Mechanical Analysis of the equipment hatch behaviour for the French PWR 900 MWe under severe accident

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ABSTRACT

This paper presents the mechanical analysis carried out by the French institute IRSN (Institute for Radiation Protection and Nuclear Safety) on the equipment hatch of the French PWR 900MWe containment building under severe accident, in order to quantify the possibility of failure due to pressurization effects cumulated with thermal effects. Calculations are carried out with CAST3M code using the finite element method and three-dimensional deterministic model. The equipment hatch is identified as the weakest part of structure in the global model of the French PWR 900MWe containment building shown in another paper of SMIRT 2007, presented by IRSN [1]. Calculations are based on a multi-scale method using the results of the global model, so that each model is on the scale of the mechanical phenomena represented, by preserving a reasonable calculation cost. Incertitudes are quantified by sensibility studies. The scenario of severe accident is based on a progressive increase of pressure and temperature inside the containment building due a large break of primary circuit at full power with peak pressure due to hydrogen combustion and long-term loading due to Melt-Corium Concrete Interaction and inner containment water vaporization.

Two kinds of failure may happen : a crack in the leaktight steel structure and a disjunction of the two flanges of the closing system when the internal pressure increase. A maximum gap of 40 µm leads to a leakage area of about 1 cm². Because of irradiation, the seal between the flanges may lose its elasticity and its capacity of leaktighness and is not taken into account in calculations. This is why detail models are needed to modelise the screws tightening the two flanges, with contact and shearing phenomena.

The exact 3D geometry and the realistic boundary conditions constitute an innovative approach of the closing system : at conception, the equipment hatch has been assumed to support essentially axisymmetric efforts. The detailed models enable to understand for the first time how it is working and the main results is that there is a shear force applied to the screws due to the non-uniformity of efforts, deformations, contact and friction along the circumference of the two flanges and then, the necessity of providing new screws made of higher grade steel with larger diameter. This is why EDF is now changing the screws of the equipment hatch in all French PWR900 MWe.

INTRODUCTION

The IRSN used numerical models to asses the behaviour of the equipment hatch in case of severe accident, which is not directly available by experiment. The containment building is made of prestressed reinforced concrete. The equipment hatch, composed by a steel sleeve embedded in the concrete, a torospherical head and two 70 mm thickness flanges tightened by 88 screws is a sensitive point of the containment. The screw dimensions are very short, compared to the ones of the containment building. This is why a detailed model is needed. It also includes the concrete and the steel liner around the sleeve.

The local model presents some insufficiencies because of the use of shell elements for the flanges and truss elements for the screws. As a consequence, the sliding and the friction between flanges and the shearing of the screws could not be modelised easyly. The contact is simplified. This is why a more refined model called “restricted model” was

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developed, representing the exact 3D geometry of the structure, including, in volumic finite elements with a finer mesh : the sleeve, the two flanges, the torospherical head, the screws, the spacers assuming the contact between the two flanges and room for seals.

Then, deterministic calculations are carried out with CAST3M code using the finite element method to assess pressurization effects cumulated with thermal effects obtained in the case of a severe accident.

THE MULTI-SCALE STEPS METHOD

This multi-scale steps method enables the assessment of a small part of the structure with a fine mesh, and with a numerical description of phenomena which could not be possible on the whole structure because of the CPU cost. In the local model, the boundary conditions between the two flanges on which is based the equipment hatch closing could be defined close to the reality and the very small screws compared to the dimensions of the containment building could be modelized. The method is based on two major steps :

The first step is to define the initial state of the thirty years old structure. The concrete deferred deformations fields (shrinkage and creep), the stress field of the prestressed tendons are projected from the global 3D full turn model on to the local model. The forces equilibrium is calculated but the result is not consistent with the global model because of the elastic contraction of the concrete with the prestressing of the tendons. An iterative processus enables to obtain the same balanced state of the global and the local model corresponding to a cinematic balance at each Gauss point.

The second step is to calculate the behaviour of the structure during the accident under the internal pressure and the own weight. The mechanical and thermal conditions are similar to whose of the global model, and at each time, displacements of the global 3D quarter model of the containment building [1] are projected onto the limits of the local model. Calculations are carried out with imposed displacements.

