Ultimate Capacity of Expansion Bellows in a BWR Containment

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ABSTRACT

Expansion bellows are used in containment penetrations to minimize the forces arising from differential movements between the pipe and the containment shell. In some containment designs, such as the BWR Mark I containment, bellows are also used to soften the connection between two parts of the containment structure. This is the case of the bellows mounted along vent and vacuum breaker lines. Bellows are an integral part of the containment pressure boundary and, in the event of a severe accident, they are subjected not only to an increase of pressure and temperature but also to substantial differential movements. The paper describes the three-dimensional finite element analyses requested by Nuclenor and carried out by Principia, to evaluate the ultimate capacity of a vent line bellows and a vacuum breaker bellows in a BWR Mark I containment. In this particular plant the bellows turned out to be the weakest point of the containment structure

INTRODUCTION

In the context of a level 2 Probabilistic Risk Assessment (PRA), Nuclenor commissioned Principia to evaluate the ultimate capacity of several bellows of the Santa María de Garoña NPP in a postulated severe accident scenario.

After defining the most severe accident scenario, an anticipated transient without scram (ATWS), the containment ultimate capacity study was carried out using a standard global-local approach. First, the global response of the containment structure under the accident loads was obtained. Then, from the global response, several potential failure modes were identified and analyzed. The local failure modes selected for further study included possible failures at or around large openings, like the equipment hatch and the personnel airlock. Other failure modes considered were failures of the drywell head, mechanical and electrical penetrations and the expansion joints or bellows located along the vent lines and vacuum breaker lines.

Available experimental results of complete bellows tested [1,2] were not considered to be applicable, since the analysis of global response showed that the conditions of these particular bellows during the postulated accident would differ substantially from test conditions. In particular, the tests were performed on bellows under compression and the global response is such that the bellows tend to stretch.

The paper describes the three-dimensional finite element analyses carried out by Principia to evaluate the ultimate capacity of a vent line bellows and a vacuum breaker bellows.

BELLOWS DESCRIPTION

Expansion bellows are used in containment penetrations to mitigate the effects of differential movements between the penetrating pipe and the containment shell. In some containment designs, such as the BWR Mark-I, bellows are also used to soften the connection between parts of the containment structure. This is the case of the bellows mounted along the vent and vacuum breaker lines in Santa María de Garoña NPP in Spain, as shown in figure 1.

These bellows are made of a cylindrical steel sheet, with convolutions designed to avoid the severe stress concentrations that differential movements may cause. In Garoña NPP two types of bellows are used along the lines connecting the drywell and wetwell (vent lines and vacuum breaker lines). The first type is located in the vent lines, which go from the drywell into the wetwell; the vacuum breaker bellows are placed in a secondary line connecting the drywell to the wetwell atmosphere. Both bellows are an integral part of the containment pressure boundary and, in the event of a severe accident, they are subjected not only to increases in pressure and temperature, but also to considerable differential movements.

The configuration of vent lines has two serial bellows linked by a coaxial cylinder. The dimension of the internal diameter is 1831 mm, whereas the combined length is 692 mm. The thickness of the steel sheet is 1.52 mm. Each bellows is formed by 5 convolutions, with a radius of 11.5 mm, as represented in figure 2.

