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Limit Strains for Severe Accident Conditions
Description of an European Research Program and First Results

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ABSTRACT

The failure strains for a large variety of specimens from reactor pressure vessel material will be investigated. Of special interest is the dependence of the failure strains on the size of the specimens. The research program and first results are outlined. Based on the findings limit strains will be proposed which should be acceptable under severe accident conditions.

1. INTRODUCTION AND OVERVIEW

The current design rules, which allow only small deformations, are appropriate for the present design basis accidents. These rules and the analyses rely on a stress based concept. Much larger plastic deformations with strains up to a certain fraction of the failure strain should be acceptable for extremely unlikely severe accidents. In this case the analyses must use a more realistic strain based concept. However, reliable information about the failure strains is lacking and therefore, larger strains which should be acceptable under severe accident conditions can hardly be defined. Among others, the influence of the component size is not known; but such information is indispensable, if results from small scale specimens and model tests are to be applied to reactor dimensions.

Therefore, an extensive research program **LISSAC** (Limit Strains for Severe Accident Conditions) with 13 European partners and **sponsored by the European Community** has been launched to determine the failure strains and to propose limit strains, i.e. acceptable strains for essential reactor vessel components under severe accident conditions. The expected results give a chance to reduce undue over-conservatisms of current severe accident analyses.

The main part of work consists of test families with different specimen shapes under uniaxial and biaxial static and dynamic loads at room temperature (RT), at 400 °C and at 850 °C. Within one test family the specimen shapes and the other conditions are the same, but the size is varied up to reactor dimensions. The material for the specimens is taken from the cylindrical section of an unused reactor pressure vessel. Special attention is given to test families where the specimens have a hole or a notch causing non-uniform stress and strain distributions typical for local structural discontinuities in reactor vessel components. There are indications that for such non-uniform distributions size effects may be more pronounced than for uniform distributions. Thus, the investigations should allow to determine size effects on the failure strains and failure processes under conditions close to design configurations.

Also the scatter of the mechanical properties of the material used is carefully studied. To provide a reliable data basis, a large number of material qualification tests including standard tension and Charpy impact tests have been carried out for specimens taken from different locations of the test material.

To deepen the understanding of structural degradation and fracture and to allow extrapolations to other loadings and geometric shapes, advanced computational methods including damage models are under development. In some cases so-called non-local concepts, in other cases the description of stochastic properties at the grain size level are considered.

Similar investigations have been carried out within the previous program REVISA, also sponsored by the European Community [1]. It covers a smaller number of specimen shapes and a reduced geometry scale factor, but it applies to several reactor steels and it includes smooth specimens as well as extensive dynamic and creep testing. Size effects of smooth specimens tested previously have been discussed in [2, 3, 4].

2. TEST FAMILIES

Fig. 1 shows the different specimen shapes and the different load and temperature conditions considered. The flat specimens with a hole tested under six load and temperature conditions define six test families. The flat specimens with a slot are tested only under static loading and at room temperature and therefore, define just one test family. All together the tests listed in Fig. 1 comprise 22 test families.

Within each test family the specimens are geometrically similar; only their size is varied. The first family of the flat specimens with holes under static loading at room temperature includes five specimen sizes starting with a wall thickness of 4 mm up to a thickness of 200 mm which is almost the wall thickness of the reactor pressure vessel. Recently one partner has added two smaller specimen sizes of 0,2 and 0,8 mm wall thickness. Thus, the size scale (length scale) covers a factor of 1000! This is illustrated in Fig. 2.

