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Codification process for the design of a steel liner for the EPR containment Comparison between American and Europeen code

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1 ABSTRACT

The opportunity to build an EPR in different countries during the next decades has inclined EDF Engineering Department presently involved in the construction of Flamanville 3 NPP to develop a new codification for the design of the Civil Works with a double goal: the first one is to comply with the Europeen Regulation (eurocodes) the other one is to take into account the specificity of this project in term of safety improvement. This code is entitled ETC-C (EPR Technical Code for Civil works)

The design of the containment steel liner gives a good exemple of this process. Placed on the inner face of the containment in order to minimise leakage, this liner, which is also used as concrete shuttering during the construction phase is bound to the concrete by an anchoring system made up of a net of angles and studs. As a consequence of this strongly pre-stressed concrete wall combined with high temperatures inside containment in case of Severe Accident, the design studies of this steel liner has popped up the necessity to consider blistering as a normal mode of deformation due to the presence of unavoidable manufacturing defects.

Difficulties related to the application of the former codification (ASME section III, Division 2) while using modern numerical methods are in a large extent due to the small strain allowable for the liner plate. Thus this paper shows how the new design code for EPR Civil works (ETC-C) matches this problem while complying with the safety requirements.

2 INTRODUCTION

After several years of operation, the first French NPPs (PWR 900 MW type) have shown that their internal containment metallic liner could be locally blistered. This phenomenon, which has been observed owing to regular surveys, was the subject of a study to determine its impact on the safety. This study, after having completed a mechanical analysis, established that the case was a normal mode of deformation considering the presence of imperfections and the level of strains. In the same time it concluded that the leaktightness of the containment was not affected considering the results of the periodical tests. This was corroborated by the surveys showing that the liner was in no case weakened by rust.

This background is the origin of the present approach for a more realistic design of the new generation NPPs containment with metallic liner. This paper deals with the different steps leading to a new codification brought by the ETC-C (EPR Technical Code for Civil works).

3 TECHNICAL ISSUE

On this type of concrete containment, the steel liner is mainly designed to provide leak-tightness during normal operation, containment tests and accidental events.

Fig.1 shows its general disposition covering the inner surface of the containment including the base mat. The only temporary openings are those dedicated to penetrations or anchor plates supporting equipments, subsequently welded to the liner and it is used as a formwork during the erection of the concrete wall.

The anchorage system welded to the liner comprises:

- Continuous anchorage, crossing at right-angles, delimiting areas of liner known as meshes

- Localized anchorages (studs) within the meshes, in a square pattern.

The continuous anchorages transmit concrete deformations to the liner. In addition they provide the liner sufficient rigidity during its assembly and during the concreting work.

The localized anchorages prevent the mesh from buckling. The spacing of the studs is such that local blistering, which may occur in the liner after pre-stressing of the wall or when heated, due to geometrical manufacturing imperfections, remains in acceptable limits.

3.1 Description of the loadings and general design of the containment steel liner

It is important to point out that after the erection of the concrete wall and particularly when the reactor is operating, the different loadings able to produce buckling (permanent or not), which apply on the containment induce exclusively secondary stress on the liner. The different loading situations (other than construction) expressed in terms of average strain of the liner are shown on the fig.2 diagram.

On this strain diagram, the common zone of the liner appears to be always in compression. However, considering the accidental situation and focusing on the L.H.' sequence (coming back to the low temperature), tensile stress may appear. This is due to the fact that during this accident the liner has plastified. This can be shown on the next diagram (fig 3) featuring the average strain versus stress.

In order to design this kind of liner, ASME code (Section III, Division 2) has defined allowable strains in CC 3720-1; their values are very small, max 1,4 % in compression. If these limits can be verified for a liner without defect, this is not the case when considering that the steel plates are not perfectly shaped. Then, local imperfections may initiate blistering and strains may locally exceed the allowable values of CC 3720-1.

With present 3D elasto-plastic calculations, we are able to model buckling in a very precise way, and consequently the results of these calculations are not global strains but local ones.

Consequently, the anchoring system plays a more complex role in the general design, as it has to cope with the multi-axial character of the liner behavior. By testing these anchors in every configuration it is necessary to verify that all of them fails without tearing the liner.