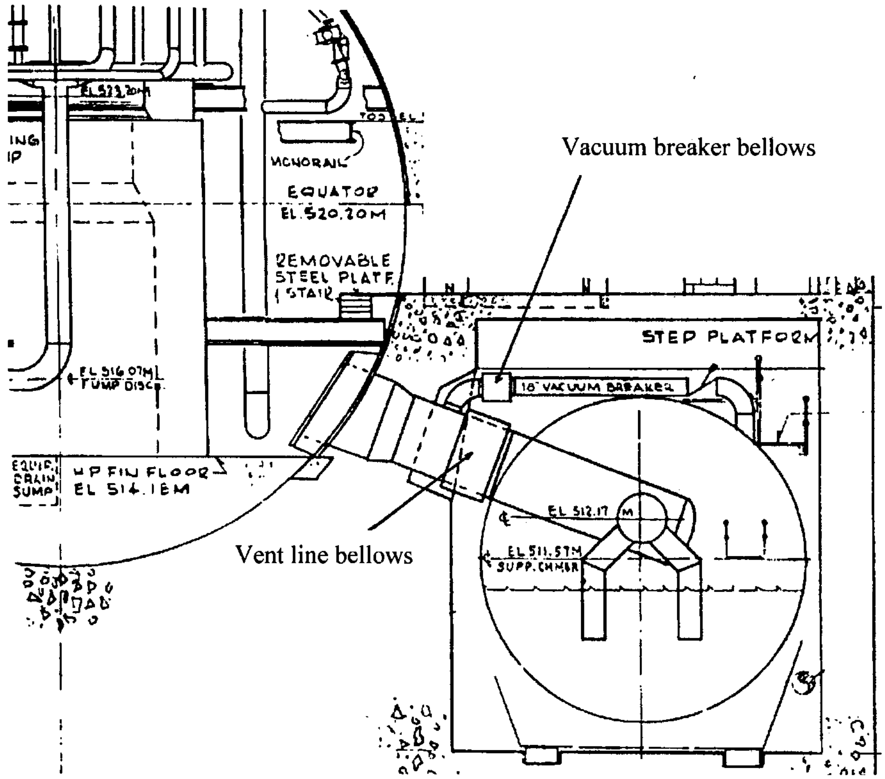

Figure 1 Bellows position

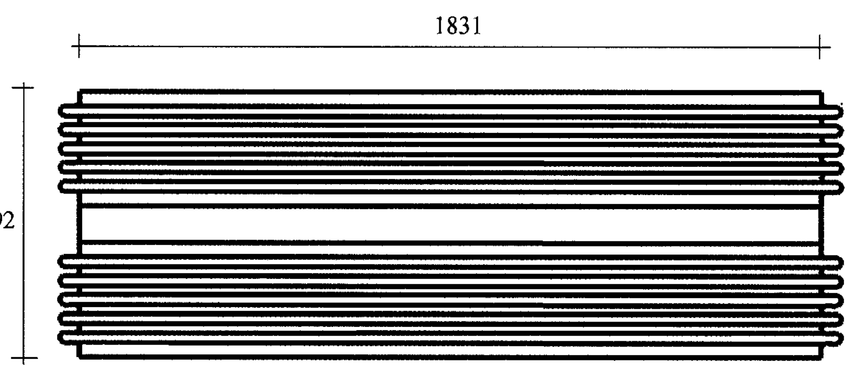

Figure 2 Vent line bellows (dimensions in mm)

The second configuration is the vacuum breaker bellows, which connects the wetwell atmosphere with the vent lines upstream of the wetwell. In this case only one bellows is placed; the dimensions are 411 mm in diameter and 356 mm in length, hence considerably smaller than the previous one. In this case, the shell thickness is 0.76 mm; the bellows is formed by 16 convolutions with 4.6 mm radius. The configuration of the vacuum breaker bellows is represented in figure 3.

Bellows are made of stainless steel ASME SA240 Gr.304. The properties of this material have been taken from NUREG/CR-6154 [1]. This document gathers results of uniaxial tests performed in the same material by the NRC at the Sandia National Laboratories. Of special concern is the dependence of these properties with respect to the temperature, since there are significant thermal variations in the surrounding atmosphere in the course of the postulated accident.

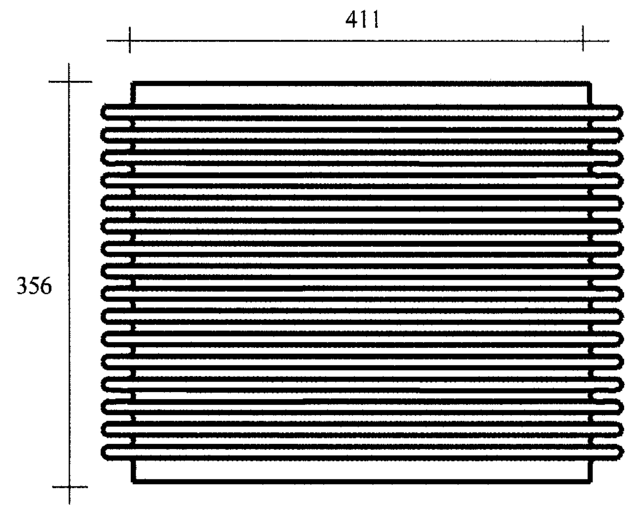

Figure 3 Vacuum breaker bellows (dimensions in mm)

Based on a statistical treatment of the results of the physical tests, median and deviations were derived for each of the properties. This allowed introducing the corresponding data tuples in the model for various confidence levels. Table 1 presents the statistical characterization of the properties.