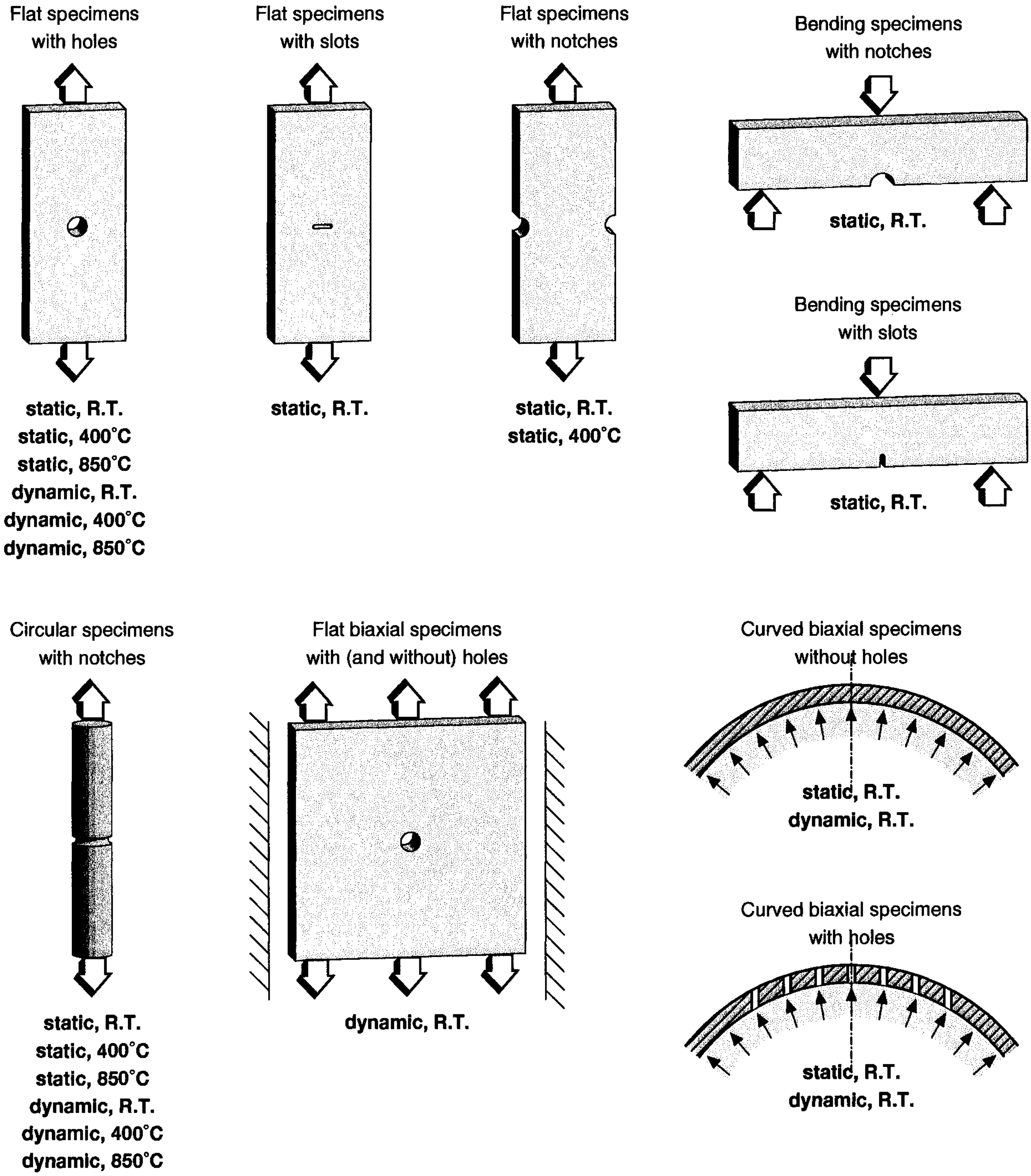

Fig. 1: The different specimen shapes under the listed load conditions define 22 test families