Therefore a new approach based on the following mechanical analysis has been developed and codified by EDF in ETC-C.

3.2 Mechanical analysis

The metallic liner is considered as being linked to the concrete, in a continuing manner without elastic or non-elastic sliding (continuous anchors transmit the strains of the concrete to the metallic liner). Therefore, each elementary mesh is independent from the others. Consequently, to analyze the behavior of the metallic liner in the common zones, the basic structure is an elementary mesh subjected, on its boundaries, to strains imposed by the containment wall for every combination to be taken into account. The thermal expansion of the liner is prevented leading potentially to the blistering of the metallic liner (induced by elastic or elasto-plastic buckling). Furthermore, accepting initial shape imperfections leads to consider the blistering as a normal mode of deformation for the metallic liner.

Out of the singular zones of the liner (penetrations, supporting plates, gussets…), the membrane strains are constant along the sides of a mesh. On the boundaries of the elementary mesh, imposed displacements are therefore uniform and can be either compression or traction.

Four cases have to be analyzed:

- An elementary mesh without shape defect (therefore assumed to be plane if curvature is ignored) submitted to traction can only have a behavior of pure membrane, which does not induce damage if traction is restricted.
- An elementary mesh without shape defect submitted to compression may have an elastic or elastic-plastic buckling if the compression reaches a critical value.
- An elementary mesh with shape imperfections (according to the manufacturing tolerances) subjected to traction has a behaviour, which tends to reduce the initial blistering.

- An elementary mesh with shape imperfections (according to the manufacturing tolerance) subjected to compression has a behavior that tends to increase the initial blistering.

According to the respective values of transversal and longitudinal strains acting on the elementary mesh, the buckling can appear on horizontal stripe, vertical stripe or "square" zone (see Fig.4).

The lost of leaktightness of the metallic liner can result from:

- The tearing of the metallic liner (base metal or welds), all the anchors being safe,
- The consequence of the possible failure of the continuous anchors or studs due to the modification of the metallic liner resulting from blistering.

Depending on whether the metallic liner is blistered or not, criteria to be respected concerning force or displacements differ. For a plane metallic liner, the studs are submitted to in plane forces that generate shearing forces in the studs. For a blistered metallic liner, the studs are submitted to in plane and out of plane forces that generate a combination of shearing force, normal force and bending moment in the stud as shown on fig. 5 and 6.

Therefore, design criteria for metallic liner have to take into account the multi-axial character of metallic liner behaviour.

In any case, when designing the liner, the real design of the anchors must be validated by adequate tests to:

- Prove that stud anchors shall be designed to fail before tearing the liner
- Determine the normal and tangential forces to the liner corresponding to the anchorage yield point and to the anchorage breaking point

3.3 Codification

The first step of the assessment of the liner was to produce detailed calculations in order to understand its behavior versus loadings, getting at the same time accurate values such as local strains due to strain controlled buckling.

The second step was to use ASME in order to compare results with allowable values. However some difficulties arose when comparing the local strains induced by buckling to the limits given in the code but also due to the lack of explanation on what and how to consider calculations results (i.e. ASME limits a single force on stud, but calculations show buckling and therefore a combination of forces and moments on the liner at the stud junction).

This situation led us to establish a set of consistent rules for the liner, which are today formalized in the ETC-C code. The table given below summarizes the main lines of the ETC-C approach with comparison to ASME.

4 TABLES AND FIGURES

<table>
<tr><th>ETC-C DESIGN RULES</th><th>ASME III – division 2</th></tr>
<tr><td></td><td><u>CC-3610 General</u>
(a) An analysis shall be prepared in sufficient detail to show that each of the design allowables of CC-3700 is satisfied when the liner, penetrations, brackets, and attachments are subjected to the loadings of CC-3200.
(b) Experimental results may be used to evaluate the capacity of components to withstand static or cyclic loading.</td></tr>
<tr><td><u>Loads categories</u>: 3 levels
Level 1
Construction, normal operation, test, serviceability earthquake
Level 2
Ground water level, LOCA, Severe accident (0.55 MPa), piping rupture, design earthquake or aircraft impact including vibration.
Level 3
Severe accident (0,65 MPa), LOCA + Design earthquake
Level 3bis
Internal explosion (H2)</td><td><u>Loads categories</u>:

