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Concrete monitoring analysis during the prestressing of a containment and comparison with foreseen design values

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ABSTRACT

For the second unit of the nuclear power plant of CIVAUX (which is the latest PWR 1400 MW-N4 unit), measurements on the instrumentation device have been automatically done since the beginning of the erection. According to the actual date of prestressing of each tendon and with the theoretical laws for the creep and for the shrinkage, the theoretical strains in the containment are calculated and compared to the measured values.

1. DESCRIPTION OF THE CONTAINMENT

On the site of CIVAUX, near the town of Poitiers (France), Electricite de France is leading the construction of the two latest PWR units of the French 1400 MW - N4 project which should be respectively placed into operation by the end of 1997 and by 1999.

The containment of each reactor building of these units has already been completed and has successfully undergone its commissionning pressure test.

This containment is designed to resist to an internal pressure equal to 0.53 MPa absolute and to insure the confinement of fission products in case of a loss of coolant accident (LOCA); it is also designed to resist to external hazards as earthquake, airplane crash, explosion... It is constituted with a 120 cm thick inner containment wall in prestressed concrete and with a 55 cm thick outer containment wall in reinforced concrete (see figure 1).

As in the previous French double containment units, the inner containment of the first unit of CIVAUX has been designed and built with an ordinary concrete (fc = 36 MPa). On the other end, the inner containment of the second unit of CIVAUX, though designed identically, has been built with a High Performance concrete (more than 50 MPa) which has specially been developed in order to improve the containment leaktightness and experiment the materials which will be used in future nuclear projects.

2. DESCRIPTION OF THE INSTRUMENTATION DEVICE

As the other N4 reactor units, the inner containment walls of both CIVAUX units have been equipped with instrumentation device in order to provide strains and displacement at particular steps of the prestressing phase, during the air pressure tests and more generally during the life of the containment.

2.1. Standard instrumentation device

The N4 standard instrumentation device consists in sensors which enable measures of the global deformation of the inner containment wall, local measures in concrete and measures of tendon tension variation. The N4 standard and the CIVAUX 1 instrumentation device consists in:

- 12 pendulums and 4 invar wires for the measuring of the global deformation of the inner containment wall,
- 60 extensometers and 46 thermocouples embedded in concrete for the local measuring in concrete,
- 4 dynamometers on prestressing tendons for the tendon tension variation.

2.2. CIVAUX unit 2 additional instrumentation device

In order to know the behaviour of the experimental high performance concrete used in CIVAUX unit 2, the inner containment wall of this unit has been equipped with additional instrumentation device. So the CIVAUX 2 instrumentation device consists in (see figure 3) :

- 12 pendulums and 4 invar wires,
- 110 extensometers and 46 thermocouples embedded in concrete,
- 4 dynamometers on prestressing tendons.

2.3. Automatic remote monitoring

In order to facilitate the measuring operation and to increase the measuring accuracy and frequency, it has been decided to install an automatic remote monitoring system. In CIVAUX unit 2, this system has been operating since the beginning of the erection of the containment, which made possible to follow everyday the behaviour of the HP concrete during the pouring operation and the deformation of the containment wall during the different phases of the construction. In comparison, the measure frequency during the prestressing of CIVAUX unit 1 was around once a month.

3. PRESTRESSING OF THE INNER CONTAINMENT WALL

Except for three 54T16 tendons in the polar crane corbel of CIVAUX unit 2, the prestressing of both CIVAUX containments is assured with 37T16 tendons ; these tendons are constituted with 37 strands, each of which having a section equal to 1.5 cm^2 and a guaranteed rupture limit equal to 1860 MPa. The cylinder is prestressed with a set of vertical and horizontal tendons (cf. figure 2). The vertical tendons constitute two main families :

- 60 pure vertical tendons prestressed from their lower ends in the basemat gallery and passively anchored in the dome belt,
- 112 " gamma " tendons which are vertical tendons turning over the dome ; they are prestressed from both ends in the basemat galery and in the dome belt.

