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Finite Element analysis of Vittoriano building based on InSAR data

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***Abstract* – This paper discusses a novel methodology for evaluating buildings performance through advanced Finite Element Analysis (FEA) based on the data given by Interferometric Synthetic Aperture Radar (InSAR). A cracked wall of Vittoriano building, Rome, Italy is chosen as the case study. A detailed 3D numerical model of the wall was developed in ABAQUS. Concrete Damage Plasticity (CDP) model was utilized for defining the masonry material based on the macro-modeling approach. The ground deformation acquired by InSAR is applied to the wall's base. The crack propagation and stress concentration of the numerical model was in line with the real cracks observed on the wall. The results highlighted the high reliability of the InSAR data which could be used in structural behavior assessment.**

I. INTRODUCTION

Heritage buildings can play crucial roles in transferring cultural identity to future generations: conserving cultural heritage and sustaining a national community, based on 'historical memory', can be helpful to future generations to understand where they are coming from. According to the preamble of the Venice Charter [1], heritage buildings are living witnesses of old traditions, and remaining for the present generation. This statement further implies the significance of preservation of heritage buildings against damaging factors (e.g., ground movement). It is noteworthy that cultural heritages are generally built from masonry materials namely stone, mortar and brick. These materials can sustain gravity loads sufficiently, however, they are notably vulnerable against dynamic loads (e.g., earthquake) because of their low tensile strength, poor capacity of dissipating energy, weak connection between elements (e.g., beam-column joints, roof-wall interfaces), and material deterioration due to environmental conditions (e.g., humidity, dust, decomposition, vegetation) [2]. Taking the mentioned shortcomings into account, serviceability of masonry buildings should be monitored regularly. In fact, if they are not monitored and retrofitted (if necessary), they might cause severe issues in terms of human loss and economy. A collapse of a minaret at the entrance of Taj Mahal in Agra, India due to a heavy rain and wind is an evidence for necessity of structural health monitoring [3].

As a result, evaluating performance of buildings over time, which is known as structural health monitoring (SHM), has become a topic of interest in the field of structural engineering. The methods proposed and investigated by researchers in order to monitor a building's response could be categorized as experimental and analytical approaches. Experimental techniques (i.e., testing on buildings' samples or installing measuring instruments) is not possible for many buildings since they are not legally accessible and even touchable.

The analytical SHM, on the other hand, is generally conducted by developing numerical models through

Finite Element Analysis (FEA). The high reliability of FEA, if performed accurately, has made it one of the most appropriate techniques for assessing ancient buildings' behavior. Several numerical analysis have been carried out to discuss the performance of heritages buildings namely St. Giuliano church, Sidoni Palace, St. Agostio church in Italy, Banloc Castle in Romania, Arge-Tabriz in Iran [2] using ABAQUS commercial software. As another example, Valente and Milani investigated heritage buildings in Mantua (Northern Italy) in terms of damage distribution, energy dissipated by tensile damage and maximum displacement using FEA and ABAQUS. Based on their study, non-linear dynamic analysis of masonry buildings modeled by concrete damage plasticity (CDP) returns reliable results which could be used for evaluating the performance of ancient buildings [4]. Defining a proper boundary condition, which could be based on either external loads or displacement (acquired by in situ surveys or remote sensing method like InSAR), plays a crucial role on the simulation accuracy.

Synthetic Aperture Radar (SAR) performs based on different imaging methods for monitoring earth surface resources over time. Interferometric Synthetic Aperture Radar (InSAR) is a powerful tool for mapping ground movement by SAR data. In this technique, the data are acquired by the satellites' movement in North to South (ascending), and South to North (descending). It is worth noting that InSAR data are obtained by sending and receiving radar signals to the earth surface along the radar Line of Sight (LOS) [5].