The same method is applied, to obtain at each step, the boundary conditions of the restricted model "sleeve and flanges" and an iterative process enable to balance the initial state of scews, with the correct tightening value.

The figure below shows global 3D full turn model used for the prestressed concrete calculation, the quarter building used for the global severe accident, the equipment hatch model, and the restricted model composed of sleeve, flanges and screws.

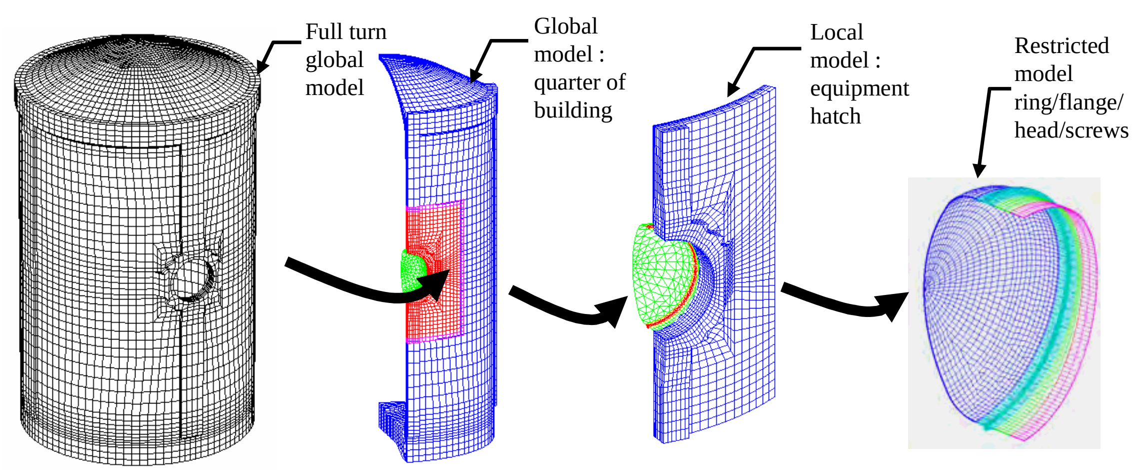

Figure 1. Finite elements models of the multi-scale method

Then, the global 3D model provides the boundary conditions of the local model (the equipment hatch) which gives in its turn the boundary conditions of the restricted model "sleeve and flanges". CPU cost for the severe accident with the local model is about ten time smaller than for the global model. So, many calculations could be conducted, modifying some mechanical parameters, boundary conditions, dimensions of the local models, characteristics of the screw... Numerical results do not vary significantly when dimensions of the local model increase, this point shows the validity of the method.

THE LOCAL MODEL

The equipment hatch is composed by a steel sleeve, a ring, an hemispherical head and two 70 mm thickness flanges tightened by 88 screws, the coupling flanges and corner brackets ensuring the anchoring of the sleeve in the concrete. The local model includes also the concrete around the equipment hatch, the steel liner and the sleeve, the anchoring of the sleeve in the concrete. By reason of symmetry, calculations are carried out on a half-geometry. The mesh is composed of linear elements, truss elements for screws, rebars and tendons, volumic elements with Ottosen smeared crack material for concrete, and shell elements.

