2023 IMEKO TC-4 International Conference on
Metrology for Archaeology and Cultural Heritage
Rome, Italy, October 19-21, 2023

FEM-based models of real-time dynamic structural behavior in archaeology and monumental heritage: the case of ancient Greek colonnades

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***Abstract* – The preservation of historical buildings and infrastructures requires a multidisciplinary approach to provide a real-time knowledge of their dynamical structural behavior. For this task, an effective procedure can be based on the integration between tailored dynamic models, optimized through an iterative synergic process, and an adaptive and modular distributed monitoring system. With respect to modelling, a Finite Element Model (FEM) is a valid solution. In fact, it is not only an effective reference dynamical model, but it can also be used to support the definition of the potential technical requirements for the sensors (e.g., typology, sensitivity, band and number) that will be installed to monitor the chosen structure. We applied this idea to the case of an ancient Greek colonnade, building a FEM validated through published experimental measures. The obtained results prove that this model, behind its traditional use to describe the dynamic structural behaviour of a monument, can serve as a the basis of a metrological tool, especially during the iterative optimization process, to define the technical characteristics of distributed structural monitoring systems.**

I. INTRODUCTION

The preservation of historical buildings and infrastructures in cultural heritage sites requires a multidisciplinary approach and suitable tools. Within this framework, a real-time knowledge of their dynamic structural behavior plays a relevant role, For this task, we designed an evolving tailored model tuned with data provided by a distributed monitoring system, optimized in terms of number, sensitivity and position of sensors [1, 2]. This approach requires the implementation of an iterative process, based on a mutual and synergic optimization of both the model and the monitoring system. Although preliminary measurements are, in general, required to have a first insight on the most relevant structural characteristics of a monument, parallel actions to implement a reliable dynamic model are also key to guarantee the quality of the proposed iterative procedure.

Finite Element Models, whose design and outputs are obtainable through several digital tools and commercial software, are widely used by engineers for the design and visual dynamic behavior representation of complex structures, as well as components, with different spatial scales being subject to fatigue and to the risk of fractures. These models require to be validated through experimental data, which serve as input for their parameterization. In particular, in the field of cultural heritage, they are used to infer the structural health of different structures, are calibrated with data sampled from field campaign measures on a real building or infrastructure or from a scaled laboratory copy of the same building or infrastructure [3,4]. In the same field, Finite Element Models are also integrated to support into archaeo-seismological models [5,6] and structural models [7,8].

Here, we propose the implementation of a modular and adaptive system, based on the application of a Finite Element Model (FEM). Generally, FEM are applied to this research domain to assess the structural health of sites and buildings. Instead, FEM simulations can be used in integration with tailored modular field monitoring systems to produce evolutive structural dynamic models of the monitored structure. Virtual sensors, often available as integrated tools in commercial products, can be designed and applied in a FEM to infer what could be the dynamic behavior of a certain structure, based on the model parameters given by the operator. Instead, we propose to apply the use of virtual sensors integrated in a FEM with a reverse logic. In particular, instead of using the monitoring system data to provide the input to the simulations, which, in turn, give a dynamic picture of the structural behavior evolution, the FEM model with the integrated use of virtual sensors comes first. In detail, the model output, based on available structural data and from the survey on materials, is used to give some preliminary metrological indications about the sensors and installation technical characteristics, such as the number, position and technical requirements (e.g., sensitivity) of selected instruments.

We implemented a possible application of this reverse innovative approach, considering an ancient Greek colonnade, whose model was validated through literature data, collected during field observations and scaled-model laboratory measures. The same approach can be applied to any complex historical structure, where the structural heath assessment would be desirable for its preservation. Considering our case study, the large number of ancient classical temples remains, spread around all the Mediterranean area (mainly located in Italy and Greece) proves the wide potential application impact, since their state of preservation is either surprisingly good or, sometimes, really poor, when remains mainly consist of a few free-standing multi-drum columns or of a few columns with epistyles. The following sections will illustrate the basic characteristics of the proposed model, the application to a case study of a simple classic Greek colonnade unit, constituted of two equal columns and an epistyle, having the same physical parameterization of the Temple of Apollo at Bassae (Arkadia, Western Peloponnese, Greece).

