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Experimental modal analysis and finite element model updating for structural health monitoring of reinforced concrete radioactive waste packages

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HIGHLIGHTS

- Modal analysis is proposed to control the structural health of radioactive waste packages.
- FEM updating is conducted on radioactive waste packages at different boundary conditions.
- Design of experiments and a genetic algorithm are combined for FEM updating.
- Specific aspects for the implementation of a modal-based SHM in a radioactive waste repository are summarized.

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ABSTRACT

This study envisages the use of modal analysis for monitoring the structural health of radioactive waste packages. To this end, the calibration of a numerical model that describes the dynamic behavior is a critical issue for the success in damage detection. In this study, experimental modal analysis was conducted on a radioactive waste package mockup. The container was tested under different boundary conditions. Then, the experimental modal analysis data was used to update finite element models that describe the observed behaviors. The latter consists in the formulation of an optimization problem that minimizes the differences between the experimental and the numerical data. A two-step methodology is proposed for finite element model updating. First, a full factorial design of experiments allowed estimation of a set of parameters of the numerical model that minimize a cost function. Second, a genetic algorithm was conducted, wherein the initial population of parameters was generated as a function of that set of parameters obtained in the previous step. This study serves as preliminary step towards the implementation of a structural health monitoring based on modal analysis. Specific aspects for the implementation of a modal-based structural health monitoring system in a radioactive waste repository are also summarized.

1. Introduction

Andra (the French National Radioactive Waste Management Agency) is designing a geological repository —project *Cigéo*: "Industrial Center for Geological Disposal"—, for disposal of long-lived high- and intermediate-level radioactive wastes. Detailed description of the *Cigéo* project can be consulted in [1]. In the particular case of long-lived intermediate-level waste, the use of reinforced concrete containers as a disposal package seems to be the preferred solution in many countries [2,3]. The waste packages consist of i) a primary waste package in the form of metallic drums which contain the immobilized radioactive waste, and ii) a precast reinforced concrete container, which is designed to host the primary waste package. Reinforced concrete containers provide a physical protection to the primary waste package, and they can be produced in a shape that eases handling operations. Fig. 1a shows a schematic of a radioactive waste package prototype and its constitutive parts. This type of waste package prototype is being considered in the *Cigéo* project. It is foreseen that the waste packages be stacked (up to three packages) and stored in an underground cell with sufficient capacity. Fig. 1b shows a schematic description of the radioactive waste packages stored in an underground repository cell.

The management and control of concrete in radioactive waste repositories entails several challenges. Despite concrete is being considered for radioactive waste disposal, there is no previous experience on concrete withstanding nuclear environments

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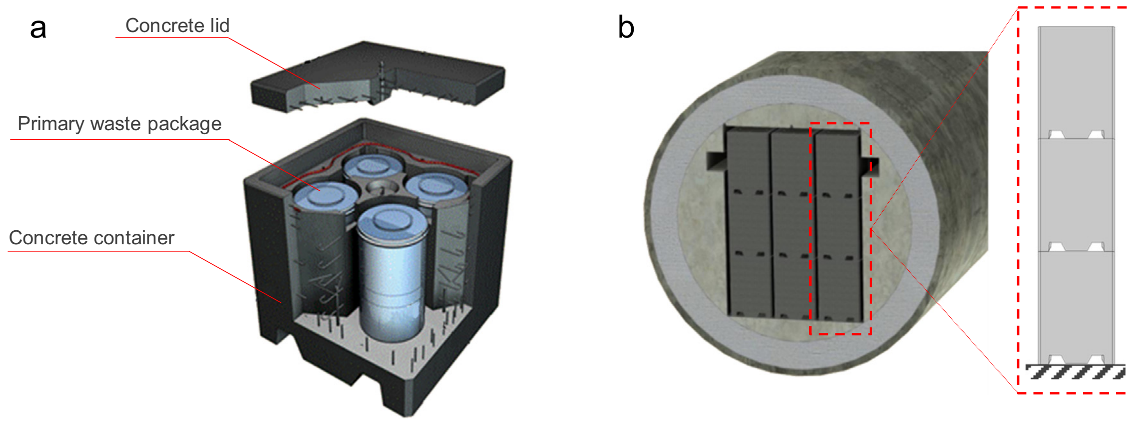

Fig. 1. a) Typical reinforced concrete container designed to host intermediate and low level radioactive waste, and b) schematic description of the final disposition of waste packages in an underground repository cell, and detail of three stacked containers.