The main aim of this study is to propose a novel method for monitoring cultural heritage implementing FEA based on the data acquired by InSAR. To this end, Vittoriano building located in Rome, Italy is considered as a case study. An accurate 3D model is developed by nonlinear FE software ABAQUS. Then, the ground displacement given by InSAR is applied to the wall and the model is validated by comparing the numerical outcomes with the cracks observed on the real wall.

II. VITTORIANO BUILDING

Vittoriano building is considered as a case study to be analysed nonlinear FEA based on the data given by InSAR. This masterpiece building, known also as "Victor Emmanuel II National Monument" or "Alter of Fatherland (Altare delle Patria)", is located in Piazza Venezia on the northern slope of the Capitoline Hill-at the symbolic heart of Rome, Italy, adjacent to both the Foro Romano and the Campidoglio. It was designed by the architect Giuseppe Sacconi (1885-1905) and constructed in the late 19th century, and dedicated to the first king of unified Italy, Vittorio Emanuele II. The building's maximum height and plan area are roughly 70 m and 717000 m^2, respectively. The monument was rehabilitated for approximately four decades and was reopened in 2000. Botticino marble extracted from quarries near Brescia was utilized for constructing the building. Based on what is reported in the literature [6, 7], since the beginning of its construction, cracks have been observed in different parts of the building, particularly in the western side. According to the results of previous studies, the cracks are mainly due to (a) soil condition of the region in which the building is constructed, and (b) the heavy traffic in the roads surrounding the building [6, 7].

Mechanical properties of soil should be necessarily taken into account for an accurate analysis of a building. Different studies have extensively evaluated geological properties of the area in which Vittoriano building is built [6]. The most notable point is that this monument is constructed on various soil classification. The Northewestern part of the building, where the cracks could be clearly observed on the wall, rests on Anthropogenic and Tiber alluvial deposits as depicted in Fig. 1(c). The poor deformability and low shear strength of these soil layers caused the ground movement and consequently building settelment resulting in the western wall's cracks. The other parts of the building, on the other hand, are located on soil classifications (i.e., Villa Senni Formation, Fosso del Torrino Formation, Platino Unit and Fosso della Crescenza Formation) with high deformability resistance which prevent any ground movement [6].

Fig. 1 demonstrates the building and the cracked wall considered as the case study in this paper.

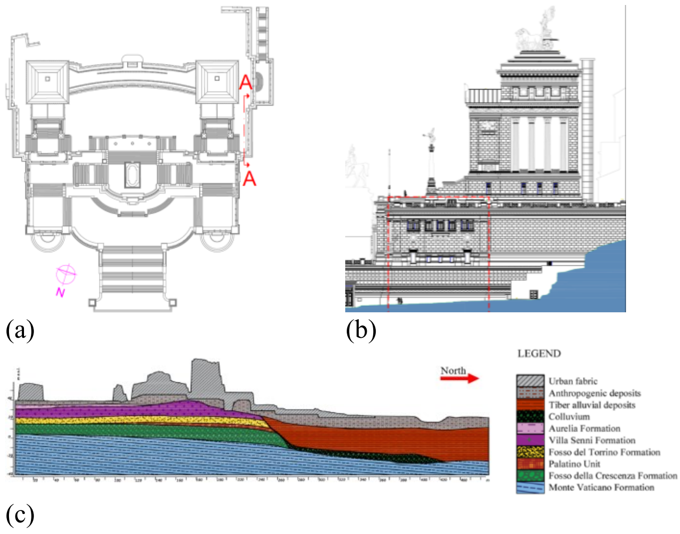


Fig. 1. Vittoriano monument (a) plan, (b) side view, and (c) the soil profile [6].