The horizontal tendons go round the cylinder and are anchored and prestressed from both ends. They are arranged in two layers (an inner layer and an outer layer) which are anchored on two diameterly opposed buttresses. The dome is prestressed with the " gamma " tendons mentionned above which are arranged in two perpendicular layers. In the N4 containment, there are neither pure dome tendons nor additional prestressing around discontinuities.

The prestressing of the CIVAUX unit 2 containment has been applied progressively during about 8 months in a specific order according to the following planning (table 1):

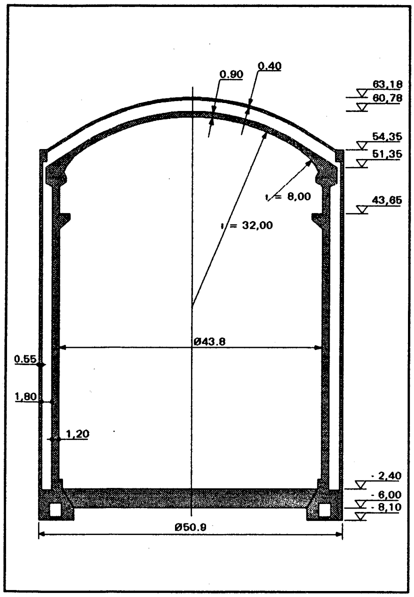


Figure 1. Geometrical characteristics of CIVAUX containments

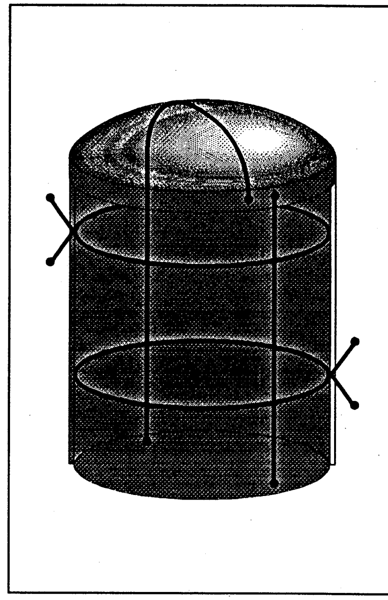


Figure 2. Prestressing tendon types of CIVAUX containments

Tendon type	phase	prestress beginning	prestress end
14 pure vertical	0	06/09/1994	07/09/1994
42 horizontal	1 to 2	26/09/1994	29/09/1994
33 horizontal	1 to 2	12/10/1994	19/10/1994
29 horizontal	3	28/10/1994	07/11/1994
21 horizontal	4	17/11/1994	21/11/1994
21 horizontal	5	28/11/1994	30/11/1994
16 gamma	1	13/12/1994	18/12/1994
20 gamma	2	03/01/1995	05/01/1995
27 horizontal	1 to 2	13/10/1995	24/01/1995
3 horizontal (54T16)		02/02/1995	07/02/1995
16 gamma	3	20/02/1995	23/02/1995
16 gamma	4	02/03/1995	06/03/1995
24 gamma	5	28/03/1995	30/03/1995
20 gamma	5'	13/04/1995	19/04/1995
4 pure vertical (dyna)		25/04/1995	26/05/1995

Table 1. CIVAUX 2 - prestressing phase planning

During the prestressing of the containment, the instantaneous strains under applied stresses and the delayed strains are simultaneous. If the measurements are limited to some measures at the beginning and at the end of the prestressing, as it was the case in CHOOZ B units, the part of each strain is not very well known. On the contrary, in CIVAUX unit 2, the daily measurements made possible to follow the strain evolution due to :

- shrinkage before and during the prestressing,
- each prestressing phase,
- creep after each prestressing stress.

4. THEORETICAL ANALYSIS

During the prestressing, the containment wall is subject to membrane stresses and to temporary bending stresses. According to the actual date of prestressing of each tendon and with the theoretical laws for the creep and for the shrinkage, the theoretical strains in the containment are calculated.

