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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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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.

Keywords

Finite element model updating, experimental modal analysis, radioactive waste package, reinforced concrete, dynamic properties.

33 **1 Introduction**

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

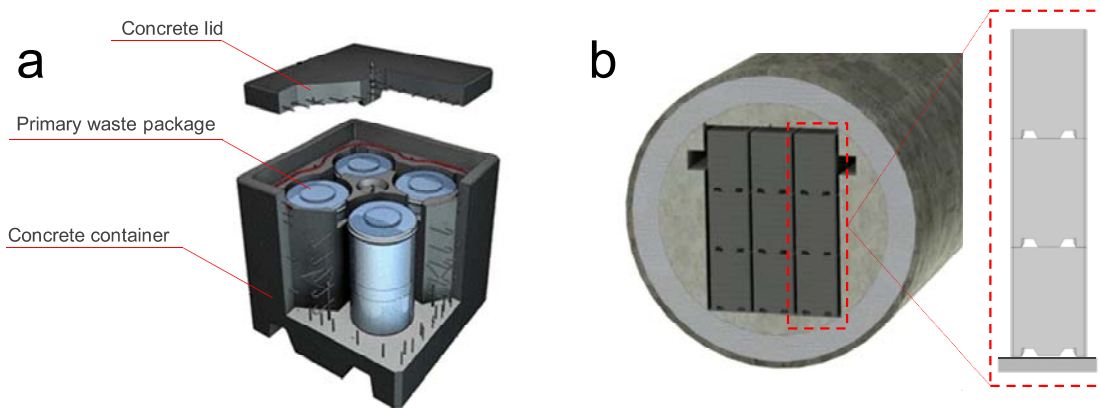


Figure 1. a) Typical reinforced concrete container designed to host intermediate and low level radioactive waste, and b) schematic description of the final disposition of waste packages in an underground repository cell, and detail of three stacked containers.

50 The management and control of concrete in radioactive waste repositories entails
51 several challenges. Despite concrete is being considered for radioactive waste disposal,
52 there is no previous experience on concrete withstanding nuclear environments beyond its
53 expected service life; ~100 years and at high temperatures (~65°C), for intermediate-level
54 waste. A number of studies claim that further research on concrete durability is needed, to
55 account for the simultaneous and synergistic actions of moisture, thermal, and mechanical
56 loads along with radiation damage [3]–[8]. In addition, most of these studies also appeal to
57 the need of developing nondestructive evaluation techniques and structural health
58 monitoring (SHM) systems, that inform about the mechanical and durability performance
59 of concrete in nuclear facilities. In particular, the difficulties arise from the limits on access
60 to the structures and the harsh environment [3]. Previous studies investigated the feasibility
61 of different nondestructive techniques, for the inspection of concrete in radioactive waste
62 repositories. Iliopoulos and coworkers [9] combined the application of different
63 nondestructive techniques on a radioactive waste container prototype subjected to high
64 temperatures. Digital image correlation and acoustic emission were able to monitor the
65 evolution of thermal induced cracking damage, while the depth of already formed cracks
66 was successfully investigated through the ultrasonic pulse velocity. Davis and coworkers
67 [10] applied different stress wave techniques aiming at periodic inspection of in-service
68 radioactive waste tanks made of reinforced concrete. The investigated techniques included
69 impulse response technique, ultrasonic pulse velocity and sonic logging. From this set of
70 techniques, the authors were able to investigate the uniformity of concrete, and thus detect
71 vulnerable zones. Andrade and coworkers [5], and Duffó and coworkers [6] have focused
72 their researches in the application of electrical resistivity measurements, aiming at the
73 service-life prediction of the steel reinforced concrete containers. In the particular case of
74 the *Cigéo* project, Andra has instrumented prototype concrete containers with embedded
75 optical fibers, so mechanical strains can be monitored since their production, and during
76 their final disposition in the geological repository [11], [12].

77 This study envisages the use of modal analysis for monitoring the structural health
78 of radioactive waste packages. In modal-based SHM applications, sensors are permanently
79 installed in structures and continuously record their dynamic characteristics. Since dynamic
80 properties are related to the mechanical integrity of structures, the eventual apparition of

81 distress may be detected [13]. In turn, the modification of the dynamic properties because
82 of damage may also provide an indication of its severity and position within the structure.
83 These contentions lay on the classification of damage assessment methodologies
84 established by Rytter [14]: i) detect, ii) localize, iii) quantify, and lastly, iv) make a
85 prognosis of remaining service life. Different approaches for detection and localization of
86 damage from vibration responses have been reviewed in [15]–[17]. These approaches are
87 classified as i) response-based methods, or ii) model-based methods. The former only
88 depends on measured data, and is commonly used for damage identification, and eventually
89 localization. The latter leverages an analytical or numerical model of the structure at the
90 intact state, which is used to identify, localize, and in addition quantify the damage severity,
91 by comparing an updated model at the damaged state [18]. Both approaches (response-
92 based and model-based) are complimentary, since in most practical cases, response-based
93 methods are used to detect damage occurrence, while model-based damage are used to
94 detect and quantify damage severity [18]. Furthermore, the success of model-based
95 methods depends on the model quality. Very often, model assumptions, and errors in
96 estimated model parameters (e.g. geometry, material properties, and boundary conditions)
97 lead to significant discrepancy with regard to experimental data. In this respect, model
98 updating techniques have become a subject of intense research. Model updating consists in
99 the process of correcting the relative mismatch between experimental and numerical
100 modelling data of a structure, for obtaining better agreement between both, and so
101 improving the predictions of its dynamic and static mechanical behavior [19], [20]. This
102 implies the formulation of an optimization problem wherein the differences between
103 experimental and modelling data are minimized.

104 In civil engineering applications, modal analysis and finite element model (FEM)
105 updating techniques have been applied and adapted for the evaluation and damage
106 assessment of already existing structures [21], such as bridges [22], [23], footbridges [24],
107 [25], buildings [25-27], dams [21], towers [28], [29], and cultural heritage [29], [30]. In this
108 study, experimental modal analysis (EMA) and FEM updating was conducted on a
109 radioactive waste container prototype. It was tested under different boundary conditions.
110 First the radioactive waste package was tested empty. Second, after loading it with a
111 dummy (non-radioactive) primary waste package. Such a dead load (the load of the primary

112 waste package) affected the resonant frequencies of the concrete container. Then, different
113 finite element models that describe the loaded and unloaded concrete containers are
114 considered. The parameters of the finite element models are then adjusted to fit the EMA
115 data. Different algorithms and methodologies have been proposed to solve the optimization
116 problem [19], [31], being the nonlinear simplex algorithm [32], the trust-region algorithm
117 [27], neural networks [26], [28], [33], [34] and genetic algorithms [35] the most appealed
118 alternatives. In this study, a methodology for FEM updating is proposed, and applied on a
119 radioactive waste package. To do so, an initial global sensitivity analysis is conducted,
120 which is based on a full factorial design of experiments (DOE). This initial analysis allows
121 determination of the most influential FEM parameters on the cost function values, and
122 obtaining indicative values that minimize it. This indicative minimum solution is used to
123 narrow the space solution for solving the optimization problem through a genetic algorithm.
124 Finally, a local sensitivity analysis is conducted using a one-at-a-time approach. This
125 process analyzes the impact of the variations away from the attained optimum value for
126 every updating parameter. The updated numerical models may serve i) to predict the
127 mechanical performance of the waste packages under different loading scenarios, which
128 saves efforts and budget in cumbersome experiments, and ii) to obtain finite element
129 models for model-based detection techniques, as a baseline condition. To the authors'
130 knowledge, this is the first study that proposes modal analysis as an alternative to monitor
131 the mechanical performance of radioactive waste packages. This study constitutes a
132 preliminary analysis towards the implementation of a modal-based SHM system for
133 controlling the mechanical integrity of radioactive waste concrete containers. The
134 implementation of a modal-based SHM on a radioactive waste repository faces particular
135 challenges which are also summarized herein. These concerns are subject of ongoing
136 research.

