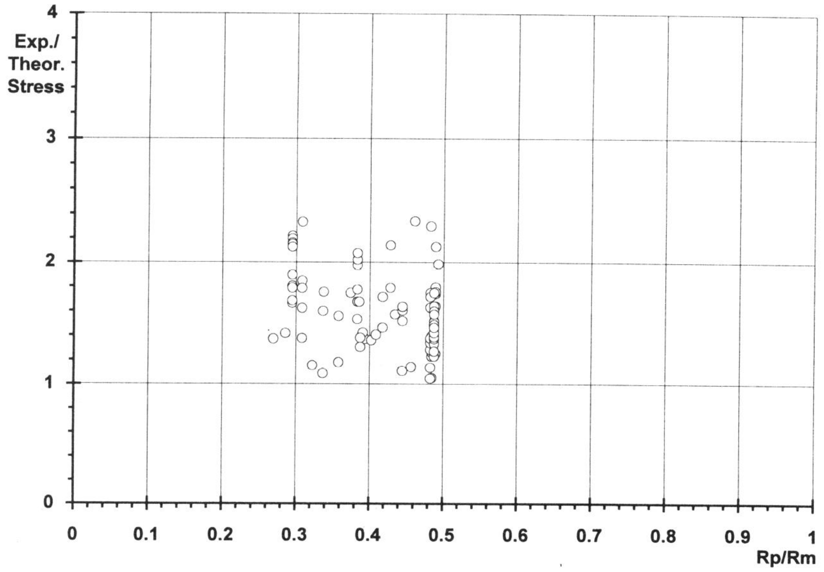

Figure 4 Experimental / theoretical stress using FSC in dependance of Rp/Rm (only austenitic material)

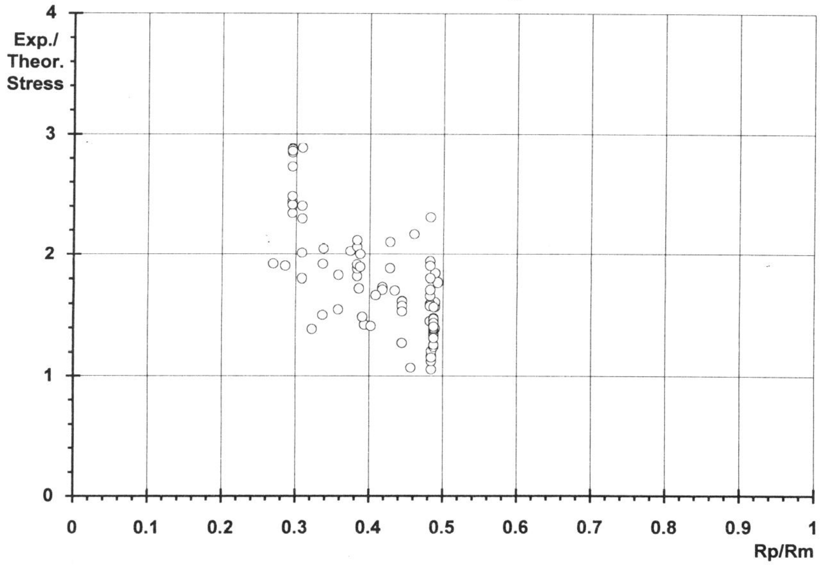

Figure 5 Experimental / theoretical stress using PLL in dependance of Rp/Rm (only austenitic material)

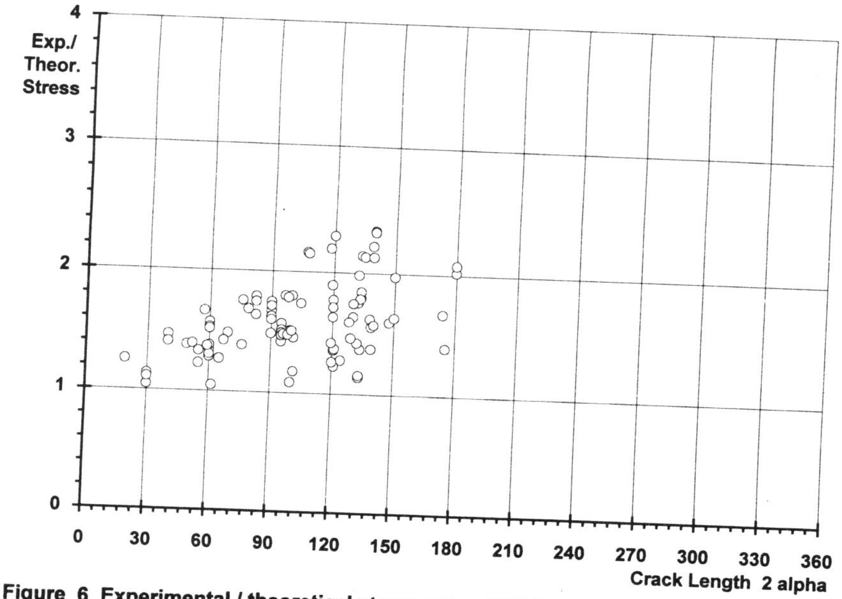

Figure 6 Experimental / theoretical stress using FSC in dependance of crack length (only austenitic material)

