Increased plastic strains in containment steel liners due to concrete cracking and discontinuities in the containment structure

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ABSTRACT

It has been shown in containment scale-tests that the global displacement measured at liner failure does not correspond to the critical strain level for the liner. A general conclusion from these results is that some type of strain concentration has to take place to get this “early” liner failure. The main reasons for strain concentrations are in this paper assumed to be; (1) concrete through-wall cracking and (2) discontinuities such as penetrations. In the presented study analytic results are compared to results from a 1:4-scale containment model tested by over-pressurization in year 2000 at Sandia National laboratories (Sandia 1:4). Effects of through-wall cracks (1) are studied in a general section in mid-height of the containment. From this study it is concluded that concentrations of plastic strains could be highly increased by the friction between the liner and the concrete, especially for thin liners. The effect of discontinuities (2) is exemplified by an FE-analysis of the penetration region in Sandia 1:4 where the first liner tears appeared. From this analysis it is shown that of out-going folds in the liner tends to be straighten out when the containment expands. It is concluded that this behaviour most likely contributed to the tears found in the penetration region of Sandia 1:4. The presented paper summarizes a part of the work in a PhD project performed at University of Lund.

INTRODUCTION

A substantial part of the concrete reactor containments in US and Europe are constructed with an inner steel liner which constitutes the ultimate leak-tightness barrier. The liner, which has no intended load-bearing function, is securing the leak-tightness at high internal pressure load levels. The liner is attached to the inner surface of the concrete containment by anchors made up of studs or by continuous structural shape (L- or T-sections).

The actual containment leak-tightness capacity is difficult to define. Complex interaction between liner and concrete as well as discontinuities in the containment structure complicates the failure mechanism for the liner. Two large scale tests on concrete containments with steel liners have been made in US, at Sandia Laboratories. The aim of these tests was to provide test data to improve and confirm methods for calculating the containment response at high pressure loads. The first scale test (Sandia 1:6) was performed in 1987 where a 1:6 scale model of a reinforced containment was pressurized [1]. The second scale test (Sandia 1:4) was performed in year 2000 and in this test a 1:4 scale model of a prestressed containment was pressurized [2].

In both Sandia 1:6 and 1:4 tears in the liner was obtained at global strains (measured change in radius/original radius) less than 1%, which is low compared to the strain capacity of a typical liner. One common conclusion from the two performed scale tests was that some concentration of strains has to take place to get the early liner tears shown in these tests. In both Sandia 1:6 and 1:4 early tears in the liner was obtained near penetrations, in regions with large radial expansion (mid-height of the containments). In the Sandia 1:4 test the first tears were obtained near the equipment hatch (penetration E/H). The tears were located in vicinity of the vertical fold between the general curved part and the embossment (vertical bend line).

The aim of this paper is to show possible mechanisms of liner strain concentration, which have contributed to the tears found in Sandia 1:4. Strain concentration effects are assumed to arise from; (1) concrete through -wall cracking and (2) discontinuities like penetrations. Effects of through-wall cracks (1) are studied in a general section in mid-height of the containment. The effect of discontinuities (2) is exemplified by an FE-analysis of the E/H penetration region in Sandia 1:4, where the first liner tears appeared. The presented paper summarizes a part of the work in a PhD project performed at University of Lund. Details about the through-wall crack study and the study of the penetration region can be found in Anderson [3] and [4].

SANDIA 1:4 MODEL

The prototype of Sandia 1:4 is the containment structure of a Japanese PWR. The model was 16.4 m high, had an inner diameter of 11.4 m and the prestressed concrete wall was 325 mm thick (see Fig 1). On the inside of the concrete wall a 1.6 mm thick liner was connected to the concrete by vertical T-shaped steel profiles (anchor profiles) welded to the liner. To stabilize the liner panels at the construction stage the vertical anchor profiles were completed with horizontal stiffeners welded to the liner. The shape of the anchors and stiffeners is shown in Fig 2 and the arrangement near the penetration E/H is shown in Fig 10. Drawings and detailed descriptions of the model can be found in Hessheimer, et al [2].