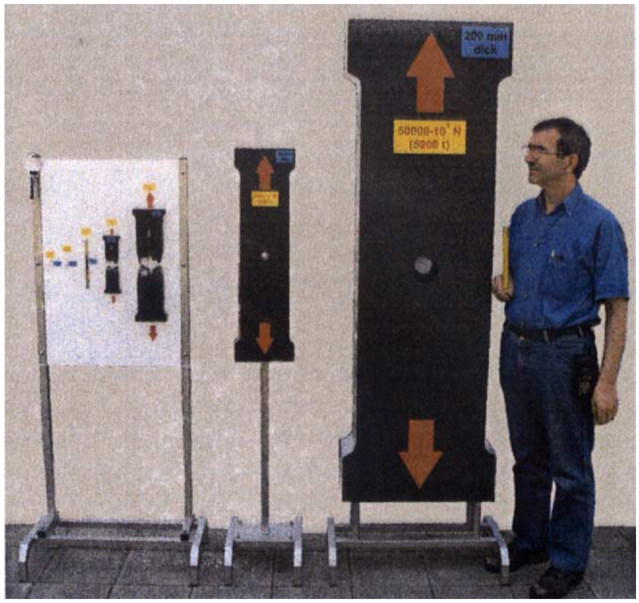

Fig. 2:
Flat specimens with holes to be tested statically at room temperature.
The smallest specimen has a wall thickness of 0,2 mm, expected tension force in the range of 50 N.
The largest specimen has a wall thickness of 200 mm, expected tension force in the range of $50 \cdot 10^6$ N

The other test families cover a smaller scale factor. The largest specimen thickness is 80 mm, the largest diameter is 150 mm. The biaxial tests include only two different specimen thicknesses, 4 or 5 mm and 20 or 25 mm. The total number of family members, i.e. the total number of different test conditions is 63. Since most of the tests are going to be repeated several times, the total number of tests sums up to 162. Furthermore, in some cases additional pretests were necessary and the material qualification tests mentioned in the next section are going to be carried out, too.

As already mentioned, special attention is given to design typical strain concentrations. The flat specimens with holes can be interpreted as strutural elements of the pressure vessel head with holes necessary for the control rod drive mechanisms. The flat and curved biaxial specimens with holes are steps towards the real geometrical shape and load conditions of the vessel head; of course, the real geometric size and temperatures could not be approached at the same time; this would have been much too expensive. The specimens with notches have been introduced to study other structural elements, for instance the transition between different component cross sections.

3. TEST MATERIAL

Fig. 3 shows the locations of the specimens within the cylindrical section of the unused reactor pressure vessel which was manufactured for the planned reactor Biblis C in Germany. The material of this pressure vessel is 22NiMoCr37. The locations were determined such that specimens belonging to the same test family are grouped together as closely as possible. In this way the influence of spatial variations of the material properties on the results within one test family is minimized.

In addition, specimens with thicknesses much smaller than the wall thickness t of the pressure vessel were located in the distance $t/4$ from the outside surface of the reactor pressure vessel. Thus the reduced material strength usually found in the middle of the wall and the enhanced material strength at the surfaces of the wall do not appear in the smaller specimens; that means the influence of variations of the material properties through the wall thickness of the pressure vessel has been minimized, too.

Nevertheless, the scatter of the mechanical material properties will be carefully studied by a large number of material qualification tests. Since the carbon content is known to affect the mechanical material properties strongly, the spatial distribution of the carbon content in the cylindrical section of the reactor pressure vessel was investigated. The variations over the cylindrical surface of the vessel were found to be rather small. The variations through the wall thickness were stronger. The most unfavorable variation occurred close to the material qualification test block QA; a somewhat smaller variation occurred at test block QB. The variations are shown in Fig. 4.

For test block QA standard tension tests are going to be performed in axial and circumferential direction and for several positions through the wall thickness. The results are expected soon. For test block QB the results are already available, Fig. 5. The dependence on the wall thickness is rather small. Note that the stress scale starts with 400 MPa.

To allow additional checks, further material qualification test blocks QC, QD, ..., QW have been reserved and a few further tests have already been performed or are going to be performed. From the results available it can be concluded that the scatter of the material properties is rather moderate. Its effect on the material strength within one test family is expected on the order of magnitude of ±1 %; its effect on the material ductility is expected to be in the range of ±5 %.