Temperature (°C)	21		176	
	Median	Deviation	Median	Deviation
Yield stress (MPa)	273.8	23.2	199.9	16.9
Ultimate tensile stress (MPa)	703.3	32.4	541.5	24.9
Ultimate strain (%)	78.0	22.0	52.0	7.0

Table 1 Material properties

As stated, the bellows are subjected to a number of different loads during the postulated accident. First, an internal pressure is applied, growing from zero to 3.6 MPa about 1.7 hours later. Simultaneously, there is a temperature increase, from the service temperature to 230°C; this induces thermal stresses and causes changes in the values of the mechanical variation of properties. Finally, relative displacements are applied to the ends of the bellows in the axial, as well as in the transversal direction. The order of magnitude of these displacements is 40 mm for the axial extension, and 25 mm for the transversal relative displacement.

METHODOLOGY

Under these postulated accident loads, the ultimate capacity was assessed using finite element analysis. The model was designed using first order (four node) shell elements. Only half line was modeled, because of the symmetry displayed both by the bellows and by the demands applied.

Contact elements were placed along the surfaces where interactions between convolutions were expected. The finite element models can be seen in figure 4.

All relevant nonlinearities were taken into account in the analyses: geometrical nonlinearities, metal yielding and hardening, and contact between components. All the analyses were performed with the general purpose commercial code ABAQUS/Standard [3].

The model of the vent bellows had roughly 60,000 degrees of freedom. On the other hand, the computational model for the vacuum breaker bellow had approximately 91,000 degrees of freedom.

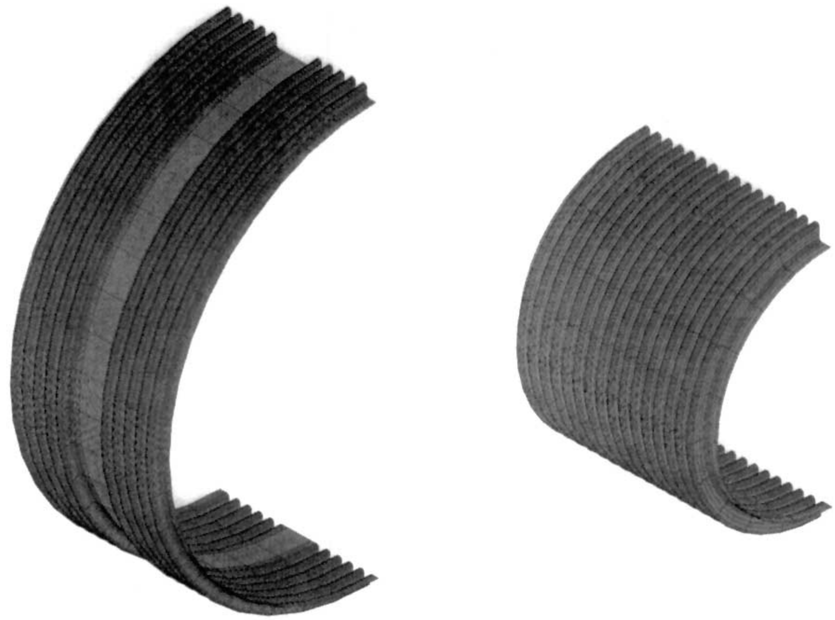

Figure 4 Finite element models for vent lines (left) and vacuum breaker lines (right)

In both cases, failure would be assumed to occur when effective plastic strains reached 2% in the middle surface of the shell or 4% in the inner or outer surfaces. These values are much lower than the ultimate strain of the material in uniaxial tensile tests at room temperature, which is typically around 75%. The reduction was meant to account for the lower ultimate strains observed at the higher temperatures, the biaxiality of the deformation and the possible shortcomings of the finite element discretization.