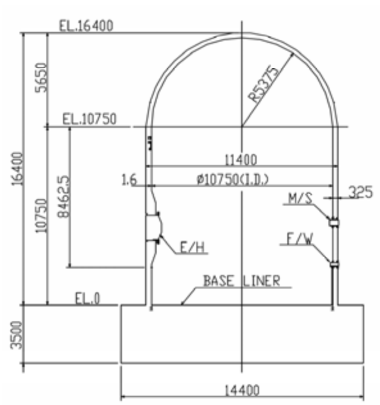


Fig 1, Layout of the Sandia 1:4 model [2].

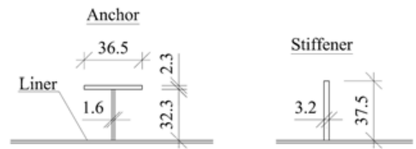


Fig 2, Liner anchor and horizontal stiffener in the Sandia 1:4 model [4].

Fig 3 shows a stretch-out sketch of the cylindrical part of Sandia 1:4 seen from the inside of the model. At the overpressurization test, the first leak was detected at an internal pressure 2.5 times the design pressure (p_d = 0.39 MPa). The test was terminated at an internal pressure of 3.3 p_d. At 3.3 p_d the leak rate exceeded the capacity of the pressurisation system and the sources of the leak was a number of tears with the approximate location as shown in Fig 3. An acoustic monitoring system detected the first leak near the penetration E/H. At the post-test inspection, 4 tears were found close to the vertical fold between the embossment and the general curved wall. It shall be noted that in the construction stage the liner was grinded in connection with welding. It was concluded in the post-test inspection that in the region of almost all tears the liner had been grinded and the liner thickness was reduced up to 50% in some cases.

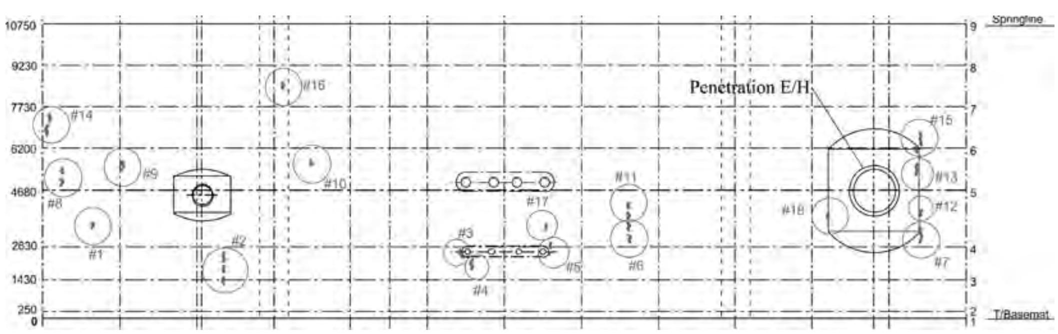
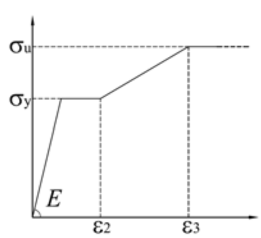


Fig 3, Stretched-out sketch of the liner in the cylindrical part [2].

Liner material properties

The liner was fabricated from steel plates with nominal yield strength of 225MPa and a nominal tensile strength of 410MPa. A number of uni-axial tensile tests were made to determine the material properties of the liner and these are presented in Hessheimer, et al [2]. Fig 4 shows an idealised stress-strain relation curve for the liner, based on the uniaxial tensile tests in Hessheimer, et al [2].



Material parameters
E = 220MPa
ε_2 = 1.3%
ε_3 = 6.5%
σ_y = 380Mpa
σ_u = 500Mpa

Fig. 4, Liner stress-strain relation (Sandia 1:4) [4].