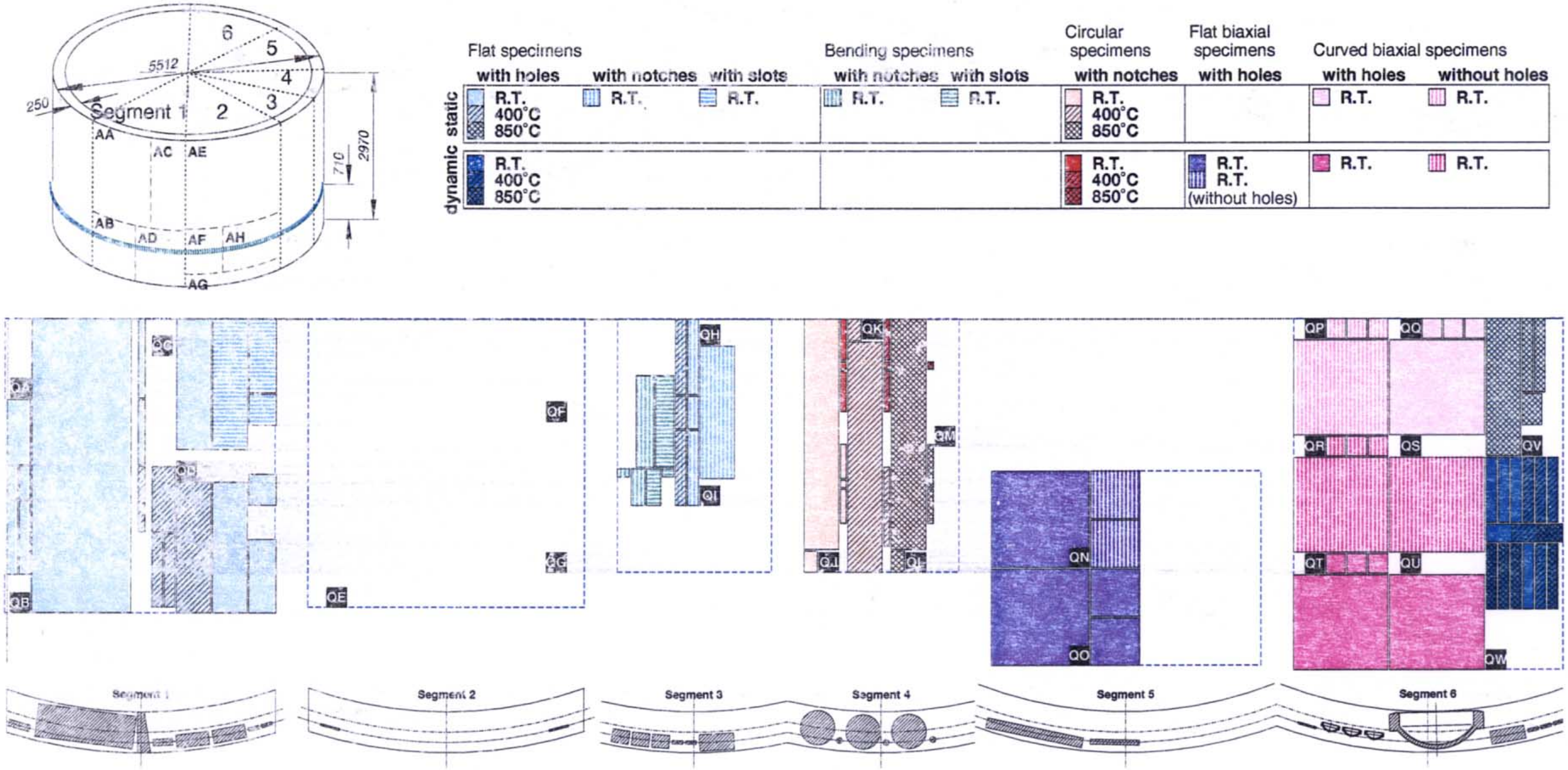

Fig. 3: Location of the specimens within the cylindrical section of the reactor pressure vessel