II. METHODS

A. Numerical modelling

The chance of replicating the complex seismic behavior of multi-drum columns and colonnades can be nowadays easily faced through the use of Finite Element Models, currently integrated in different commercial software programmes used in different engineering fields [9-11]. However, the accuracy of the modelling can be assured only if the model is able to reliably replicate the experimental tests, conducted either on full scale or on scaled specimens. This paper refers to a FEM [14], whose parameterization and validation derives from the experimental tests, previously conducted at the Soil Mechanics Laboratory of the National Technical University of Athens (NTUA) [15-17]. Experimental tests concentrated on two configurations: a free-standing multi-drum columns and two columns coupled with an epistyle. Our FEM model is based on a laboratory scaled version of a real marble column, which can be found at the Temple of Apollo at Bassae (Arkadia, Western Peloponnese, Greece), built during the 5th century B.C. The temple, included in the UNESCO sites, has the peculiarity of being one of the earliest post-Parthenonian edifices and the earliest monument in which all three ancient Greek architectural orders – Doric, Ionic and Corinthian – are found together. Further details about the columns and the epistyle are reported in the following sub-section of this work. Past results were aimed at validating the relative displacement derived from simulations with the experimental data derived from the model-scale system tested in with the NTUA shaking table. Moreover, experimental and simulation data were compared with respect to the column parameterization.

B. Simulation Results

The simulation validation, performed in ABAQUS, based on a model scale column tested at NTUA, is referred to a 1:5 scaled version of the original Greek marble column, with a density of 24 kg/cm^3, elastic modulus equal to 35000 MPa and a Poisson ratio of 0.2. The inter-drums tangential interface behavior was modelled using a friction coefficient fixed to 0.7, following both the experimental tests [17] and their application to basic validated models reported by the literature [18-20]. The contact between the drums was applied through a finite sliding "hard contact" with a penalty equal to the friction coefficient. The drums and the capitals of the column were modelled as solid brick elements with a maximum dimension of 30 mm. The materials were considered as elastic linear, while the nonlinear effects came only from the geometry and as a consequence of large displacements. The material damping was not applied for sake of conservativity of the results, as done in a previous literature work [21]. In agreement with the same work, the influence of the damping in the peak displacements was excluded from the present study. The analysis was performed into two steps. The first one consisted in the application of the gravity load (GL), while the second one consisted in the application of a ground motion in the form of an acceleration in correspondence of the base through a dynamic implicit analysis. The second order effects were directly accounted in the analysis steps.

C. Model of a basic colonnade unit

The parametric analysis was developed for two multi-drum columns coupled with an epistyle on the top. The same material was used for both the columns and the epistyle, so that the contact between the epistyle and the capitals of the two columns were modelled in the same way as the interface between the drums. The geometrical properties of the system are reported in Figure 1.

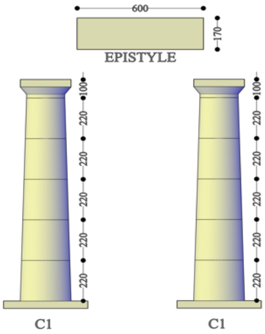

Fig. 1. Measures of the reference columns and epistyle.

The model dimensions, referring to the scaled laboratory version of the marble column, were scaled accordingly with a proportion 1:5, while all the physical parameters were scaled accordingly, as reported in the literature. In this work, we limited the number of dynamic simulations, applying only a ground motion acceleration in the direction parallel to the epistyle.

The response of the system was investigated considering two different inputs. First, a time-domain Ricker wavelet [20] was applied, being often used to produce synthetic seismograms [21], having a maximum frequency of 2.24 Hz (alternatively indicated as 4p in the article, where experimental tests were reported [16]) and a maximum amplitude of 0.6 g, as previously done in the applied reference model [21]. The time-domain Ricker wavelet signal is reported in Figure 2. This signal was used to verify that the data reproduced those of the reference model indicated above.

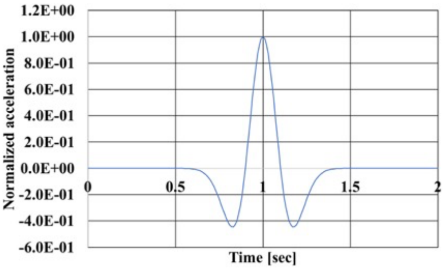

Fig. 2. Time-domain Ricker wavelet used as input for the shaking table test and for the simulation.

Then, the LT component of the earthquake occurred in Greece, in the city of Athens, with a PGA of 0.263 g and a length of 40.77 s, was selected as a the time-domain signal of a real earthquake. The temporal trend of this earthquake signal, being available through EPOS ESM Engineering Strong Motion Database, is reported in Figure 3.

