ELASTO-PLASTIC ANALYSIS OF NOZZLE INTERSECTIONS IN REACTOR CONTAINMENTS

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In this paper the elasto-plastic analysis of a nozzle intersection in a pressurized spherical reactor containment is presented. The study was performed for a model shell. Comparisons between different idealizations of the structure are given. The results are related to the usual design concept based on the corresponding codes.

The dimensions chosen for the model do not represent a real structure. The spherical shell has a radius of 1315 mm and a thickness of 30 mm. The model contains one protruding nozzle of 35 mm thickness and is pad-reinforced. The same high strength steel is used for all parts of the structure. The internal pressure taken as "design load" is 12.6 N/mm^2. Different finite element analyses are performed and compared to each other, these are linear elastic and elasto-plastic analyses based on the thin shell theory and a thick shell idealization as well. Ideal plasticity is assumed. The initial yield begins at a load level of 9.0 N/mm^2 in the case of a thin shell approximation and at 11.0 N/mm^2 in the thick shell analysis. In both studies the yield starts simultaneously at the inner and outer surface of the nozzle where high hoop stresses coincide with high axial stresses. Despite differences between the local stress distributions both idealizations lead to approximately the same yield progress. The first fully plastic region occurs in the cross section of the nozzle above the joint zone. Then this region is extended to the whole intersection zone and finally the spherical shell begins to plastify. The limit load is reached at a load level of approximately 19.0 to 20.0 N/mm^2 depending on the kind of idealization. As a consequence of the relatively thin nozzle this load level coincides nearly with the limit load of the unreinforced containment.

1. Introduction and Scope of the Study

The design of nozzle intersections in PWR-containments is usually based on linear elastic analyses using in most cases a thin shell theory. The equivalent stresses have to meet the limits of different stress categories defined in the corresponding codes. The intersection zone is mainly stressed by internal pressure and loads applied to the nozzle. Hence the additional reinforcement material ought to be placed on both structural parts, on the cylindrical as well as on the spherical shell [1]. Using this design procedure several questions have to be answered: Is the stress state at the intersection zone sufficiently represented by a thin shell analysis or is it necessary to use a thick shell idealization? Is the real response at the structure under an advanced loading condition sufficiently covered by the stress limits given in the specification? Especially the influence of the stress concentration and its classification into the different stress categories has to be studied. These questions can only be answered by a thick shell elasto-plastic analysis as it is done e.g. by Campbell and Dillon [2] who reproduced the experiments of Dinno and Gill [3]. It is the purpose of this paper to compare elastic and elasto-plastic thin and thick shell analyses in view of the usual design procedure. Furthermore the influence of the stress concentrations at the intersection point as well as in the weld zone is examined.

This study was performed for the case of a model shell under internal pressure originally tested to investigate the influence of geometric imperfections developed during the manufacturing process [4].

These experiments were recently extended to investigate also the nozzle intersection. The comparison with experimental results is still in progress and will be presented in a future study.

2. Description of the Structure

The spherical shell model has a radius of 1315 mm and a thickness of 30 mm. The intersection zone is shown in figure 1. The symmetric protruding nozzle has an inner radius of 340 mm, a thickness of 35 mm and a length of 2 x 200 mm. The shell is reinforced by a pad with a thickness of 42 mm. It should be noted that the nozzle originally had a thickness of 75 mm. The thickness was reduced to 35 mm so that yielding is initiated in the joint region. Insofar the strength of the nozzle analysed is too low. In the analyses a yield strength $\sigma_y = 460\ \mathrm{N/mm^2}$ of the high strength steel St E 51 is used throughout the structure, i. e. the increase in strength of the weld material is not taken into account. For the real containment with a radius of 28 m the design load is $0.53\ \mathrm{N/mm^2}$. The pressure has to be increased by 10 % to $0.58\ \mathrm{N/mm^2}$ regarding the strength reduction due to a different design temperature. For the model the corresponding pressure is $p_i = 12.6\ \mathrm{N/mm^2}$.

A thrust load $P = 0.5\, R_s \cdot p_i$ caused by the pressure on the nozzle head is applied. The head plate is replaced by a horizontal support at the upper end of the nozzle. Further thrust or moment loads on the nozzle are not considered in this investigation.

