PREDICTING PRE-STRESSED CONCRETE CONTAINMENT CAPACITY

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ABSTRACT

AMEC Nuclear UK Ltd has participated in two international round robin exercises aimed at predicting the capacity of lined and unlined pre-stressed concrete containments. This paper presents lessons learnt from the numerical analysis of the two models. The first exercise involved analysis of the ¼ scale steel-lined Pre-stressed Concrete Containment Vessel (PCCV) which was tested at Sandia National Laboratories (SNL) in USA. The second analysed the unlined BARC Containment (BARCOM) test model being tested by the Bhabha Atomic Research Centre (BARC), Tarapur, India. These studies have helped validate the analysis methodology and modelling techniques that can be used to predict pre-stressed concrete containment capacity and failure modes.

INTRODUCTION

A pre-stressed concrete containment is an important safety related structure as it acts as one of the final barriers to radioactive release. These structures are normally designed in accordance with the allowable stress codes to sustain the specified loading conditions. However, the compliance with the industry standard allowable stress codes does not give a reliable indication of the likely failure mode and the capacity or the limit of the structure. In the past few years, two international round robin exercises have been conducted which have provided valuable test data related to failure under over-pressurisation. The first exercise involved the numerical analysis of the ¼ scale steel-lined Pre-stressed Concrete Containment Vessel (PCCV) with design pressure (Pd) of 0.39MPa [1] which was tested at Sandia National Laboratories (SNL) in USA and the second exercise analysed the unlined BARC Containment (BARCOM) test model with Pd of 0.1413 MPa [2] being tested by the Bhabha Atomic Research Centre (BARC), Tarapur, India. Vertical and hoop tendons were used in both the designs for pre-stressing. The SNL model had post-tensioned tendons whereas all the BARC tendons were grouted except 8 cables which were left ungrouted to measure loss of pre-stress.

It is an acceptable normal practice for designers to assume linear elastic response when designing a structure but prediction of failure or capacity will require a much more detailed analysis that takes account of nonlinearities arising from the yielding of material, cracking of concrete, changes in geometry and attendant load redistribution. Such models are complex and require careful attention to modelling details. This paper discusses the modelling features used in both studies and the predicted response.

Both SNL and BARCOM tests have shown that the collapse of the containment structure is not expected to occur soon after the design pressure is exceeded. There is no ‘cliff edge’ but a gradual progressive damage of the containment structure under over-pressurisation which indicates safety margin against collapse. The structure may suffer local failures leading to functional failure well before the ultimate structural collapse. The computational models help us understand this progressive collapse and give a measure of safety margin between the functional failure and the ultimate collapse. Furthermore, these computational models can be used to predict behaviour under combined mechanical and thermal loadings that are postulated under accident conditions. It should be noted that both SNL and BARCOM tests are limited to mechanical loading and do not apply thermal loading.

COMPUTATIONAL MODELS

In both tests, displacements, loads and strains are monitored at selected locations giving a unique opportunity to assess the accuracy and reliability in predicting failure modes and limit loads of PCCV structures using Finite Element Analysis (FEA). The FEA models employed for both studies [1, 2] are sophisticated 3D full global models, which take account of the interaction between all the main structural features. Non-linear FEA of the full 3D model has been conducted using the commercially available ABAQUS computer code. The concrete material model is allowed to crack with tension stiffening behaviour. Steel reinforcements and tendons are allowed to yield. Frictional loses in the post-tensioned tendons are simulated. In the case of the Sandia model (Fig.1) the hoop tendons are allowed to slide resulting in load re-distribution upon pressurisation whereas in the BARC model (Fig.2) all the tendons are fixed to the concrete to simulate the grouted condition. Failure due to overpressurisation has been studied for the BARC model whereas thermal loading was also applied to the SNL model under the ISP48 project [3]. The temperature loading in this case is a non-linear increase from 100^{o}C to 200^{o}C with linear increase in pressure from 0 MPa to 1.46 MPa.