137 In the following, the present article is structured as follows: Section 2 describes the
138 waste package prototype, and provides a detailed description of the EMA test
139 configuration. Section 3 describes the experimental results: the obtained resonant frequency
140 peaks and their corresponding modal shapes. Section 4 presents different finite element
141 models that describe the experimental data. Section 5 describes the optimization
142 methodology for finite element model updating, and analyzes the sensitivity of the finite

143 element models to the input parameters. Finally, section 6 summarizes the conclusions that
 144 are drawn from this study, and summarizes practical aspects and challenges related to the
 145 implementation of a modal-based SHM strategy on a radioactive waste repository.

146 2 Experimental details

147 2.1 Description of the radioactive waste package

148 Figure 2a shows a schematic of the waste package and its parts: i) the primary waste
 149 package in the form of a metallic drum, and ii) a concrete container which is designed to
 150 host the primary waste package. A lid, also made of reinforced concrete, is fixed to the
 151 container through four partially threaded screws. The Figure 2b shows the container
 152 dimensions. The container rests on four L-shaped feet (see Figure 2b). Overall, it measures
 153 2.25m x 1.54m x 1.54m, and weights roughly 12 tons when it is loaded with the primary
 154 waste package. Table 1 lists indicative values of mass for the different parts.

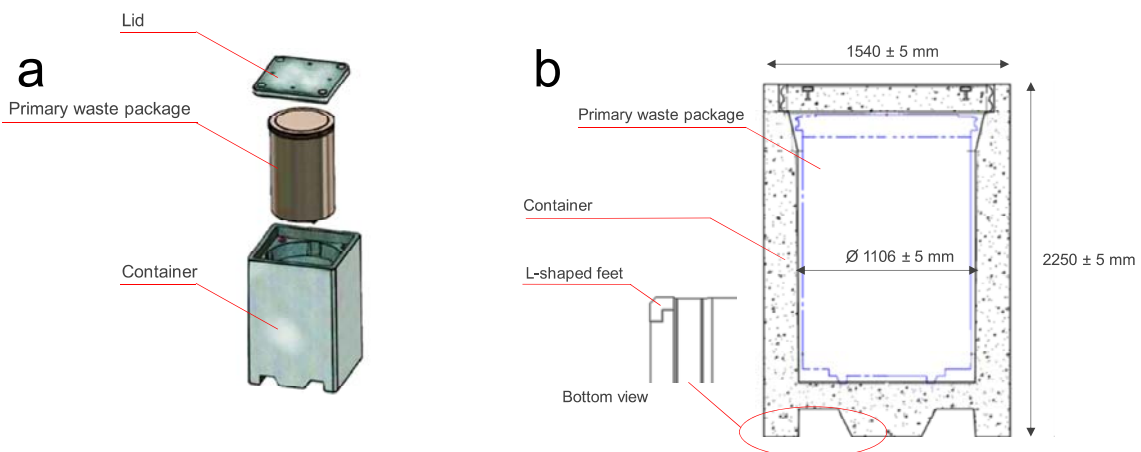


Figure 2. Description of the radioactive waste container prototype: a) schematic of the different parts of the radioactive waste package, and b) detailed dimensions of the concrete container.

155 Table 1. Approximated mass specifications of the different elements of the reinforced concrete
 156 container prototype.

Total steel reinforcement	360 kg
Lid	662 kg
Primary waste package	3831 kg
Reinforced concrete container (empty)	8417 kg

157 Experimental modal analysis was conducted on a radioactive waste package
158 prototype. It was tested under two different states. First, the concrete container was tested
159 empty. At this state the four screws on the lid were incompletely threaded, and a thin foam
160 was placed in between the two bodies. Second, the concrete container hosted a dummy
161 (non-radioactive) primary waste package; at this state the four screws on the lid were
162 completely threaded. The applied torque onto the screws was not ascertained at both states;
163 yet, they were noticeably different. Figure 3 shows three photos that describe handling
164 operations of the dummy primary waste package and the concrete lid in between modal
165 tests. The package was placed on a metallic platform, which was conceived to distribute the
166 load during mechanical tests. Typical mechanical tests conducted in this platform consist in
167 piling up several containers, which reproduce the in-service conditions [12]. These tests are
168 not discussed herein.



Figure 3. General overview and handling of the dummy primary waste package, a) remove the lid, b) loading the container with a dummy primary waste package, and c) closing of the waste package

169 Indicative values for elastic moduli and density of the precast concrete container
170 were obtained on three cylindrical samples (length $\sim 0.225\text{m}$ and diameter $\sim 0.115\text{m}$), which
171 were produced with identic concrete composition to the waste packages. To that end, the
172 dynamic modulus and Poisson's ratio were ascertained according to the standard resonant
173 frequency method ASTM C215-14 [36]. The dynamic modulus was derived from the
174 longitudinal frequency mode, and Poisson's ratio was derived from the torsional mode of

175 vibration, using the formulae provided in ASTM C215-14. The density of the concrete
 176 samples was measured from the mass at the moment of test and the actual dimensions of
 177 every sample, which were verified with a caliper. At the moment of test, the samples were
 178 fully matured (more than 1 year after casting). For reference, the 28-day compressive
 179 strength is ~45 MPa. The Table 2 lists the physical properties of the concrete samples.
 180 These physical properties are used later on as guidance in the numerical simulations.

181 *Table 2. Physical properties of the concrete samples. Mean values \pm standard deviation.*

Dynamic modulus, E (GPa)	Poisson's ratio, ν	Density ρ (kg/m³)
39 \pm 1	0.18 \pm 0.01	2320 \pm 10

182

183 *2.2 Experimental modal analysis*

184 The ways to conduct experimental modal analysis (EMA) are manifold. In this
 185 study, a roving hammer test was conducted to identify resonant frequencies and modal
 186 shapes of the concrete container. The advantages of a roving hammer test against other
 187 alternatives are that it is relatively inexpensive, it can be set-up in very short time, and
 188 virtually, an unlimited number of degrees of freedom can be tested. The roving hammer test
 189 was conducted on a regular grid placed on a face of the container. It consisted of 80 degrees
 190 of freedom: 10 rows by 8 columns every 20cm. The vibration responses were obtained by
 191 striking the surface of the container with a modal hammer (Bruel & Kjaer model 8207,
 192 0.225 mV/N). An accelerometer (Bruel & Kjaer model 4525B, 1.046 mV/m·s⁻²) was glued
 193 on the surface which sensed the out-of-plane vibration. Figure 4 shows a schematic
 194 representation of the test configuration, and the relative positions of the grid with regard the
 195 accelerometer.

196 The modal characteristics were extracted using the peak amplitude method [37]. At
 197 every degree of freedom (p), the accelerance $H_p(\omega)$ is obtained as

$$198 \quad H_p(\omega) = \frac{X_p(\omega)}{F_p(\omega)}, \quad (1)$$

199 where $F_p(\omega)$ is the Fourier transform of the force signal, and $X_p(\omega)$ is the Fourier transform
 200 of the acceleration signal. Since not all resonant frequencies have meaningful spectral
 201 amplitude at all measured degrees of freedom p , the squared singular values of the vector
 202 $[H_1(\omega_i), H_2(\omega_i), \dots, H_{80}(\omega_i)]$, were computed at every frequency (or spectral line, ω_i), to
 203 obtain a representative spectrum of the whole grid. This approach is termed complex mode
 204 indication function [37], [38]. The imaginary part of the accelerance (Eq. 1) is much more
 205 discriminating with respect to close modal frequencies [38]. Therefore, only the imaginary
 206 part of the accelerance was used to identify the resonant frequency peaks. Furthermore, the
 207 corresponding modal shapes were obtained by mapping the corresponding imaginary part
 208 of Eq. 1 onto the grid. Recall that the imaginary part of the accelerance is proportional to
 209 the modal displacement at a given resonant frequency peak [37], [39]. Only modes up to
 210 ~ 1000 Hz were considered. This cutoff frequency was determined for a decrease of 90% of
 211 the input energy force.