3. Computational Models

Basically two idealizations of the structure are studied. First a thin shell analysis is performed using the BOSOR-5 program [5] which is based on the finite difference energy method. In a second finite element study the intersection zone is modelled as a "thick" shell, or being more specific, several axisymmetric elements are placed across the thickness. A quadrilateral isoparametric displacement element with 8 nodes is used [6]. Figure 2 shows the element configuration chosen in the nozzle/sphere joint region. In both studies elastic-perfect plastic material is assumed. The v. Mises yield criterion and the Prandtl-Reuss flow rule are adopted. The nonlinear response of the structure is solved by an incremental/iterative solution procedure using the tangent stiffness approach.

4. Elastic Analyses

Comparing thin and thick shell analyses in the elastic range distinct differences of the stress state could be observed. It is well known that the thin shell idealization produces fictitious stress concentrations at the ideal intersection of nozzle and containment. At the inner surface of the nozzle this leads to remarkably overestimated axial stresses as shown in figure 3 a but also to not justified reduced hoop stresses as shown in figure 3 b. At the outer surface of the nozzle the three dimensional stress state is also not represented by a thin shell analysis. Hence the stress concentrations in this region are not realistic either. On the other side a thin shell analysis is not able to reproduce the increase in stress occurring in the weld zone. These peak stresses in meridional as well as in the hoop direction are shown in figure 4 for the thick shell idealization.

The maximum equivalent stresses are determined according to the hypothesis of the strain energy of distortion using the thin shell analysis. The bending stresses at the intersection point are not reduced. For the pressure of 12.6 N/mm^2 this leads to a maximum value of 759 N/mm^2 at the inner surface of the nozzle for primary and secondary membrane and bending stresses. The maximum primary local membrane stress is 363 N/mm^2. These stresses are compared with the requirements of proposal III of the specification [7].

a) $759\ N/mm^2 = 1.65\, \sigma_y < 1.67\, \sigma_y$

b) $363\ N/mm^2 = 0.79\, \sigma_y > 0.75\, \sigma_y$

Hence the primary local membrane stresses are slightly above the limit. According to [7] the nozzle thickness ought to be increased.

5. Elasto-Plastic Analyses

A load-deflection diagram is shown in figure 5 for either kind of idealization. The radial expansion of the nozzle at the intersection point is chosen as characteristic displacement. The initial yield begins at a load level of 9.0 N/mm^2 in the case of the thin shell approximation and at about 11.0 N/mm^2 in the thick shell analysis. In figure 6 the deformed nozzle region is plotted at a load level of $p = 20.0$ N/mm^2. Figure 7 shows the progress of yielding in the joint zone. The yield starts at a cross section of the nozzle above the intersection simultaneously on both surfaces. Again note that no higher yield strength was taken into account for the weld material. At the inner side high hoop stresses coincide with high axial bending stresses. At the outer surface the peak stresses at the fillet weld cause the material to yield first. Although the reason of the stress concentration is different both idealizations lead to nearly the same yield progress. It is the cross section above the joint zone where the first fully plastic region occurs, see figure 7. In the thin shell theory the elastic plastic interface has already moved into the spherical shell at the same load level of 15.0 N/mm^2. However, in the thick shell analysis the whole intersection zone is yielding before the containment begins to plastify at a pressure of 18.0 N/mm^2. During the further load increase the yield interface proceeds rapidly into the spherical shell thus showing that the nozzle does not contribute anymore to the load carrying capacity. Defining a limit load when the maximum total strain is about 2 % in the structure a pressure level of approximately 19.0 N/mm^2 for the thin shell analysis and 20.0 N/mm^2 for the thick shell analysis is reached. At this stage the radial expansion of the nozzle at the intersection is about 2.5 mm in both cases. Thus basically no severe differences between either way of idealization could be observed. Therefore, in this case there is no significant influence of the peak stresses occurring in the weld zone provided the ductility of the material is sufficient. The ratio of the pressure at first yield and the limit load is 2.1 or 1.8, respectively, in both studies. It should be mentioned that the full yield load in the unreinforced spherical shell is 21.0 N/mm^2, i.e. this pressure nearly coincides with the limit load of the total structure.

6. Conclusions

For the idealized case of a containment model with a protruding nozzle under internal pressure the following conclusions may be drawn:

* Elasto-plastic thin shell analysis as well as thick shell analyses lead to approximately the same results in yield progress, load deflection characteristic and limit load.

* Peak stresses in the weld zone seem to have no severe influence on the ultimate strength of the structure provided there is no cyclic loading.

* Comparing the limit pressure with the "design load" $p_i = 12.6$ N/mm² an overall safety factor of 20.0/12.6 = 1.59 (19.0/12.6 = 1.51 in the thin shell analysis) is reached. Note the nozzle thickness has to be increased according to the specification [7].