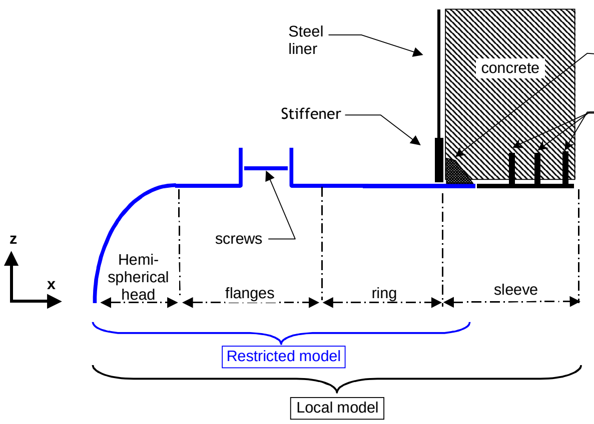

Figure 2. Geometry of local and restricted models

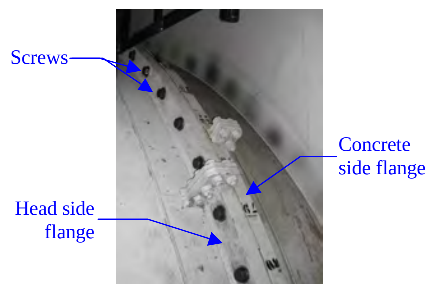

Figure 3. Picture of the two flanges

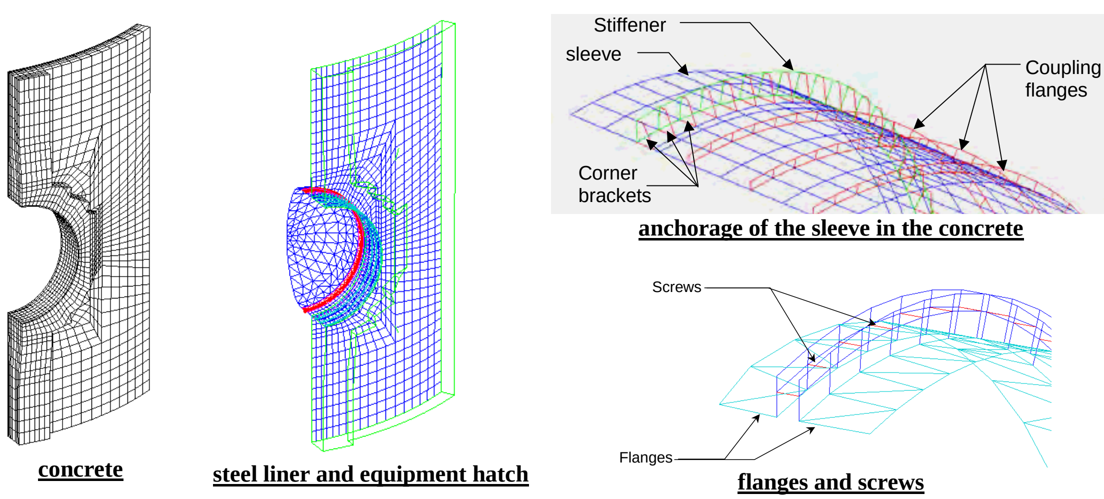

Figure 4. Meshes of the local finite elements model

The local model includes reinforcing bars (rebars), with a diameter of 16, 20, 25 and 32 mm and prestressing tendons (see figure 5). Rebars and prestressing tendons are modelised in their exact location with truss elements, by attaching particular care to the deviations around the equipment hatch and to the anchoring in the concrete around the sleeve because the model shall reflect the initial state of the structure before the accident. The mesh of rebars and tendons are independent of the concrete mesh, this makes a strong point of modelling, the mechanical adhesion is ensured by linear relations between the nodes degrees of freedom of each mesh, which leads to an important cost of calculation by the numerous nodes for modelling tendons (4500 approx.) and rebars (12200 approx.) and concrete (7200 approx.).

