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Calibration of the dynamic behaviour of incomplete structures in archeological sites: the case of Villa Diomede portico in Pompeii

F. Lorenzoni[a]*, M. R. Valluzzi[b], A. Minello[a], M. Salvalaggio[a], C. Modena[a]

[a] *University of Padova, Department of Civil, Environmental and Architectural Engineering, 35131 Padova, Italy*
[b] *University of Padova, Department of Cultural Heritage: Archaelogical and History of Art, Cinema and Music, 35139 Padova, Italy*

Abstract

This paper reports the research activities carried out on Villa Diomede in Pompeii, built during the "Pre-Roman period" (i.e. the 3rd century BC) and discovered between 1771 and 1774 during the archaeological excavations. It is one of the greatest private buildings of Pompeii and it is located on the western corner of the modern archeological site. Three levels compose the building: the ground floor, the lower quadriportico with a square plan and a series of colonnades on the four sides around the inner garden and the cryptoportico. Villa Diomede was damaged by the strong earthquake occurred in AD 63 that caused the collapse of the western pillars of the quadriportico and later damaged after the big eruption of Vesuvius in AD 79. In June 2015 a series of non-destructive tests (NDT) were carried out by the authors in order to obtain information on the state of conservation of the building and to assess its structural behavior. Direct and tomographic sonic pulse velocity tests, ground penetrating radar, endoscopies and operational modal analysis were performed on the remaining structural elements on the two levels of the Villa. The present paper reports the main outcomes and findings of ambient vibration tests implemented to extract the modal parameters in terms of eigenfrequencies, mode shapes and damping ratios. Operational modal analysis and output-only identification techniques were applied to single stone pillars of the quadriportico structure and then to the entire square colonnade of Villa Diomede. Results are then used to study the soil-structure interaction at a local level and extend the gained information for the numerical calibration of the whole structure. Thanks to this methodology a detailed model updating procedure of the quadriportico was performed to develop reliable numerical models for the implementation of advance structural and seismic analysis of this "incomplete" archaeological structure.

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Keywords: operational modal analysis; archeological structure; non destructive tests; model updating

* Corresponding author. Tel.: +39 049 827 5560; fax: +39 049 827 5613.
E-mail address: filippo.lorenzoni@dicea.unipd.it

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1. Introduction

In recent years conservation issues and seismic vulnerability assessment of archaeological sites have become of great interest among the scientific community. Archaeological heritage (like the city of Pompeii) represents an important opportunity to attract tourism and investments, provided that adequate safety and preservation conditions are fulfilled. Theses type of structures are in fact particularly prone to deterioration of materials, damages induced by environmental factors, repeated loading and exceptional events. This means that conservation, repair and strengthening are constantly necessary. In this process, on site non-destructive (ND) testing play a major role, providing information on the structural conditions and existing damage, and allowing to define adequate remedial measures. The paper reports part of the complex investigation campaign carried out by the authors on Villa Diomede, a beautiful building located in the western corner of the modern archaeological site of Pompeii. Ambient vibration tests on the "Quadriportico" structure of the villa are presented with the aim of assessing its structural condition and calibrating numerical models to be used for successive structural analyses. The dynamic-based assessment, involving both theoretical and experimental modal analysis, includes the following main steps: (i) Ambient vibration testing; (ii) Operational Modal Analysis; (iii) Finite element analysis FEA and identification of uncertain structural parameters by minimizing the difference between theoretical and experimental behavior.