Due to the assumed displacement controlled behaviour of the liner, the failure criterion for the liner is based on strain. The uniaxial strain at failure (ε_u) was measured in the tensile test presented in Hessheimer, et al [2] and the average value was concluded to be 34% [5]. The failure strain for the real structure will be reduced in relation to ε_u, depending on the appearance of welds and due to the multi-axial stress state in the liner. In the pre-test analysis for the Sandia 1:4 project [5] these two factors was investigated. By an empirically based strain failure criterion based on Manjoine [6] it is concluded that the failure strain level can be reduced up to 40% due to the biaxial stress state in the liner. Based on the tensile tests with welds in Dameron [5], the reduction of failure strain near welds also is in assumed to be around 40%.

LINER BEHAVIOUR NEAR A CONCRETE THROUGH-WALL CRACK

The analysis of the liner behaviour near a through-wall crack is studied by a generalised horizontal segment at midheight of the containment wall (see Fig 5). The liner failure mode is studied in the hope direction and effects from the vertical direction are neglected. The main arguments for this simplification are based on results from the performed scale test (Sandia 1:4 and 1:6). Liner tears in the tests were only found in regions with large radial displacement and the orientation of the tears was in mainly vertical (caused by hoop strains). It is also concluded from the tests that the radial displacement are much larger than the vertical displacements.

The parameters which are assumed to influence the liner behaviour in a generalised segment is the concrete crack width (w), the distance between liner connectors (c), the internal pressure (p), the friction coefficient between concrete and liner (μ) and of course the liner material and thickness (t).

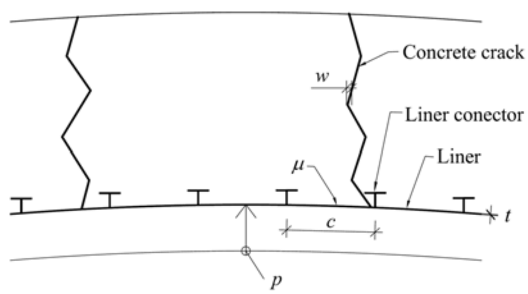


Fig 5, Generalised segment of the Sandia 1:4 containment wall.

Interaction, concrete and liner

Crack formation in reinforced concrete has a random nature, where the maximum space between cracks can be in the order of two times the minimum crack space. For Sandia1:4 estimated crack spacing together with the measured radial displacement can be used to estimate the crack width. In Table 1 the maximum crack space is calculated according to two different codes, Eurocode 2 [7] and Model Code 1990 [8]. The strain in the concrete between the cracks is assumed to be insignificant, i.e. all stain is assumed to be concentrated to the crack. In Sandia 1:6 some crack widths where measured during the test and some of the cracks where more than 3mm wide [1].

Table 1, Estimated crack widths for Sandia 1:4 at 3.3p_d.

Code	Measured average hoop strain at midheight (%) [2]	Calc. max. crack space from code (mm)	Max. crack width (mm)
CEB/FIB Model Code	0.4	350	1.4
Euro Code 2	0.4	590	2.3

Friction between the liner and the concrete wall will be activated due to the internal pressure load (p) which presses the liner to the concrete. In this study the contact pressure is assumed to be equal to the internal pressure load (p). For containments in general, the axial stiffness of the liner is low compared to the concrete wall stiffness and therefore the contact pressure will be close to the internal pressure load (p). The friction coefficient (μ) between steel and concrete has been investigated in several research studies. From a friction test made within this study (see Anderson [3]) μ is concluded to be around 0.6. This value agrees with friction tests made in Rabbat et al [9] and Baltay et al [10].

Model

To study different parameters influencing the liner strains around a concrete crack, a one-dimensional bar model is used (see Fig 6). The model describes a liner segment between two liner anchors, with fixed support at one end and a displacement (w) corresponding to the crack width at the other end. The friction between liner and concrete is modelled by a uniformly distributed axial load (μp). The steel material for the bar model is given non-linear characteristics (see Fig 7).

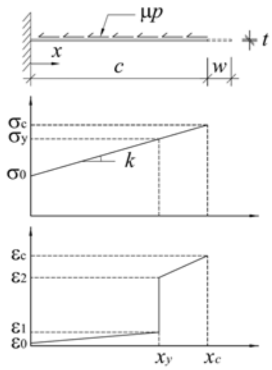


Fig. 6, Stress and strain along the bar model [3].