The theoretical strain value due to the mechanical forces are calculated according to formula for cylindrical tube under axially symmetrical loading. The effect of the dead load or of a group of vertical tendons is assumed to create uniform vertical forces, vertical strains and tangential strain due to Poisson's effect. The effect of one horizontal tendon is assumed equal to the effect of a radial symmetrical force, which creates hoop forces and vertical bending moment. The uniform (horizontal or vertical) strains and the variation of the strains in the thickness can be estimated according to the forces and to the moments with a value of Young's modulus and Poisson' s ratio.

The shrinkage is estimated according to the FIP-CEB model code 1990 which uses two parameters for the calculation of the shrinkage strains:

- the notional shrinkage coefficient ε_{cso} and
- the development of the shrinkage with the time $\beta_s(t-t_s)=\left[\frac{(t-t_s)}{\beta_{sH}+(t-t_s)}\right]^{0,5}$

  (with t_s the time of concrete pouring and β_{sH} a parameter for the shrinkage development).

The creep deformation is estimated according to the FIP-CEB model code 1990 which uses two parameters for the calculation of the creep compliance:

- the notional creep coefficient ϕ_o and
- the development of the creep with the time $\beta_c(t-t_0)=\left[\frac{(t-t_0)}{\beta_H+(t-t_0)}\right]^{0,3}$

  (with t_o the time of loading and β_H a parameter for the creep development).

In conclusion, the strains in the containment can be estimated according the time with six parameters (Young's modulus, Poisson's ratio, total shrinkage, shrinkage kinetic ratio, creep coefficient, creep kinetic ratio) and with the load forces and their corresponding time. The theoretical analysis can be conducted in the current area of the cylinder or in particular areas as the lower or the upper part of the containment.

5. COMPARISON BETWEEN THEORETICAL VALUES AND MEASUREMENTS

The theoretical strains in the inner containment wall and the diameter variations are compared to the measured values. The following figures 4, 5 and 6 show the comparison between the theoretical values and the measured values in the current area at level 25,40 m for the CIVAUX unit 2. The three figures give:

- the mean strain in the tangential, vertical and radial directions (figure 4),
- the vertical strain difference between the extrados and the intrados (curvature) (figure 5),
- the diameter variation (figure 6).

The Young's Modulus and the Poisson's ratio are estimated according to the measures and the other parameters are calculated according to the FIP-CEB formula. The curve comparisons show a good correlation between the actual values and the calculation. The strains and the deformation due to membrane stresses and the strains due to the temporary bending stresses which can be calculated are similar to the measured values.

The comparison between theoretical mean strains and the measured mean strains for the CIVAUX unit 1 (where the measuring frequency was much lower than for unit 2) is given in the figure 7. It is the same type of containment located on the same site and so built with the same concrete aggregates. The only difference with unit 2 is that the concrete used is only an ordinary concrete instead of a high performance concrete.

The confrontation of these measurements on a high performance concrete and measurements on an ordinary concrete shows the favourable effect of the high performance concrete on the Young's Modulus and in the delayed strains. The six concrete parameters for each containment are given in the following table 2:

	CIVAUX UNIT 1	CIVAUX UNIT 2
E (MPa)	26500 MPa	34 000 MPa
υ	0,22	0,25
ε_{cso}	580 µm/m	386 µm/m
β_{sH}	50 400 days	50 400 days
ϕ_o	4,1	3,06
β_H	1500 days	1500 days

Table 2. concrete parameters of the CIVAUX inner containment walls

The Young's modulus (E) and the Poisson's ratio (v) are estimated according to the measures and the other parameter are calculated with the following characteristic strength fc_{28} = 36 MPa for the unit 1 and 65 MPa for the unit 2. The concrete modulus is 30 % higher for the high performance concrete and the time dependent strains are 30 % lower for the high performance concrete. Two years after the prestress beginning, the horizontal strain is 800 µm/m for the unit 1 and 550 µm/m for the unit 2 and the applied loads are the same. The results enable to predict that the use of such a high performance concrete provides a higher compressive stress ratio at the end of the life of the containment.

