Delayed phenomena analysis from French PWR containment instrumentation system

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1. INTRODUCTION

French 900 MW reactors containments have been equipped with comprehensive instrumentation systems in order to provide strain and displacements measurements in concrete as well as stresses in presstressing tendons first during the preoperationnal air pressure test and then during the life of the structure.

More than 20 reactors containments have been so regularly monitored over several years of normal operating (since May 1977 for the Tricastin 1 unit, the first of these similar containments) and through one (or two for a few of them) air pressure test.

A large amount of measurements on concrete or tendons is now available; we intend to analyse them to study delayed phenomena such as concrete creep and shrinkage and steel relaxation of prestressing tendons.

2. DESCRIPTION OF MONITORING SYSTEM

The french PWR 900 MW reactor containment consists of a reinforced concrete raft, a prestressed cylindrical wall and a prestressed spherical dome; the inner face of the whole containment is covered with a steel liner which ensures air tightness.

The main dimensions of the structure are :

mean radius of cylindrical wall	:	18.95 m
height (from upper face of raft to dome)	:	60.35 m
raft thickness	:	3.5 m
cylindrical wall thickness	:	0.9 m
dome thickness	:	0.8 m

Basically, the instrumentation system consists of vibrating wire strain gauges (extensometers), pendulums for displacements measurements and dynamometers on prestressing tendons.

The more complete instrumentation systems have always been installed on the first containment unit of each project, the following units being more simply equipped.

Strains gauges are usually positioned in pairs, near the outer or inner surfaces of dome, containment wall or raft in typical or particular (hatches, prestressing ribs, ...) sections ; each of them is combined with a thermocouple, which provides local temperature measurement.

Pendulums are positioned so that they allow the determination of the dimensional variations of two diameters, approximately perpendicular.

Four vertical tendons are fitted with dynamometers at their anchorages thus providing stress measurement in prestressing steel.

Measurements have been regularly (about four or five times a year) carried out on the twenty four units in operation at present time by a specialized service of Electricité de France and stored on computer files for further treatment. To eliminate temperature effects a statistical analysis (main components) is performed on the uncorrected values. The resulting values are then graphically displayed in regular reports; thus it is possible to check the behaviour of the structure as the plant is normally operating.

3. ANALYSIS OF MEASUREMENTS

As above mentionned the purpose of this study was to compare the strain variations actually measured by the instrumentation on reactor containments to the theoretical values for concrete shrinkage and creep proposed in french regulations for prestressed concrete structures design (BPEL 83 - Règles techniques de conception et de calcul des ouvrages et constructions en béton précontraint suivant la méthode des états limites).
To carry out these comparisons we shall first analyse the strains measured by vibrating wire strain gauges in selected typical sections of the standardized part of the cylindrical wall.

3.1. Strain gauges analysis

For this analyis, the selected sections are located approximately in the middle of the height of the containment (at a level of + 24 m or + 29 m depending on sites) in four different angular positions (42 gr., 176 gr., 242 gr. and 376 gr.); it must be noticed that selecting this level in the containment wall ensures us that the measurements are no longer disturbed by site conditions such as soil stiffness; we can thus compare the values obtained on units belonging to different sites.

On the other hand, we have usually choosen the results obtained from the instrumentation of the first unit of each site as they are generally more completely equipped (so we can more easily reject gauges suspected to be faulty).

To carry out a more valuable comparison between measured and predicted values for the cumulated actions of concrete creep and shrinkage we prefered to limit our study to the reactor containments for which measurements were available on a long space of time, in fact TRICASTIN 1, DAMPIERRE 1 and GRAVELINES 1, units which have been continuously followed for more than five years after their first air pressure test.

Theoretical strain variations have been calculated, using analytical formulas from BPEL 83 which take into account :

ambient air moisture ratio
wall thickness
concrete age when prestress forces have been applied
concrete elastic modulus
normal stress in concrete.