Service
Construction, normal, test

Factored
Severe environmental, extreme environmental, abnormal, abnormal/severe environmental, abnormal/extreme environmental</td></tr>
<tr><td colspan="2">Comments on ETC-C
These criteria are those already considered for the concrete wall. They were also considered in the same way for the metal skin.
In each case, loads to be considered result from the simultaneous action of the concrete displacement fields (weight, prestressing, earthquake, etc.) and of the loads applied on the liner wall (pressure, temperature)</td></tr>
<tr><td>1.5.1.3 Design rules for construction situation
Prevention of P type damage in the liner :
σeq < 0.67 Rp02</td><td><u>Table CC-3720</u><table><tr><td>Level of criterion</td><td>membrane</td><td>Membrane+ bending</td></tr><tr><td>Construction</td><td>fst=fsc =0,67fpy</td><td>fst=fsc= 0,67fpy</td></tr></table></td></tr>
<tr><td colspan="2">Comments on ETC-C
The liner is used as formwork. For the construction, the liner thickness shall be such that there is no type P damage, no buckling and that concrete thrust is acceptable.
With a 6 mm thick skin, typical heights for concrete pouring are about near to 60 cm</td></tr>
<tr><td><u>1.5.1.4. Design rules for the other situations</u>
<u>1.5.1.4.1 determination of size and spacing of studs</u>
Liner supposed to be perfect.
No buckling behavior for level 1 situations, using a design (safety) factor of 1, defines spacing.</td><td><u>CC-3730 Liner Anchors</u>

The anchorage size and spacing shall be chosen so that the response of the liner is predictable</td></tr>
<tr><td><u>1.5.1.4.2 Design rules for liner without defect</u>
- No shape imperfections and all anchorages are present
- Elastic- plastic analysis using isotropic strain hardening rule and minimum tensile curves
- Criteria on ε_m and $\varepsilon_m+\varepsilon_b$ depending on the criterion level:<table><tr><td>Level of criterion</td><td>ε_m</td><td>$\varepsilon_m+\varepsilon_b$</td></tr><tr><td>1</td><td>$-0.002 \le \varepsilon_m \le 0.001$</td><td>$-0.004 \le \varepsilon_m+\varepsilon_b \le 0.002$</td></tr><tr><td>2</td><td>$-0.005 \le \varepsilon_m \le 0.003$</td><td>$-0.014 \le \varepsilon_m+\varepsilon_b \le 0.010$</td></tr><tr><td>3</td><td>$-0.007 \le \varepsilon_m \le 0.004$</td><td>$-0.018 \le \varepsilon_m+\varepsilon_b \le 0.012$</td></tr><tr><td>3bis</td><td>$-0.010 \le \varepsilon_m$</td><td></td></tr></table></td><td><u>CC-3620</u>

The liner analysis shall consider deviations in liner geometry due to tolerances

<u>Table CC-3720-1</u>
Criteria on ε_m and $\varepsilon_m+\varepsilon_b$ depending on the criterion level<table><tr><td>Level of criterion</td><td>ε_m</td><td>$\varepsilon_m+\varepsilon_b$</td></tr><tr><td>Service</td><td>$-0.002 \le \varepsilon_m \le 0.002$</td><td>$-0.004 \le \varepsilon_m+\varepsilon_b \le 0.004$</td></tr><tr><td>Factored</td><td>$-0.005 \le \varepsilon_m \le 0.003$</td><td>$-0.014 \le \varepsilon_m+\varepsilon_b \le 0.010$</td></tr></table></td></tr>
</table>