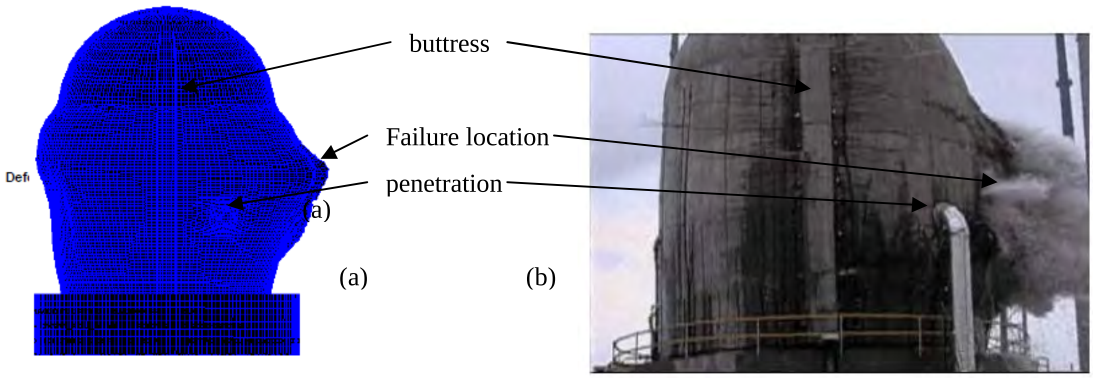

Fig.1: Predicted failure mode of the SNL model (a) FEA results vs (b) test at 3.65 P_d

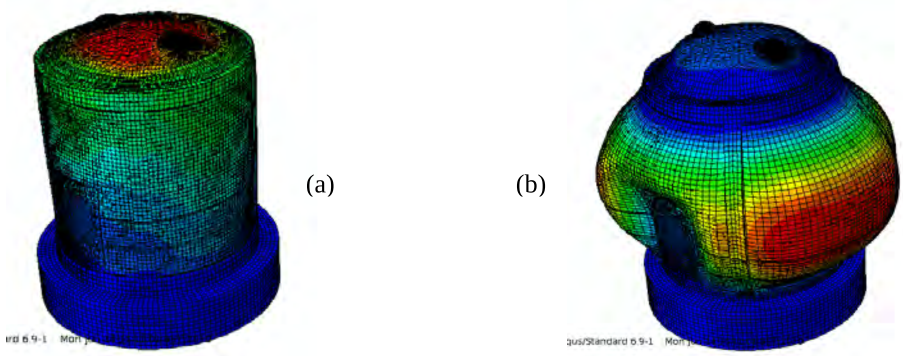

Fig.2: Predicted response of the BARC model (a) under prestress and (b) at 2.89 P_d

MODELLING OF STRUCTURAL FEATURES

Functional failure of a containment, when leakage exceeds acceptable levels, is likely to be dictated by a local failure of a structural feature. This could be yielding or rupture of the liner, rebar or tendon. Therefore, it is important to model the strain concentration caused by the liner joints, geometric discontinuities at penetrations and stiffness discontinuities at the buttresses. The liner can be modeled using membrane type elements as they are primarily loaded by inplane tension and shear. Because of large strains, the formulation of the elements selected to represent the liner should be suitable for finite strains. Also, care should be taken to convert the engineering stress-strain data to true stress – true strain data when specifying the plastic material properties. It is recommended to apply pressure directly on to the concrete face and not on the membrane elements. To simulate stretching and shearing of the liner, it is important to model the liner anchorage stiffness, which can be done by use of spring elements. Local models with refined mesh can be used to study the strain concentration features such as the joint between thick and thin sections of the liner. Information from such locally refined models is essential to establish the general strain levels at which liner rupture may occur. Many FEA packages have the facility to model reinforcements as a smeared layer of metal. This approach has been found to be adequate to model the general stiffness behaviour but it may not give accurate strain information in the corner regions. The smeared layer approach can also be employed to model the post-tensioned tendons but only in the regions where there is no large relative sliding between the tendons and the concrete. In pre-stressed pressure vessels, the horizontal tendons in the hoop direction expand with the concrete bulk and can be modelled using the smeared layer approach, but the ungrouted vertical tendons in the wall must be modeled explicitly using beam or truss elements to allow for relative sliding as the wall bends under pressure loading. Geometric features of a penetration must be modelled accurately to capture the extra stiffening provided by local thickening of the wall and deviations in the tendon layout. Such features have been shown to provide local stiffening which influences the structural behaviour. The same is true for the representation of the buttresses and the ring beams as the extra stiffening provided by the tendon anchorages prevents uniform radial expansion of the wall. Overall, modeling of a container with a liner and post-tensioned tendons is more complex than the one with no liner and grouted tendons.