III. FE SIMULATION

A detailed 3-dimensional model of the western wall was developed in the FEA software ABAQUS. Note that the 3D model was firstly developed in AutoCAD and then imported into ABAQUS. It should be also pointed out that: (a) in order to facilitate meshing, some parts which do not affect the wall's performance (e.g., sculptures and narrow ledges) are not modeled, (b) the internal elements (i.e., walls, roofs, and stair ramps) are simulated by the projection of 50 cm for the potential interaction between the wall and aforementiond elements to be considered by the FEA. It should be also noted that the projection is limited to 50 cm because of the existing voids and other complicated details which are not clearly shown in the available drawing materials. The developed 3D-model of the wall is depicted in Fig. 4.

There are three different techniques for simulating masonry material: micro-scale model, meso-scale model, and macro scale model. Macro-scale model is generally utilized in the studies assessing the performance of a large ancient masonry buildings [2, 4]. In the present study, the macro-scale approach is also applied by defining the Concrete Damage Plasticity (CDP) model to the material. An extensive description of CDP could be found in literature [8], and it is not presented here for the sake of shortness.

The CDP model could be defined by five parameters: (i) eccentricity ($\mathscr{E}$) which is a small positive value for determining the rate at which the hyperbolic flow reaches its asymptote. (ii) f_{b0}/f_{c0} which is the ratio of initial equiaxial compressive yield stress to initial compressive yield stress , (iii) K_c which is used for adopting Drucker-Prager strength criterion in the CDP model, and is defined as the ratio between the second stress invariant on the tensile meridian and the one on the compressive meridian, (iv) viscosity parameter (μ) which is generally used for enhancing the convergence rate of a model in the softening branch without affecting the results significantly, and (v) dilatation angle (ψ) which represents the angle due to a variation in material volume after applying a shear force [9]. Table 1 gives values of the CDP parameters adopted in the model.

Table 1. CDP parameters.

Dilatation angle (ψ)	Eccentricity ($\mathscr{E}$)	f_{b0}/f_{c0}	K_c	Viscosity parameter (μ)
10	0.1	1.16	0.667	0.002

Uniaxial stress-strain values in both compressive and tension as well as the tension damage, reported in Table 2, are assigned to the masonry material in the model. It is worth noting that a linear trend of the scalar tension damage parameter which stands for the stiffness of the material is assumed.

Table 2. Table caption.

Compressive behavior		Tensile behavior		Tension damage	
Stress (MPa)	Inelastic strain	Stress (MPa)	Cracking strain	d_t	Cracking strain
1.9	0	0.150	0	0	0
2.4	0.0051	0.075	0.00025	0.95	0.00121
0.96	0.0102	0.018	0.00057		
0.48	0.0307	0.009	0.00121		

Since only the cracked wall is simulated in this study, defining a proper boundary condition representing the wall interaction with other building's elements is of high importance. As denoted previously, the Northwestern part of the building rests on Tiber Alluvial deposit with a high deformation capability. According to the results of relevant researches [6] (see Fig. 2), and based on the crack propagation on the wall, it could be articulated that the lateral surface of the wall (connected to the building from South), and roughly the half Southern part of the wall have not experienced any deformation. The main settlement is reported on the half Northern part of the wall. Accordingly, the rigid restraint was defined for the Southern part while the roller restraint (free displacement in vertical direction) was assigned to the Northern part.

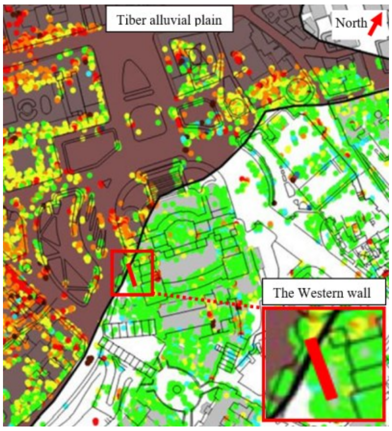


Fig. 2. Location of the western wall regarding the Tiber alluvial plain [6]

The main novelty of this study is the load application in numerical simulation. It is worth explaining that building settlement is not applied to its base in common analytical analysis. Instead, the base displacement due to various loads (e.g., static, and dynamic loads) and soil-structure interaction is assessed. In the current methodology, however, the ground settlement acquired by InSAR is used. It should be highlighted that the given InSAR displacement is due to both building's loads and geological properties of the location.