ETC-C DESIGN RULES	ASME III – division 2
Comments on ETC-C *- in that case, in current part, the liner remains stuck in the concrete and the criteria for the membrane are in fact the limits already considered for the concrete, directly applied to the skin* *- Using non linear buckling analysis considering the lower bound characteristics, It was also verified that, even in case of buckling, the 6 mm skin remained safe.* *Note: the criteria "membrane+bending" were specifically introduced for the singular zones (penetration, mounting plates, gussets.).* *The use of a high performance concrete which limits the effects of the creep would allow to face more severe criteria (in compression).*	
1.5.1.4.3 Design rules for liner with imperfections (for stud analysis) . **configurations to be studied:** - strip between 2 rows of localized anchorages and limited by two continuous anchorages (in any direction). - square area a or a√2 (a= studs spacing) - square area 2a (one stud anchorage broken), - rectangular area limited by continuous anchorages (all stud anchors in a mesh are broken). **Buckling Analysis** - defect proportional to buckling mode, amplitude proportional to tolerances - elastic plastic analysis as in 1.5.1.4.2 **Design rules** : **- No criteria** are given for the **strains** in the liner. Criteria are only relative to the **behavior of anchorages.** **-** Determination of: +Normal and tangential forces acting on stud and continuous anchorages + Normal and tangential displacements of studs and continuous anchorages **Tests must be achieved to:** - prove that anchors shall be designed to fail before tearing the liner -determine normal and tangential forces to the liner corresponding to anchorage yield and breaking point Note : set of criteria to be used for normal and tangential forces.	**CC 3630 Liner anchors** The anchors may be analyzed assuming the liner remains elastic under all conditions […]. Plasticity may be taken into account if liner yield stress determined by biaxial test. **CC 3810 Liner anchors** Anchor design shall consider : a) unbalanced loads resulting from variation of liner curvature b) liner thicker than nominal, c) yield strength higher than minimal. d) weld offset, structural discontinuities and concrete voids behind the liner, e) variations in anchor spacing, f) Variation in anchor stiffness due to variation of the concrete modulus, g) local concrete crushing in the anchor zone, h) stud anchors shall be designed to fail before tearing the liner, **Table CC-3730-1** : Liner anchorage allowable values

Criterion	Mech. loads	Displ. Limited loads
1	Min (0.67 Fy; 0,5Fu)	0.25 U
2	Min (0.9 Fy; 0,7Fu)	0.5 U
3	Min (Fy; 0,8Fu)	0.6 U
3bis	Min (Fy; 0,8Fu)	0.6 U

Criterion	Mech. loads	Displ. Limited loads
Test, normal, severe environment	Min (0.67 Fy; 0,33Fu)	0.25 δu
Abnormal, Abn/severe environment/ extreme environment	Min (0.9 Fy; 0,5Fu)	0.5 δu

ETC-C DESIGN RULES	ASME III – division 2
Comments on ETC-C *For checking mechanical behavior of the studs, buckling of the liner is to be taken into account by supposing the presence of a shape defect. In practice the favorable curvature of the building is neglected and a flat liner with the allowable defect resulting from manufacturing is considered.* ***- the amplitude of the defect which has the shape of the buckling mode*** *has to be a function of manufacturing tolerances presented in part II of the ETC-C.* *The initial amplitude of the shape defect has an influence all the weaker on the results that the load in imposed deformation is important.* *- According to calculation results, the* ***deformation of the skin*** *after buckling can take values of the order of 3 %. For the considered material, the tests showed that this value was acceptable.* *- The blistering, by "leverage effect", risks to induce failures of the studs (cf tests). Thus the minimum curves of traction are used for the skin in order to privilege the buckling and maximize the efforts on the studs.* ***Configurations to be studied*** *The stiffener frame does not consider an integer number of steps of studs (150mm) and the horizontal and vertical forces imposed by the concrete are not the same. So the buckling of a line becomes likely and must be considered. The case of an elementary mesh with a square length a√2 must be also considered.* ***Criteria*** *The criteria given for forces and displacement movements are applicable to studs and to continuous anchors frames and are determined experimentally.* *Field experience indicates that the fuse is rather the angle iron than the stud:* *- the stud breaks (by tests) in the cylindrical part (the weld in the liner remains sound) and the presence of the concrete is practically without influence on the results. For traction loadings, there is a mechanism of "necking", for shear loads the stud is slightly lifted at first, then breaks below the weld.* *- at the contrary, the angle iron resists to the forces imposed by the concrete: it does not break, but the concrete does.* *All the indicated limits are related to a step of 150mm, one given diameter of stud, one given thickness of angle iron, one given material. All this is related to French NPP!*	
<u>1.5.1.5 Material</u> Liner : P265 GH Continuous anchorages S235JR Connectors S235J2	
Comments on ETC-C *The current rules of the ETC-C are justified by tests. They are applicable only for the considered materials*	

