Analysis of the Battistero di San Giovanni's behavior subjected to seismic events

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Abstract. The analysis behavior of historical structures over the years constitute a fundamental research's field to perpetuate the constructive methods and the cultural heritage of civilizations. Such analyzes involve not only the static aspect but also the seismic action, present in a large part of the world territory and which subjects several structures to vibrations. Evaluating the historic masonry construction's vulnerability against earthquakes, many studies are carried out to guarantee the protection of structures and consequently the cultural heritage. With the ease of access to computational means, a large part of the historic building's studies has been carried out using the finite element method, with the aid of computational tools made available by commercial software. In this context, the Italian municipality of Florence, which has the highest concentration of universally renowned works of art, is in a seismic zone, presenting episodes of earthquakes in the month of June 2023, with 4.0 Mw of magnitude. Thus, the present work aims to numerically analyze the dynamic behavior of the Battistero di San Giovanni, from the 4th-5th centuries, located in Florence. Its behavior against seismic events is evaluated from the structural analysis by the finite element method, using the ABAQUS software.

Keywords: dynamic, modal, earthquakes, historical monument, Florence

1 Introduction

The study and conservation of historic buildings has important role in the world's cultural heritage as they contain sociological, economic, cultural and political elements of the place to which they are located. The analysis and modeling of historic buildings, however, is complex and presents difficulties, even impossibilities, in the direct application of the usual assumptions of modern structural analysis when trying to fit them into the laws of statics and the resistance of materials, as for example, in the consideration of integrally homogeneous materials and uniform structures.

Structural assessment of historic buildings, however, must be performed in order to indicate the cause of existing damage and the effect of the source of damage on the useful life of the structure [1]. Such analyzes must involve both the static characteristics of the construction and the dynamic ones, since a large part of the world's territory is found in seismic zones that subject structures to vibrations not always supported by the constructive elements.

Despite the peculiar characteristics of historic masonry constructions guaranteeing a good level of safety against common destructive agents, in the event of seismic events this safety is lower due to characteristics of the structure itself: slender and high walls, shallow foundations, limited structural reinforcements and intrinsic characteristics. of the material does not support traction tension. All these elements alone mean that historic buildings, especially large ones such as churches, temples, aerial aqueducts, have a low resistance to the horizontal forces generated during a seismic event. Thus, dynamic analysis constitutes a field of investigation of great interest, not only due to the possible damage generated to the structure, but also to the uncertainties associated with the occurrence of this phenomenon in property and social security.

Florence, the capital of Tuscany, is located between two very seismic areas: Mugello, to the north, and Chianti, to the south. Its historic center of about 505 ha was declared a World Heritage Site, in 1982 by the United Nations Educational, Scientific and Cultural Organization (Unesco) it was subjected to earthquakes, with the epicenter located in the Chianti area, between the municipalities of Impruneta and San Casciano Val di Pesa, with a maximum magnitude of 3.70 Mw [2] in May 2022 and 4.00 Mw in June 2023.

Admitting that the Italian city of Florence and its invaluable cultural heritage is subject to seismic events, the present work aims to numerically analyze the dynamic behavior of the Battistero di San Giovanni, located in the historic center of the city, in the face of seismic events. Numerical analysis is performed using the finite element method, using the ABAQUS software.

2 Structure analyzed

As mentioned, the structure studied is the Battistero di San Giovanni, indicated in Fig.1.

Figure 1. Battistero di San Giovanni, Florence

The Baptistery of San Giovanni was built over an ancient temple after the Roman victory in the city of Fiesole, ancient Florence. Among the written documents, the first citation of the monument dates to the year 897, but only in 1128 did the building officially become a baptistery [3]. The octagonal shape, the most common for baptistries of the first Christian centuries, was preserved in the medieval expansion of the current construction.

The octagonal structure has an internal width of 27.00 meters and a height of 35.00 m, consisting of an octagonal domed roof about 20.00 meters high. The Battistero has three levels, so that the first floor is supported, on each of the eight sides, by four cylindrical columns distributed symmetrically and the second floor, gives access to the Dome.

The framework was instrumented for modal analysis in 2013 by Lacanna et al. [4], using 10 seismic stations and a test duration of 42 hours, obtaining the following values of natural frequencies and vibration modes: 2.67 Hz (north - south vibration) and 2.88 Hz (east - west vibration), respectively. Such experimental results were used to update the proposed model.