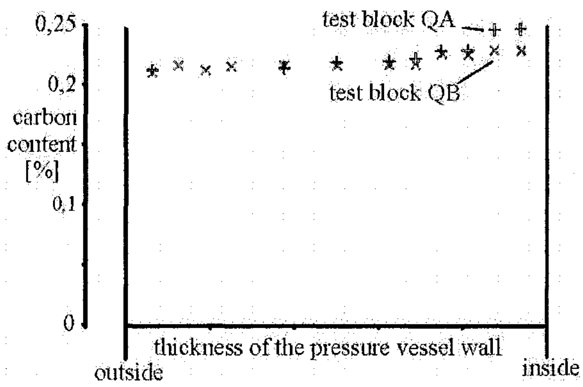

Fig. 4: Carbon content over the pressure vessel wall. The strongest variation occurs at test block QA

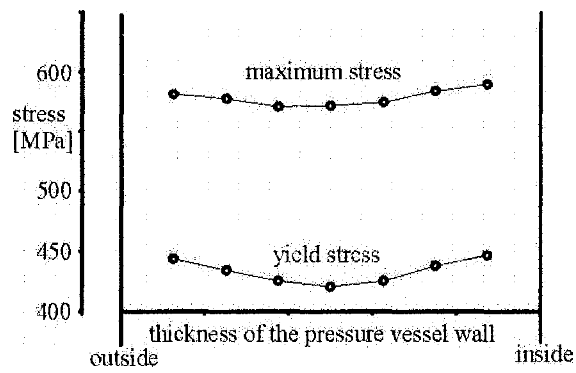

Fig. 5: Material strength over the pressure vessel wall

4. TEST EQUIPMENT

For the specimens varying strongly in shape, loading and size very different testing machines are necessary.
For the small tension tests standard machines may be sufficient. However, the measurement of local maxima of strains requires sophisticated methods such as the object raster technique. For the largest tension tests a very strong machine is needed as shown in Fig. 6, upper left. For dynamic tension tests with well defined strain rates a machine is needed where the specimens are placed between very long pre-stressed steel cables; Fig. 6, upper right. For dynamic tests of shell specimens an impact machine will be used, where a large number of lead spheres is shot against the specimens; Fig. 6, lower right. Furthermore, a lot of additional test equipment and measuring techniques including micro-structure investigations will be applied, too.

5. FIRST RESULTS

To date specimens of the following families have been tested:

Flat specimens with holes,	static, R.T.;	thicknesses:	4, 20, 40 mm
Circular specimens with notches,	static, R.T.;	diameters:	20, 150 mm
Circular specimens with notches,	static, 400 °C	diameters:	20, 150 mm
Circular specimens with notches,	static, 850 °C	diameters:	20, 150 mm

As stated before, the maximum local strains of the specimens are of interest. Thus, the best representation of the results would be to show the tension forces versus the growing maximum local strains which occur in the holes or notches of the specimens. However, the determination of these local quantities is difficult and requires special evaluations. Here it is important to note that the growing maximum local strains are well represented by the growing vertical diameter of the holes or the growing opening of the notches of the specimens. The determination of these integral quantities has turned out to be possible with the available measuring system.

Thus, as results, the tension forces are shown versus the growing vertical diameter of the holes or the growing opening of the notches, Figs. 7a – 7d. Results from tests belonging to the same family are shown in the same figure. To allow a comparison of the results, the forces are divided by the smallest initial cross-sections of the specimens which yields a nominal stress. If no size effect would occur, the curves for the tests of the same family would be identical.