PREDICTED RESPONSE

Failure of a containment structure is dictated by the strain levels experienced by the tendons, rebars and the liner. In case of the SNL model, catastrophic failure occurred in the general area of the vessel wall at mid-height as shown in Fig 1. Hoop tendons at this location ruptured and its response is shown in Fig 3. Development of strain in the outside rebar layer at mid-height in both hoop and meridional directions is presented in Figs 4 and 5 respectively. Tearing of the steel liner in the SNL model dictated the functional failure due to excessive leakage (1% mass per day). Variation in the liner strain at the same location is presented in Fig 6. Taking this failure criteria obtained from the test, it can be seen that the predicted functional failure pressure will increase from 1.1 MPa to 1.25 MPa when thermal loading is applied. This is because the thermal expansion of the steel liner delays its rupture.

The test to reach structural collapse of the BARC model has not been completed at the time of writing this paper so the comparison is incomplete. Examination of the predicted deformed shape of the BARC model shown in Fig 2 indicates likely failure areas in the region above the main penetration which is not allowed to deflect and the general regions of the wall at mid-height which experiences excessive radial expansion. Bending of the wall above the main penetration causes excessive axial strain in the rebar which is shown in Fig 7. Rebar hoop strain in the outer layer at mid-height is shown in Fig 8. Both responses indicate likely functional failure at 0.33 MPa and structural collapse at 0.41 MPa.

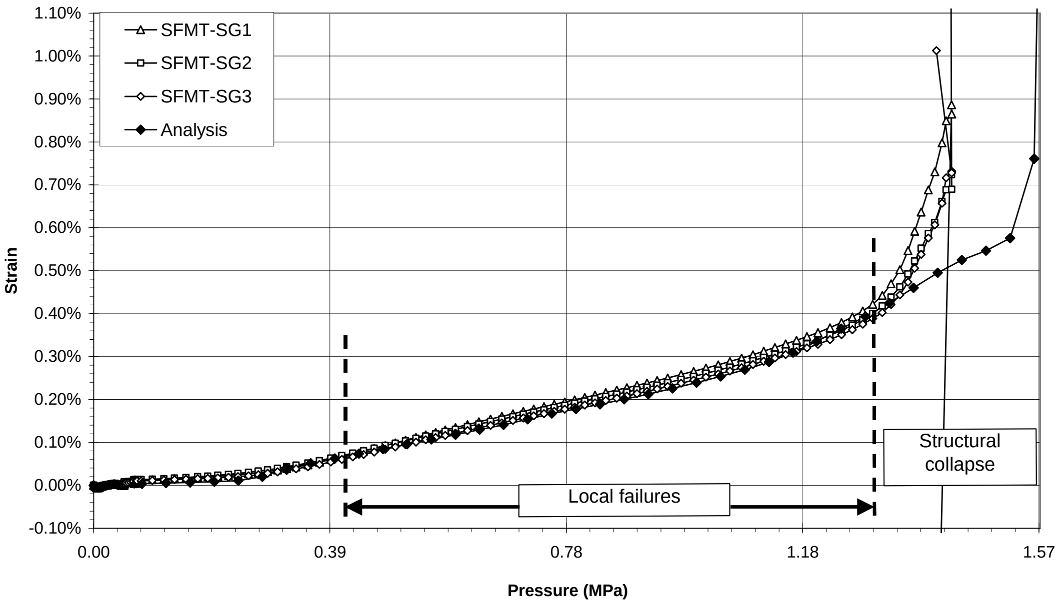

Fig.3: Strains in the hoop tendon near the failure region defining the structural collapse of the SNL model