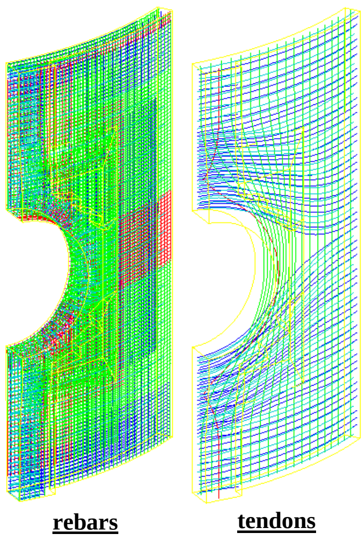

Figure 5. Rebars and tendons

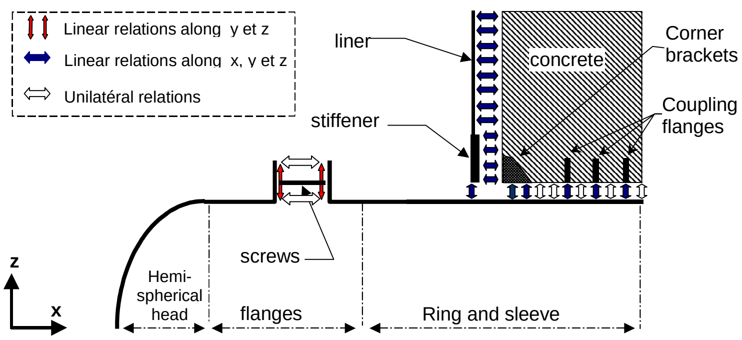

Figure 6. Boundaries conditions of the local model

The local model makes it possible to represent realistically boundary conditions : linear and unilateral relations between degrees of freedom of nodes enable to model the anchorage of the sleeve into the concrete and the relations between the two flanges, the spacing of the flanges without interpenetration, the blocking of the relative sliding of the two flanges. Figure 6 shows these boundary conditions.

Many aspects of modelling are analyzed. They constitute a sensitivity study. Among those, the zone of application of displacements on the local model, the sensitivity to the type of loading, the boundary conditions sleeve/concrete (with or without friction), the concrete and screws mechanical characteristics, the screws tightening, the level of prestressing. The dimensions of the local model as well as the quality of the mesh. The good correlation of the results obtained makes it possible to validate the method of projection from the global model onto the local one. The variability of the results makes it possible to quantify uncertainties.

The local model presents some insufficiencies because of use of shell elements which modelise the average layer of the structure, with as a consequence, a distance between the two flanges equal to the free length of the screws (84 mm) and a blocking of the relative sliding between flanges. The contact is simplified, and there is no friction. Truss elements modelling the screws are working only in traction without shearing. This is why a "restricted model" is developed, <u>representing the exact 3D geometry</u> of a reduced part of the equipment hatch.

THE RESTICTED MODEL

The restricted model included in volumic finite elements, the sleeve, the ring, the two flanges, the hemispherical head, the screws, the seam clamp and the external spacer assuming the contact between the two flanges, with a finer mesh. The screws of the equipment hatch are presstressed with a tightening value, as an initial constraint introduced in calculations (figure 7). The initial balance calculation disrupts the screws prestressing. An iterative process enables to determine free gap between flange and screws, in order to simulate the tightening of the screws after the prestressing of the building containment (drilling of the holes and borings after containment prestressing) and to thus remove parasitic shearing forces in the screws at the beginning of the accident in order to obtain a prestressing of the screws equal to the value of the tightening selected.

Linear or unilateral relations, the exact geometry and the management of the contact with friction make it possible to model the relative movement of the two flanges one compared to the other, but with a high cost of calculation. These realistic boundary conditions are completed by the possibility of defining a free lateral gap between flange and screws.