A problem is the definition and determination of the maximum deformation of the holes or notches. It should be preferably the deformation when a macro crack starts to develop. But the curves shown in Fig. 7a for the flat specimens with holes include also the process of crack opening and crack propagation from the hole to the outer surfaces. To exclude this later phase the following procedure was used: The growth of the vertical diameter has been measured after the test and the crack opening has been subtracted as indicated in Fig. 8. The resulting values were defined as the maximum deformations and marked by stars in Fig. 7a. A similar procedure was applied for the tests with circular specimens, Figs. 7b – 7d. Here the crack opening seems to be moderate as indicated in Fig. 9; but in the center of the specimens it might be larger and corresponding corrections in the figures might be necessary.

The general finding is that the specimen size has no significant influence on the maximum nominal stress, but a rather strong influence on the maximum growth of either the vertical diameter of the holes or the opening of the notches. More details on some of the tests may be found in [5]. On the other hand, the effect of temperature on the maximum deformations seems to be moderate. However, it should be pointed out that both, the above evaluation and the conclusions are very preliminary. Additional work and test results are urgently needed for more reliable conclusions.

Fig.6: Testing machines used for the LISSAC experiments;

upper left: 10.000 t tension machine, Staatliche Materialprüfungsanstalt Stuttgart;

upper right: Large Dynamic Test Facility LDTF, Joint Research Centre Ispra

lower right: Impact test facility (Impakt-Versuchsanlage) IVAN, Forschungszentrum Karlsruhe;