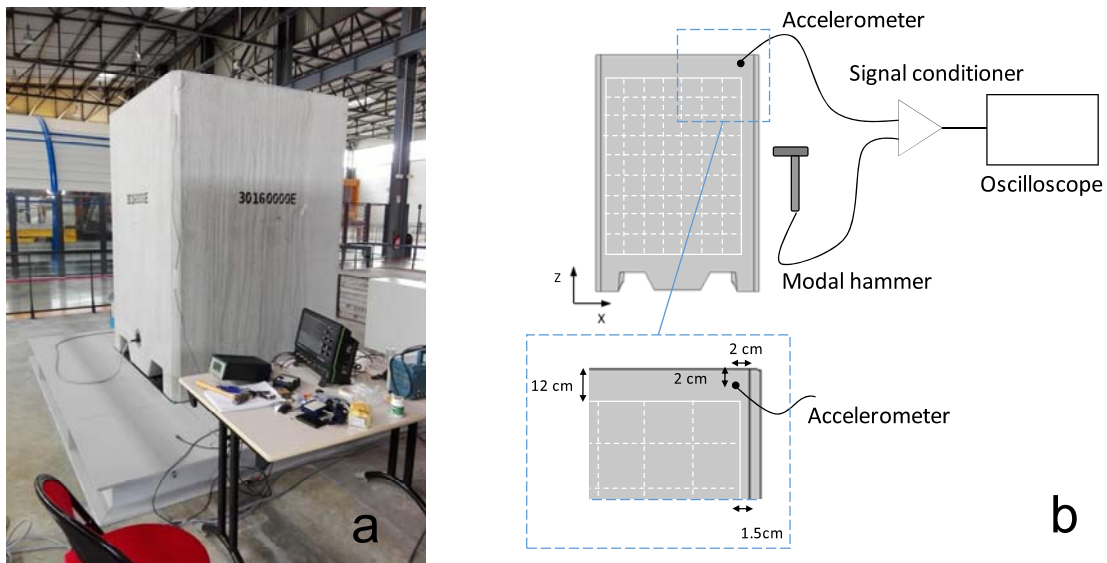


Figure 4. General overview of the container which lays on a metallic platform, and b) schematic representation of the test configuration showing the relative position of the measured degrees of freedom with regard the geometry of the container: a 10x8 grid every 20 cm placed on the front face (not to scale).

212 3 Experimental modal analysis results

213 The Figure 5 shows the eigenvalue spectra resulted from the singular value
 214 decomposition of the imaginary part of the accelerance obtained for the unloaded and

215 loaded conditions. The spectra show different frequency peaks, which frequently appear
216 closely spaced. In both cases, a number of 20 resonant frequency peaks were identified,
217 ranging from 200 to 1000 Hz. These are shown as vertical dashed lines in Figure 5. Low
218 frequency contributions (<100 Hz) were also identified, which correspond to rigid body
219 modes. However, their amplitudes are two orders of magnitude lower than those
220 corresponding to resonant mode peaks (note logarithmic scale in Figure 5). Figure 6 shows
221 the mode shapes corresponding to the 20 extracted resonant frequency peaks at the
222 unloaded state. Similar mode shapes and in the same order were obtained after loading.
223 However, after loading, all resonant frequency peaks shifted upward in different extents:
224 between 0.1 and 4%. The biggest difference was found for the lowest identified resonant
225 frequency mode. This effect indicates that the load of the dummy primary waste package
226 modified the dynamic properties of the structure. In the following, finite element modeling
227 was used to interpret the observed behavior.

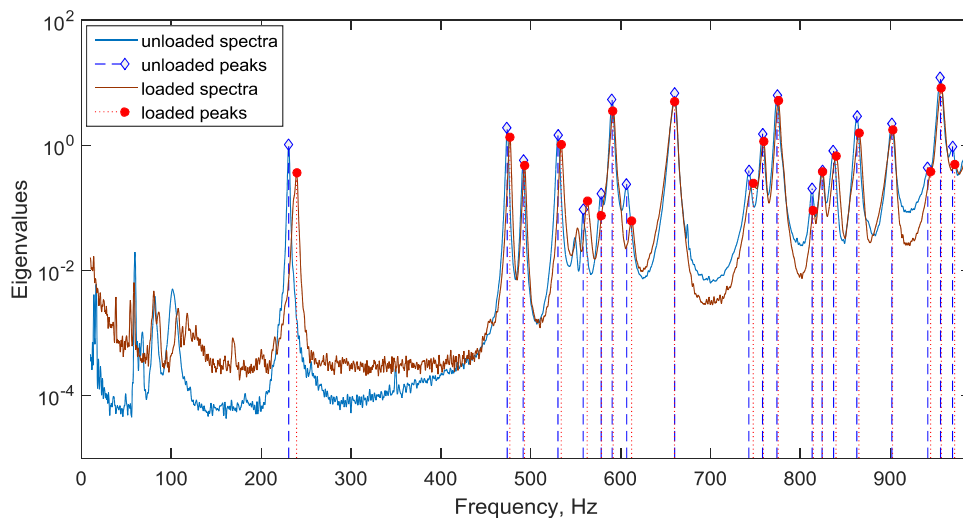


Figure 5. Resonant spectra obtained before and after loading the container with a dummy primary waste package. A number of 20 resonant frequency peaks were detected between 200 Hz and 1000 Hz.