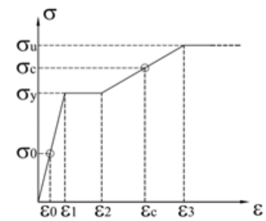


Fig.7, Idealized stress-strain relation [3].

The stress distribution (see Fig 6) along the model will be linear with a slope (k) governed by equilibrium with the friction force. The stress level and also the strain distribution depend on the stress-strain relation for the steel material. When the stress in the crack section (σ_c) exceeds the yield limit (σ_y) and the stress in the fixed section (σ_0) is between 0 and σ_y the strain distribution can be described as in Fig 6. One part will be in the elastic stage (0 to x_y) and the other part will be in the plastic stage (x_y to x_c). The sum of strain along the segment will be equal to the displacement load (w).

Using this model and the description of the material, it can be stated that the capacity of the liner is exhausted when ε_3 is reached even if the ultimate strain capacity (ε_u) is much larger (ε_u is in the order of three times ε_3). The reason for this is that when ε_3 is passed the stress in the liner will not increase and then the remaining displacement can not be distributed along the liner due to the friction force. This means that in theory the remaining displacement will be localized to an infinite small part in the cracked section which will lead to infinite large strains i.e. failure.

More details of this model and an analytic description of the stress in the cracked section are presented in Anderson [3]. The behaviour of tensioned steel plates influence by friction is verified in an experimental study also presented in Anderson [3].

Parametric study

The maximum stress i.e. the stress in the crack section (σ_c) is studied as function of different parameters. In Fig 8 σ_c is shown as function of the crack width and different friction coefficients (other parameters are kept constant p=1.3 MPa, t=1.6 mm, c= 450 mm and material parameters as in Fig 4). The maximum stress σ_c increases with increased friction (and increasing crack width). For μ=0.6 the stress have almost increased 50MPa at a crack width of 3mm compared to μ=0 (no friction). To reach the ultimate stress (σ_u), which corresponds to liner failure, the crack width has to reach 10mm for μ=0.6. The friction coefficient have high influence on the crack width which leads to failure (critical crack width, w_u), for μ = 0.4 w_u=14.5mm and for μ = 1.2 w_u=5.1mm. In Fig 9 σ_c is shown as function of the liner thickness and different friction coefficients (other parameters are kept constant p=1.3 MPa, w=3 mm, c= 450 mm and material parameters as in Fig 4). The stress is decreasing for increasing values on t, especially for high friction coefficients. This is due to the constant friction force, which have higher influence on the stress for thin liners. One important conclusion of this is that scale models are not representing the actual full-scale containment in the aspect of increased stress and strain due to friction. The effect of friction will be larger for scale models than for the full-scale containment.

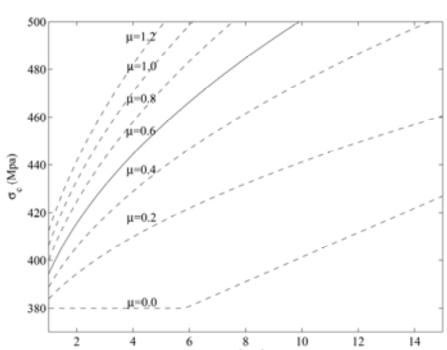


Fig. 8, Influence of crack width on the stress in the crack section [3]

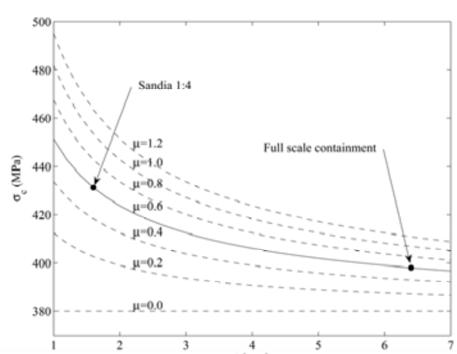


Fig. 9, Influence of liner thickness on the stress in the crack section [3]

ANALYSIS OF THE LINER NEAR THE EQUIPMENT HATCH IN THE SANDIA 1:4 MODEL

Fig 10 shows the backside of the liner near penetration E/H. In the post-test investigation four liner tears were found in the vicinity of the vertical bend (see Fig 10). To analyse the mechanism giving these tears, a 3D FE-model describing the penetration region and a 2D plane strain model describing the vicinity of the bend line is used. Details of the models and the results shown in this section are described in Anderson [4].