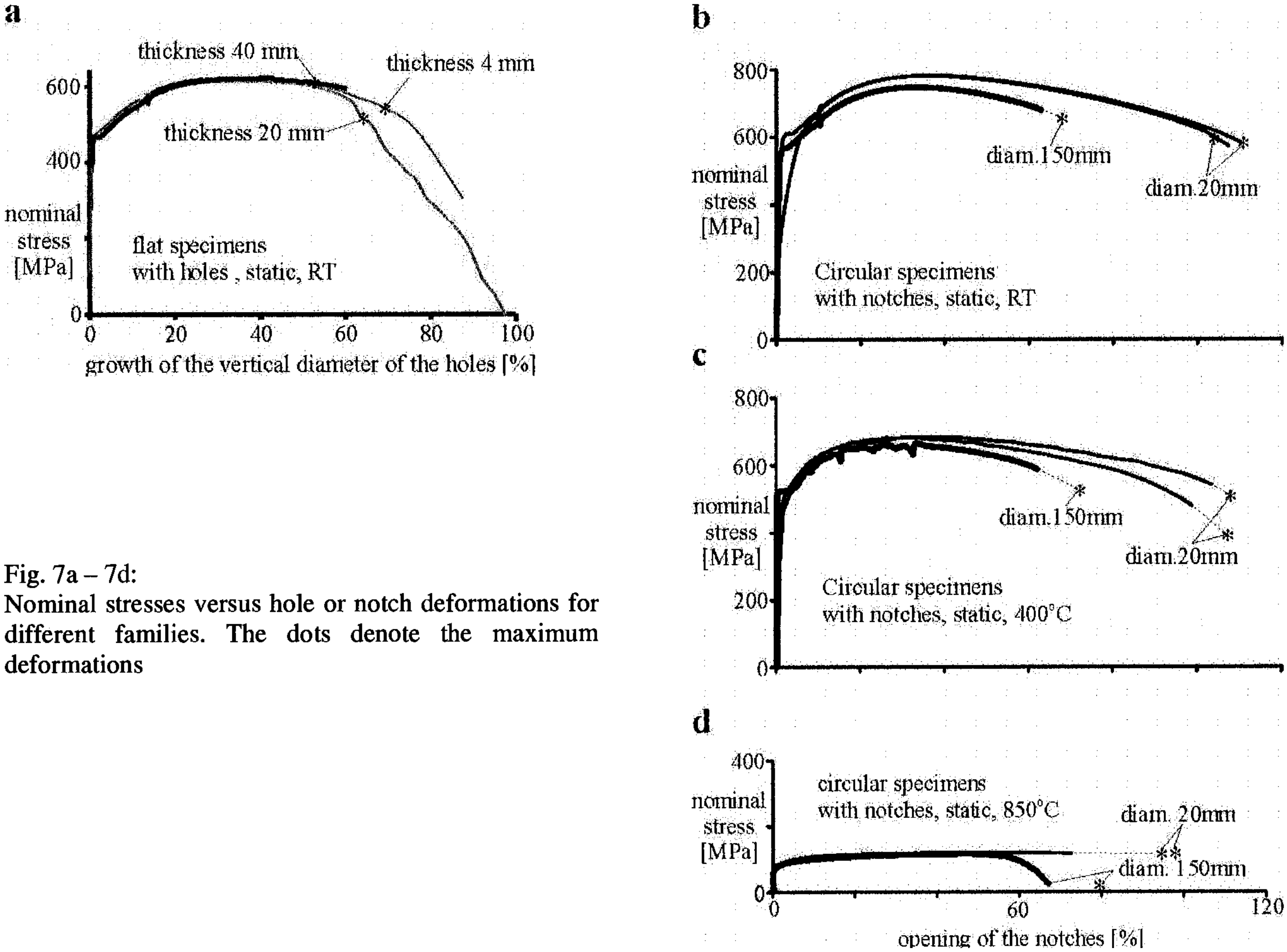

Fig. 7a – 7d:
Nominal stresses versus hole or notch deformations for different families. The dots denote the maximum deformations

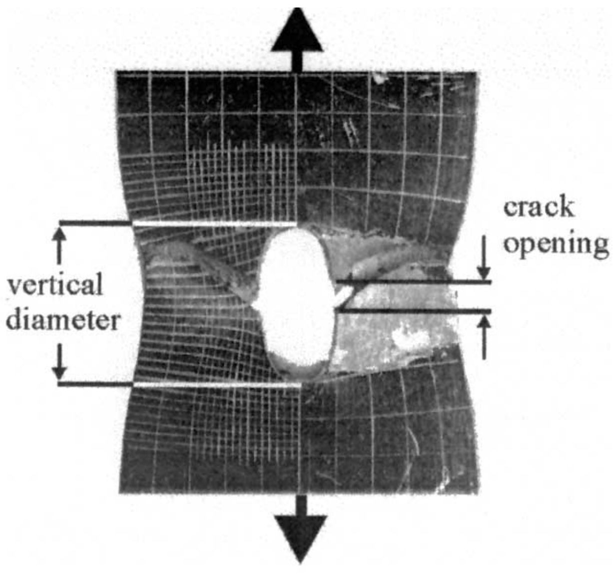

Fig. 8:
Growth of the vertical diameter and crack opening of a flat specimen of 20 mm thickness after failure

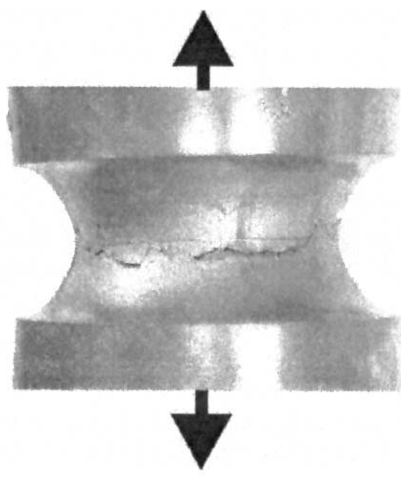

Fig. 9:
Crack opening of a cylindrical specimen with notch after failure

6. THEORETICAL MODELS

As stated above, the failure strains, i.e. the strain when a crack starts to develop and the size dependency of these strains are of main interest. This implies that the corresponding theoretical models will have to include both, the phenomenon of damage and a material related length – often called intrinsic length – affecting the deformation and damage process. The classical continuum material models for elasticity, plasticity or damage do not introduce such a length and even viscous or thermal effects do not suffice to reproduce the observed size effects. Therefore, an extension of the classical models or the development of new models is necessary. By the way such models are able to remedy the so-called ill-posedness of deformation behavior emerging when the softening effects rule out the material hardening. Actually, this ill-posedness means a malign mesh size dependency of the numerical results, which is unacceptable.