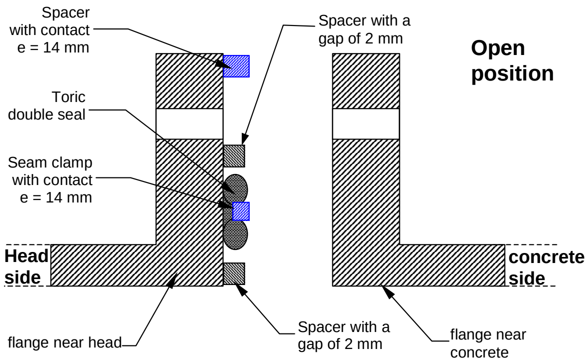

Figure 7. geometry of the restricted model

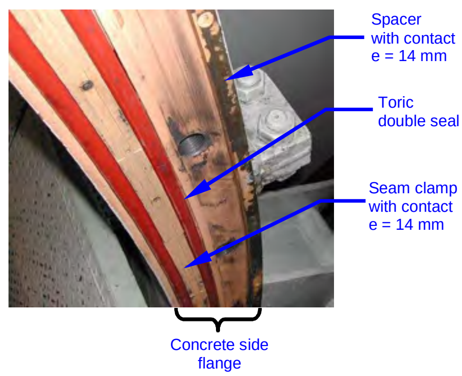

Figure 8. Picture of the concrete side flange

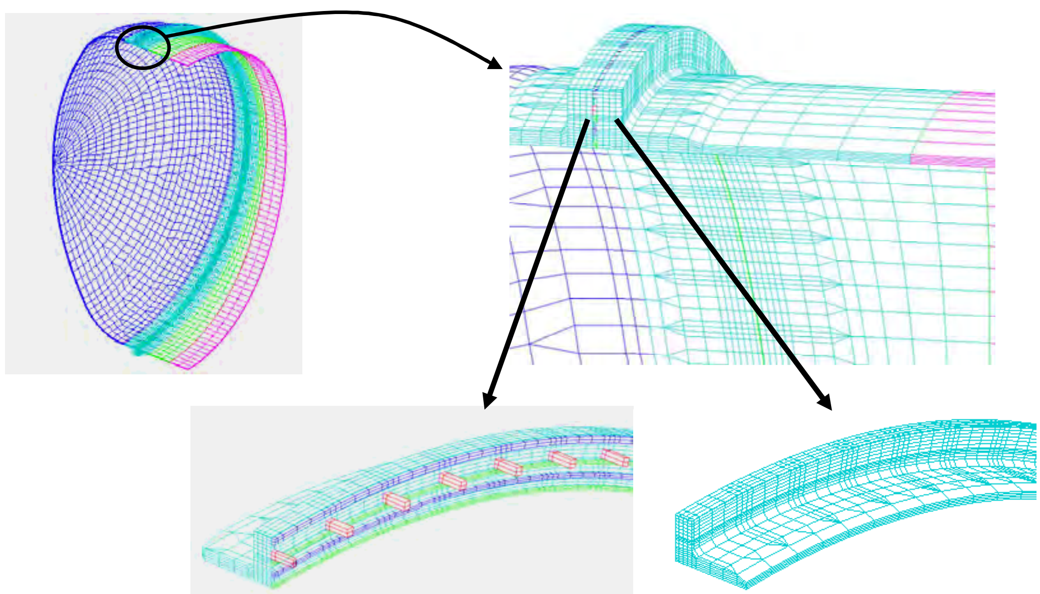

Figure 9. Meshes of the restricted model, the two flanges, the head side flange, the concrete side flange

The implementation of the calculation of the loading is based on :

- the projection of the displacement fields from the local model onto the boundary of the restricted model at each time step
- the nonlinear thermal calculation specific to the restricted model
- the application of the internal pressure and own weight

Three types of screw are studied with several mechanical characteristics and several diameters, corresponding to existing screws, and to different kinds of new screws which could replace the existing ones :

- E24 steel (mild steel - yield stress of about 210 MPa at 100°C), diameter 33 mm (thread of screw 3,5 mm)
- Z6 CNU 17.4 Steel (yield stress of about 730 MPa at 100°C), diameter 33 mm (thread of screw 1,5 mm)
- 40 CNDV 07.03 Steel (yield stress of about 850 MPa at 100°C), diameter 24 mm (thread of screw 3,5 mm)

RESULTS OF NUMERICAL STUDIES

The results are expressed through stress and strain fields, differential warping and differential ovalization of the flanges, contact forces on spacers and seam clamp, friction efforts between flanges, shearing and tensile forces in the screws.

The local model allows to better understand how the concrete becomes deformed around the sleeve subjected to many phenomena of inflection, how the cracking of the concrete develops, how these inflections generate an ovalization and a warping of the flanges. By the more precise and more detailed modelling of the elements composing the equipment hatch, one can define more realistic boundary conditions, between the sleeve and the concrete and between the anchorage of the sleeve and the concrete on the one hand, between the two flanges in opposite on the other hand. The restricted model, as for it, by the more realistic boundary conditions between flanges and screws, by the contact with friction make it possible to modelise the sliding of the flanges one compared to the other, which determine the traction and the shearing of the screws. An initial free lateral gap between flanges and screws is taken into account.

The differential displacement of the various generating lines of the ring, imposed by the concrete, causes a warping and an ovalization of the concrete side flange, which are opposed to the deformations of the hemispherical head side flange (see figure 10). The differential warping of the two flanges is responsible for the flanges opening. The differential ovalization of the two flanges is responsible for the screws shearing. As a consequence, contact forces are not uniform along the circumference on the seam clamp and on the external spacer (see figure 11) and screws plasticize at low pressure by shearing.