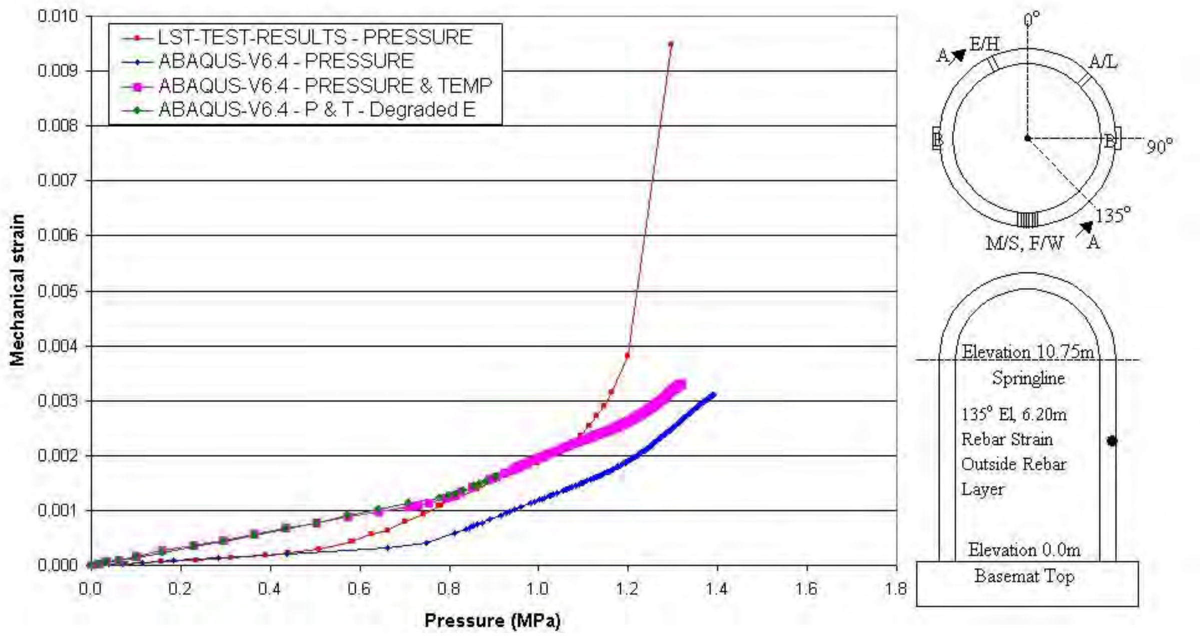

Fig.4: Strains in the outside layer of the hoop rebar at mid-height of the SNL model