2.1 Constituent materials of the baptistery

From March 2014 to September 2015, a cooperation between the Opera del Duomo di Firenze and the Dipartamento di Scienze della Terra dell'Università degli Studi di Firenze allowed studies and analyzes of the constituent materials of the Battistero di San Giovanni to be carried out, with the help of of the Consiglio Nazionale delle Ricerche and Istituto per la conservazione e la Valorizzazione dei Beni Culturali [5]: bricks and mortar.

Two types of bricks were found, of different dating, in the structure. The first, composed silicate composition's fragments of quartz and feldspar and a carbonate component represented by rock fragments, dates from the 4th-5th centuries. The second group consists of quartz fragments, mica flakes, feldspars and dated to the period between the year 1000 [5]. As for the composition of the mortar, the presence of silica sand and fragments of carbonate rocks were mainly found, which gave the mixture low resistance to water.

Regarding the physical properties, however, no data were found regarding the modulus of elasticity, density and Poisson's coefficient, necessary for the complete characterization the structure's materials in its static and dynamic structural analysis. For this purpose, the values of the physical properties obtained for the Dome of the

Duomo di Santa Maria del Fiore, in Florence, dated 1420, were used as a reference (Table 1) [6], as well as the value of 5600 MPa suggested by Manual for the Detection of Seismic Vulnerability of Masonry Buildings in the Tuscany Region, for the modulus of elasticity of masonry made up of bricks with cementitious mortars.

Table 1. Physical properties of the Dome of the Duomo di Santa Maria del Fiore's constituent materials [6]

	Modulus of elasticity (MPa)	Poisson Coefficient	Density (Kg/cm³)
Bricks	10870	0.18	2390
Mortar	7700	0.27	2430
Average	9285	0.225	2410

Assuming the values of the physical properties listed in Table 1, an average of 2410 Kg/cm³ was adopted for the density of the Battistero di San Giovanni and 0.18 for Poisson's coefficient. As for the modulus of elasticity, an analysis was carried out to verify which value fits the analyzed building, in the range of 5600MPa - 10870MPa, by computer simulation of modal analysis, guaranteeing great reliability to the model because the dynamic parameters are much more complex and sensitive to small geometric and constitutive variations of the structure in relation to static parameters.

2.2 Battistero's cracks

The Battistero di San Giovanni's numerical model (Fig. 3) was created in the environment of the computer program ABAQUS [8]. For this, a tetrahedral finite element mesh composed of 53180 elements was used (Fig. 4).

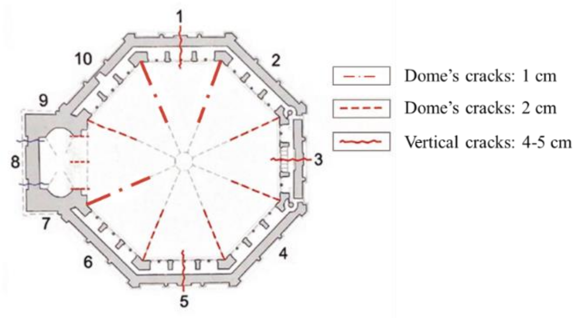

Figure 2. Indication of the Battistero's cracks [7]

3 Numerical model

The numerical Battistero di San Giovanni's model (Fig. 3) was created in the ABAQUS [8] computer program environment for the proposed analyses. For this, a tetrahedral finite element mesh composed of 53180 elements was used (Fig. 4).

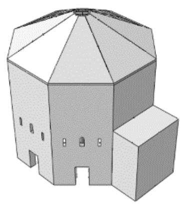

Figure 3. Three-dimensional model of the Baptistery of San Giovanni

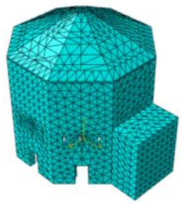

Figure 4. Discretized three-dimensional model in finite element mesh

3.1 Numerical model's adequacy based on modal analysis

Due to the no knowledge of the Baptistery's physical properties materials, values of modulus of elasticity were applied varying within the previously established range of values, keeping the density and Poisson's coefficient constant. The natural frequencies and modes of vibration were compared with the experimental results of Lacanna et al. [4] and its physical properties continued until obtaining a model with the lowest possible error.

Among the simulations, the one that simultaneously provided the first and second frequencies closest to the values determined by Lacanna et al. [4] was the one composed by the modulus of elasticity of 6000 MPa. The frequencies obtained were 2.66 Hz (-0.38% error) and 2.78 Hz (-3.47% error), with north-south and east-west modal vibrations, respectively. Table 2 indicates the material properties adopted for the simulation.