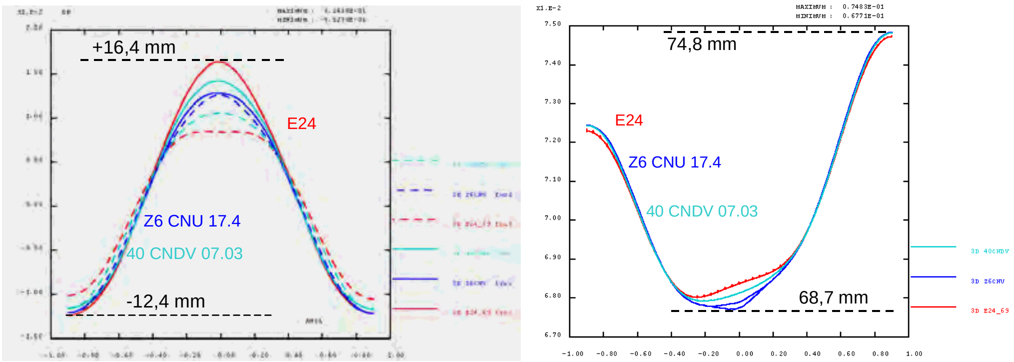

Figure 10. ovalisation and warping of the two flanges around the circumference

The two models lead to two complementary modes of loss of containment, according to possibilities of relative sliding of the flanges one compared to the other. A first mode is obtained in the local model with a spacing of the flanges and a break of the screws in traction, the second one is obtained in the restricted model, with a rupture of the screws by shearing. According to the friction between flanges and to the effects of site (difficult to quantify), reality will be between these two extreme situations. This is why both models should be taken into account.

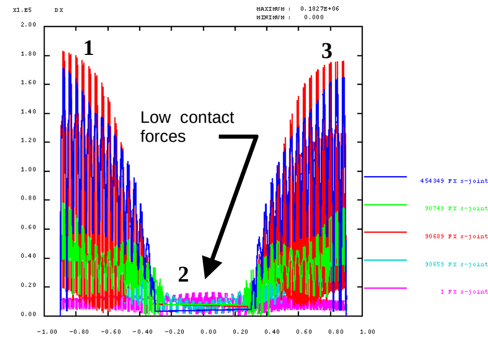

Figure 11. Distribution of contact forces along the equipment hatch circumference

The curves below present the maximum plastic deformation of the screws according to the relative pressure. There is a threshold which marks the beginning of an irreversible behaviour of the screws and thus of an irreversible opening of the flanges. This threshold strongly varies with the choice of the screws (see figure 13). The comparison between the results obtained and the three types of screws shows that spacing of the flanges and the screws plastification are delayed by a high yield stress (6 bar abs. for the screws out of E24 steel of diameter 33, 8 and 10 bar abs. for screws of high yield stress of diameter 24 and 33 mm).

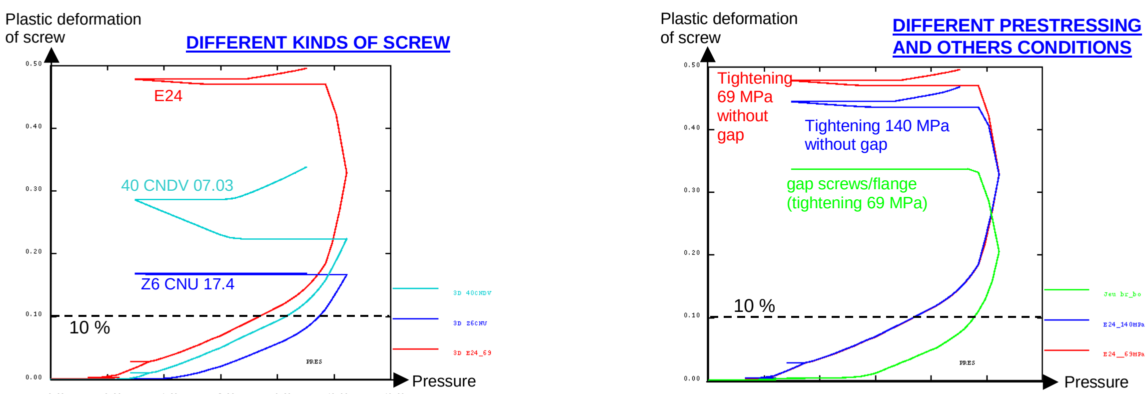

Figure 12. plastic deformation of the screws in the restricted model vs. pressure under different hypotheses