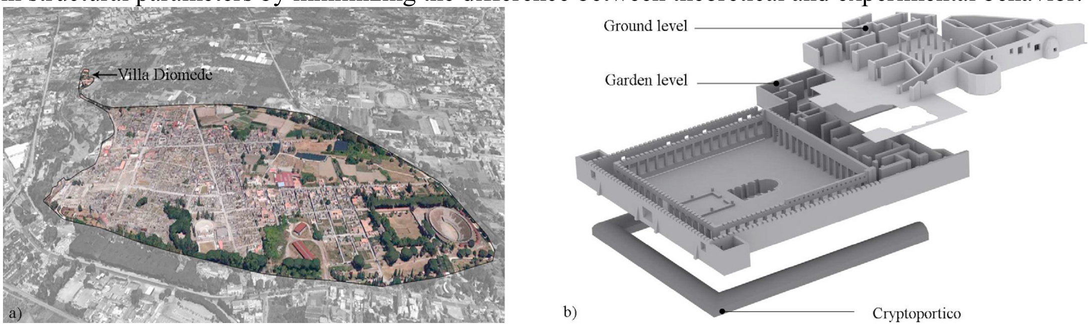

Figure 1. a) archeological site of Pompeii - b) levels of Villa Diomede

2. Villa Diomede in Pompeii: historic notes and description

Pompeii is located in southern Italy and rises on upland with volcanic origin. The city is well known thanks to the presence of one of the most important and well conserved archeological site worldwide (Figure 1a).

Villa Diomede, discovered between 1771 and 1774, is one of the greatest private buildings of Pompeii and lies on the western corner of the modern archeological site. The luxurious ancient villa is characterized by a complex historical evolution both in terms of materials and modifications. However, its history can be divided into three main periods: Pre-Roman period, Augustan period and Nero-Flavio period [1]. Villa Diomede was damaged by the strong earthquake occurred in AD 63 that caused the collapse of some portions of the structure and later involved in the big eruption of Vesuvius in AD 79. The current configuration of Villa Diomede, is the result of interventions occurred over centuries. The ancient building can be outlined in three levels: the road level, which contains the entrance and it is located at the highest quote, the lower garden level, which hosts the quadriportico structure and the underground level named cryptoportico (Figure 1b). Masonry is the main structural material, with use of a wide range of resistant elements, such as Nocera tuff, Sarno limestone, yellow tuff, gray tuff and lava stone. The masonry structural elements are mainly built with *opus incertum* technique for both ground and garden levels. In the pillars of the garden level a more widespread use of *opus mixtum* is recognizable [2][3].

3. On site inspections

In march 2015 a detailed survey of the villa was performed to obtain geometric and structural data and then plan the following experimental campaign. A critical survey was also carried out, including damage and crack pattern survey and the identification of masonry typologies. The most diffused structural material is stone, which is naturally sensitive to water and humidity. Chemical, physical and biological attacks are the main cause of decay and most of masonry elements are affected. Decay of masonry is particularly present in the Quadriportico structure, mainly composed by tuff stone.

In June 2015 a series of non-destructive tests (NDT) were carried out in order to obtain information on the state of conservation of the building and to assess its structural behavior. Direct sonic pulse velocity tests, sonic tomography, ground penetrating radar, endoscopies and operational modal analysis were performed on the remaining structural elements of the Villa. Within this paper only the results of dynamic identification tests of the "Quadriportico" structure will be presented.

4. Ambient vibration tests and modal identification

Dynamic identification tests of Villa Diomede were performed through ambient vibrations tests (AVT) and output-only identification techniques. Two dynamic tests are reported in this paper: (i) ID03 on pillar P15 which belongs to southern colonnade to characterize the single element; (ii) ID06 on the southern and western colonnades of the Quadriportico structure, with the aim of identifying the global modal behavior (Figure 2).