Comparisons have been made for the two main stress directions in the containment wall, vertical and horizontal the design values being respectively 9.2. MPa (including dead weight) and 11.4 MPa.

Elastic modulus under instant loading have been determined from the results of containment air pressure tests and range from 28800 MPa (DAMPIERRE 1) to 36000 MPa (TRICASTIN 1). These elastic moduli have been used for theoretical calculation of creep.

The results of these comparisons are graphically displayed on fig. 1 to 10.
It appears that the predicted theoretical values fit well to the measured ones for practically all vertical strain gauges when calculations are carried out with a 55 % air moisture ratio ; on the other hand slight discrepancies appear for the horizontal gauges, the measured strains being generally higher by 10 % than the values given by the analytical formulas.
The above mentionned discrepancies relative to horizontal strains have probably their origin in the actual horizontal stress in concrete which can locally exceed the design values.

3.2. Diameter variations analysis

By mean of four pendulums, radial displacements are measured on two diameters; we analysed the results obtained from these devices at the same level on the containment wall as for the strains gauges; taking into account the relation between horizontal strain and radial displacement in a cylinder : $\varepsilon_T = U_r/R$

We were able to get an other evaluation of the horizontal strain variations versus time; it then appeared that the values estimated from the measurements were closer (for GRAVELINES 1) or quite similar (for DAMPIERRE 1) to the theoretical quantities (see fig. 11 to 12).

These results corroborate the hypothesis made about the slight differences we have noticed between theoretical predicted values and measurements for horizontal strain gauges; when measured in typical sections, diameter dimensional variations depend essentially, on mean horizontal stresses in containment wall; consequently, they are closer to the values we can get from analytical formulas based on the design mean stress.

3.3. Force losses in prestressing tendons

At the same time steps as for strain gauges, tensile forces in four vertical tendons are regurlarly measured using dynamometers set under their anchorage plates.
In order to compare the evolution of actual tensile force losses in these tendons to those we can calculate from the formulas given for

steel relaxation in french regulations BPEL 83 we analysed the results of measurements on dynamometers for several containment buldings on different sites.

To carry out this comparison we have first calculated from BPEL 83 steel relaxation losses which must have occured in the selected tendons since they are under tension and cumulated these stress.
Losses to those created by creep and shrinkage, the latter being evaluated directly from strain gauges located next to the tendons.
The total losses we have so obtained were then compared to the measured ones. As we can notice on the fig. 13 to 17, describing five such calculations made on GRAVELINES 1, DAMPIERRE 1 and TRICASTIN 1 units, predicted values are in good agreement which the measurements except for one cable (GRAVELINES 1, Tendon 20) were the estimated losses notably exceed the measured ones).

4. CONCLUSION

The analysis of the large amount of measurements which has been now gathered by Eectricité de France on its twenty two PWR 900 MW shows that the behaviour of concrete under creep and shrinkage effects is in good agreement with the values given as correct estimates by french regulations and taken into account for the design of nuclear prestressed structures.

None of the containment buildings studied here showed significant differences with the regulations theoretical values and consequently all the measurements remain in the field of the allowable strain variations used for design.

On the other hand, if the instant loading elastic modulus is clearly determined for each containment, and its effect on theoretical creep taken into account, it was not possible up till now to extract from measurements some particular effects such as type of concrete and agregates or climatic effects.

Strains : $e_t \times 10^{-6}$ Time : days

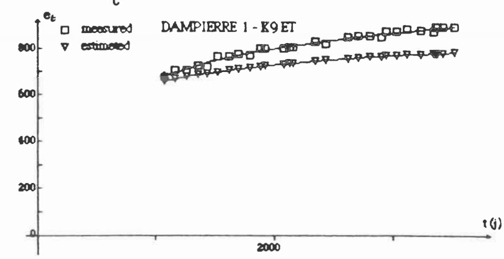

Fig . 1 -Estimated and measured horizontal strains in typical section of PWR 900 MW containment wall - Dampierre 1 unit , strain gauge K9 ET