The figures 8 and 9 show the comparison between the theoretical values and the measured values in the particular area of the internal structures floor at 6,60 level. The main difference for the particular point is that there is a permanent bending moment in the wall due to the effect of the floor on the cylinder. The two figures give:

- the mean strain in the tangential and vertical directions (figure 8),
- the vertical strain difference between the extrados and the intrados (curvature) (figure 9),

The 6 parameters used in current part are the same for the lower part, only the radial stiffness of the floor at level 6.60m is estimated according to the measures. The curve comparisons show a good correlation between the actual values and the calculation. The strains and the deformation due to membrane stresses and the strains due to the permanent bending stresses which can be calculated are similar to the measured values.

6. CONCLUSION

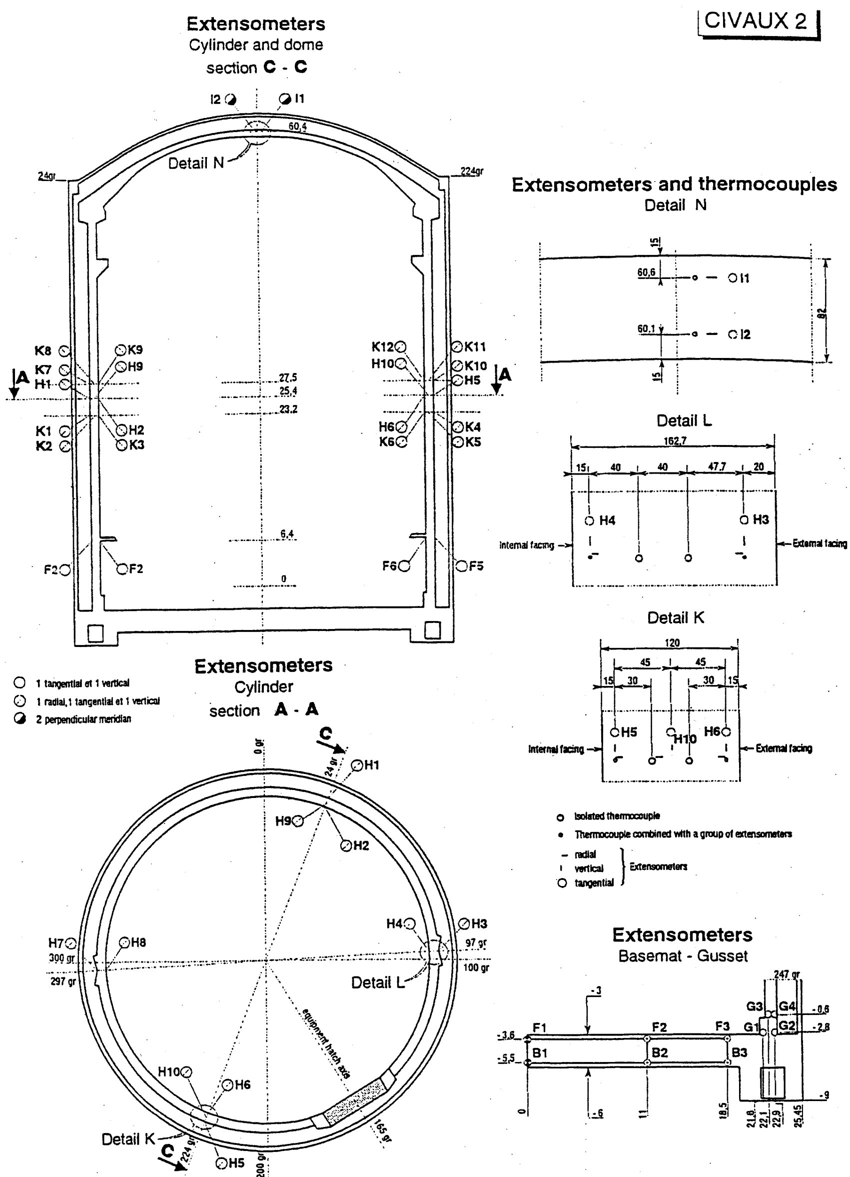
The operation of an automatic remote monitoring system in the CIVAUX unit 2 since the beginning of the pouring of the inner containment wall, has significantly improved our knowledge about the behaviour of this kind of structures. In addition to information about thermal strains of HP concrete during the setting phase, the daily measures which could be taken thanks to this monitoring system, enabled to control the effect of the prestressing of almost each tendon on the whole structure and to confirm our theoretical deformation calculation.