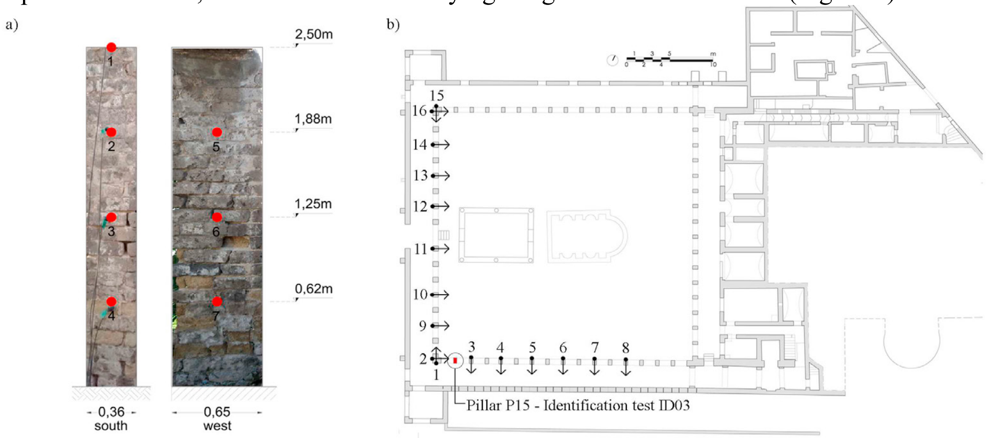

Figure 2. Setups of accelerometers: a) Pillar 15 - b) Quadriportico structure

Both tests were performed using high sensitivity piezoelectric accelerometers connected to a data acquisition system for A/D conversion of the electric signals and storage of digital data. Experimental tests were performed by recording time histories (sampling frequency 100 Hz and 10 minutes duration) of acceleration in 8 nodes for the single pillar and 16 nodes for the Quadriportico, installed along the two horizontal directions (x and y). Acquired data were pre-processed by applying a high-pass filter with a frequency cut-off of 1Hz and then processed with segment length of 2048 points and 66.67% window overlap.

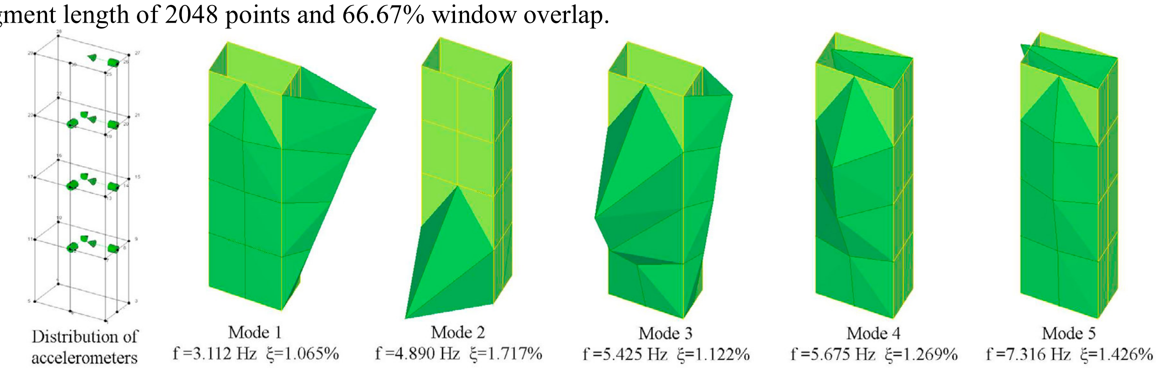

Figure 3. Experimental mode shapes of Pillar 15

System identification was performed implementing two non-parametric frequency domain methods: FDD and EFDD which estimate the vibrational modes using a Singular Value Decomposition (SVD) of each of the spectral density matrices [4]. Peaks in the frequency domain related to structural frequencies were selected and the corresponding mode shapes defined. Mode shapes vectors resulting from the application of FDD and EFDD were compared by using the Modal Assurance Criterion (MAC) [5].

Both OMA techniques prove to be very effective and reliable in the identification of modal parameters. The first five fundamental modes of the pillar P15 were extracted in the frequency range 3-7 Hz. And the results are presented in Figure 3. Time histories acquired on the entire Quadriportico provided interesting results. ID_06 test identifies the southern and western colonnade. Six modes were extracted and reported in Table 1 and Figure 4. The two first mode shapes are the first order bending modes at 2.610 Hz for the southern side and at 2.662 Hz for the western side. The successive modal parameters represent the second order bending modes (3.156 Hz south and 3.249 Hz west) and the third bending modes (3.56 Hz south and 4.016 Hz west).