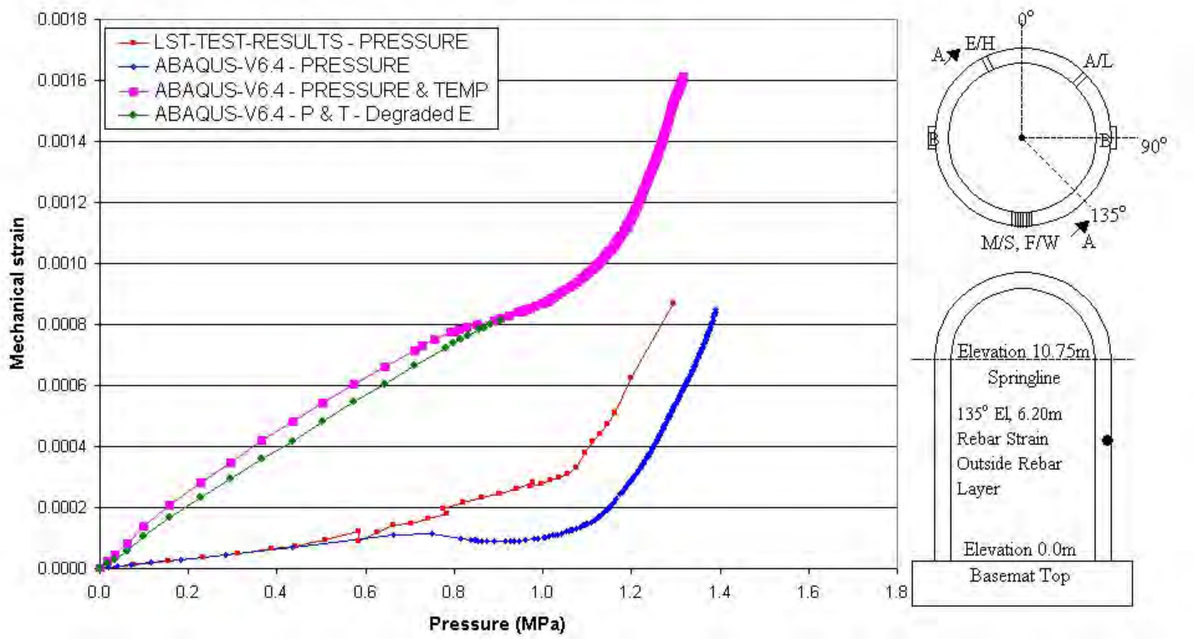

Fig.5: Strains in the outside layer of the meridional rebar at mid-height of the SNL model