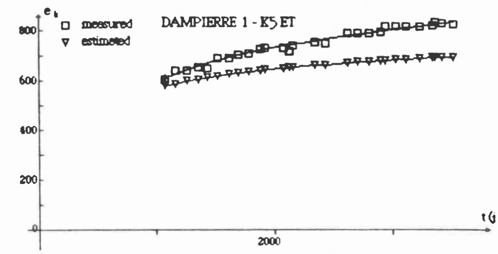

Fig . 2 -Estimated and measured horizontal strains in typical section of PWR 900 MW containment wall - Dampierre 1 unit , strain gauge K5 ET

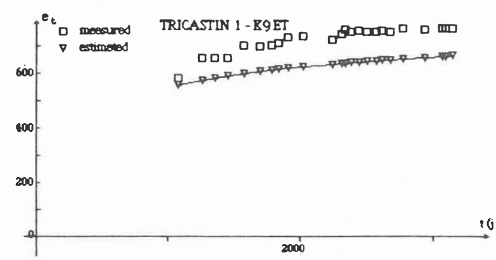

Fig . 3 -Estimated and measured horizontal strains in typical section of PWR 900 MW containment wall - Tricastin 1 unit , strain gauge K9 ET

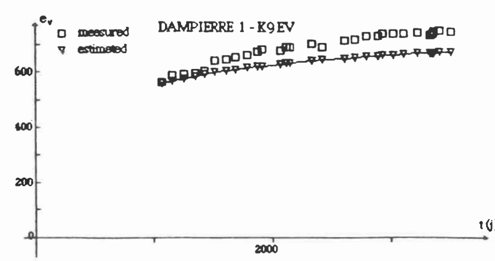

Fig . 4 -Estimated and measured vertical strains in typical section of PWR 900 MW containment wall - Dampierre 1 unit , strain gauge K9 EV

Strains : e_t x 10-6 Time : days

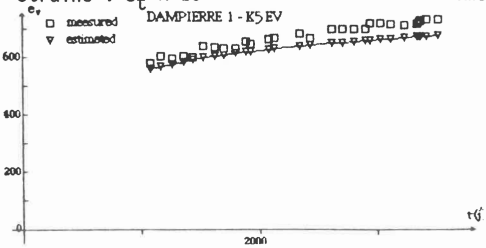

Fig . 5 -Estimated and measured vertical strains in typical section of PWR 900 MW containment wall - Dampierre 1 unit , strain gauge K5 EV

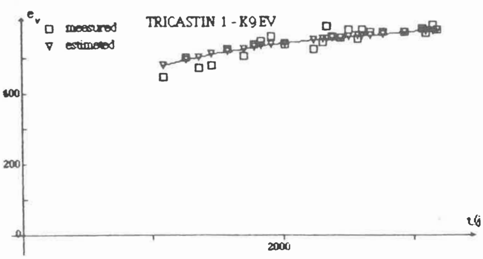

Fig . 6 -Estimated and measured vertical strains in typical section of PWR 900 MW containment wall - Tricastin 1 unit , strain gauge K9 EV

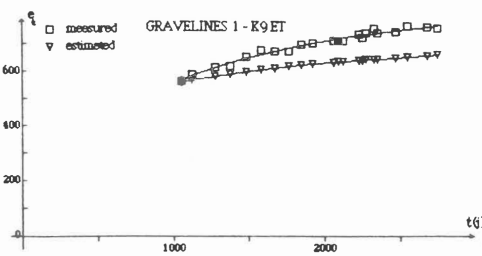

Fig . 7 -Estimated and measured horizontal strains in typical section of PWR 900 MW containment wall - Gravelines 1 unit, strain gauge K9 ET