<table>
<tr><th>ETC-C DESIGN RULES</th><th>ASME III – division 2</th></tr>
<tr><td>

1.5.2 Containment Penetration assemblies

1.5.2.3 Design rules

- Prevention of P type damage by elastic analysis

Criterion	Pm	PL	PL+Pb
Level 1	0,67Rp02	Rp02	

- Prevention of P type damage by limit analysis

Criterion	Limit
Level 2	0.9Rp02
Level 3	0.7Rm

- Prevention of buckling

Consideration of elastic buckling
Safety factors for load controlled buckling :
2.5, 2.0, 1.3 (resp for levels 1, 2, 3)
Safety factors for strain controlled buckling :
1.67, 1.4, 1.1(resp for levels 1,, 2, 3)

1.5.2.4 Optional design rules

If design rules are not satisfied, elastic plastic analysis can be implemented.
Shape defect = first buckling mode with intensity depending on tolerances
No excessive deformation or plastic instability must occur using the appropriate safety factors.

</td><td>

CC 3640 Penetration assemblies

Same procedures as those used for metal containment in division 1.

CC 3740 Penetration assemblies

For parts not backed by concrete, Design allowables are the same as those for division 1

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<tr><td colspan="2">

Comments on ETC-C

For penetrations, the rules are the same as for the shells

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</table>

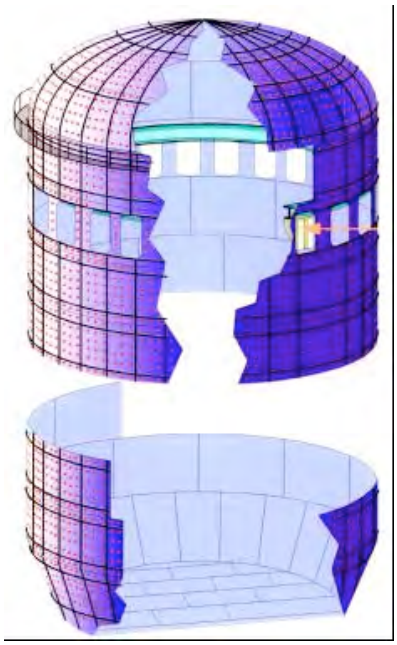
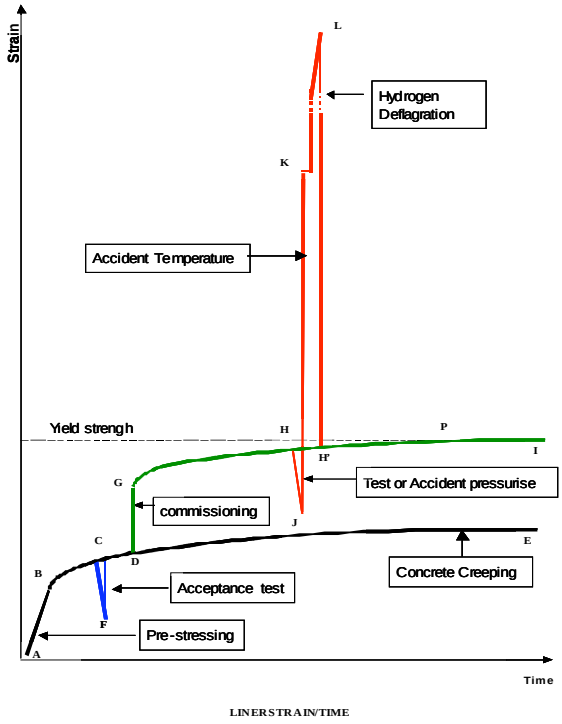
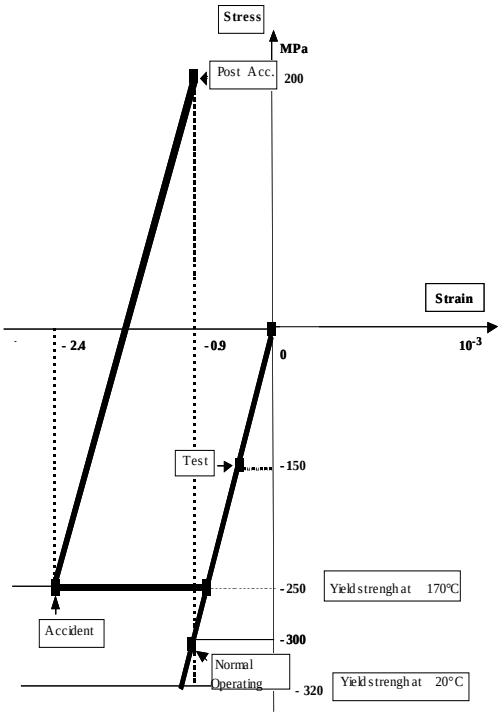