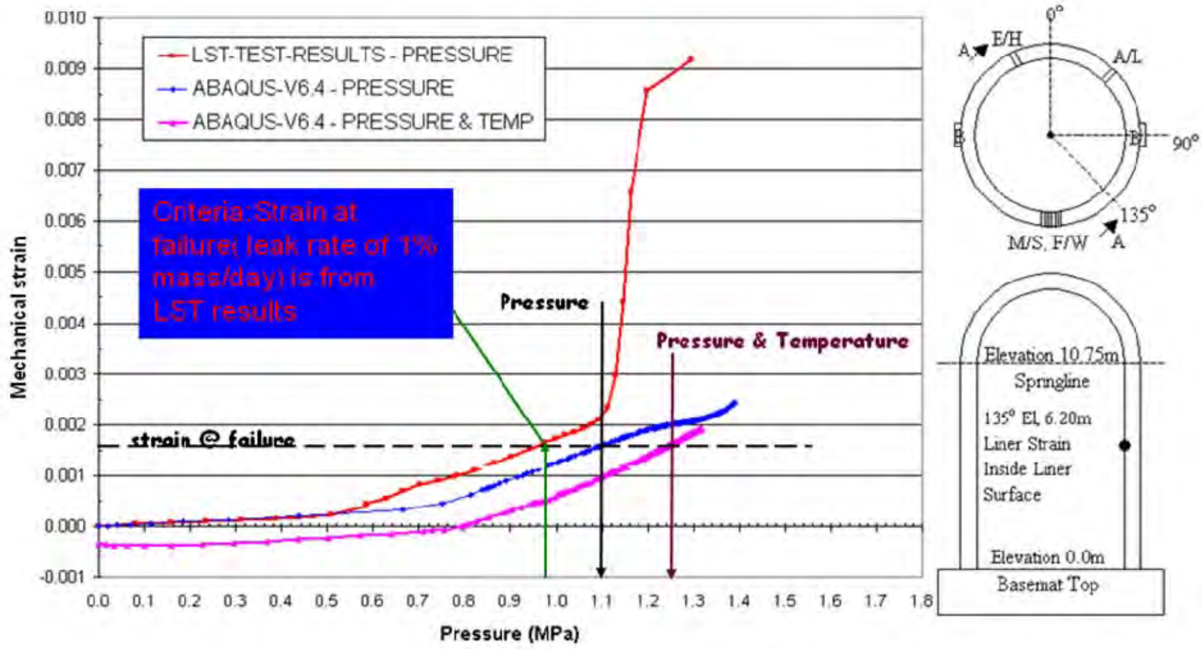

Fig.6: Liner strain defining the functional failure of the SNL model

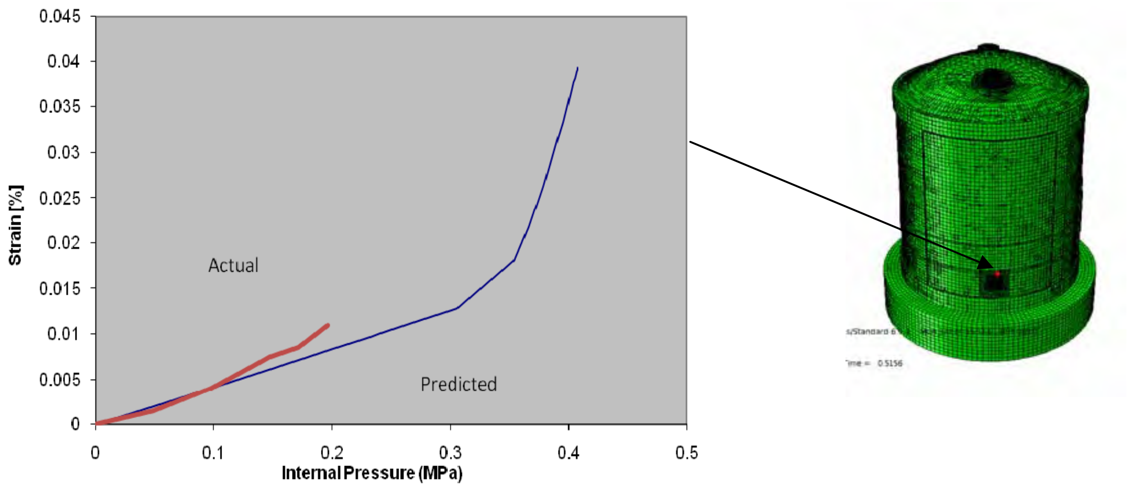

Fig.7: Rebar axial strain on the outer layer above FMLB in the BARC model (SSL30)

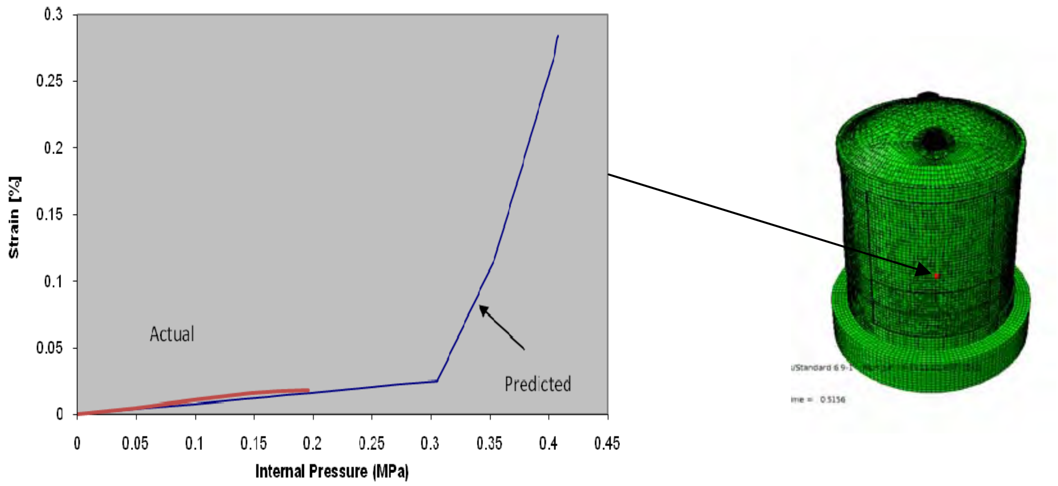

Fig.8: Rebar hoop strain on the outer layer at approximate mid height of the BARC model (SSL14)