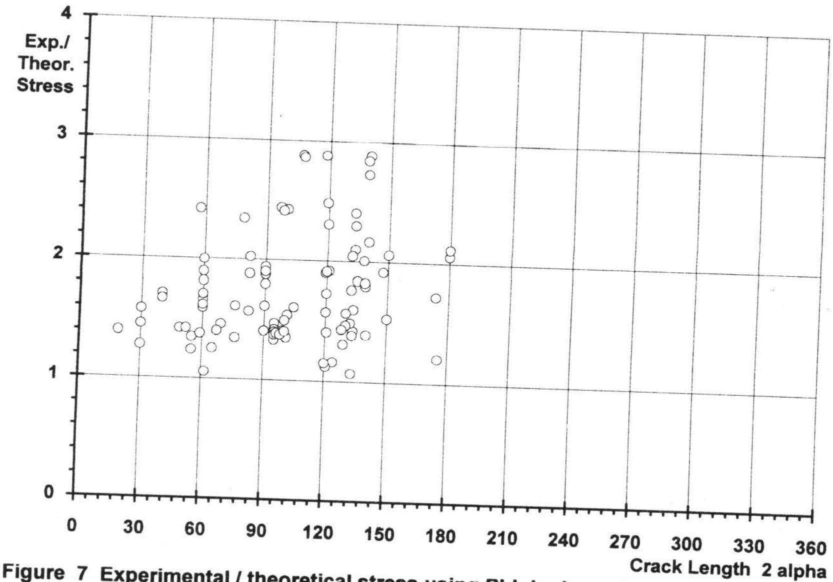

Figure 7 Experimental / theoretical stress using PLL in dependance of crack length (only austenitic material)

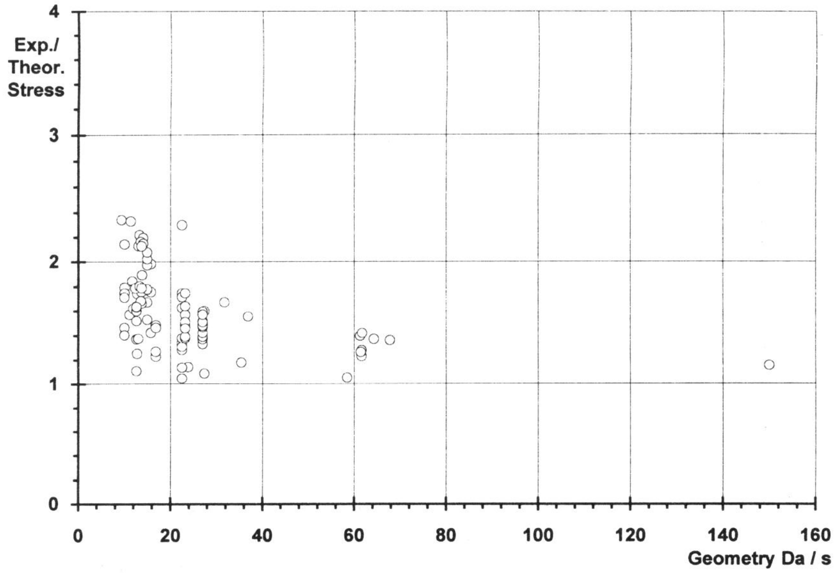

Figure 8 Experimental / theoretical stress using FSC in dependance of geometry (only austenitic material)

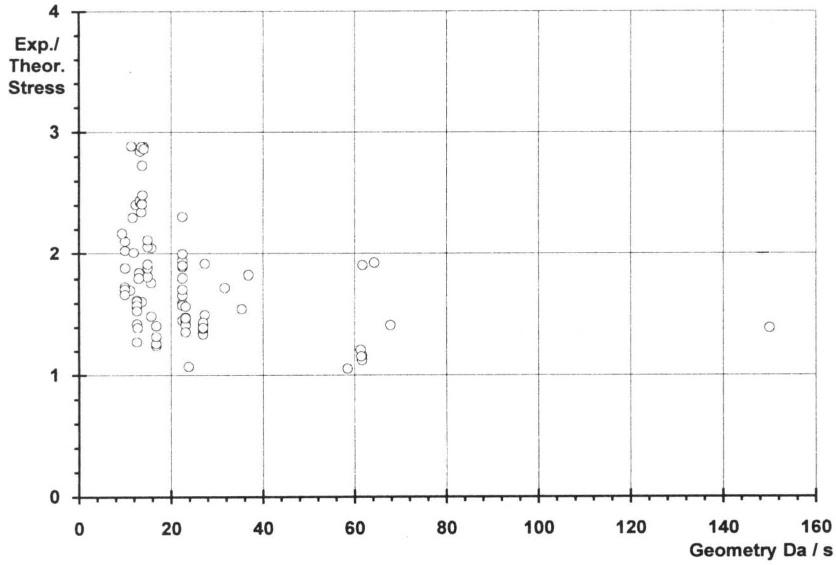

Figure 9 Experimental / theoretical stress using PLL in dependance of geometry (only austenitic material)