The most accurate InSAR data should be chosen for applying the ground deformation on the wall, and therefore the data at the point A, as demonstrated in Fig. 3 (a), with a high accuracy are applied along the wall. Note that the data given by InSAR is the displacement along Line Of Sight (LOS) while the vertical movement should be applied to the wall base. A simple equation (Eq. 1) commonly used for converting the LOS displacement (d_{LOS}) to vertical displacement (d_{InSAR}) is utilized here as well [10]. The vertical displacement time-series at point A is provided in Fig. 3 (b).

$$d_{InSAR} = \frac{d_{LOS}}{Cos\,\theta} \quad (1)$$

(a)

(b)

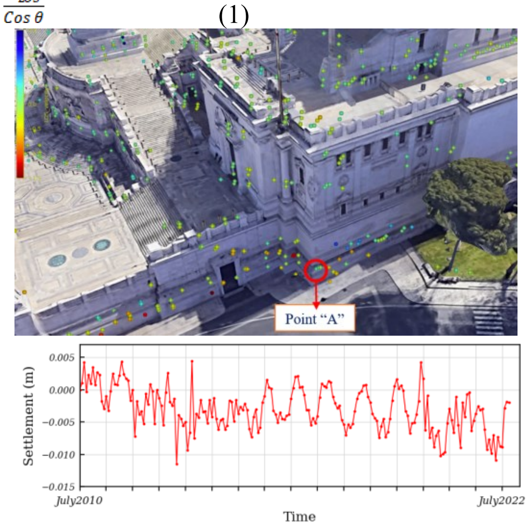
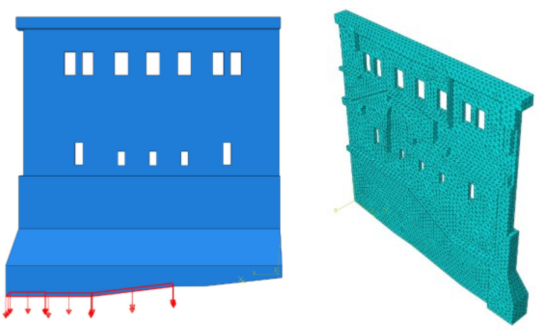


Fig. 3. (a) point A with the highest accuracy, and (b) displacement time-series acquired for the point A and applied to the wall's base.

The length of the wall in which the time-series displacement is applied is illustrated in Fig. 4(a). Based on a sensitivity analysis, a uniform mesh size of 50 cm was considered to mesh the wall as demonstrated in Fig. 4 (b). In terms of element type, 4-node linear tetrahedral element (C3D4) was used to perform non-linear dynamic explicit analysis through ABAQUS.



(a) (b)

Fig. 4. (a) The length at which InSAR displacement is applied, and (b) the meshed wall.

IV. MODEL VERIFICATION AND RESULTS

The model is verified by discussing three parameters: Von Mises stress, tensile damage, and stiffness degradation. Fig. 5(b) displays the maximum Von Mises stress distribution during the analysis. Similar to the crack pattern observed on the wall (Fig. 5(a)), the highest stress values are distributed in the middle of the wall. Moreover, the stress concentration at the vicinity of openings, which is a common issue in masonry buildings, is also noticeable. Accordingly, it could be claimed that that the stress distribution in the FE model matches well with the existing cracks on the wall. Tensile damage variable (*DAMAGET*, d_t) referring a nondecreasing quantity associated with tensile failure of the material and stiffness degradation variable (*SDEG*, d) reflecting the stiffness recovery effects associated with the cracks' width are also depicted in Fig. 5 (c) and (d), respectively. Both d_t and d take values between 0 (no damage) and 1 (full damage): $d_t>0$ and $d>0$ reflects an open crack while $d_t>0$ and $d=0$ shows a closed crack [11]. The tensile failure (Fig.5 (c)) and the open cracks (Fig. 5(d)) are in line with the wall cracks depicted in Fig. 5(a).