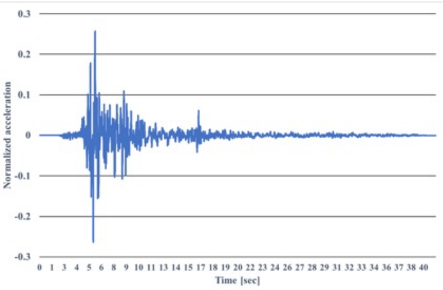

Fig. 3. Time sequence of Athens earthquake, occurred on Dec 24, 2017, as recorded by ITSAK Strong Motion Network at the site - station code ATH3.

Based on the fact that the krepidoma (i.e. the base on which the column is found) and the columns were made of the same materials, the earthquake signals were applied directly to the column base.

D. Output analysis

Based on the system shown in Figure 4, relative displacement and acceleration data were determined, as commonly done with ABAQUS software, generating a set of virtual sensors [22, 23], which were placed at the interface between each column drum, the upper drum and the capital, as well as between the capital and the epistyle. The position of each virtual sensor is indicated with the capital letter D, followed by a number, reported in the same figure.

Considering that, at the initial time of the simulation, all the drums of both columns are aligned along their axis, whose distance is equal to the length of the epistyle, it is possible to monitor the variation of the inter-axial distance for each couple of drums, belonging to the two columns. Considering that our model is constituted by drums having the same height, it is possible to couple two different virtual sensors, one from each column, being each couple at the same height. In particular, looking to Figure 4, it is possible to couple the sensors D1 with D7, D2 with D8, D3 with D9, D4 with D10, D5 with D11 and D6 with D12.

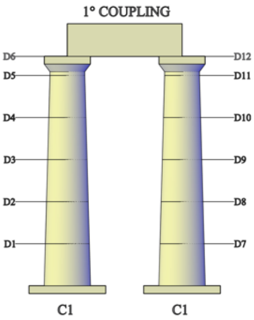

Fig. 4. Position of the virtual sensors in ABAQUS model for the two equal columns.

Then, in order to assess the inter-axial distance variation along the time with respect to the initial time, it is possible to calculate, for each couple of sensors, the following variable:

$$NIRV = \frac{D_a + EL + D_b}{EL} \quad (1)$$

where NIRV is the normalized inter-axial relative variability of inter-axial distance at a given column height, D_a and D_b are the relative displacements for the two columns at a certain time and EL is the epistyle length.

The calculated index, in particular, shows the variation of interaxial relative distance with respect to the reference distance, being equal to the epistyle length. Consequently, NIRV is an index, that, based on the simulation, indicates whether the columns get closer or farer at different heights.

III. RESULTS

The maximum relative displacement of the two columns at different levels is represented in Figure 5. In the considered case study, it is possible to observe a higher relative displacement of the right column with respect to the left one. Moreover, the right column has a higher displacement than the left one, with the exception of the capital, maybe due to the presence of the epistyle, acting as a mechanical link between the two columns.

The maximum acceleration for the two columns is reported in Figure 6. The maximum acceleration occurs for the second column at 660 m, corresponding to the upper part of third drum.

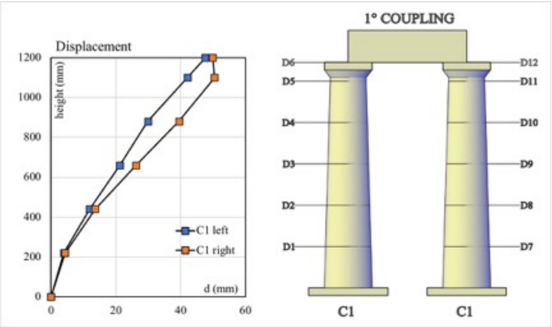

Fig. 5. Maximum relative displacement for the two columns, being subject to the Athens earthquake signal.

It is interesting to observe both the declining acceleration with the height for the left column and the increase, up to 660 m, followed by a decrease, at heights major than 660 m, for the right column, showing a different mechanical behavior. Again, there is the exception of the top virtual sensors for both columns, corresponding to the contact between the capitals and the epistyle, acting as a link.

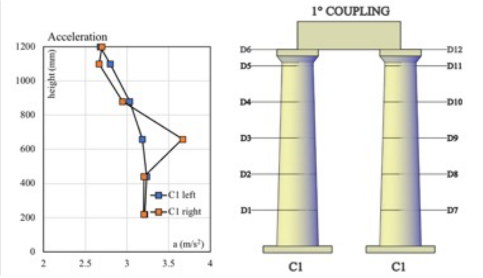

Fig. 6 Maximum acceleration for the two columns, being subject to the Athens earthquake signal.