RESULTS

The previously specified loads were applied to the model. In the course of the analyses, severe numerical difficulties had to be overcome. They are associated with a "snap-through" instability, as the convolutions of the vent line bellows suddenly reverse their original shape. Interactions between convolutions in the vacuum breaker bellows give rise to similar problems.

In addition, nonlinearities grow also because of the large changes in geometry caused by progressive yielding of the material. However, simulations were carried out until 10% of equivalent plastic strain was reached in the shells. As stated, failure of the material was assumed to occur at 2% in the mid of the shell and 4% in the surface.

With median material properties, vent bellows failure takes place with 0.80 MPa of internal pressure, a temperature of about 170°C and relative displacements between the ends of 10 mm (axial) and 15 mm (transversal); as a reference, the design pressure of the containment is 0.43 MPa. A typical analysis took 20 CPU hours in a small workstation for reaching failure strains in the bellows.

In the case of the vacuum breaker bellows, with median material properties, failure takes place with 0.74 MPa of internal pressure, a temperature of about 170°C and relative displacements between the ends of 15 mm (axial) and 30 mm (transversal), and a typical analysis took just 7 CPU hours in a small workstation up to the point of reaching failure strains. As is well known, this design is more sensitive to lateral displacements than the “universal” type of design used for the vent line bellows. Hence, for the same level of temperature and pressure, even though the inner diameter in this case is smaller, the higher magnitude of the transversal displacements results in a lower ultimate capacity.

Figure 5 shows two deformed shapes at failure, where equivalent plastic strains at the external surface of the shell have been contoured. These simulations have been carried out with median material properties.

Reversal of the shell in the vent line bellows, as well as contact between convolutions in the vacuum breaker bellows can be observed in the outcome of the simulations.