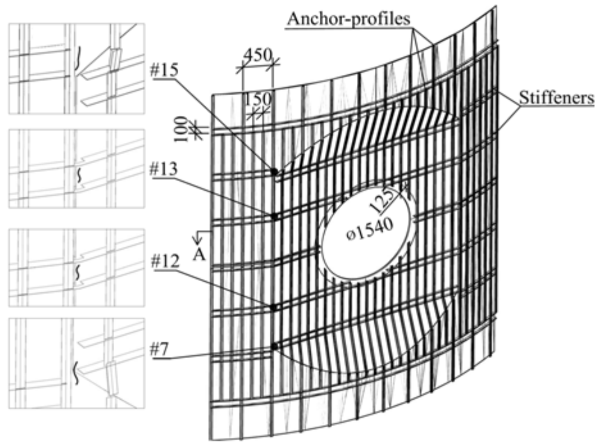


Fig 10, Liner near penetration E/H (against concrete wall), Approximate location of tear 7, 12, 13 and 15 (also see Fig. 3) [4].

3D model of the penetration region

A 3D FE-model is used to analyse the behaviour of the liner in this region. The non-linear liner behaviour is described by the stress - strain relation given in Fig 4 and von Mises yield criterion. The interaction between liner and concrete is described in detail, which includes contact behaviour in free fields, at vertical anchors, at horizontal stiffeners and at the penetration pipe. The liner behaviour is assumed to be controlled by the displacement of the concrete wall i.e. the influence of the liner stress state on the containment expansion is insignificant. This assumption allows an analysis with prescribed displacement action. In the model the wall displacement is assumed to be equally distributed, i.e. no local effects due to through-wall concrete cracks are modelled. BRIGADE/Plus[1], a general purpose finite element program was used for the FE-analysis. All parts are modelled with 4 nodes shell elements (ABAQUS element S4R). To account for large geometrical changes in the model the analysis was run using the non-linear geometry option. Details of this 3D model are given in Anderson [4].

Large strain and stress concentrations are found in the region of the out-going bend lines near penetration E/H. A significant difference of the strain and stress state between the inside and the outside of the liner is found in the region of the bend-line. This difference shows that the elevated strain in the bend line region is related to some type of flexural behaviour. Fig 11 shows the opening between nodes on concrete wall part and the liner part at the internal pressure of 3.3 p_d. The whole liner is in contact with the wall except for the region of the out-going bend lines (see Fig 11). In this region the liner has separated from the wall and the opening along the vertical bend line is around 4mm. The reason for the opening is that the anchor profiles diverge when the containment wall expands and this movement tends to straighten out the liner between the anchor profiles. In general the pressure load will press the liner against the concrete wall, but in the bend line the tensioned liner will separate from the concrete wall.

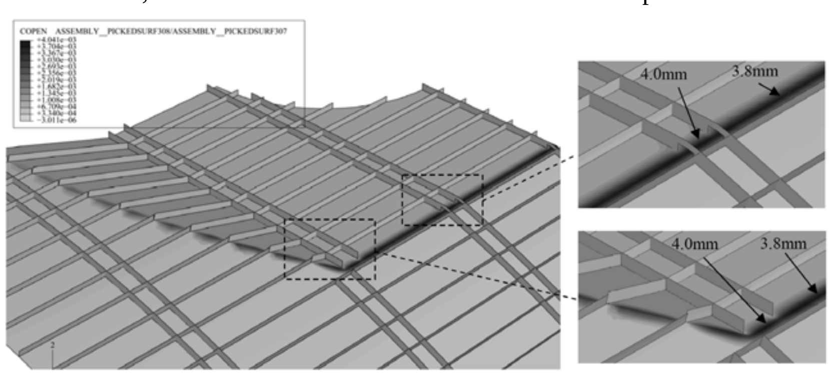


Fig 11, Contact opening at nodes between wall and liner (in dark areas the liner has separated from the concrete wall) [4].

