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Fully coupled, hygro-thermo-mechanical sensitivity analysis of a pre-stressed concrete pressure vessel ☆

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ABSTRACT

Following a recent world wide resurgence in the desire to build and operate nuclear power stations as a response to rising energy demands and global plans to reduce carbon emissions, and in the light of recent events such as those at the Fukushima Dai-ichi nuclear power plant in Japan, which have raised questions of safety, this work has investigated the long term behaviour of concrete nuclear power plant structures.

A case example of a typical pre-stressed concrete pressure vessel (PCPV), generically similar to several presently in operation in the UK was considered and investigations were made with regard to the extended operation of existing plants beyond their originally planned for operational life spans, and with regard to the construction of new build plants.

Extensive analyses have been carried out using a fully coupled hygro-thermo-mechanical (HTM) model for concrete. Analyses were initially conducted to determine the current state of a typical PCPV after 33+ years of operation. Parametric and sensitivity studies were then carried out to determine the influence of certain, less well characterised concrete material properties (porosity, moisture content, permeability and thermal conductivity). Further studies investigated the effects of changes to operational conditions including planned and unplanned thermal events.

As well as demonstrating the capabilities and usefulness of the HTM model in the analysis of such problems, it has been shown that an understanding of the long-term behaviour of these safety–critical structures in response to variations in material properties and loading conditions is extremely important and that further detailed analysis should be conducted in order to provide a rational assessment for life extension.

It was shown that changes to the operating procedures led to only minor changes in the behaviour of the structure over its life time, but that unplanned thermal excursions, like those seen at the Fukushima Dai-ichi plant could have more significant effects on the concrete structures.

1. Introduction

Until recently, in many parts of the world, such as in the UK and other parts of Europe nuclear energy has fallen out of favour. But, with an ever increasing world demand for energy and the threat of global warming, nuclear power is now seen again by many as a reliable, plentiful and most importantly low carbon supply of electricity [1,2]. As a result of this, there is currently a worldwide resurgence in the development and application of nuclear power with several countries including China, India and the UK recently approving the development of new build plants [1].

However, while the international treaties to reduce carbon emissions must be enacted in relatively short timescales [3,4] the previous stagnation of the nuclear industry has resulted in a lead in time of many years before new nuclear plants can be commissioned [1]. To fill this gap, the lives of the existing stock of nuclear power plants in the UK and Europe, many of which are reaching the end of their original design lives, will need to be extended.

At the same time, the incidents following the Great East Japan earthquake in 2011, where a loss of cooling at the Fukushima **Dai-ichi plant** led to the overheating of several reactors and the release of radioactive material, have again raised questions as to the safety of nuclear power plants [5]. The main line of defence around a reactor to prevent escape of radioactive material is the containment vessel. To ensure that there is not a repeat of some of the past nuclear accidents, it is important that structural integrity of the

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containment vessel is maintained under all conceivable circumstances and conditions. To achieve this, it is essential that not only their mechanical properties are understood but, as they are subjected to extreme environments, also how these change over the operational life of the reactor vessel.

This paper presents an assessment of the long term behaviour of pre-stressed concrete pressure vessels (PCPV), typical of designs currently employed in the UK, that have been operating at elevated temperatures for periods in excess of 30 years. This assessment is important as it evaluates the current mechanical properties of the concrete which may then be used to ensure the structural integrity and containment of facilities whose life is to be extended.

The current state of these vessels cannot be identified without accounting for the full history of the operating conditions experienced by the structure and consideration of the effects of thermal and mechanical loads on the concrete including transport of moisture and the development of gas pressures within the pore structure of the material.

To achieve this, a fully coupled hygro-thermo-mechanical (HTM) model for concrete, originally developed during the EU FP5 Euratom *MAECENAS* (Modelling of Ageing in Concrete Nuclear Power Plant Structures) project, was employed to examine the behaviour of a typical UK PCPV over the course of its 30+ year life span under various operating conditions.

In the first instance analysis of a typical PCPV is carried out to determine the current condition of the concrete structure. A parametric analysis is then presented in which consideration is given to variations in the concrete with respect to less well characterised properties such as porosity, moisture content, permeability and thermal conductivity. Although the records from the original design and construction of UK PCPV plants are well documented and maintained, little is known about some of these properties and examination of the literature shows that very wide ranges may exist (see for example Fig. 1).

This work demonstrates that the long term behaviour of these safety–critical structures is very susceptible to small changes in material properties and a good understanding of this sensitivity is therefore vital.