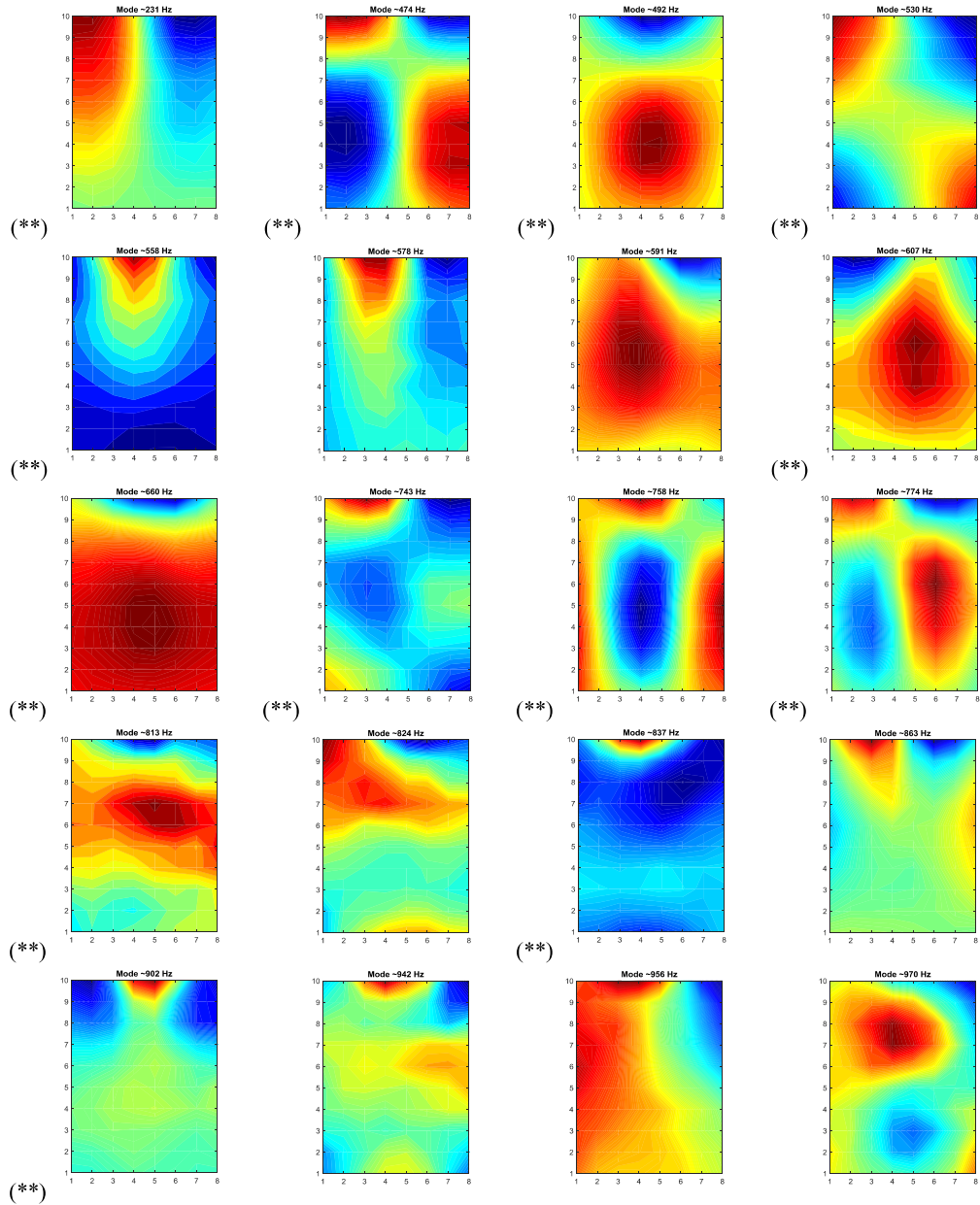


Figure 6. Experimental modal shapes (out-of-plane motion) obtained on the front face of the container. The symbols (**) denote that these mode shapes were paired and used for the FEM updating later on.

229 4 Finite element modelling

230 Figures 7a and 7b show a schematic description of the boundary conditions of the
 231 numerical model of the concrete container, for the unloaded (Figure 7a) and loaded states
 232 (Figure 7b). Massless spring elements (denoted with subscript *tel*, which stands for thin
 233 elastic layer) were used to describe the boundary condition between the lid and the concrete

234 container. These springs accommodate the different nodal displacements between the two
235 bodies in x , y and z directions, with a preset spring constant (K_{tel}). These springs were
236 considered to have similar stiffness values in every direction, thus $K_{tel,x} = K_{tel,y} = K_{tel,z}$.
237 Analogously, massless spring elements (K_{spf} , subscript spf stands for spring foundation)
238 model the boundary condition between the floor and the four L-shaped feet of the
239 container. Both, K_{spf} and K_{tel} elements were distributed on their respective contacting areas.
240 Moreover, additional mass (A_{mass}) was added to the bodies to consider the mass of the steel
241 reinforcement, along with deviations from the measured concrete density ($\rho=2320 \text{ kg/m}^3$).
242 Therefore, the density of concrete was kept constant in the numerical simulations, and the
243 parameter A_{mass} was used as updating parameter. Linear elastic and isotropic behavior was
244 considered. In the particular case of the loaded container (Figure 7b) the load corresponding
245 to the weight of the primary waste package was distributed on the available surface ($\sim 1\text{m}^2$),
246 and massless spring elements (K_{spf}^l) were used to constrain the movement at this zone.
247 Again, these springs were considered to have similar stiffness values in x , y and z
248 directions.

249 Different alternatives were considered to render an explanation of the relative
250 increase of resonant frequencies with regard the unloaded state. On the one hand, dead
251 loads on the container may lead to a local increase of stiffness because of geometric
252 nonlinearity, and so, leading to an increase of resonant frequencies [40], [41]. On the other
253 hand, nonlinear elastic behavior can further lead to stress dependent resonant frequency
254 variations [42]. However, for given boundary conditions ($K_{tel} = K_{spf} = K_{spf}^l = 1 \text{ GN/m/m}^2$), and
255 considering third-order elastic constants for concrete —for instance, those obtained for
256 concrete by Payan and coworkers [43] or by Lundqvist and Rydén [42]—, the sole effect of
257 the dead load lead to very weak variations (less than 0.0001%) of resonant frequencies with
258 regard the same model without load. For reference, the effect of the load of the primary
259 waste package ($\sim 3831 \text{ kg}$) distributed on the available surface ($\sim 1\text{m}^2$, see Figure 7b) leads to
260 a maximum Von Mises stress of roughly $\sim 0.7 \text{ MPa}$ in the volume of the container. Hence,
261 the load of the primary waste package container is low enough to disregard nonlinear
262 behavior. Conversely, the sole incorporation of the spring elements that constrain the
263 loaded zone (K_{spf}^l) cause a meaningful increase of the resonant frequencies with regard the
264 unloaded model (Figure 7a). In addition, the dead load may plausibly further constrain the

265 boundary conditions on the four feet, and so, contributing also to increase the resonant
 266 frequencies. This latter option was considered henceforth.

267 A number of $N= 45$ eigen-frequencies (f_n) and their corresponding modal shapes
 268 (ϕ_n) were computed numerically for both models (Figures 7a and 7b). Figure 7c shows a set
 269 of representative mode shapes extracted out of the 45 computed modes. They were obtained
 270 for the unloaded state, and for the parameter values of $K_{tel} = K_{spf} = 1 \text{ GN/m/m}^2$, $A_{mass} = 360$
 271 kg, and the material properties listed in Table 2. A number of modal shapes correspond to
 272 the own resonant frequencies of the lid. For this particular set of model parameters, the
 273 modes 1 to 12, 15 to 17, 26, 27 and 45 correspond to the own resonant frequencies of the
 274 lid; an example of a resonant frequency of the lid is shown in the last picture in Figure 7c.
 275 Experimental and numerical mode shapes were compared through the Modal Assurance
 276 Criterion (MAC) as [44],

$$277 \quad MAC_{m,n} = \frac{|\phi_n \cdot \phi'_m|^2}{|\phi_n \cdot \phi'_n| \cdot |\phi_m \cdot \phi'_m|}, \quad (2)$$

278 wherein ϕ_m is the modal shape of the m experimental mode, and ϕ_n is the numerical modal
 279 shape corresponding to the n eigen-frequency. The MAC is a measure of the similarity
 280 between the m experimental modal shape, and the n numerical modal shape. MAC values
 281 vary between 0 and 1. Figure 8 shows the pairwise comparison of the 20 extracted
 282 experimental modal shapes (those shown in Figure 6) with the 45 computed numerical
 283 modal shapes (those shown in Figure 7c). Herein, a pair was assigned for the maximum
 284 attained MAC value, and if that was higher than 0.65. Moreover, those resonant modes
 285 corresponding to the lid were disregarded, since they produce negligible out-of-plane
 286 displacement on the measured surface. In some cases, the experimental modal shapes could
 287 be attributed to several numerical modal shapes. For instance, the 16th experimental mode
 288 shape could be assigned to two different numerical modes (see Figure 8, and inset
 289 captions). This particular mode of vibration was not used to prevent from false assignation
 290 during the optimization process. As a result, a number of 13 modes could unequivocally be
 291 assigned, out of the 45 numerical modes (circle markers in Figure 8). These vibration
 292 modes were retained for the inversion of the parameters of the numerical model.