DISCUSSION

The available test data and the FEA results show that the structural response of the pressurised PCCV is indicated by progressive damage in three stages. The first stage of predominantly elastic response can be predicted with very good accuracy. The second stage involving inelastic response with extensive concrete cracking requires specialist concrete material models and detailed geometric representation of the main structural features. It is important to model the interaction between various structural elements to simulate load redistribution as some components yield or fail. Such local yielding or rupture may lead to loss of functionality or breach of pressure boundary. The third stage involving gross deformation leading to the structural collapse requires solution of a highly non-linear problem. Extensive concrete cracking, well beyond the tension stiffening range, occurs and requires robust constitutive models capable of simulating extensively cracked concrete. In case of the Sandia model further analysis was conducted [3] to study the effects of accident temperatures on the containment capacity. The nonlinear behaviour starts soon after the design pressure is exceeded. Between 1 P_d and 3.5 P_d, local failures mostly due to yielding in the steel components and extensive cracking in the concrete occur. Beyond 3.5 P_d, the global collapse is initiated leading to catastrophic structural failure. This typical deformation behaviour is summarised in Fig 9.

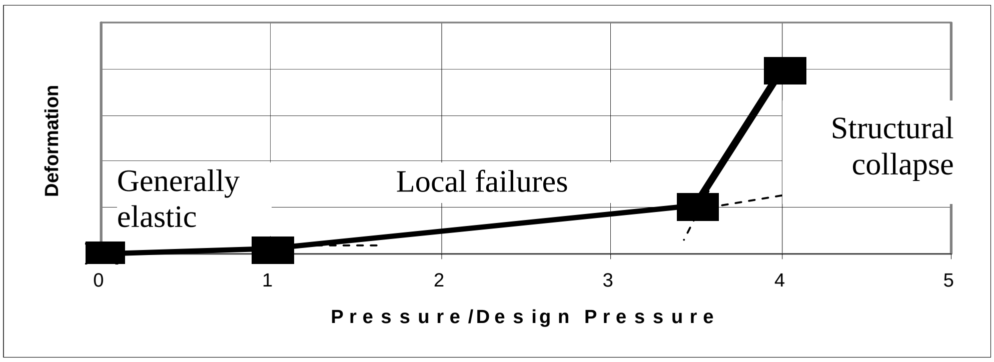

Fig.9: Progressive damage of the Sandia model in three stages

Functional failure pressure (P_f) is defined here for the unlined containment as the pressure at which through wall cracking occurs and in case of the containment with a steel liner P_f is defined as the pressure at which the liner tears. This is a type of local failure and can happen any time during the second stage of the progressive damage. For both types of containments, the structural collapse pressure (Pc) is the pressure at which catastrophic failure occurs. Table 1 presents a summary of Pf and Pc for both models.

Table 1: Summary of predicted functional failure and structural failure pressure

	SNL Model		BARC Model	
	Press. Only	Press. + Therm	Press. Only	Press. + Therm
Design press (Pd)	0.39 MPa	0.39 MPa	0.1413 MPa	0.1413 MPa
Functional Failure (Pf)	1.1 Mpa	1.25 Mpa	0.33 MPa	
Structural Collapse (Pc)	1.4 MPa	1.5 MPa	0.4077 MPa	
Pf / Pd	2.8	3.2	2.3	
Pc / Pd	3.6	3.8	2.9	
Pc / Pf	1.3	1.2	1.2	

CONCLUSIONS

It is demonstrated that with a judicious use of a specialist FEA package, an experienced analyst can predict the collapse limit and failure mode of a pressurised PCCV with fair accuracy. An added advantage of such test-based round robin analysis exercises is that it validates the structural models of containments which can then be used to study the effects of accident temperatures on containment capacity to ascertain the margin between onset of leakage and the burst pressure in full size containments.

RECOMMENDATIONS

Following two further studies are recommended:-

(a) Another exercise should be conducted to analyse the performance of the BARC model under combined pressure and thermal loading similar to the ISP48 exercise carried out with the SNL model.

(b) Apply the well known structural reliability methods to this problem by developing a failure equation for each of the three stages of failure, identify the variables influencing the failure and apply structural reliability method to obtain probability of failure.

(c) The probability of failure data obtained from (b) can be used to compare against the target probability of failure used in the limit state design codes.

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