Table 2. Physical properties of the materials adopted in the Battistero di San Giovanni's model

Modulus of elasticity (MPa)	Poisson Coefficient	Density (Kg/cm³)
6000	0.18	2410

Figure 5 and Figure 6 below are graphical representations of the first two vibration modes of the structure, north-south and east-west.

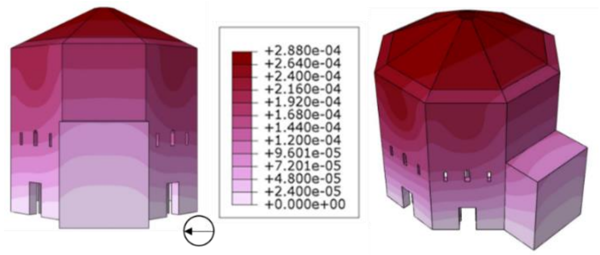

Figure 5. First frequency modal shifts for the Baptistery structure

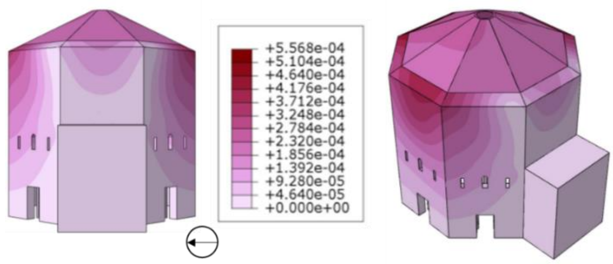

Figure 6. Second frequency modal shifts for the Baptistery structure

3.2 Static analysis

Figure 7 indicates the strains of the Baptistery model as a function of its own weight, with a maximum value of 7.160 mm on the monument's roof. Figure 8 indicates the stress distribution in the model, with values between

-0.40 MPa and 0.80 MPa in most of the structure, so that the maximum values are -1.00 MPa and 1.00 MPa, mainly located at the connection of the inner arches on the first level, rectangular passageways on the ground floor, connections between the sides at the dome's base and at the structure's base walls on the outer side.

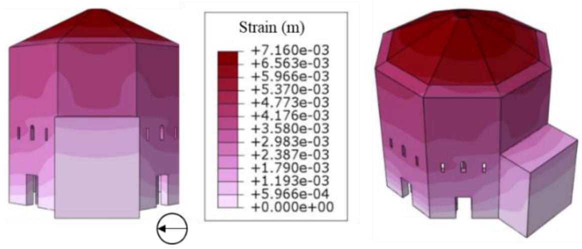

Figure 7. Static strain of the Battistero's structure subjected to its own weight

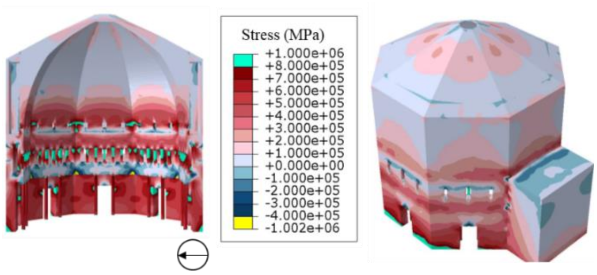

Figure 8. Stress distribution in the Battistero's structure subjected to its own weight

3.3 Seismic Analysis

The seismic analysis of the three-dimensional model was carried out using the database provided by the SCALCONA 3.0 software [9] from natural accelerograms, with a return time of 50 years, of seven seismic events recorded in rocky outcrops that meet the compatibility requirements of spectrum with the regulatory response spectrum for anywhere within the Tuscany region. The accelerogram that causes the greatest acceleration in the structure of the Battistero was analyzed. For all seismic events, the maximum accelerations were in the same location: immediately before the roof, on the northeast side. Thus, the Fig. 9 indicates the acceleration graph for this location in each of the seven events analyzed.