[1] BRIGADE/Plus is based on ABAQUS code.

Detailed behaviour in the vertical bend line

The detailed behaviour in the vertical bend line is analysed by the 2D FE-model (see Fig 12). The same principle describing contact and boundary conditions are used for the 2D model as for the 3D model. In the 2D model the concrete wall part is described by bar elements which are given prescribed uniform radial deformation in all nodes. The liner part is described by four node plane strain elements. The interaction between the wall and liner part is described by a contact definition and by non-linear spring elements in the locations of the anchors.

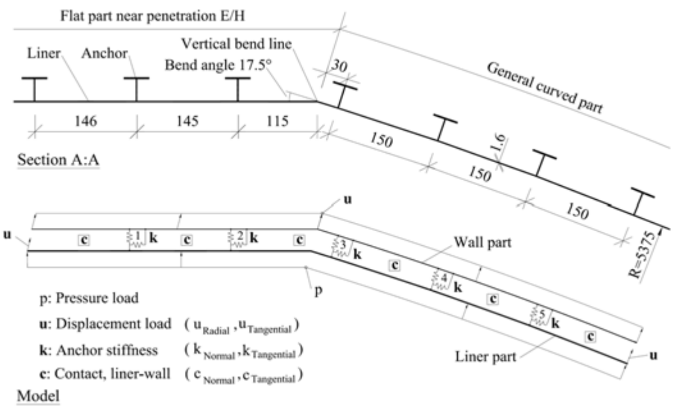


Fig 12, Geometry and model of the vertical bend line (section A see Fig 10) [4].

The 2D model show the same flexural behaviour near the bend line as the 3D model in the previous section. Fig 13 show the deformed 2D model near the vertical bend line and the liner has separated 4mm from the wall (at internal pressure 3.3 p_d). The highest plastic strain is located on the inside of the bend line and on the outside near the right anchor (location A and B in Fig 13).

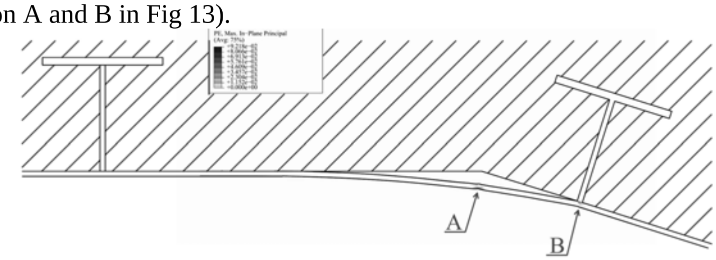


Fig 13, Deformed model at 3.3 p_d. Elevated plastic strain in location A and B [4].

Fig 14 shows the opening between the liner and the wall at location A as function of the internal pressure. As the containment wall expands the opening grows. The highest value (4mm) is reached at an internal pressure of 3.0 p_d and after this the opening is almost constant. At an opening of 4mm the bend line is almost straighten out (see Fig 13) and therefore the opening will not change significantly after this.

Fig 15 shows the plastic strain in locations A and B as function of the internal pressure. The plastic strain shows an almost constant growth from 1.7 up to 2.8 p_d and after this the growth decreases. The curve shape is similar to the contact opening curve in Fig 14. The growth of contact opening in A and the growth of plastic strain in A and B start to decrease at the same internal pressure p.

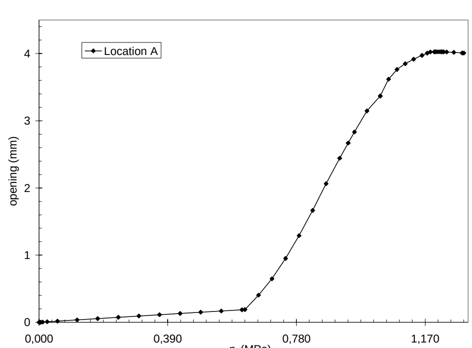


Fig 14, Contact opening between liner and wall in the bend line as function of the internal pressure [4].