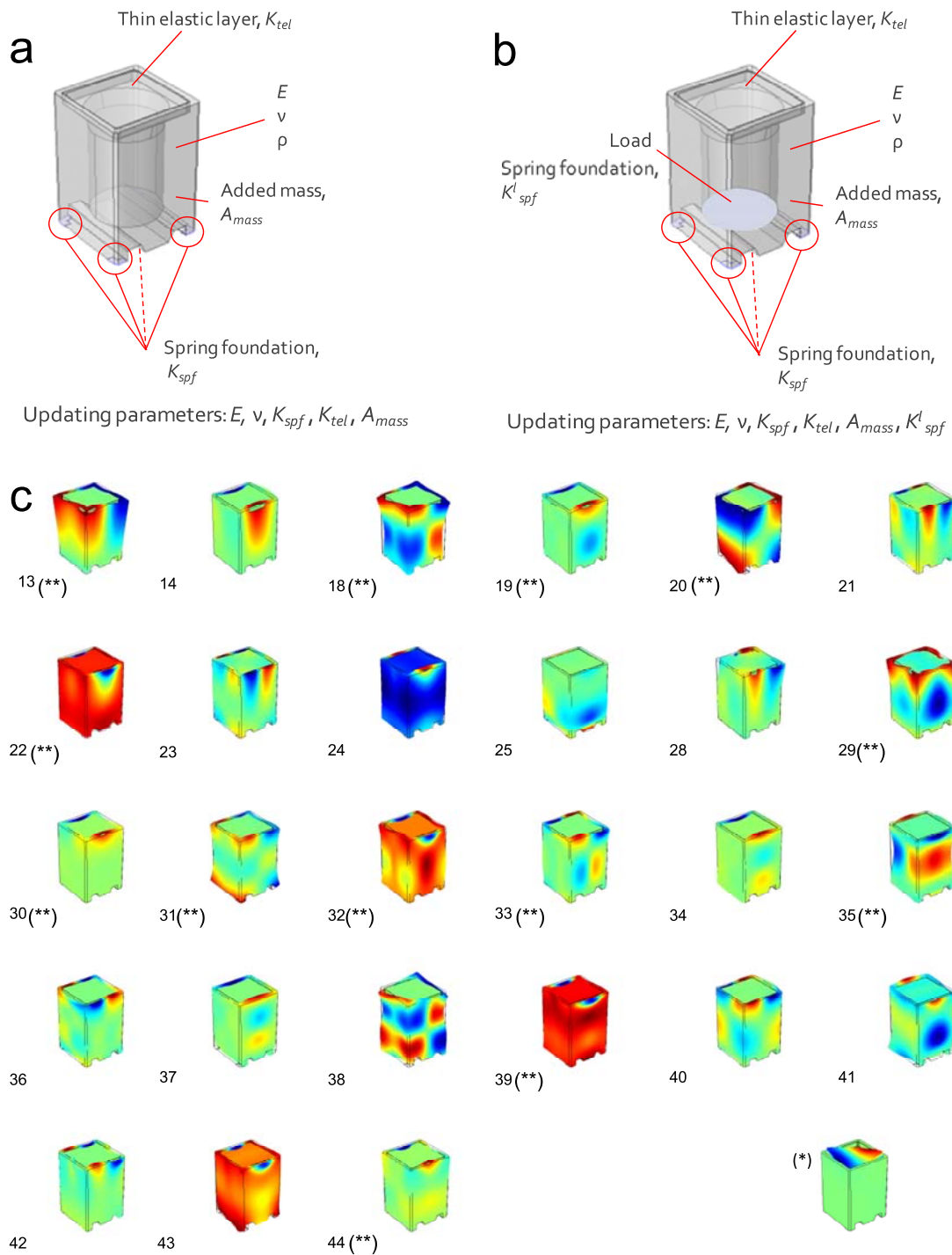


Figure 7. Description of the boundary conditions and the physical parameters of the numerical mode, a) unloaded, and b) loaded container. c) Representative modal shapes corresponding to the out-of-plane displacement of the front face of the unloaded container; (*) last picture (bottom right) shows a representative mode of vibration of the lid. The symbols (**) denote that these mode shapes were paired and used for the FEM updating.

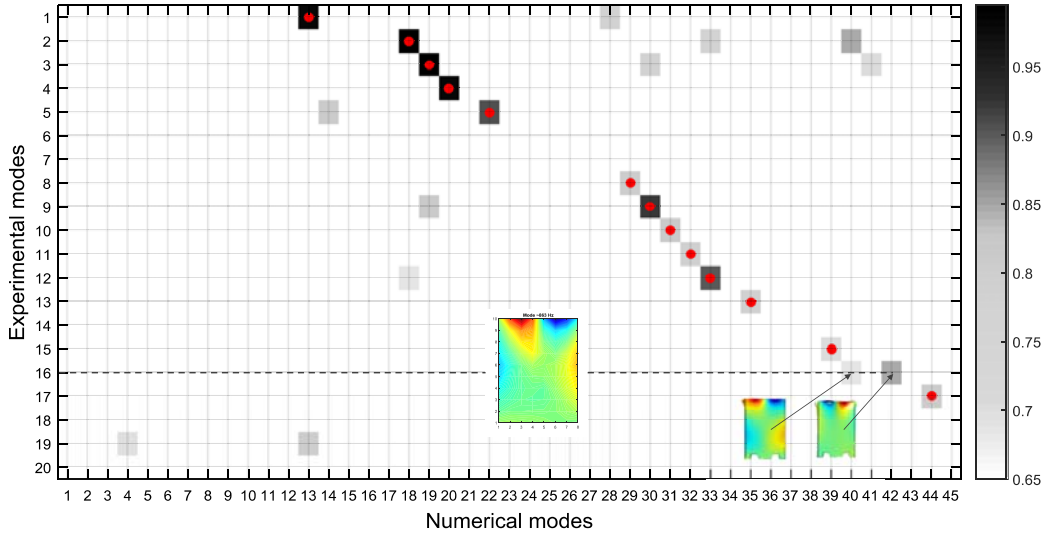


Figure 8. Modal Assurance Criterion values obtained for pairwise comparisons between numerical and experimental modal shapes. Circle markers represent paired modes, which were retained for the optimization problem.

293

294 5 Optimization problem and sensitivity analysis

295 Given that the actual material properties and boundary conditions are unknown, an
 296 optimization problem can be formulated. That is, to find the values of the set of unknown
 297 parameters of the numerical model (\bar{p}), that minimize the differences between
 298 experimental and numerical results. In case of the numerical model corresponding to the
 299 unloaded state, the set of the unknown parameters are: the modulus (E), the Poisson's ratio
 300 (ν), the spring constant of the spring foundation (K_{spf}), the spring constant of the thin elastic
 301 layer (K_{tel}), and the added mass (A_{mass}). Therefore, the optimization problem can be
 302 formulated as

$$303 \quad \min f_c(\bar{p}), \quad (3)$$

304 subjected to upper and lower boundaries, $\bar{p}_{lower} \leq \bar{p} \leq \bar{p}_{upper}$, and where the cost function
 305 $f_c(\bar{p})$ can be written as the sum of weighted squared relative differences between
 306 experimental (subscript m) and numerical (subscript n) frequency values as

$$f_c(\bar{p}) = 1/N \cdot \sum_{m=1}^M \sum_{n=1}^N w_{n,m} \cdot \left(\frac{f_n - f_m}{f_m} \right)^2; \quad (4)$$

308 $w_{n,m}$ is a weighting factor that equals 1 if the mode is paired, and 0 elsewhere. Note that not
 309 all selected experimental modes may be paired during the optimization process, hence the
 310 cost function in Eq. 4 represents an average error per mode. Other cost functions have been
 311 considered elsewhere wherein *MAC* values also weight on the cost function; see for
 312 instance references [23] and [31].