Fig 1



LINER STRAIN/TIME

Fig 2

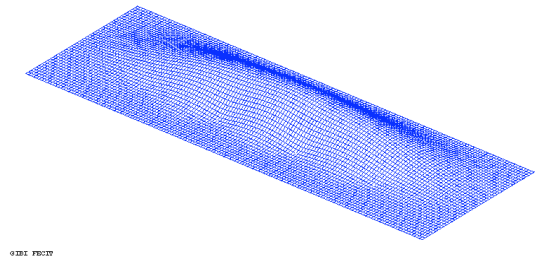


STRESS / STRAIN DIAGRAM

Fig 3

Schematically, three main sequences can be distinguished all along the containment lifetime.

1) A.B.C.D.E.: pre-stressing, concrete creep and shrinkage
   C.F. : acceptance test.
2) D.G.H.H.'I. : Unit in operation
   D.G. : temperature change from 20 to 45°C
   G.I. : concrete creep
3) H.J.K.L.H'. : accidental situation
   H.J. : pressure effect
   J.K. : temperature increase : liner becomes plastic
   K.L. : hypothetical hydrogen deflagration : liner is further plastified
   L.H.' : come back to standard situation



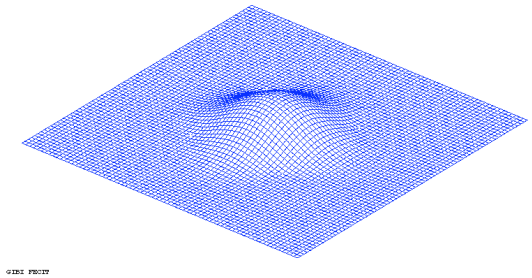


Fig 4

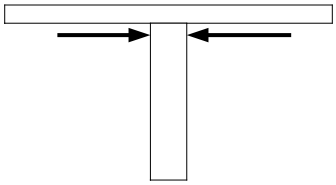


Fig. 5: In plane behavior

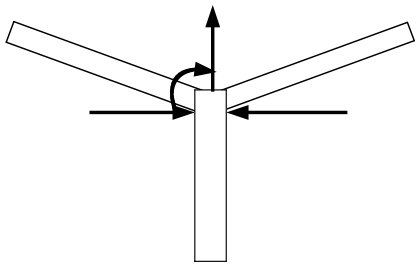


Fig. 6 : Out of plane behavior

5 CONCLUSION

The present ETC-C issue is one solution to take into account the blistering of the containment metallic liner in the design rules. It has been experienced on the new French NPP design including tests on the anchoring system. Some complementary studies seem necessary to promote more realistic criteria based on local stress (strains) as could be obtained by the modern numerical methods. This possible solution would allow designing such a structure taking into account singularities and local geometric heterogeneities.

In this chapter you should summarise the most important achievements presented in this article.

REFERENCES

2007 ASME Boiler and Pressure Vessel Code - Section III, Division 2 –Code for Concrete Containment.

2008 ETC-C – EPR Technical Code for Civil works