Table 1. Modal parameters of the Quadriportico identified by FDD and EFDD techniques

Modes	*frequency (f_{FDD}) [Hz]*	*frequency (f_{EFDD}) [Hz]*	*Damping (ξ_{EFDD}) [%]*	*$MAC_{FDD-EFDD}$*	*Type*
1	2.612	2.610	0.255	0.9991	Bending 1st (western side)
2	2.661	2.662	0.763	0.9757	Bending 1st (southern side)
3	3.137	3.156	0.965	0.9862	Bending 2nd (southern side)
4	3.247	3.249	0.685	0.9889	Bending 2nd (western side)
5	3.564	3.560	1.011	0.9978	Bending 3rd (southern side)
6	4.016	4.016	-	-	Bending 3rd (western side)

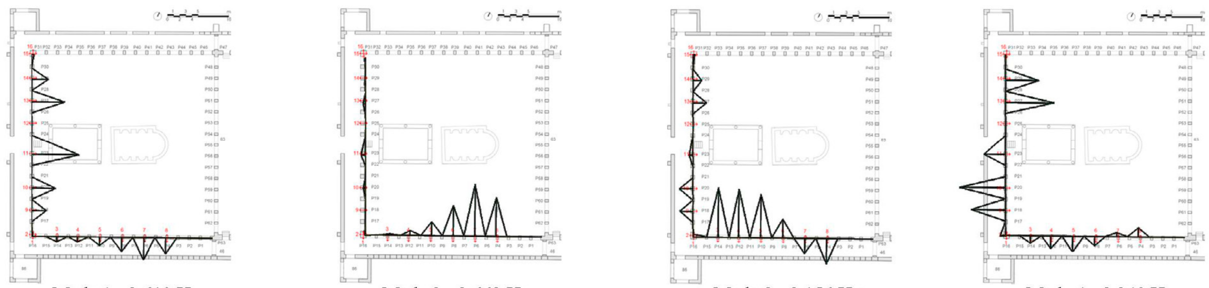

Figure 4. First four experimental mode shapes of Quadriportico structure

5. FE model calibration

A FE model of the entire Quadriportico was constructed using the software DIANA FEA [6]. The model includes the southern and western colonnades and it is composed by 64800 3D 8-noded HX24L elements and 85582 nodes. Structural elements and loading conditions that are relevant in relation to the structural problems have been directly inserted into the numerical simulation. Portions of structures not included in the model but directly involved in the structural interaction (e.g. the two other sides of the portico) are considered by the introduction of corresponding boundary conditions.

Masonry is simplified as an isotropic and elastic material and perfectly fixed at the base of the pillars. Several portions have been identified and characterized with different mechanical proprieties: pillars of the (i) western and (ii) southern side, architrave of the (iii) southern and (iv) western sides and (v) corner pillars. Input characteristics of masonry are derived by the Italian Code i.e. Table C8A.2.1 of "Circolare 2 febbraio 2009" [7].

Initially soft stone and irregular stone masonry typology is chosen adopting a range of variation for the elastic modulus (E=690÷900 MPa) and mass density (ρ=16÷19 kN/m^3). In this first step rigid foundations are introduced and Young's moduli and mass densities are simultaneously updated in order to match numerical and experimental frequencies and optimize MAC index and frequency discrepancy values. The results provide Young's moduli lower than 400 MPa, completely out of the predefined ranges (see Table 2). The unreliability of the Young's moduli for this type of masonry brought to the modification of the initial assumptions, introducing elastic foundations instead of rigid ones.

The first step was the creation of a local model to study in detail the soil-interaction of the Quadriportico. Pillar 15 (object of ambient vibration tests presented in §4) has been modeled with a structured mesh composed by 459 nodes and 228 3D 8-noded (HX24L) elements (of about 20 cm size) (Figure 5b).