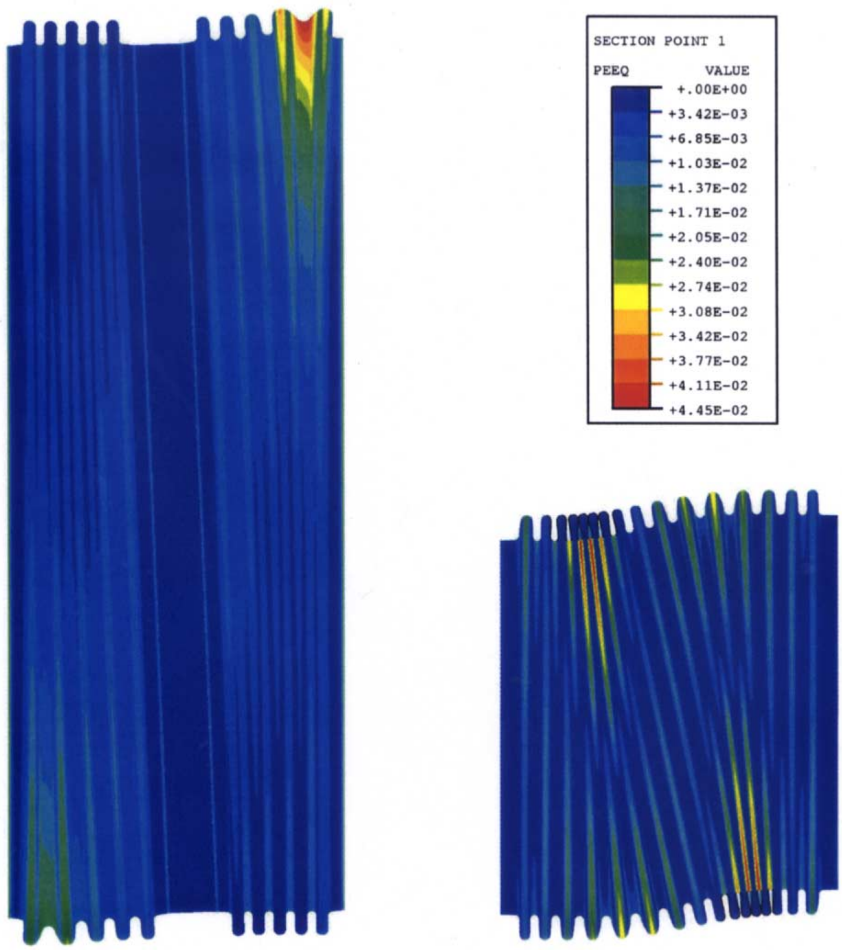

Figure 5 Shape and equivalent plastic strains at failure for median properties

In addition to the results produced with median properties, similar analyses were carried out with characteristic properties. This allowed to obtain high confidence results. The ultimate capacity of the vent line was 0.66 MPa, while only 0.61 MPa could be sustained before failure of the vacuum breaker bellows. These results were introduced together with the other potential failure modes in the fragility curve of the containment, represented in figure 6.

The bellows capacity had significant contribution in the global results, since other high confidence failure modes had a capacity about 3 times greater than the design pressure. The final fragility curve of the containment leads high confidence capacity of 0.566 MPa. This value is on the order of 1.3 times the design pressure of the containment.

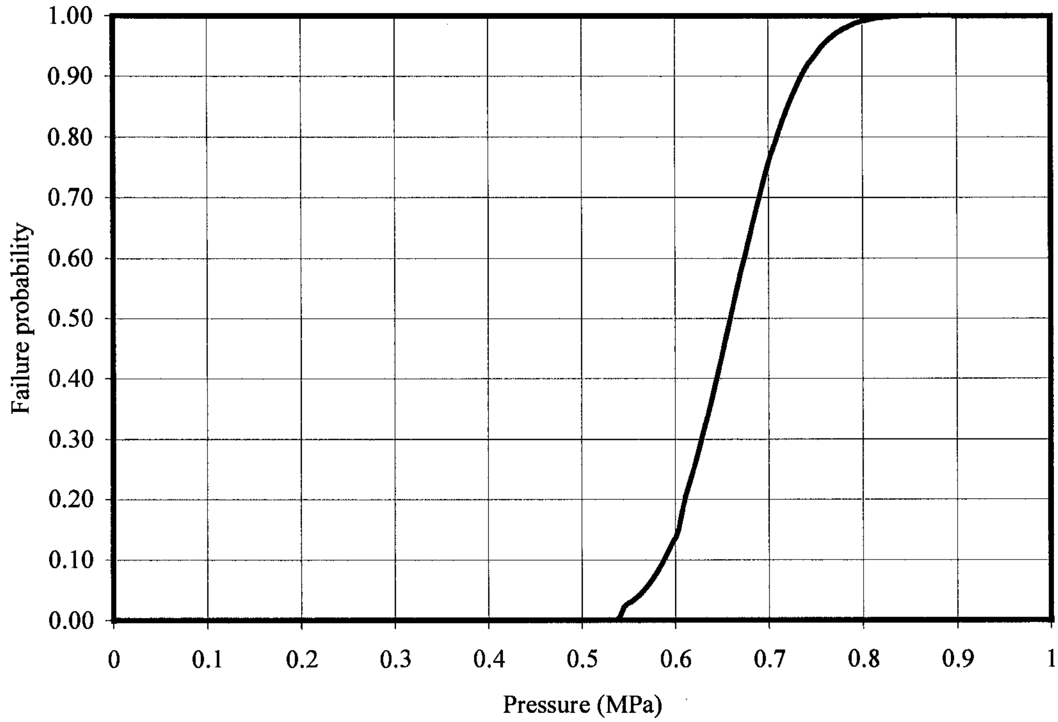

Figure 6 Fragility curve of the containment

CONCLUSIONS

Following detailed analyses, vent line and vacuum breaker bellows can be seen to limit the ultimate capacity of the containment.

As usual, the assessment of the ultimate capacity of a component requires advanced analyses that take into account all the nonlinear phenomena involved in the problem: geometrical nonlinearity, material yielding and interaction between components. Numerical difficulties arise because of this variety of factors. Obviously, these difficulties become more evident when the component approaches collapse load.

Nevertheless, current methodologies and numerical tools allow taking into account the nonlinearities in the analyses, leading to robust and accurate solutions.

REFERENCES

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[3] Hibbitt, Karlsson and Sorensen, Inc. (1998). "ABAQUS/Standard User's Manual", V5.8.