The Figure 7 shows the time variability of NIRV. The NIVR data indicate a coherent variation of inter-axial relative distance during the event, with the exception of the contact point between the epistyle and the capitals, confirming the mechanical action of the epistyle, operating as a link.

In the specific case study, considering the given input and the model parameters, it is possible to summarize the following results. First, the modelled multi-drum columns, being connected through the epistyle into a colonnade basic unit, display a variable relative displacement and acceleration, being equal, for modelling reasons, at the base, and at the interface between the capitals and the epistyle, due to the epistyle. Second, the system displays a higher relative displacement between the upper drum and the capitals of both columns, especially for the right-side column.

Conversely, in the case of acceleration, the maximum variation occurs at a lower inter-drums connection level.

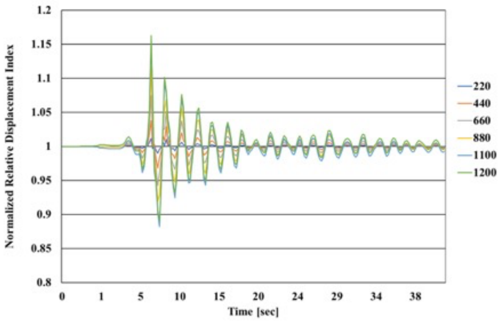

Fig. 7. NIVR as derived from the virtual sensors data in the case of Athens earthquake (Dec 24, 2017) used as the FEM input

For the given earthquake system, the colonnade acts as coherent system, with the exception of the contact point between the epistyle and the capitals, since its relative inter-axial distance has a lower variability along time.

IV. DISCUSSION

Given the results of the model, being applied as a preliminary metrological reference, it is important to discuss the potential application of any simulation for monitoring purposes. In particular, the results can be used to indicate what we should expect from a real measure, depending on the quality of the chosen model parameters, which, in our case, were guaranteed by a previous experimental validation available in the literature.

Here, used a simulation, based on a high-quality geometrical model integrated with validated parameters, to support the design of monitoring networks of archaeological sites and buildings of historical relevance, that, due to their complex and extended nature, are resources-consuming and, consequently, require an optimization.

In particular, we could derive some metrological indications, that can be useful to optimize the set-up of a field monitoring network. The case study shows that, under the given conditions, it would be possible, instead of monitoring both columns from the base to the connection between the capital and the epistyle, to monitor both column at 660 m (in the case of acceleration measures) or at the top-drum level (in the case of displacement measures), limiting the measure points to one, in the case of the base and of the top part of the capitals, being in contact with the epistyle. Obviously, the number of sensors for each point should be fixed in a second step. From these facts, we can see that a validated simulation could support the design of a monitoring system, depending on the type of variable that we wish to observe.

There are some key limitations, that must be stressed. The first one is the need of a detailed geometrical model and of validated parameters for the simulation. The second one is that the information derived from the simulation output depends on the chosen input (i.e., the earthquake). Based on the duration and spectral characteristics of the input, the output becomes different. Thus, the derived qualitative information should consider a certain number of historical case studies as inputs to derive how much the output is variable.

Nonetheless, independently from the above limitations, the discussed approach, applied for a limited case study, proved the validity of using such a simulation technique for a qualitative support to the design of a complex monitoring network. Obviously, the model could be scaled-up to consider more complex structures, based on the availability of data on materials properties and the structure morphological details.

V. CONCLUSIONS

This work proposed the use of FEM-derived simulations to infer the potential structure of monitoring system, being applied to the case of a classical Greek colonnade. Despite the limitations of FEM, whose output validity relies on the availability of high-quality parameters and is dependent on the signal inputs, it is possible to see that, from the model outputs, specific monitoring system design elements can be inferred, such as the most suitable number of measuring points and their positions, depending on the variable under observation.

Future implementations of this approach could support the design of more efficient monitoring networks, contributing to a reduction of complexity and costs of the monitoring system, proving that FEM use can be extended from the domain of archaeological and monumental heritage structural health monitoring to the domain of monitoring system design having the same purpose of protecting and preserving the immovable cultural heritage.

VI. ACKNOWLEDGEMENTS

Marco Casazza acknowledges the financing of his working position through the Italian Ministry of University PON fund, Azione IV.4 Asse IV “Istruzione e ricerca per il recupero – REACT-EU”.

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