313 As a first approximation to the optimization problem a full factorial three level (3^k)
 314 design of experiments (DOE) was conducted; k stands for the total number of factors,
 315 herein $k=5$ for the numerical model corresponding to the unloaded state (see Figure 7a), and
 316 $k=6$ for the numerical model corresponding to the loaded state (see Figure 7b). The
 317 objectives of this initial analysis are i) to estimate the global sensitivity of the numerical
 318 model to model parameters variations, and ii) get an initial estimation of the parameter
 319 values that minimize the cost function (Eq. 4). This was achieved through the surface
 320 response methodology [45]. The surface response methodology consists in fitting an
 321 empirical model to the data generated by the application of a DOE, and find their critical
 322 values (in this case the minimum). The 3^k full factorial design allows estimation of a
 323 quadratic model as

$$f_c'(p) = a_0 + \sum_{i=1}^k a_i X_i + \sum_{i=1}^k \sum_{j=1, j < i}^k a_{ij} X_i X_j + \sum_{i=1}^k a_{ii} X_{ii}^2 + error, \quad (5)$$

325 wherein, a_0, a_i, a_j, a_{ii} and a_{ij} are the fitting coefficients of the quadratic model, and the set
 326 of parameters is $\bar{p} = [X_1, \dots, X_k]$. Table 3 shows the factor levels for the set of parameters
 327 considered in the numerical models: 5 parameters for the unloaded state (X_1 to X_5), and 6
 328 parameters for the loaded state (X_1 to X_6). The factor levels were chosen close to the
 329 indicative values obtained for the elastic modulus and Poisson's ratio of the concrete (those
 330 listed in Table 2). Conversely, since indicative values for boundary conditions (K_{spf} , K_{tel} ,
 331 and K_{spf}^l) are not available, these were allowed to vary in a wider range. The numerical

332 models were evaluated at the resulting 243 parameter combinations for the unloaded state,
333 and at the 729 for the loaded state. Then, the resulted numerical eigen-frequencies and
334 modal shapes were paired to the EMA data, and so the cost function (Eq. 4) was evaluated
335 for every parameter combination. Once the empirical model in Eq. 5 is fitted to the cost
336 function values obtained for all the 3^k combinations of parameters, a minimum point can be
337 estimated. Such estimated minimum can be then used to narrow the space solution to be
338 explored by a genetic algorithm (GA). From an initial population (say sets of parameters),
339 genetic algorithms mimic “natural selection” to select sets of parameters that enhance the
340 cost function. The members of the population are combined and selected as a function of
341 how they perform on the cost function (or fitness value), to reproduce an enhanced
342 generation. Crossover and mutation operators are applied through generations. The
343 crossover function defines how members of the population create next generation, and the
344 mutation function, introduces diversity in the population by introducing random changes on
345 them. In general, the initial population can be generated randomly. However, the use of a
346 priori knowledge may accelerate the convergence to a solution. Herein, the initial
347 population was narrowed to $\pm 10\%$ of the estimated minimum by the surface response
348 method. Note, that the space solution is not strictly constrained within these boundaries, but
349 they serve to provide an initial population which is randomly generated within these
350 boundaries. There is a number of applications wherein the application of the surface
351 response methodology has been successfully combined with genetic algorithms in
352 optimization problems [46]. The population size was set to 25 in both cases. The crossover
353 and mutation rates were set to 0.8 and 0.1. The GA was stopped once a preset number of
354 generations or a threshold value of the cost function is attained; herein, 25 generations or
355 10^{-4} respectively. Further refinement in the optimization problem can be achieved by using
356 the obtained solution by the GA algorithm, as starting point in a nonlinear constrained
357 minimization; herein, through the interior point algorithm. Examples of successful
358 application of such hybrid genetic algorithms for FEM updating applications can be found
359 in [23], [31], [34]. Figure 9 summarizes the optimization process conducted herein.

360

361

362 Table 3. Factor levels used in the three level full factorial design.

Parameter		Upper level	Intermediate level	Lower level
X ₁	Modulus (GPa)	40	35	30
X ₂	Poisson's ratio	0.300	0.225	0.150
X ₃	K_{spf} (GN/m/m ²)	10.00	5.05	0.10
X ₄	K_{tel} (GN/m/m ²)	10.00	5.05	0.10
X ₅	A_{mass} (Kg)	1000	500	0
X ₆	K_{spf} (GN/m/m ²)	10.00	5.05	0.10

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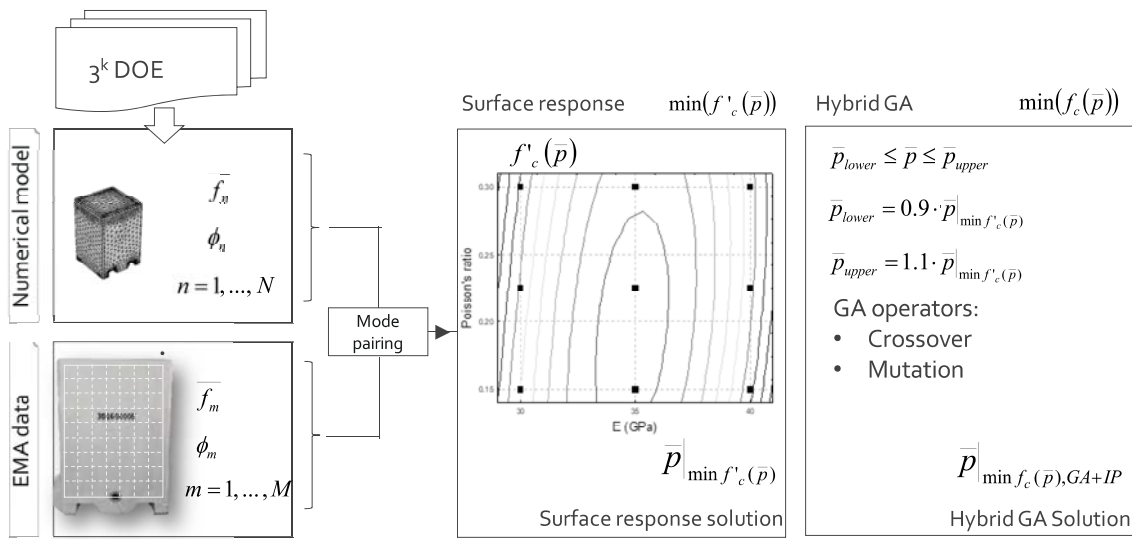


Figure 9. Flowchart representing the data analysis conducted for FEM updating in this study.

364 One of the interests of performing a 3^k DOE is to analyze the global sensitivity of
 365 the FEM to the model parameter variations. For the sake of conciseness, only the main
 366 effects are shown. Figures 10a to 10f show the main effects for the cost function. From
 367 results it is drawn that the cost function is sensible to the variations of E , K_{tel} , and A_{mass} ,
 368 within the levels of the DOE. It was the less for all the cases where E was set to 35 GPa
 369 (Figure 10a). In addition, the cost function increases monotonically when K_{tel} increases
 370 (Figure 10d), and decreased with increasing A_{mass} (Figure 10e). Conversely, the cost
 371 function showed less variability with the variations of Poisson's ratio (Figure 10b), K_{spf}
 372 (Figure 10c), and K_{spf}^l (Figure 10f). Yet, the regression analysis showed that all the linear
 373 terms were statistically significant in both cases, including a number of quadratic and the
 374 interaction terms in the Eq. 5 (we deemed statistical significance for p-values<0.05; the

375 regression results are not shown herein). The explained variance was 98% for the unloaded
 376 case, and 85% for the loaded one. Subsequently, the fitted equations were used to obtain the
 377 set of parameters that minimize f'_c , and initialize the GA.