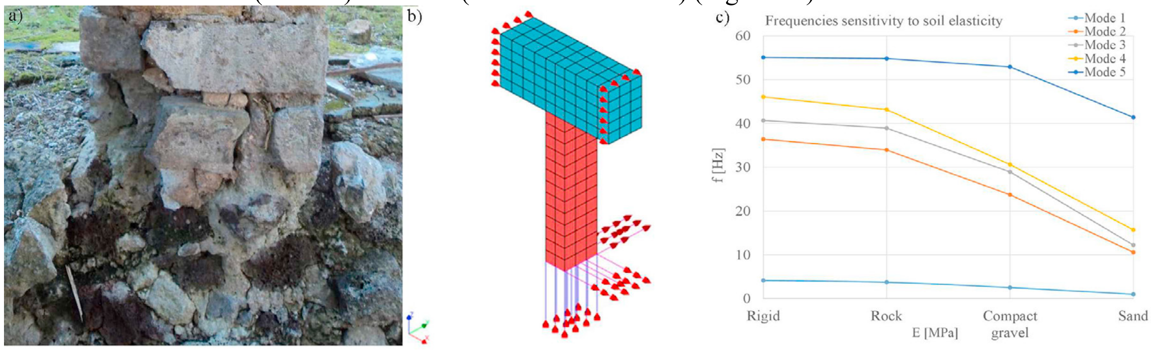

Figure 5. a) Picture of the pillar's base - b) FE model – c) graph of sensitivity analysis

Sensitivity analyses were carried out to study the influence of soil-structure interaction on the local model. Analyses cover the range from rigid foundations to rock, compact and sand soils, adopting the Winkler soil model [8]. Soil elasticity has been implemented in the model by a bed of 1D spring elements with a vertical and horizontal stiffness [9]. The mechanical properties of masonry are constant and derived from the values suggested by the Italian code [7]: Young modulus E=900 MPa and the mass density ρ=16 kN/m^3.

Analyses results are summarized in Figure 5c and some important aspects of the soil-structure interaction emerged:

- The variation from rigid constraints to a rock model for soil (with high values of spring stiffness) has a limited influence on the modal behavior of the structural element;
- Higher frequency variations are noticed for the other types of soil considered, i.e. compact gravel and sand;
- It was decided to establish a range of variation of Winkler modulus between $K_s=10^{10}$ N/mm^3 and $K_s=10^9$ N/mm^3 (that correspond to rock and compact gravel soils respectively) to be used in the calibration process of the entire Quadriportico.

Table 2. Updated mechanical properties of the materials composing the Quadriportico: comparison between rigid and elastic foundations

			Mechanical properties with rigid foundations		Mechanical properties with elastic foundations	
Structural portion	*Material*	*Italian Code: range of variation E [MPa]*	*Mass density ρ [kN/m³]*	*Elastic Modulus E [MPa]*	*Mass density ρ [kN/m³]*	*Elastic Modulus E [MPa]*
Southern pillars	Soft stone masonry	900÷1260	14	400	16	1100
Southern architrave – lower part	Soft stone masonry	900÷1260	15	390	16	900
Southern architrave – upper part	Irregular stone masonry	690÷1050	-	-	16	600
Westerm pillars	Soft stone masonry	900÷1260	16	350	17	690
Westerm architrave	Irregular stone masonry	690÷1050	15	390	17	600
Corner pillars	Soft stone masonry	900÷1260	16	390	16	900
Winkler modulus $K_{s,\,vertical}$ [N/mm^3]	-	$5x10^8÷10^{10}$	∞		10^9	
Winkler modulus $K_{s,horizontal}$ [N/mm^3]	-	$5x10^7÷10^9$	∞		10^8	

The calibration of the Quadriportico numerical model was performed through a modal matching procedure varying iteratively the Winkler modulus (K_s) of the elastic foundations within the defined ranges until reaching an optimal correspondence between experimental and numerical modal parameters. Young's modulus (E) and mass density (ρ) of masonry have been changed within a small range of variation around the values suggested by Italian code [7]. The values of the selected parameters before and after the model updating are reported in Table 2. The final results of the calibration are reported in Table 3. It is possible to note a satisfying matching in terms of frequency between numerical and experimental models with a maximum average error below 10% for all modes, except mode no.5. The calculated MAC index demonstrates a rather good match of mode shapes for modes from no.2 to no.6 (with a value always greater than 0.75). Only the first mode show a low MAC value probably due to the severe state of damage of the western colonnade, hardly to represent numerically.