The shearing is significant and responsible for the screws plastification for relatively low pressures. Shearing is due to the differential displacement of the two flanges in the plane of contact. The taking into account of a lateral gap between flange and screws give a significant margin and delay in the shearing and the screws plastification (see figure 12). But that theoretical gap of 3 mm depends on positioning of the flanges on site, according to the care taken during the closing of the equipment hatch. The modification of the tightening of the screws has little effects on the results, which confirms that the most influent parameter is the resistant section of the screw.

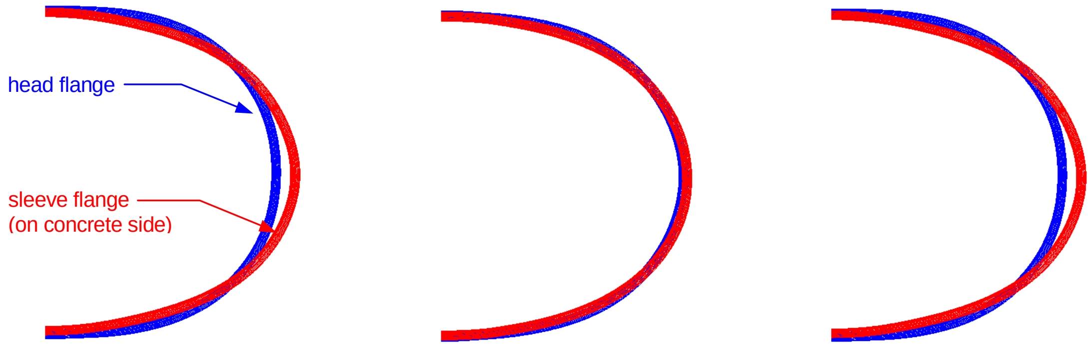

Figure 13. Deformation (ovalisation) of the faces flange

CONCLUSIONS

The aim of modelling the equipment hatch behaviour, during a severe accident, is to assess the possibility of failure due to pressure effects cumulated with thermal effects. Deterministic calculations with CAST3M code using the finite element method belong to a multi-scale step method so that each modelling is on the scale of the mechanical phenomena represented, by preserving a reasonable calculation cost. Sensitivity studies enable to validate the method and to quantify uncertainties.

The local model allows a better understanding of how the concrete loses its shape around the sleeve subjected to many phenomena of bending, how the cracking of the concrete develops, how these bendings generate an ovalization and a warping of the flanges. It confirms the results of the global model in terms of integrity of the liner and in terms of mechanical stability of the structure by elastic behaviour of tendons.

The restricted model in volumic finite elements, representing the exact 3D geometry makes it possible to study the screw shearing. According to possibilities of relative sliding of flanges one compared to the other, according to the non-uniform friction, both models lead to two complementary modes of containment loss, due either to the break of screws in traction or by shearing. There is a threshold, depending on the choice of the screws, which marks the beginning of any irreversible behaviour of the screws (plastic deformation) and thus of an irreversible opening of flanges and then a direct leak in the environment. The site effects depend on the exact location of screws into flange holes which is variable according to the quality of the closing of the equipment hatch. Such effect could be taken into account with a lateral gap between flange and screws that may give a significant margin and delay the shearing of screws.

The restricted model shows the need to have a very fine and complex model with contact and friction between flanges and screws, with the simulation of tightening after the setting in prestressing of concrete (difficult to be implemented numerically) in order to understand the effects of non-axisymmetric solicitations. Theses studies show, for the first time, i) the insufficiency of mild steel screw in the closing system of the equipment hatch in the event of severe accident, ii) the importance of the screw shearing, which is uncontrolled and variable with the lateral gap between screws and flanges and iii) the necessity of using new screws composed of higher grade steel with a larger diameter.

REFERENCES

[1] G. Nahas and B. Cirée, “Mechanical Analysis of the containment building behavior for the French PWR 900 MWe under severe accident” Proc. of SMIRT 2007.