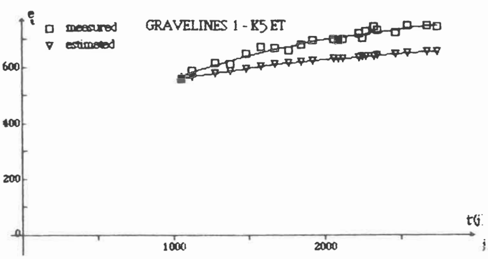

Fig . 8 -Estimated and measured horizontal strains in typical section of PWR 900 MW containment wall - Gravelines 1 unit, strain gauge K5 ET

Strains : $e_t \times 10^{-6}$ Time : days

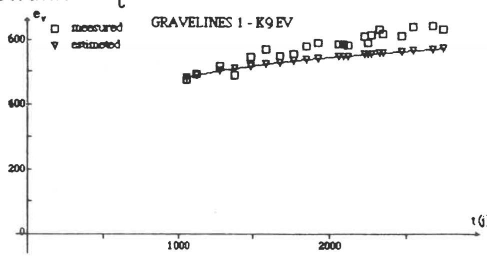

Fig . 9 -Estimated and measured vertical strains in typical section of PWR 900 MW containment wall - Gravelines 1 unit, strain gauge K9 EV

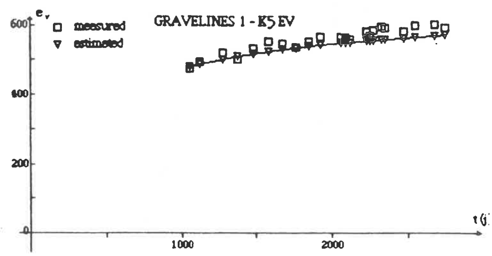

Fig .10 -Estimated and measured vertical strains in typical section of PWR 900 MW containment wall - Gravelines 1 unit, strain gauge K5 EV

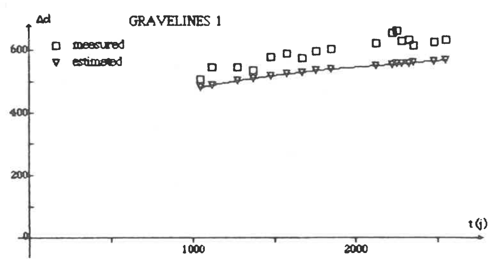

Fig .11 -Estimated horizontal strains in typical section compared to measured values (computed from diameter variations)in PWR 900 MW containment wall - Gravelines 1 unit ,level +26 m

DAMPIERRE 1

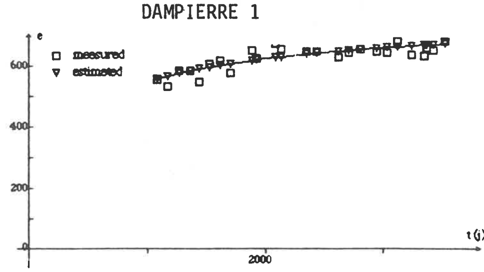

Fig .12 -Estimated horizontal strains in typical section compared to measured values (computed from diameter variations)in PWR 900 MW containment wall - Dampierre 1 unit ,level +26 m

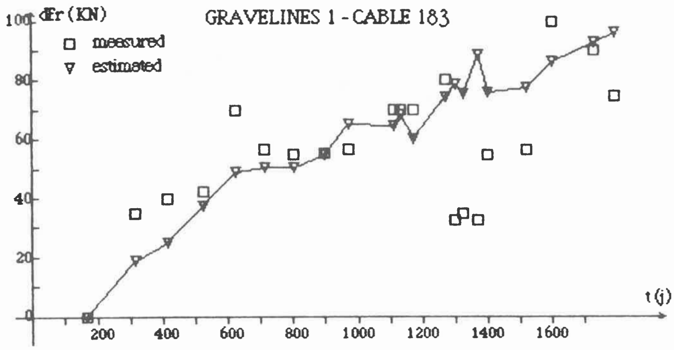

Fig .13 -Estimated and measured prestressing forces losses (in KN) in vertical tendons of PWR 900 MW containment wall - Gravelines 1 unit , tendon 183