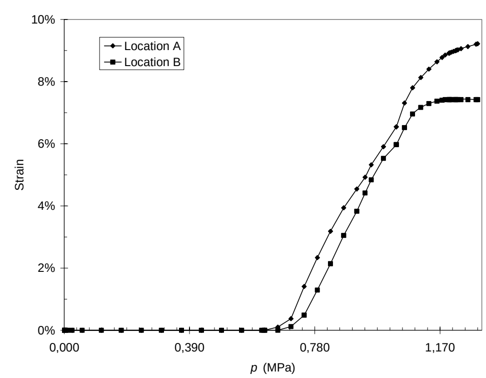


Fig 15, Plastic strains for the liner as function of the internal pressure (A and B, see Fig 13) [4]

CONCLUSIONS

From the study of a general liner segment near a concrete crack it is concluded that:

- The friction between the liner and the concrete wall will concentrate the plastic strains to through-wall concrete cracks.
- Due to the influence of friction the liner can not be stretched beyond the hardening part. When the characteristic steel curve is flattened out after the hardening part, the remaining displacement will be concentrated to the crack location.
- Concentration of strain will increase with decreasing liner thickness. One important conclusion of this is that localisation of strain due to friction will be more significant for scale models than for the full scale containment.
- The effect of a thinner liner due to grinding is studied in Anderson [3]. A model show that grinded welds (25% reduction) in the area of a concrete crack could give strain levels that explain the early liner tears obtained after the Sandia 1:4 test.

From the study of liner failure mechanism near penetration E/H (Sandia 1:4) it is concluded that:

- When the containment wall expands, anchor profiles will diverge and this tends to straighten out the liner between the anchor profiles. For regions with general curved shape the internal pressure load will press the liner against the concrete wall. Near the vertical bend line the liner will separate from the concrete wall.
- The weld in the vicinity of the bend line will get exposed to high concentrations of strain. The peak strain will reach around 10% at the internal pressure of 3.3 p_d. The ultimate strain considering biaxial stress and influence of welding is evaluated to around 12%.
- Both the calculated strain in the bend line and the failure strain are associated with uncertainty. However, the analysis made in this study show that the flexural behaviour in the bend line most likely contributed to the tears found in the Sandia 1:4 post-test investigations.

A general conclusion from these two studies is that the liner failure is very sensitive to the non-linear plastic steel behaviour, the detailed geometrical design and the interaction between the liner and the concrete.

REFERENCES

[1] Horschel D.S., Experimental results from pressure testing of a 1:6 scale nuclear power plant containment. 1992, NUREG/CR-5121, SAND88-0906.

[2] Hessheimer M.F., Klamerus E.W., Lambert L.D. and Rightley G.S., Overpressurization Test of A 1:4-Scale Prestressed Concrete Containment Vessel Model. 2003, NUREG/CR-6810, SAND2003-0840P.

[3] Anderson P., Concentration of plastic strains in steel liners due to concrete cracks in the containment wall. 2007, Submitted for publication.

[4] Anderson P., Analytic study of the steel liner near the equipment hatch in a 1:4 scale containment model. 2007, Submitted for publication.

[5] Dameron R.A., Zhang, L., Rashid Y.R. and Vargas M.S., Pretest Analysis of a 1:4-Scale Prestressed Concrete Containment Vessel Model. NRC-report, Sandia National Laboratories, August 2000, NUREG/CR-6685.

[6] Manjoine, M.J., Creep-rupture behaviour of weldments, Welding J., 1982, 61, 50-56.

[7] Eurocode 2: Design of concrete strucutes - Part 1: General rules and rules for buildings - ENV 1992-1-1.

[8] Model Code 1990. Design code. CEB/FIP, ISBN 0-7277-1696-4.

[9] Rabbat B.G. and Russell H.G., Friction coefficient of steel on concrete or grout. J Struct Eng, 1985, 111:505-515.

[10] Baltay P. and Gjelsvik A., Coefficient of friction for steel on concrete at high normal stress. J Mater Civ Eng, 1990, 1:46-49.