At present quite different models are under discussion. However, little is known about their success. Therefore, in the LISSAC project several models and solution methods are going to be developed in parallel.

Non-local Concepts

Here the main activities are related to higher gradient models. First steps in this direction have been made within the REVISA project. Mostly these models extend the material law, e.g. the yield function or the evolution equation for internal variables by additive terms containing strain gradients. Two directions are followed in LISSAC. One is the a more pragmatic way based on a Gurson-Tveergard damage model and a strain gradient extension proposed by Aifantis [1, 3, 4]. The relative simplicity allowed to have an early implementation in the FEM code ABAQUS. Thus first calculations of experiments revealing size effects and parameter fittings could be already provided. The other way includes the development of a thermodynamically consistent micro-morphic approach. Because of the complexity its implementation will possibly last until the end of the project.

Mathematically closely related to these approaches are the integral concepts. Here the local values of some model variables are replaced by their spatial averages. The radius delimiting the domain for the spatial averaging can be correlated with the material intrinsic length. One easy use of this idea is the following. The critical state of a structure is reached when the damage, calculated in a conventional FEM analysis using a continuum damage model, exceeds a critical value in all points of the given domain and not only in one point.

Somehow related are the so-called advanced discrete modeling concepts. One partner has already implemented such a method. It uses the mesh size as the material intrinsic length, which is associated with the average distance of hard manganese sulphur inclusions. This procedure, combined with a Rousselier damage model, is able to model size scaled experiments even beyond the critical damage state in the domain of fracture. However, one major drawback of coupling the element sizes of the numerical scheme to microscopic quantities is that for large specimens a very large number of elements is needed.

Stochastic Concepts

In one approach a Voronoi tessellation method is used for a more direct modeling of the heterogeneous material at the meso-scale of grains. The individual grains are treated as continuous and are subdivided in finite elements. With the help of these simulations representative macro-models can be defined or statistical data on the mean values of the internal variables and on their temporal and spatial correlations may be derived. In the present state only two-dimensional simulations are possible.

With the help of the latter statistical data a stochastic extension of the conventional flow function of a continuum damage model is going to be developed. The material intrinsic length enters the model via the spatial correlation of the white noise background field. Like with the weakest link theories, which were successfully applied for brittle materials, this more empirical approach should be able not only to model size effects, but also experimentally observed scatter.

REFERENCES

[1] Malmberg, T., Krompholz, K., Solomos, G., Aifantis, E.C., "Size Effects in Deformation and Fracture of a Ferritic Reactor Pressure Vessel Steel", *SMiRT-16*, Washington 2001, division F

[2] Jordan, T., Malmberg, T., "Failure Strain of the Reactor Pressure Vessel Head under Impact Loading", *SMiRT-15*, Seoul 1999, division L

[3] Malmberg, T., Krompholz, K., Solomos, G., Aifantis, E.C., "Investigations on Size Effects in Ferritic and Austenitic Materials", *SMiRT-15*, Seoul 1999, division L

[4] Malmberg, T., Tsagrakis, I., Elefteriadis, I., Aifantis, E.C., "On the Gradient Plasticity Approach to Size Effects, Part I: Reviews", *Forschungszentrum Karlsruhe*, Scientific Report FZKA 6321, Dec. 2000

[5] Aktaa, J., Hädrich, H.J., Julisch, P., Klotz, M., Schmitt, R., "Investigations to Size Effects on Plastic Deformation and Failure Behavior of In-homogenously Loaded Structures", *SMiRT-16*, Washington 2001, division F