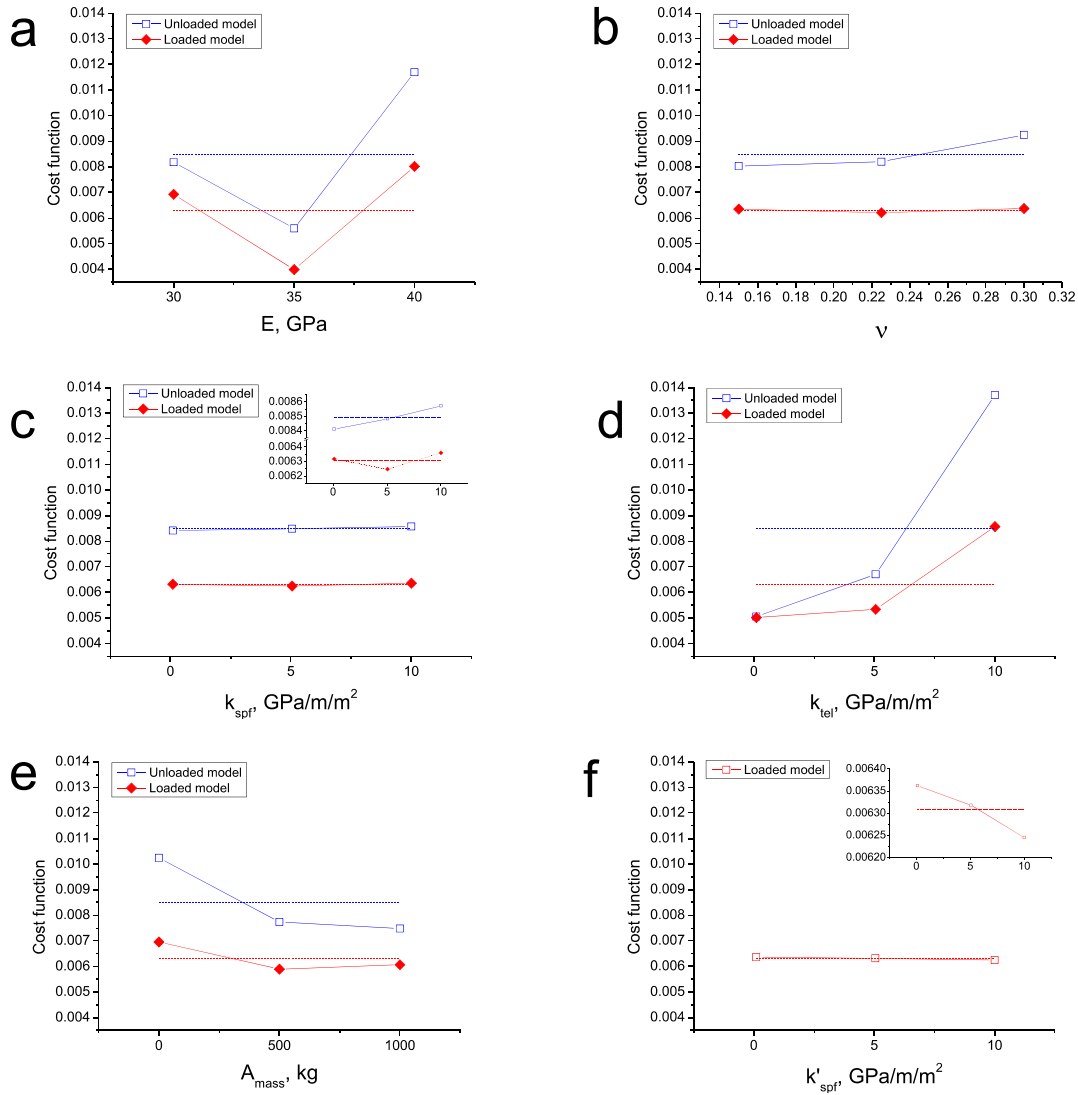


Figure 10. Main effects plots (data means) for cost function values investigated at the 3^k DOE points, for loaded and unloaded FEM. a) Elastic modulus, b) Poisson's ratio, c) K_{spf}^1 , d) K_{tel}^1 , e) A_{mass} , and f) K_{spf}^1 . Dashed lines represent the global mean.

378 Table 4 summarizes the results of the FEM updating for unloaded and loaded states.
 379 For reference, intermediate solutions across the different steps of the optimization process
 380 are also listed: the best 3^k DOE point, and the surface response minimum. The elastic
 381 properties (E and ν) were found to be in good agreement with those found for cylindrical

382 samples (Table 2). From results, it is found that the loaded containers may be well
383 represented by increasing the stiffness of the spring foundation elements. Moreover, Table
384 5 compares the EMA data and the FEM results obtained during the different steps, and for
385 both investigated states. *MAC* values remained almost constant across the optimization
386 steps, while the resonant frequency values varied in larger extent. The symbol (--) denotes
387 modes that were not paired; thus $MAC < 0.65$ at this optimization step. Finally, Figure 11a
388 and 11b show the predicted values as a function of the observed values and the resulted
389 residuals for both states. Noticeably, the first four resonance modes are predicted with a
390 relative error below 1%. However, at higher frequencies, the relative error increases,
391 roughly to 2%. The relative misfits in FEM updating are in general attributed to the model
392 assumptions: i) model structure errors, ii) model order errors (nonlinear behavior); iii)
393 model parameter errors, and iv) errors in experimental data [20]. Notwithstanding, the
394 resulting numerical models describe fairly well the dynamic mechanical behavior of the
395 packages. These results are expected to be used as a reference condition for future
396 experimental campaigns. Finally, a local sensitivity analysis was conducted through a one-
397 at-a-time approach. It consists in investigate the effect of every parameter individually to a
398 higher and a lower value, while keeping other parameters at the reference value. Herein, we
399 investigated the local sensitivity within a $\pm 10\%$ parameter variations. Figures 11c and 11d
400 show the local sensitivity analysis results for unloaded and loaded states. From, these
401 results it is drawn that the cost function is dominated by the elastic modulus variations in
402 both cases, while Poisson's ratio, the added mass, and the boundary conditions variations
403 lead to minor variations of the result.

404 *Table 4. Results of the set of the parameters of the numerical mode for both investigated states.*

	E (GPa)	v	K_{spf} (GN/ m/m ²)	K_{tel} (GN/ m/m ²)	A_{mass} (kg)	K_{spf}^d (GN/ m/m ²)	f'_c ($\cdot 10^{-4}$)	f_c ($\cdot 10^{-4}$)
Unloaded (Figure 7a)								
Best 3 ^k DOE point	35.00	0.15	5.05	0.10	500.0	--	--	3.16
Surface response minimum	38.74	0.18	0.10	0.45	967.0	--	1.82	2.04
Hybrid GA optimization	35.85	0.17	5.26	0.77	576.8	--		1.77
Loaded (Figure 7b)								
Best 3 ^k DOE point	35.00	0.30	10.00	0.10	0	5.005	--	5.89
Surface response minimum	38.24	0.29	10.00	1.27	1000	10.00	12.63	3.57
Hybrid GA optimization	35.59	0.19	7.72	1.23	524.7	6.58	--	1.98

405 Table 5. Comparison of EMA data and FEM results across the different optimization steps.

	Mode	EMA	Best 3 ^k DOE point		Surface response minimum		Hybrid GA optimization	
		Freq. (Hz)	Freq. (Hz)	MAC	Freq. (Hz)	MAC	Freq. (Hz)	MAC
Unloaded	1	230.7	220.9	0.98	228.4	0.98	231.1	0.98
	2	474.0	470.9	0.99	479.5	0.99	475.3	0.99
	3	491.7	486.0	0.99	493.9	0.99	489.7	0.99
	4	530.3	521.4	0.98	518.7	0.98	523.1	0.98
	5	558.3	540.9	0.89	548.2	0.90	544.6	0.90
	6	606.9	605.8	0.82	616.5	0.80	612.1	0.81
	7	660.2	659.4	0.92	675.2	0.92	667.9	0.92
	8	742.8	749.2	0.81	740.4	0.82	751.6	0.82
	9	758.0	757.6	0.81	769.6	0.79	763.3	0.80
	10	774.0	761.3	0.90	775.8	0.90	767.1	0.90
	11	813.1	802.5	0.76	818.5	0.77	807.8	0.75
	12	837.1	842.0	0.74	852.2	0.70	846.3	0.74
	13	901.9	--	--	--	--	928.2	0.83
Loaded	1	239.5	232.3	0.99	241.03	0.99	237.7	0.99
	2	476.8	485.0	0.99	480.16	0.99	479.4	0.99
	3	493.2	490.8	0.99	486.20	0.99	491.4	0.99
	4	534.0	524.3	0.98	524.19	0.98	534.3	0.98
	5	562.8	553.0	0.75	550.09	0.75	553.6	0.75
	6	612.3	622.5	0.73	620.08	0.82	617.2	0.74
	7	660.0	686.1	0.95	675.48	0.94	670.6	0.94
	8	747.7	764.8	0.67	752.84	0.67	760.9	0.65
	9	759.1	786.7	0.81	772.25	0.81	766.1	0.80
	10	775.5	790.0	0.89	775.50	0.88	769.4	0.88
	11	824.7	--	--	--	--	--	--
	12	839.7	--	--	839.83	0.83	848.6	0.70
	13	902.8	--	--	944.00	0.89	933.0	0.85