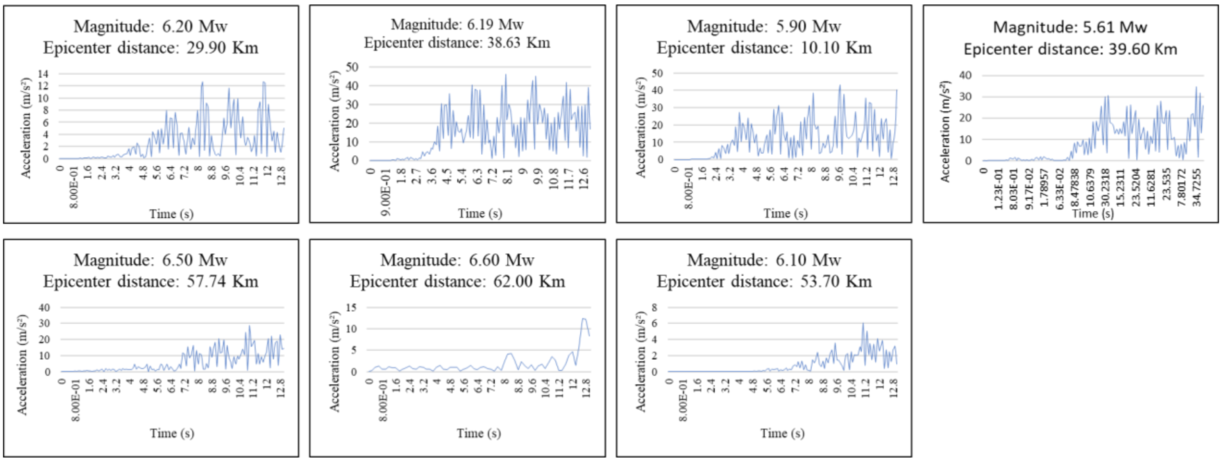

Figure 9. Graphs of accelerations at the point of greatest acceleration due to each of the seven seismic events

With the application of accelerations at the structure's base, it was evaluated that the seismic event of 6.19 Mw (distance from the epicenter 38.63 Km) generated the biggest acceleration in the structure, 46.13 m/s² (Fig. 10), in time 8.00 seconds. Such acceleration generated a stress state in the structure with the same range of values as the static state, however, the maximum stresses were mainly restricted to the top of the structure immediately before the roof. The largest deformations were also observed in this same region, of 180 mm.

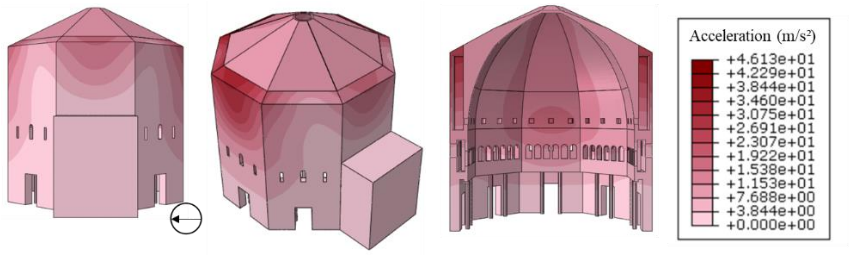

Figure 10. Indication of accelerations in the Battistero's model due to the seismic event of magnitude 6.19 Mw, at time 8.00 s

Figure 11 indicates the stress distribution in the Baptistery structure due to the seismic event, whose most part of the structure had stress values between -4.00 MPa (compression) and +4.00 MPa (traction). Figure 12 represents the acceleration history in the regions of greatest acceleration: top of the structure immediately before the roof (northeast side).

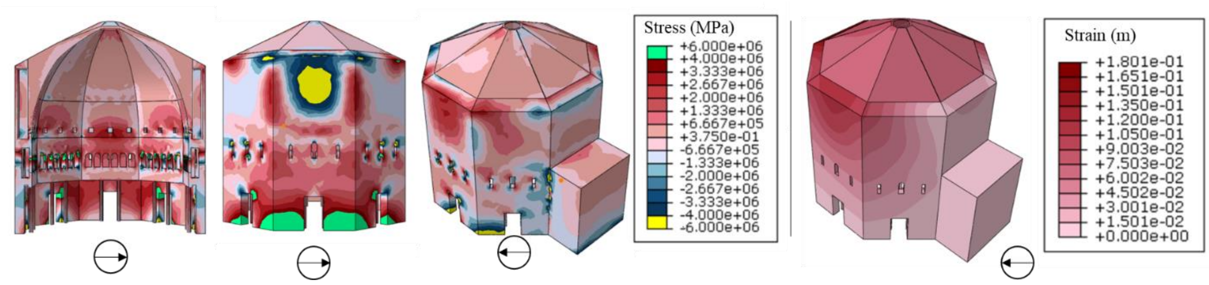

Figure 11. Graphic representation of tensions and deformations in the Battistero's structure as a function of the seismic event of magnitude 6.19 Mw, at time 8.00 s