beyond its expected service life; ~100 years and at high temperatures (~65 °C), for intermediate-level waste. A number of studies claim that further research on concrete durability is needed, to account for the simultaneous and synergistic actions of moisture, thermal, and mechanical loads along with radiation damage [3–8]. In addition, most of these studies also appeal to the need of developing nondestructive evaluation techniques and structural health monitoring (SHM) systems, that inform about the mechanical and durability performance of concrete in nuclear facilities. In particular, the difficulties arise from the limits on access to the structures and the harsh environment [3]. Previous studies investigated the feasibility of different nondestructive techniques, for the inspection of concrete in radioactive waste repositories. Iliopoulos and coworkers [9] combined the application of different nondestructive techniques on a radioactive waste container prototype subjected to high temperatures. Digital image correlation and acoustic emission were able to monitor the evolution of thermal induced cracking damage, while the depth of already formed cracks was successfully investigated through the ultrasonic pulse velocity. Davis and coworkers [10] applied different stress wave techniques aiming at periodic inspection of in-service radioactive waste tanks made of reinforced concrete. The investigated techniques included impulse response technique, ultrasonic pulse velocity and sonic logging. From this set of techniques, the authors were able to investigate the uniformity of concrete, and thus detect vulnerable zones. Andrade and coworkers [5], and Duffó and coworkers [6] have focused their researches in the application of electrical resistivity measurements, aiming at the service-life prediction of the steel reinforced concrete containers. In the particular case of the *Cigéo* project, Andra has instrumented prototype concrete containers with embedded optical fibers, so mechanical strains can be monitored since their production, and during their final disposition in the geological repository [11,12].

This study envisages the use of modal analysis for monitoring the structural health of radioactive waste packages. In modal-based SHM applications, sensors are permanently installed in structures and continuously record their dynamic characteristics. Since dynamic properties are related to the mechanical integrity of structures, the eventual apparition of distress may be detected [13]. In turn, the modification of the dynamic properties because of damage may also provide an indication of its severity and position within the structure. These contentions lay on the classification of damage assessment methodologies established by Rytter [14]: i) detect, ii) localize, iii) quantify, and lastly, iv) make a prognosis of remaining service life. Different approaches for detection and localization of damage from vibration responses have been reviewed in [15–17]. These approaches are classified as i) response-based methods, or ii) model-based methods. The former only depends on measured data, and is commonly used for damage identification, and eventually localization. The latter leverages an analytical or numerical model of the structure at the intact state, which is used to identify, localize, and in addition quantify the damage severity, by comparing an updated model at the damaged state [18]. Both approaches (response-based and model-based) are complimentary, since in most practical cases, response-based methods are used to detect damage occurrence, while model-based damage are used to detect and quantify damage severity [18]. Furthermore, the success of model-based methods depends on the model quality. Very often, model assumptions, and errors in estimated model parameters (e.g. geometry, material properties, and boundary conditions) lead to significant discrepancy with regard to experimental data. In this respect, model updating techniques have become a subject of intense research. Model updating consists in the process of correcting the relative mismatch between experimental and numerical modelling data of a structure, for obtaining better agreement between both, and so improving the predictions of its dynamic and static mechanical behavior [19,20]. This implies the formulation of an optimization problem wherein the differences between experimental and modelling data are minimized.

In civil engineering applications, modal analysis and finite element model (FEM) updating techniques have been applied and adapted for the evaluation and damage assessment of already existing structures [21], such as bridges [22,23], footbridges [24,25], buildings [25–27], dams [21], towers [28,29], and cultural heritage [29,30]. In this study, experimental modal analysis (EMA) and FEM updating was conducted on a radioactive waste container prototype. It was tested under different boundary conditions. First the radioactive waste package was tested empty. Second, after loading it with a dummy (non-radioactive) primary waste package. Such a dead load (the load of the primary waste package) affected the resonant frequencies of the concrete container. Then, different finite element models that describe the loaded and unloaded concrete containers are considered. The parameters of the finite element models are then adjusted to fit the EMA data. Different algorithms and methodologies have been proposed to solve the optimization problem [19,31], being the nonlinear simplex algorithm [32], the trust-region algorithm [27], neural networks [26,28,33,34] and genetic algorithms [35] the most appealed alternatives. In this study, a methodology for FEM updating is proposed, and applied on a radioactive waste package. To do so, an initial global sensitivity analysis is conducted, which is based on a full