This instrumentation device is not only precise but also reliable since only 3% of the in-concrete embedded sensors of CIVAUX unit 2 are out of order after 5 years of operation ;

to confirm this point, it is to be precised that in CHOOZ B unit 1 (the eldest N4 unit) where the instrumentation device has been operating for 10 years, all the in-concrete embedded sensors are still working. Today, 14 French containments are equipped with such an automatic monitoring system which can be directly consulted from the EDF operational centre of Lyon where all this information is processed and analysed.

These results highlight, for each considered site, the advantage of using a high performance concrete instead of an ordinary concrete for the erection of a containment wall. The choice of an high performance concrete ensures much lower time-dependent losses for the prestressing forces together with a better leaktightness.

Figure 3. Position of instrumentation in the inner containment wall of Civaux unit 2



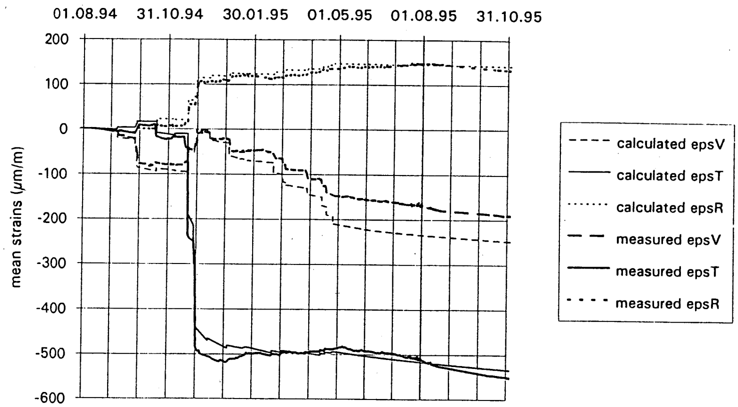


Figure 4. CIVAUX unit 2 - Mean calculated and measured strains at level 25,40 m during the prestressing phases in the tangential, vertical and radial directions

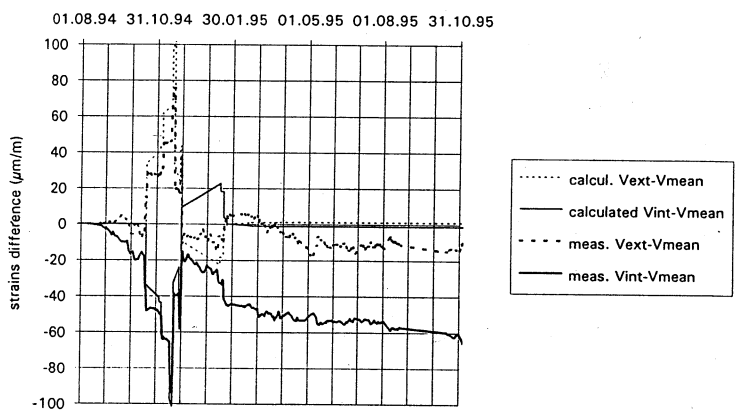


Figure 5. CIVAUX unit 2 - Calculated and measured vertical strains differences between extrados and intrados at level 25,40 m during the prestressing phases