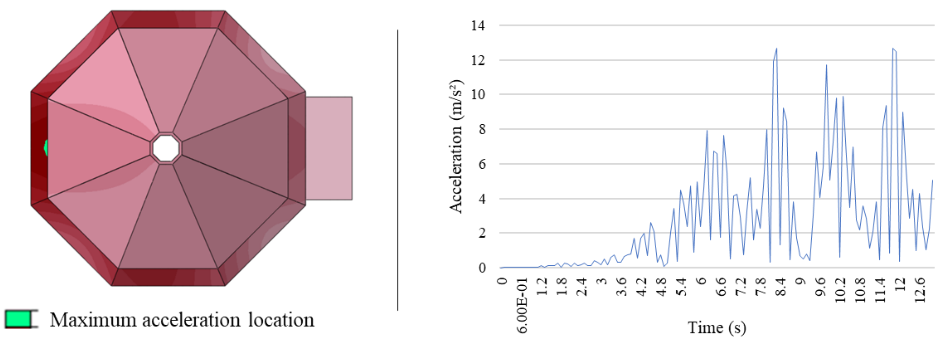

Figure 12. Accelerations' history at the points of biggest acceleration

4 Conclusions

The present work presents a numerical study of the Baptistery of San Giovanni's dynamic behavior subjected to seismic events, to allow the analysis of the efforts to which it is submitted, enabling the prediction and monitoring of the structure subjected of these loads. For this, it was decided to develop an updated model based on dynamic properties, obtaining an average error of 1.925% in relation to the first natural frequencies of the monument obtained experimentally by Lacanna et al. [4]. With the model defined, a seismic analysis was carried out from accelerograms referring to the return period of 50 years for a seismic event of 6.19 Mw, which generated a maximum acceleration in the structure of 46.13 m/s², at the top of the building, immediately before the roof (northeast side), in time 8.00 seconds. Such acceleration caused a maximum strain of 180 mm at the site and maximum stresses between +1.33 MPa and +2.00 MPa, in comparison with the maximum stresses in the region between 0.005 MPa and 0.100 MPa in the static regime.

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References

[1] R. Chmielewski and L. Kruszka, "Application of selected modern technology systes to strengthen the damaged masonry dome of historical St. Anna's Church in Wilanów (Poland)". *Case Studies in construction Materials*, 2015.
[2] INGV. "Istituto Nazionale di Geofisica e Vulcanologia", 2022.
[3] R. Corazzi. *Le cupole sotto il cielo di Firenze*. Pontecorboli Editore, Florence, pp. 52-65, 2018.
[4] G. Lacanna, M. Ripepe, E. Marchetti, M. Coli and C. Garzonio, "Dynamic response of the Baptistery of San Giovanni in Florence, Italy,based on ambient vibration test". *Journal of Cultural Heritage*, 2016.
[5] C. Garzonio, E. Cantisani, M. Coli, O. Cuzman, D. De Luca, C. Lubritto, E. Sibilia, "I materiali costitutivi del Battistero". *In: F. Gurrieri, Il Battistero di San Giovanni: : Conoscenza, Diagnostica, Conservazione*. Firenze: Mandragora, 2014.
[6] L. Barbi, B. Leggeri, V. Vasarri, R. Franchi, F. Fratini, and C. Manganelli del Fá. *Indagine sperimentale sui materiali costituenti la Cupola di Santa Maria del Fiore*. Università di Firenze Facoltà di architettur: Atti del Dipartimento di Costruzioni, 1986
[7] C. Blasi, F. Ottoni, E. Coisson and C. Tedeschi. "Battistero di San Giovanni in Firenze: Note su dissesti, lesioni e catene". *In F. Gurrieri, Il Batisttero di San Giovanni: Conoscenza, Diagnostica, Conservazione.* Firenze: Mandragora, 2014.
[8] Dassaultsystèmes®. ABAQUS, 2023.
[9] C. Lai, E. Zuccolo. *Prosecuzione delle Attività di Definizione di Input Sismici Sismocompatibili e Spettrocommpatibili per i Comuni della Regione Toscana*. Accordo di Collaborazione Scientifica tra la Regione Toscana ed il Dipartamento di Ingegneria Civile e Architettura dell'Università di Pavia, 2015