Table 3. Calibration results of FE model: comparison between experimental and numerical modal parameters

Mode	*Type*	f_{exp} *[Hz]*	f_{FEM} *[Hz]*	*Frequency error [%]*	*MAC exp-FEM*
$1_{exp} – 1_{FEM}$	Bending 1° (western side)	2.610	2.642	1.23	0.48
$2_{exp} – 2_{FEM}$	Bending 1° (southern side)	2.662	2.790	4.81	0.90
$3_{exp} – 4_{FEM}$	Bending 2° (southern side)	3.156	3.433	8.78	0.79
$4_{exp} – 3_{FEM}$	Bending 2° (western side)	3.249	3.147	3.14	0.80
$5_{exp} – 6_{FEM}$	Bending 3° (southern side)	3.560	4.510	26.69	0.88
$6_{exp} – 5_{FEM}$	Bending 3° (western side)	4.016	3.768	6.18	0.75

6. Conclusions

Ambient vibration tests (AVT) and FE modeling of the "Quadriportico" of Villa Diomede in the archaeological site of Pompeii are reported in this paper. The following conclusions can be drawn from the study:

- Dynamic identification test performed on a single pillar of the Quadriportico did not provide satisfactory results. Several local modes and not well-defined mode shapes have been extracted due to the severe state of damage of the pillar. Operational modal analysis on the southern and western sides of the Quadriportico demonstrated a unitary dynamic behavior in the frequency range 2-5 Hz
- The outcomes of the experimental investigations were used to calibrate numerical models through the modal matching technique comparing both eigenfrequencies and eigenvectors. The soil-structure interaction and the type of boundary condition play a fundamental role in predicting the dynamic behavior of the structure.
- The local numerical model (composed by the pillar and the architrave) allows demonstrating that the assumption of soil as a rigid constraint is not reliable and lead to false model updating of the elastic properties of masonry. The introduction of spring elements at the foundation level of the global model of the Quadriportico provided a good match between theoretical and experimental modal parameters.
- The execution of dynamic identification tests also on "incomplete" structures proved to be an effective tool to characterize and assess their dynamic behavior and to create more reliable models for structural analyses.

References

[1] Maiuri A., L'ultima fase edilizia di Pompei, Italia romana. Campania romana. vol 2, Istituto di Studi romani, Roma, 1942.
[2] Sogliano A., Pompei preromana dalle origini all'80 a.C., Pompei nel suo sviluppo storico vol 1, Athenaeum, Roma, 1937.
[3] Dessales H et al, "Pompéi. Villa Diomède. Campagne d'étude 2014", Cronique des activités archéologiques de l'Ecole francaise de Rome, 2015.
[4] Brincker et al. 2000; SVS, ARTe- MIS Extractor, 2006
[5] Allemang R.J., Brown D.L., A correlation coefficient for modal vector analysis, Proceedings of the 1st SEM International Modal Analysis Conference, Orlando, FL, USA, 1982
[6] TNO Diana, DIANA 9.6 Finite Element Analysis User Guide, TNO DIANA BV, Delft, 2004
[7] Circolare 2 febbraio 2009, n. 617, Istruzioni per l'applicazione delle "Norme Tecniche per le Costruzioni" di cui al D.M. 14/01/2008
[8] Elyamani A., Integrated monitoring and structural analysis strategies for the study of large historical construction. Application to Mallorca cathedral. PhD Thesis. Director. Roca P., Universitat Politecnica de Catlunya, 2015
[9] Bowles J. E., Foundation analysis and design, McGraw-Hill, United States of America, 1996, pp. 121-127, 501-509