The difference between the analytical results and the real wall could be because of the displacement applied to the simulated model which is limited to the time interval of July 2010-July 2022 while the cracks in the wall are due to ground settlement since the day of building's construction. Furthermore, the visible cracks on the wall occurred in the joints of the marbles while there might be extensive crack propagation under the facade stones.

V. CONCLUSIONS

This study aimed at introducing a novel methodology for monitoring buildings' performance by implementing FE analysis and InSAR. A wall of Vittoriano building located in Rome, Italy was simulated by the nonlinear FE analysis software ABAQUS. The displacement time-series acquired by InSAR was applied to the wall base and the results were compared to the real wall in terms of stress concentration and crack propagation. The remarkable conclusions are:

- The simulation outcomes highlighted the reliability of the proposed methodology which was mainly concerning on the application of ground settlement (given by InSAR) instead of applying external loads. This method could facilitate monitoring heritage buildings in which installing instruments is not allowed.
- Based on the results, the vertical crack on the wall is mainly due to the soil condition which causes ground settlement. The stress concentration around the openings at the middle of the numerical wall causes horizontal cracks which could be observed in the real wall as well.
- Based on the results, the wall should be strengthened against further tensile failures,

particularly at the opening zones.

- The methodology presented in this study, could be utilized for developing digital twin of buildings for better assessment of their performance.

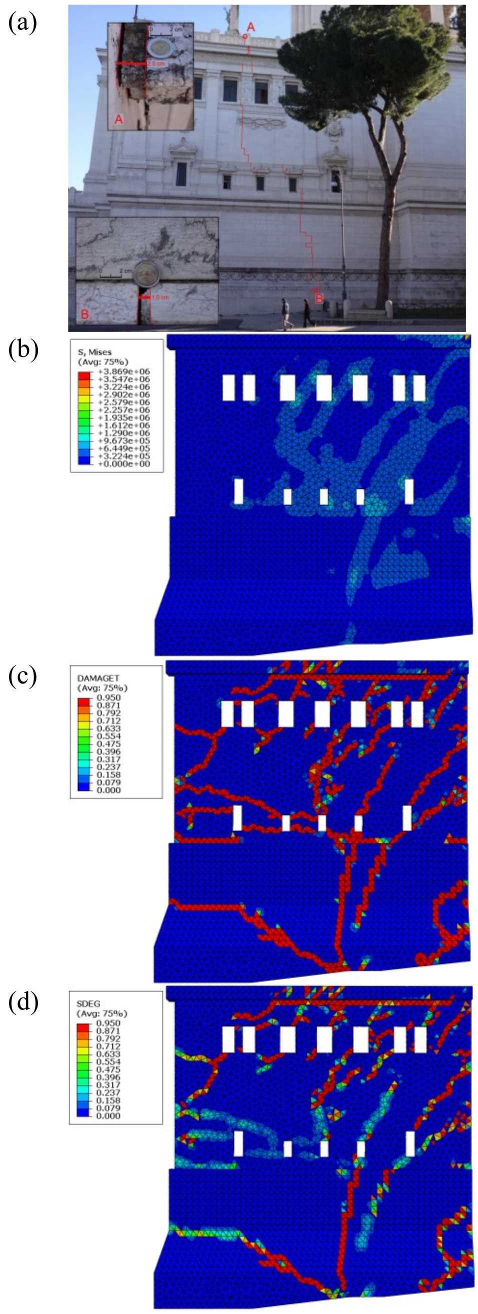


Fig. 5. Comparing (a) observed cracks on the wall [6] with FEA results namely (b) Von Mises stress (Pa), (c) tensile damage, and (d) stiffness degradation.

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