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Accounting for realistic Thermo-Hydro-Mechanical boundary conditions whilst modeling the ageing of concrete in nuclear containment buildings: Model validation and sensitivity analysis

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ABSTRACT

The prediction of large concrete structures behavior such as bridges, dams and Nuclear Containment Buildings (NCB) is a key issue with regards to the evaluation of their durability, safety and the safety of their surrounding environment. In this work, a weakly coupled Thermo-Hydro-Mechanical (THM) modeling strategy is presented within the serviceability state of large structures. It aims at (a) defining and predicting the temperature, the relative humidity, the strains and the stresses in ageing concrete structures under variable and realistic THM loads and (b) qualitatively assessing the damage risk using a stress-based criterion. With that aim in view, the effect of concrete drying on its long term behavior is highlighted by using a revisited description of drying creep adapted to variable hydric conditions. The concrete's response to variable THM boundaries is also compared to the one where mean and constant ones are considered in the case of NCBs. Two concrete types and three scales are considered for the THM study: the specimen scale for concrete properties identification, the 1:3 and 1:1 (full) scales of Representative Structural Volumes (RSV) for predictive and structural analyses. Through the FE sensitivity analysis, it is shown that the spatial variation of the temperature along the NCB's height has more effect on the concrete's ageing than its variation in time. Whereas, the temporal variation of hydric boundaries has a negligible effect away from the drying-exposed surfaces. Finally, it is demonstrated that, due to initial prestressing loads, the ageing kinetic within the NCB's wall is heterogeneous and cannot be described using constant prestressing loads. Therefore, it is recommended to account for the spatial THM boundaries' variation when predicting the global concrete ageing in large concrete structures.

1. Introduction

Basic creep and drying phenomena in large concrete volumes are two of the main factors behind structures' ageing and their continuous strain evolution in time. The loss of water (desiccation) causes a global volumetric shrinkage of the concrete's volume in addition to self-induced tensile stresses along the drying-exposed surfaces which might lead to skin damage or cracking. In the case of prestressed applications, concrete drying leads also to the amplification of creep strains (Pickett effect) and to tension losses in the cables which may reduce the structural loading capacity and jeopardize the structure's longevity. For that reason, the strain level in concrete volumes within strategic and large concrete structures is permanently monitored via a large set of embedded gauges or surface sensors. This monitoring network helps assessing the mechanical state of the structure continuously and informs operators about its day-to-day limit state design factors. However, as the structure ages, the number of working sensors decreases and the measurement uncertainties associated with old functioning ones increase. In order to still be able to monitor the structure's behavior accurately, numerical clones can be used to assess the pertinence of in-situ measurements and also predict the long term effect of ageing on the future behavior of concrete.

As a particular case of such applications there are Nuclear Containment Buildings (1:3 scale NCB in Fig. 1). For the double-walled ones, their structural tightness is ensured by two reinforced concrete walls (Fig. 1a & b). The inner one (Fig. 1a & f) is also prestressed in two

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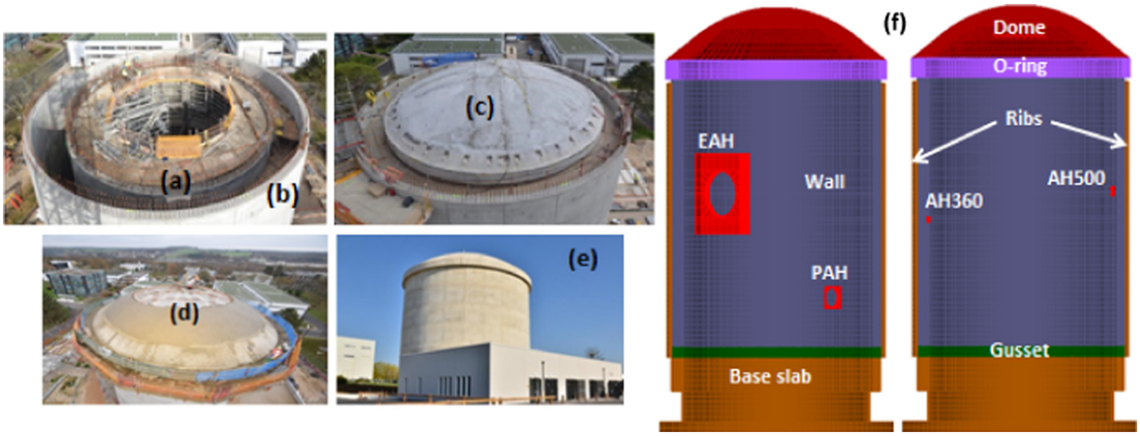

Fig. 1. VeRCoRS mock-up (a) Inner wall (b) Outer wall (c) Inner dome (d) Outer dome (e) Full mock-up (f) Structural parts of the inner wall [1] (EAH: Equipment Access Hatch – PAH: Personel Access Hatch – AH: Access Hatch) (French acronym for "VErification Réaliste du COnfinement des RéacteurS" meaning "Realistic assessment of the nuclear reactors' tightness").