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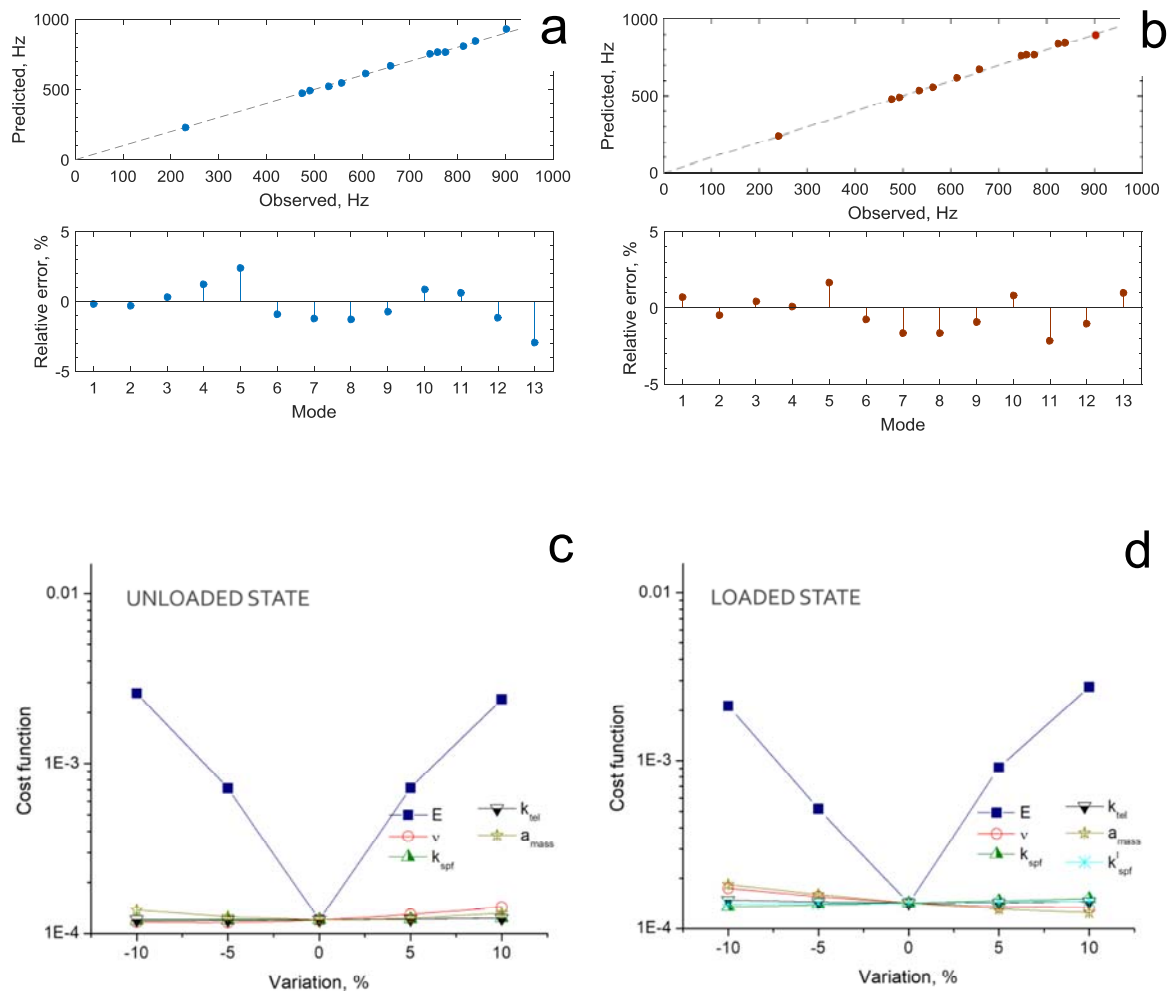


Figure 11. Comparison between experimental and numerical frequencies after the optimization for a) unloaded case, and b) loaded case, and sensitivity analysis, and one-at-a-time analysis for $\pm 10\%$ variations for c) unloaded, and d) loaded states.

410

411 6 Conclusions and prospects

412 Experimental modal analysis has been applied on a prototype radioactive waste
 413 package. The prototype was tested under two different scenarios: the concrete container
 414 was tested empty, and then, hosting a dummy primary waste package. Similar modal shapes
 415 were identified in both cases. However, after loading the concrete container, all resonant
 416 frequency modes consistently shifted upwards: between 4% and 0.1%. EMA data (resonant

417 frequencies and modal shapes) were used to benchmark finite element models that describe
418 the dynamic mechanical behavior of the concrete containers at both states. The latter was
419 achieved through the formulation of an optimization problem that consists in finding the
420 parameters of the numerical model that minimize the differences with regard the EMA data.
421 Herein, we first used a full factorial DOE which allowed investigation of the global model
422 sensitivity to the input parameters. Such an analysis allows screening the parameters that
423 dominate the dynamic properties within a range of values, get insight of the model quality,
424 and get an initial estimation of the set of the numerical model parameters that minimize the
425 differences with respect the EMA data. The optimization problem was subsequently solved
426 through a genetic algorithm, within a set of parameter boundaries ensuing the analysis of
427 the DOE. Such a methodology presented in this study was able to successfully calibrate
428 finite element models that describe the mechanical behavior of the radioactive waste
429 packages. Numerical models can be then used to predict the mechanical behavior of the
430 radioactive waste prototypes, which may save considerable labor and budget in
431 cumbersome experiments, and serve as baseline condition for the implementation of a
432 modal-based SHM. Model updating can be used also to detect, locate and quantify damage
433 severity [27], [34]. With regard this latter purpose, the following issues are subject of
434 ongoing research:

- 435 (i) In the framework of the *Cigéo* project, it is foreseen that the containers be
436 stacked (see Figure 1b). Thus, three different situations must be
437 considered depending on the position of the container, each of them,
438 being subjected to different boundary conditions. A similar FEM
439 updating procedure can be conducted to obtain numerical models of the
440 concrete containers at their final disposition in the radioactive waste
441 repository.
- 442 (ii) The radioactive waste repository is expected to work at temperatures up to
443 $\sim 65^{\circ}\text{C}$, depending on the waste type. Previous researches [7], [47] have
444 demonstrated that at and above such temperatures drying shrinkage in
445 concrete leads to a decrease of the elastic properties. Furthermore, the
446 elastic properties of concrete (as other ceramic materials) soften with
447 increasing temperature [48], [49]. Therefore, eventual temperature

448 fluctuations in the radioactive waste repository along with concrete
449 aging are expected to cause variations on dynamic properties, and yet not
450 being indicative of structural damage; or in a reverse sense, obscuring
451 the presence of damage [16], [50]. These contentions oblige
452 consideration of additional sensors that monitor operational conditions,
453 and aid to remove the trends on the modal data driven by such. The
454 interaction of these effects deserves further study.

455 (iii) In most practical cases, modal-based SHM leverages ambient vibrations
456 (say wind loads, traffic, or seismic events) to obtain the dynamic
457 characteristics of structures. Ambient vibrations do not seem feasible in
458 the case of a geological radioactive waste repository. Therefore, practical
459 implementation of a modal-based SHM appeals to the need of forced
460 excitation systems, either shock or harmonic excitation. See for instance
461 references [21], [51], [52], wherein different excitation devices have
462 been successfully applied to determine the dynamic characteristics of
463 buildings. These forced excitation alternatives can be built up in a robot,
464 or permanently installed in the repository, for promoting the excitation
465 of resonant frequencies periodically.

466 (iv) Finally, practical implementation of a modal-based SHM system must
467 consider a cost-effective disposition of sensors regarding number, power
468 consumption, maintenance and that in turn, maximize the probability of
469 damage detection [53].

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