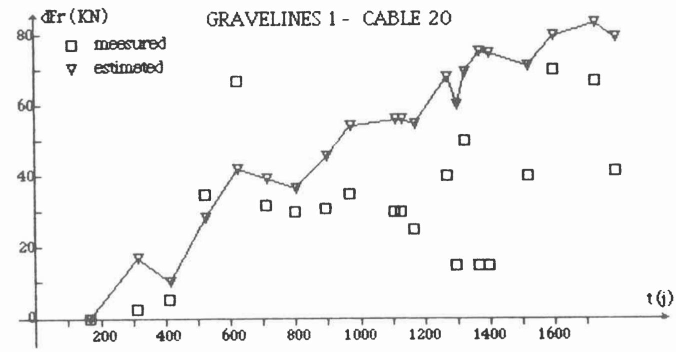

Fig .14 -Estimated and measured prestressing forces losses (in KN) in vertical tendons of PWR 900 MW containment wall - Gravelines 1 unit , tendon 20

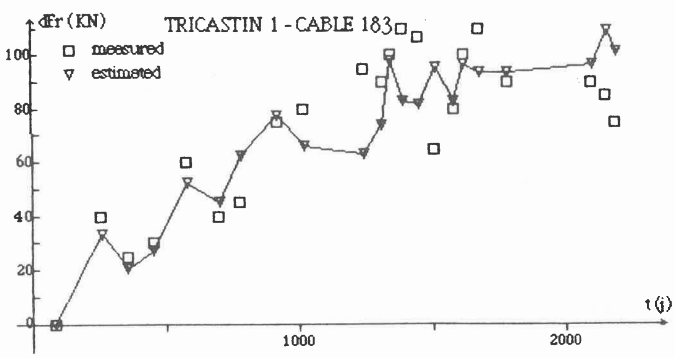

Fig .15 -Estimated and measured prestressing forces losses (in KN) in vertical tendons of PWR 900 MW containment wall - Tricastin 1 unit , tendon 183

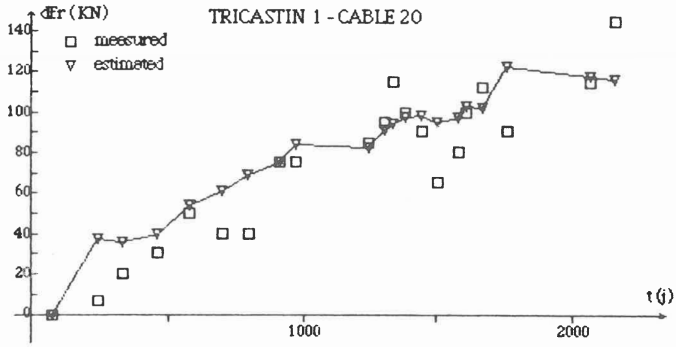

Fig .16 -Estimated and measured prestressing forces losses (in KN) in vertical tendons of PWR 900 MW containment wall - Tricastin 1 unit , tendon 20

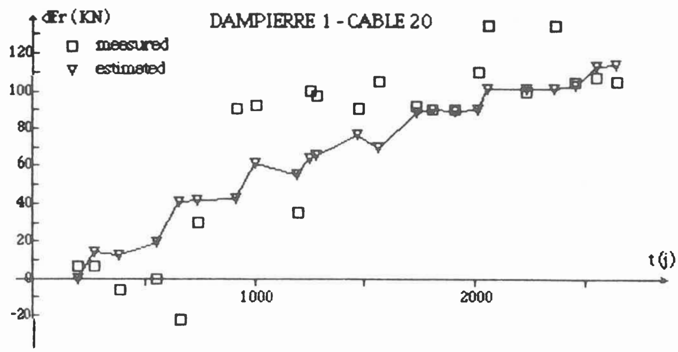

Fig .17 -Estimated and measured prestressing forces losses (in KN) in vertical tendons of PWR 900 MW containment wall - Dampierre 1 unit , tendon 20