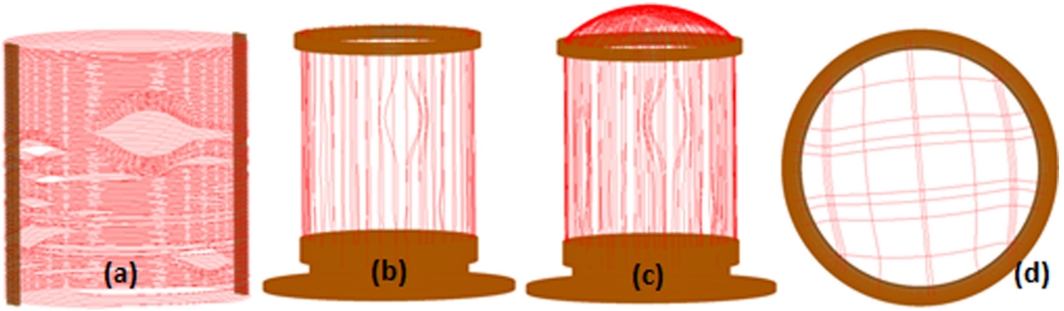

Fig. 2. Types of prestressing cables in NCBs (a) 122 Horizontal cables (b) 57 Vertical cables (c) 97 Gamma cables (d) 18 Dome cables [1].

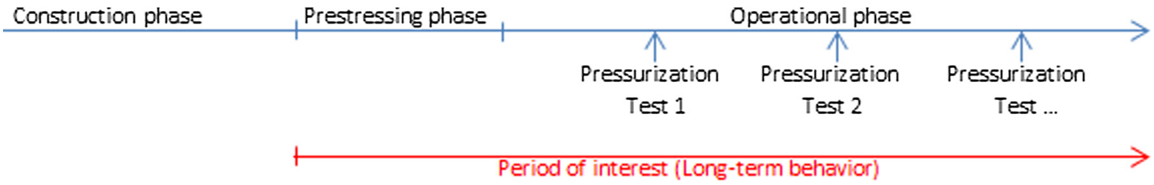

Fig. 3. Nuclear containment building lifetime phases.

main directions: the vertical and tangential (Fig. 2). Prestressing cables are post tensioned once the construction phase ends and right before the operational phase of the nuclear reactor (Fig. 3). They are inserted in ducts and are cement grouted after tension. During the operational phase, the inner temperature of the NCB rises up to ~35 °C leading to a Relative Humidity (RH) decrease and an accelerated drying of concrete (in comparison with concrete under the ambient external temperature ~15 °C). Under those combined and simultaneous Thermo-Hydro-Mechanical (THM) loads, concrete undergoes basic and drying creeps as well as the drying shrinkage (all together referred to as ageing phenomena) which reduce, in time, the tension in the prestressing cables. It is worth mentioning that the design phase does account for the effects of ageing on concrete's long term behavior in order to ensure sufficient compressive loads and prevent cracking even during an unfortunate overpressure due to a LOCA (Loss-Of-Coolant Accident) for instance. Nevertheless, as a part of the safety program, periodical unit outages are performed for maintenance or testing purposes. Herein, only the mechanical aspects of the pressurization tests are of interest. These tests (Fig. 3) consist of purposely increasing the inner relative pressure of the NCB up to 4.2 bars (see examples of pressurization profiles in Fig. 12) and observing the residual compressive loads in the concrete's volume. With that regard, the simulation of concrete ageing in time offers the possibility to predict the long term behavior of the structure and better schedule the testing and maintenance tasks.

Several numerical models are available for that purpose covering the thermal behavior of concrete [2], its hydric behavior [3–6] and finally its viscoelastic one [7–10] using either a fully coupled approaches [11,12] or chained calculation strategies [7,13,14]. However, questions are often raised with regards to the accuracy of the simulated boundary conditions (BC) at the structural scale, usually idealistic, compared to the real ones under operational loads. This makes the assessment of the model's accuracy difficult since the observed gaps between the numerical results and the experimental ones are due to the BCs themselves in addition to the uncertainties related to the concrete's properties' identification and the model's hypotheses. Particularly, the following hypotheses are usually considered to describe the global behavior of the structure's standard zone (part of the wall which behavior is comparable to an infinite hollow cylinder which domain of validity is yet to be defined):

- The temperature variation over time is overlooked and is considered homogeneous inside the NCB during the operational phase [6,7,10,13,15,16] which is opposed to in-situ observations showing a thermal gradient of ~20 °C along the NCB's height.
- The relative humidity (RH) is also considered constant and overestimated during the operational phase with no correlation with the