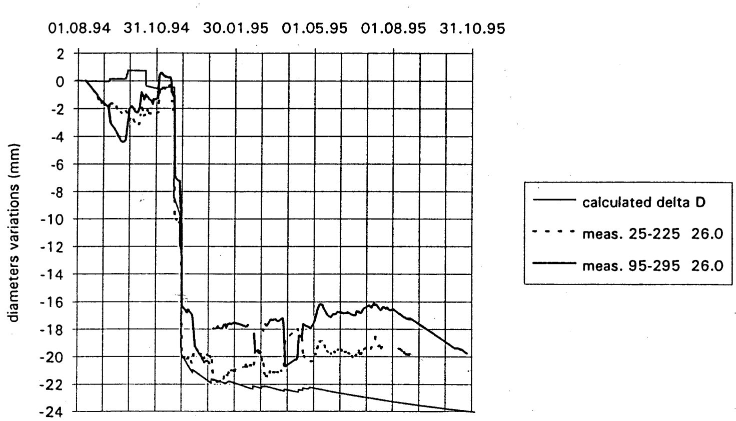


Figure 6. CIVAUX unit 2 - Calculated and measured diameter variation at level 26 m during the prestressing phases

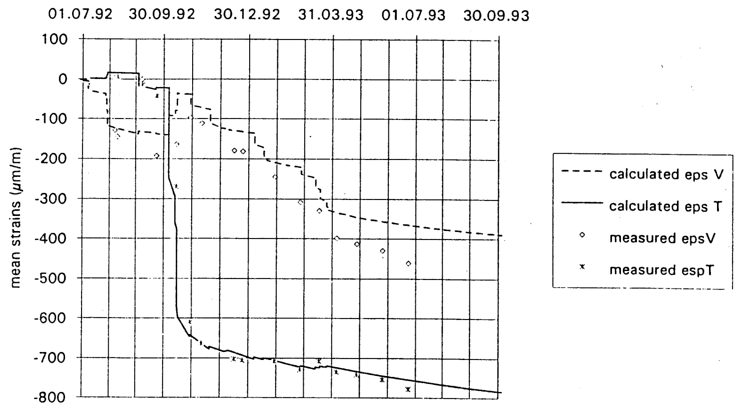


Figure 7. CIVAUX unit 1 - Mean calculated and measured strains at level 25,40 m during the prestressing phases in the tangential and vertical directions

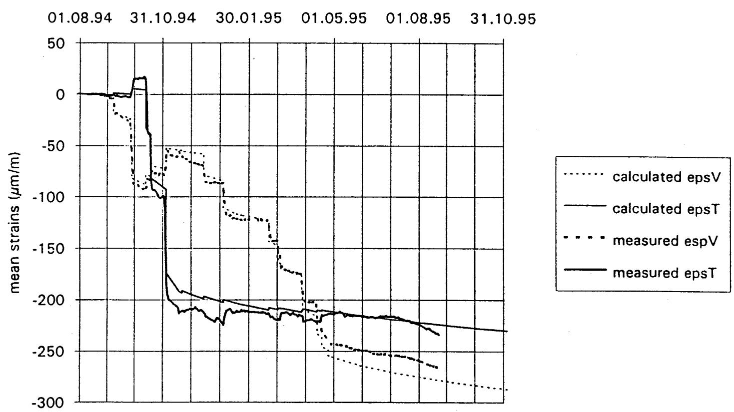


Figure 8. CIVAUX unit 2 - Mean calculated and measured strains at level 6,60 m during the prestressing phases in the tangential and vertical directions

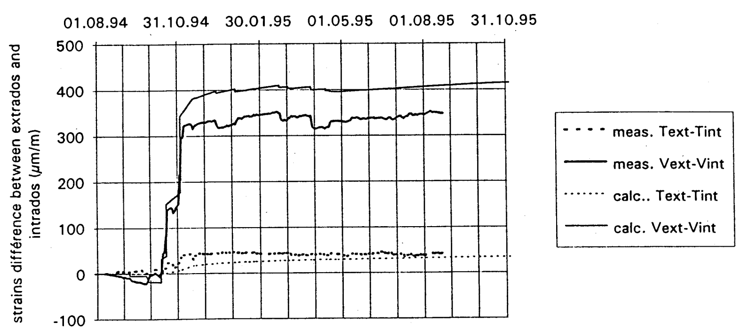


Figure 9. CIVAUX unit 2 - Calculated and measured vertical strains differences between extrados and intrados at level 6,60 m during the prestressing phases