Plastic Deformations at the Upper Core Barrel Clamping of a PWR Caused by Blowdown Loading

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Summary
In case of a postulated blowdown of a PWR the structural integrity of the reactor pressure vessel internals must be guaranteed. The advanced computer programs describing the fluid-structure interaction during blowdown are based on global linear elastic models. However, in reality some plastic deformations may influence the global dynamics and may be essential to assess the structural integrity.

In this respect stress analyses of the upper core barrel clamping are of particular interest because considerable strain concentrations have to be expected at this place. This is investigated here by FEM-calculations carried out with the computer code ADINA. As results the local plastic strain peaks and the nonlinear clamping characteristic of the core barrel flange are obtained.
1. Introduction

In safety analyses of a pressurized water reactor (PWR) with respect to the pressure vessel internal structures several accident conditions are postulated. Among these assumed accidents the blowdown caused by a sudden complete break of a primary coolant pipe results in the most severe loading conditions for the vessel internals. Within the last few years considerable theoretical and experimental efforts have been made to analyse the transient fluid- and structural-dynamic processes during blowdown. However, the developed computational models for analysing the blowdown process and the experimental investigations are not directly transferable to typical PWR conditions. The research carried out so far has concentrated an dominant physical phenomena such as fluid-structure interaction. Primary scope was the coupled motion of the fluid and the core barrel shell. For this purpose well defined boundary conditions had to be provided in the computational models and the experimental programs. They differ in some way from the real PWR conditions. For instance, in the German blowdown test program $1, 1$ carried out at the HDR facility the core barrel shell is rigidly clamped at its upper end. In a typical PWR, however, the core barrel shell is connected with a flexible upper flange. Considerable plastic deformations causing a nonlinear clamping characteristic have to be expected at this place.

It is the scope of this paper to determine the nonlinear clamping characteristic of the upper core barrel flange. This effect can then be taken into account in the existing multi-dimensional blowdown codes. Based on the resulting global deformations the local plastic strains may be determined. These local quantities are essential for a reliable assessment of the integrity of the system.

2. The Finite Element Model

During blowdown the beam bending mode of the core barrel is the dominant motion. This results in sinusoidal distributed axial membrane stresses in the upper part of the core barrel shell. However, an adequate three-dimensional nonlinear analysis of the flange flexibility is beyond present computer capabilities. Therefore the investigations have been carried out with an axisymmetrical model where the flange loading consists of axial membrane stresses which are constant along the circumference. The flexibility of the flange in the dominant first circumferential mode can then be obtained approximately by integrating the results of the axisymmetrical analysis.

In fig. 1 the finite element discretisation in the transition region between core barrel and flange is shown. The whole model includes a much longer part of the core barrel shell. The analysis has been carried out with the finite element code ADINA $2, 3$ which is able to consider nonlinear effects such as plastic deformations. The model consists of 521 8-node and 6-node elements with 2820 degrees of freedom. In order to check the influence of the discretisation effort a corresponding model with only 242 elements has been used. Since support conditions of the upper core barrel flange are not exactly known additional cases with different support conditions according to fig. 2 are also considered with this coarser mesh. The austenitic steel being used has a yield stress of 175 N/mm$^2$ and an ultimate stress of 260 N/mm$^2$.
3. Finite Element Results

In fig. 4 the obtained different clamping characteristics of the flange are shown. It turns out that the clamping characteristic is not very sensitive to radial constraints of the flange. However, preventing the flange from turning up leads to a considerable stiffening of the system. Comparing model 1 and model 4 one can conclude that the clamping characteristic is almost identical for tensile and compressive loading of the flange. Since model 3 is supposed to be unrealistic and the other models lead to similar results all the following investigations refer to model 1.

As mentioned above, the analyses for model 1 have been carried out with two different meshes. Fig. 5 shows that the structural stiffness may be considerably overestimated especially in the plastic loading range when too coarse finite element meshes are used.

In fig. 6 the deformed shape of the structure is shown. The turning up of the flange forces a certain upper part of the shell to increase its radius.

The distribution of the von Mises equivalent strain for increasing loading is shown in fig. 7. However, the less interesting local strain concentrations in the support region are not shown in the figure. Since the yield limit of the material is 0.1 % equivalent strain the propagation of the plastic zones can also be followed up in this picture. At first yielding begins in the transition region between shell and flange because of the high bending stresses at this place. However, the plastic zones at the outer and inner surface (see fig. 3) do not develop at the same load level and they also propagate in different ways from the surface into the interior of the structure. Yielding at the outer surface begins earlier because superposition of the axial membrane and bending stresses and the notch effect lead to a local stress peak at this place. At the inner surface the stress peak is smaller because axial membrane and bending stresses have different sign and no notch effect is present. For higher loads another plastic zone develops at the upper side of the flange. This is due to the high hoop stresses in this part which are caused by the turning up of the flange.

As fig. 7 shows the plastic strains strongly concentrate at the outer surface in the transition region between shell and flange. The resulting redistribution of the stresses is clearly recognizable in fig. 8. The corresponding distribution of the equivalent strain is shown in fig. 9. By comparison of stresses and strains in the plastic loading range with the corresponding quantities in the elastic loading range one recognizes that plastic deformations tend to smoothen stress distributions and to enlarge strain peaks.

4. Check of the Finite Element Computations

In the elastic loading range the finite element results have been checked with a simple model which consists of a cylindrical shell coupled with a ring. For the shell Flügge's equations and for the ring a simple description are used. The agreement of this simple theory and the finite element results (see fig. 10 and 11) is satisfactory. Of course, the simplified model is not able to yield the detailed local stress distribution in the transition region between shell and flange and it overestimates the bending stresses considerably.
5. Conclusions

The axial loading that has to be expected for a blowdown accident amounts to about 80 N/mm² at the highest loaded circumferential core barrel position. Therefore considerable plastic deformations have to be expected in the transition region between the shell and the flange. However, as may be seen by rough assessments the flange is able to withstand the global bending moment in case of a severe blowdown accident.

6. References


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Fig. 1 Finite element model

Fig. 2 Models with different boundary conditions
Fig. 3 Definitions used in the other figures

Fig. 4 Clamping characteristics for different boundary conditions
The axial displacement is related to the reference point (see fig. 3)

Fig. 5 Clamping characteristics obtained with different discretisations
The axial displacement is related to the reference point (see fig. 3)

Fig. 6 Deformed structure
Fig. 7 Distribution of equivalent strain (in %) for different axial loadings
Fig. 8 Axial distribution of hoop stresses at different shell positions according to fig. 3 for elastic loading range and plastic loading range.

Fig. 9 Axial distribution of equivalent strains at different shell positions according to fig. 3 for elastic loading range and plastic loading range.

Fig. 10 Axial distribution of axial displacements obtained with the FEM-method and the Ring-Shell-model at different shell positions.

Fig. 11 Axial distribution of axial stresses obtained with the FEM-model and the Ring-Shell-model at different shell positions.