Nevertheless further elastic-plastic studies are needed before these statements may be generalized for other nozzle intersections with different geometries, materials and loading conditions.

References

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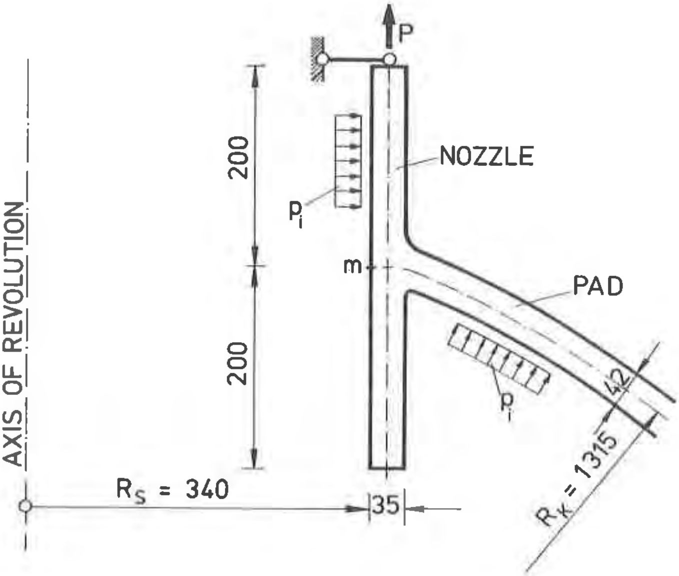

Fig. 1: Geometry

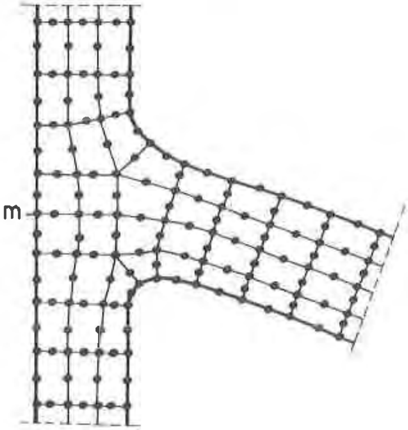

Fig. 2: Thick shell idealization of the intersection zone

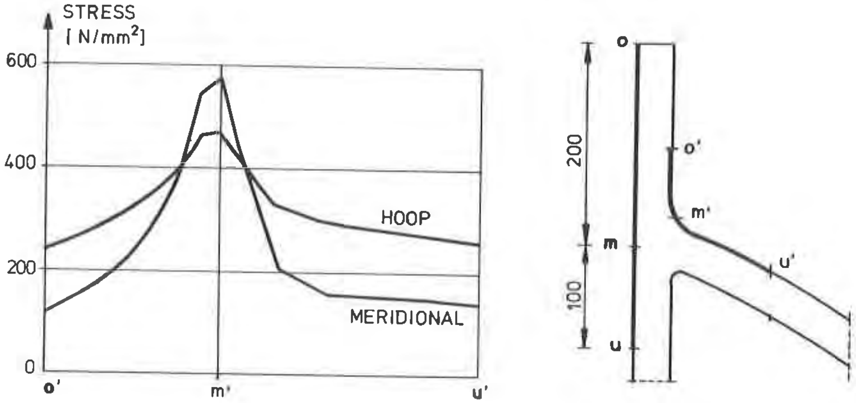

Fig. 3: Elastic stresses along the inner nozzle surface - thin and thick shell idealization