Finally, a parametric study is presented in which the influence of operational conditions on the mechanical properties of the PCPV is demonstrated. This study shows how planned or unplanned events may affect the overall structural behaviour and how this may affect the safety of the PCPV. It is furthermore concluded that the numerical tool applied in this paper may be used to predict the behaviours of existing or new build concrete power plant structures (including but not limited to PCPV).[1]

2. Numerical model

This work was carried out using the fully coupled hygro-thermo-mechanical (HTM) model for concrete initially developed during the *MAECENAS* (Modelling of Ageing in Concrete Nuclear Power Plant Structures) project and presented by Davie et al. [6]. Briefly, the model treats concrete as a multiphase porous medium consisting of solid, liquid and gas phases. The solid skeleton is considered to behave isotropically and elastically under mechanical and thermal loadings, although nonlinear responses are accounted for through the consideration of transient thermal strains, transient thermal creep and an isotropic thermo-mechanical damage formulation. The 'liquid' phase considers free liquid water in pores and adsorbed water physically bound to the surface of solid skeleton. Water liberated from the solid skeleton through dehydration is considered as a part of free liquid water since chemically bound water is assumed to be initially released as liquid water. The gas phase is considered to be a mixture of dry air and water vapour, which are assumed to behave as ideal gases. Most of the material properties, both mechanical and those related to heat and mass transport, are variable, often either directly or indirectly, as a function of temperature. A complete description of the governing equations, constitutive laws and material properties may be found in [6,7,17]. A brief outline of the components of the formulation key to this work is given below and in Appendix AI.

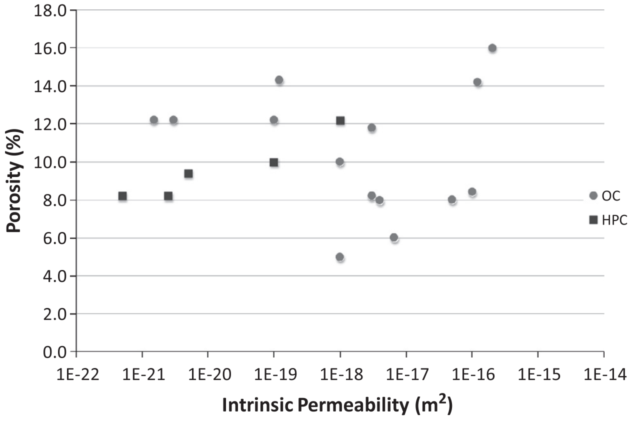

Fig. 1. Values for porosity vs. permeability for ordinary concretes (OC) and high performance concretes (HPC) described in the literature ([6–16]).

2.1. Governing equations

The model comprises four conservation equations for mass of dry air (1), mass of moisture (i.e., vapour and liquid) (2), energy (3) and linear momentum (4).

$$\frac{\partial(\varepsilon_G\tilde{\rho}_A)}{\partial t} = -\nabla\cdot\mathbf{J}_A \tag{1}$$

$$\frac{\partial(\varepsilon_G\tilde{\rho}_V)}{\partial t} + \frac{\partial(\varepsilon_L\rho_L)}{\partial t} - \frac{\partial(\varepsilon_D\rho_L)}{\partial t} = -\nabla\cdot(\mathbf{J}_V + \mathbf{J}_L) \tag{2}$$

$$(\underline{\rho C})\frac{\partial T}{\partial t} - \lambda_E\frac{\partial(\varepsilon_L\rho_L)}{\partial t} + (\lambda_D + \lambda_E)\frac{\partial(\varepsilon_D\rho_L)}{\partial t} = \nabla\cdot(k\nabla T) + \lambda_E\nabla\cdot\mathbf{J}_L \tag{3}$$

$$\nabla\cdot(\sigma' - \eta P_{Pore}\mathbf{I}) + \mathbf{b} = 0 \tag{4}$$

where ε_θ is the volume fraction of a phase θ(θ = L, V, A, G, D refer to liquid water, water vapour, dry air, gas mixture and dehydrated water phases, respectively), ρ_θ is the density of a phase θ, $\tilde{\rho}_\theta$ the mass of a phase θ per unit volume of gaseous material, $\mathbf{J}_\theta$ the mass flux of a phase θ, $\underline{\rho C}$ the heat capacity of concrete, k the effective thermal conductivity of concrete, λ_E and λ_D are the specific heats of evaporation and dehydration, σ' is the Bishop's stress (also known as the effective stress in geomechanics), $\mathbf{I}$ the identity matrix, η is the Biot coefficient, P_{Pore} the pore pressure and $\mathbf{b}$ the body force.

2.2. Fluid transport equations

Liquid water flow in the pore structure of the concrete is assumed to be driven by pressure according to Darcy's law, and gas flow is assumed to be driven by both pressure and concentration according to Fick's law. The mass fluxes of dry air ($\mathbf{J}_A$), water

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[1] While the specific example considered here is of a PCPV, the findings of the work clearly have implications for other high temperature concrete structures including but not limited to pre-stressed concrete containment vessels (PCCV). Furthermore, while the initial example considered here considers a typical existing structure, there are clear implications for assessing the long term behaviour of new build projects, under desirable and undesirable conditions.