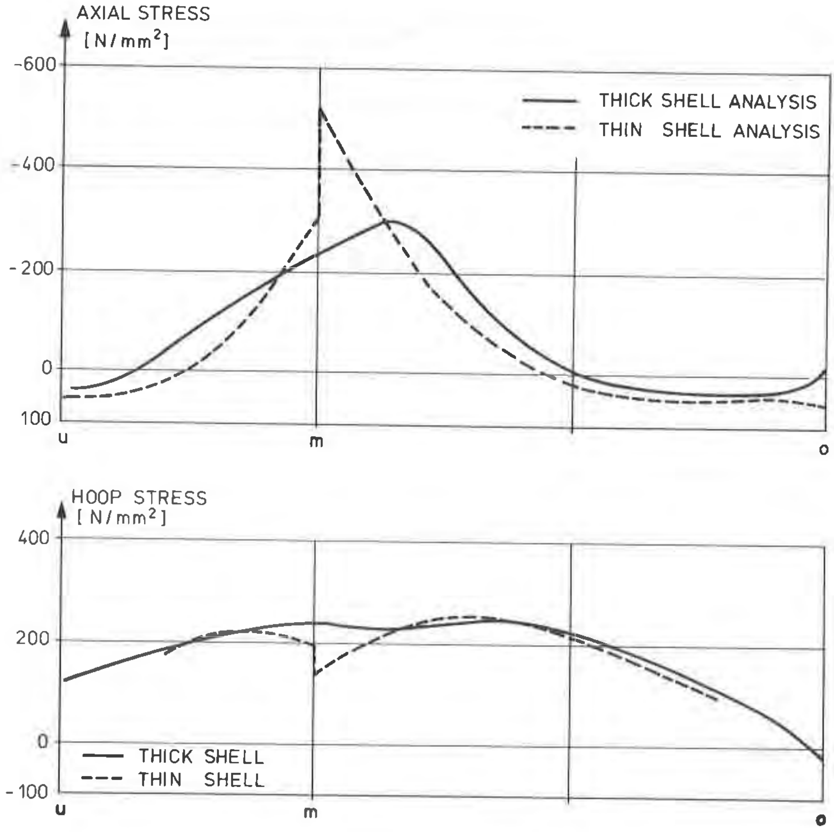

Fig. 4: Elastic stresses along the outer surface - thick shell idealization

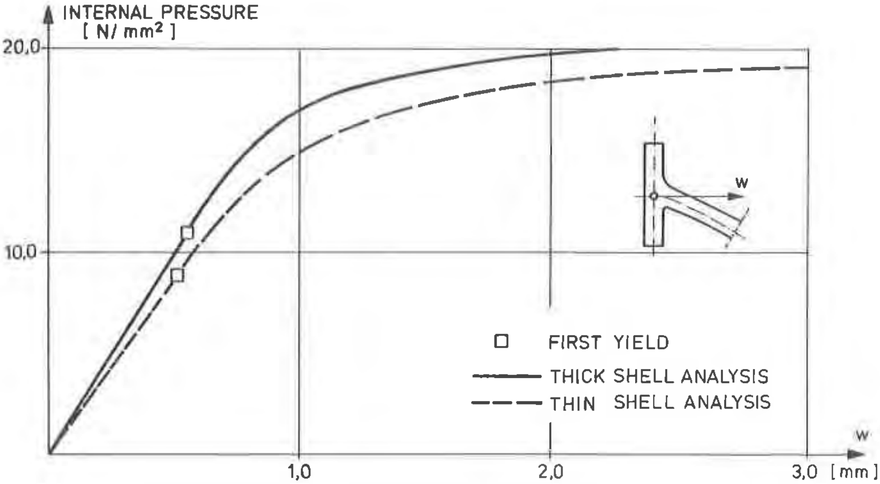

Fig. 5: Load deflection diagram

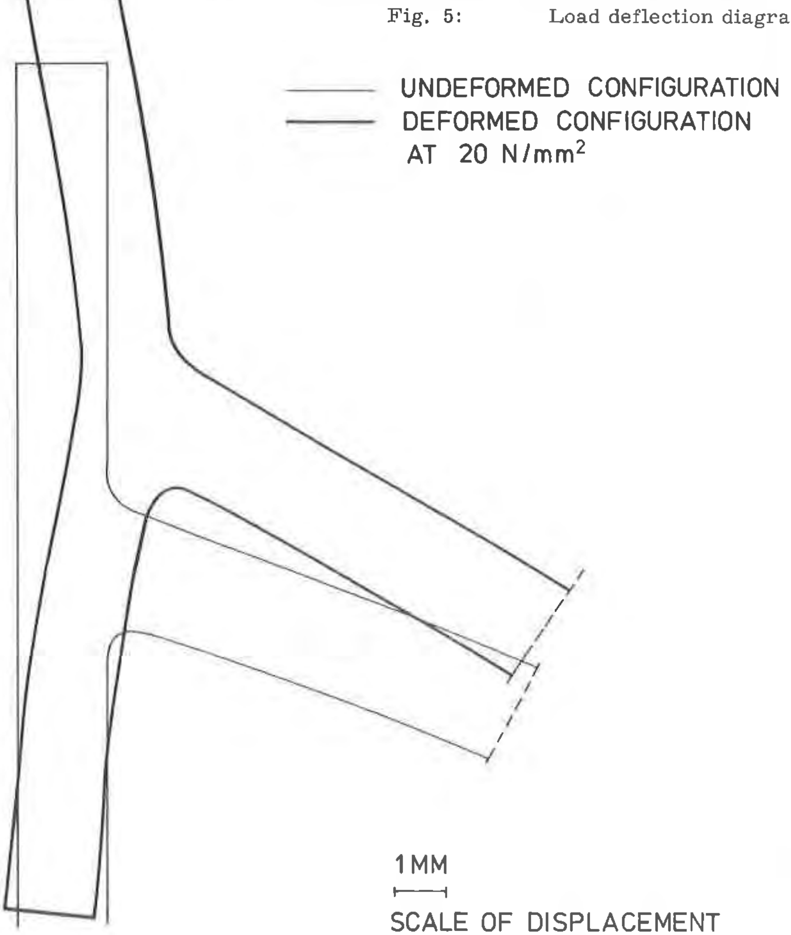

Fig. 6: Deformed nozzle

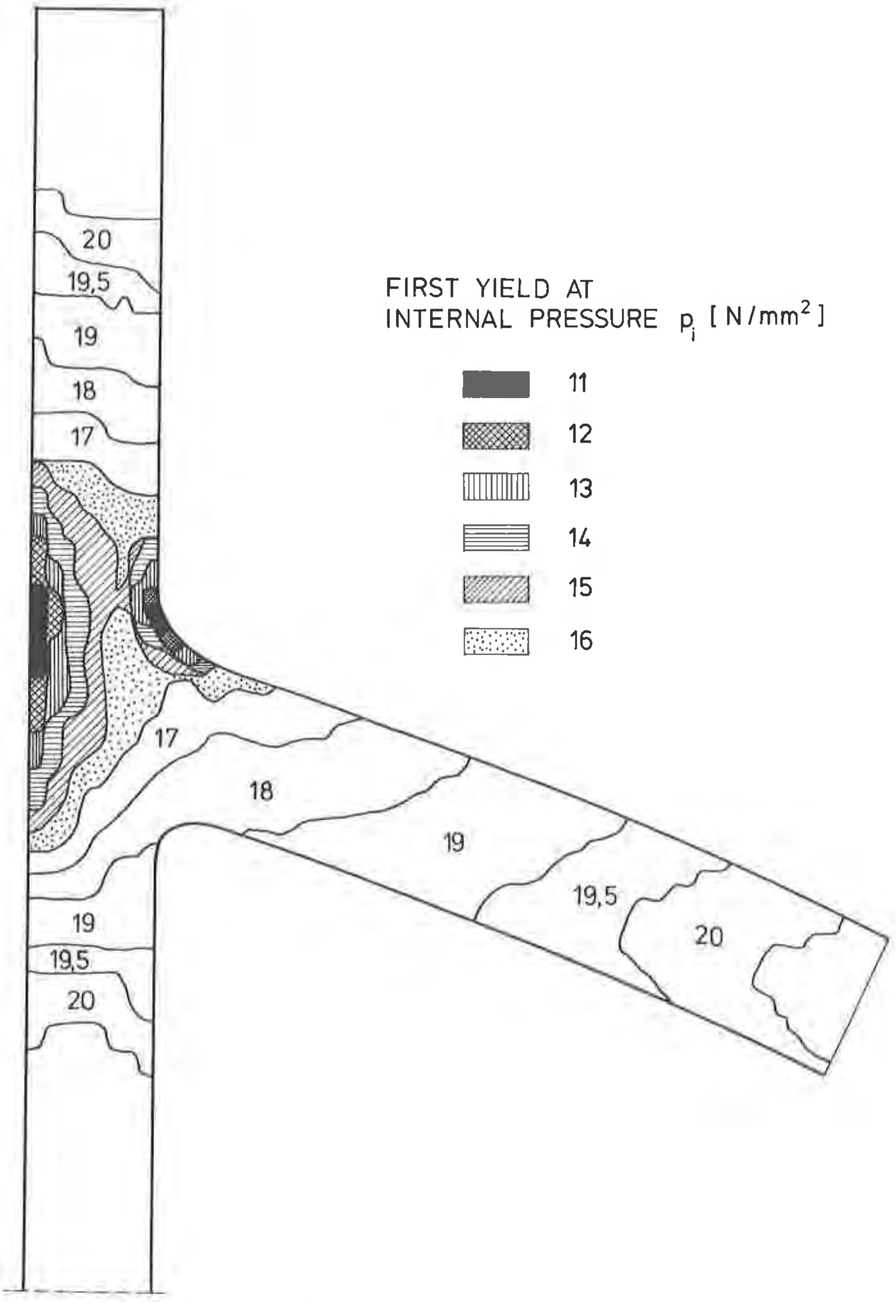

Fig. 7: Yield progression