Structural Dynamic Analysis of Huqiu Pagoda under the Influence of Earthquake

Peixuan Wang[1,2,3,*], Gabriele Milani[1], and Shengcai Li[2,3]

[1] Department of Architecture, Built Environment and Construction Engineering (ABC),
Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milan, Italy
[2] School of Architectural Science and Engineering, Yangzhou University, 225127, China
[2] Jiangsu Huajian Construction Co., LTD, 225002, China
Corresponding author: peixuan.wang@polimi.it

Abstract. As an important masonry structure, the ancient masonry pagoda represents the history and culture of a country. Damage to the pagoda is mainly caused by earthquakes. Many experts and scholars have proposed lots of feasible schemes for the simulation analysis of masonry pagoda fragility, among which finite element numerical simulation is representative. At the same time, in order to help non-professionals quickly assess the collapse mechanism of masonry structures, manual limit analysis is also a fast and effective way. In view of this, this paper chooses an ancient Chinese masonry pagoda with an octagonal horizontal plane—Huqiu pagoda as a case. It performs pushover and non-linear dynamic analysis simulations in the commercial software Abaqus environment. The research selects the processed seismic waves of the 2008 Wenchuan Earthquake in China as the accelerogram. Manual limit analysis was also used as an auxiliary technique to compare the results of the finite element simulation. The research results showed that under the action of seismic waves, Huqiu pagoda develops bottom-up crack damage and activates the bending mechanism at the bottom.

Keywords: Masonry pagoda, Finite analysis, Seismic vulnerability, limit analysis

1 Introduction

As a traditional high-rise building in China, the masonry pagoda has high artistic and cultural value. Generally speaking, a masonry pagoda consists of an underground palace, pedestal, body, and spire. As far as pagodas' structures and material properties are concerned, they have the advantages of high compressive strength, weather resistance, fire resistance, corrosion resistance, low cost, and so on. The masonry pagoda is the main high-rise structure in ancient times, generally reaching more than 50 m – 60 m. Due to the high structural height, the large volume of masonry materials, and the relatively small base area, the masonry pagoda has a relatively large effect on the foundation. The survey found that most of the foundations of the masonry pagodas have taken some scientific manual treatment methods before construction. Avoid resonance between the predominant period of the foundation and the natural vibration period of the masonry pagoda to reduce seismic damage [1,2].

The shape of the masonry pagoda is regular, and the plane structure is relatively simple and symmetrical. The pagoda is made of masonry, so the wall is generally thicker, which can reduce the compressive, tensile and shear stress, and the pagoda can resist external force without damage. From the facade, the section size of the pagoda generally adopts the step-by-step reduction technology from bottom to top, which not only makes the pagoda body present a beautiful appearance but also enhances the stability of the structure. The shape rule of the masonry pagoda can reduce the torsional effect of the earthquake, make the seismic shear force and the interlayer resistance coordinated, and avoid the disadvantageous situation that the weak layer appears in the middle and lower part of the pagoda body.

The masonry pagoda is complex in shape and diverse in structural system. The walls of the pagoda are thicker, and the integrity is better. Different pagodas have door and window openings in different positions. Opening styles are also varied, including rotating, symmetrical, and alternating, and some have real and false openings to meet the needs of the architectural and artistic effect of the facade. The existence of openings weakens the cross-sectional area of the pagoda, and the location of the cavity has also become a weak link in earthquake resistance.

However, because traditional Chinese masonry materials are mostly a mixture of glutinous rice juice, lime, and sand, the pagodas' ability to resist tensile, shear, and bending is poor. In addition, most of the existing ancient masonry pagodas are old and have been eroded by wind and rain for a long time. Most of the pagoda bodies have decreased in strength, and even some materials are broken and peeled off, which increases the risk of tower body collapse under the action of earthquakes.

Considering this, structural dynamic analysis of historical masonry pagodas can effectively help us find weak parts of pagodas and simulate the distribution and extension of damage under seismic loads. It plays a vital role in the protection and restoration of historical heritage.

Traditional masonry buildings are usually made up of bricks and mortar. Therefore, making a unit model in the finite element method will be relatively complicated. With many years of effort, the accuracy and calculation rate of the discrete model is still not very satisfactory. Nowadays, the most popular technique to simulate the material properties of masonry is Concrete Damage Plasticity (CDP) model, which has been successfully applied to many finite element simulation environments [3-7].

However, the technique mentioned above has a high requirement for the researchers who should have professional structural mechanics knowledge and software simulation skills. This is impossible for non-professionals, and it is not conducive to the development of multidisciplinary cooperation in the protection of historical heritage. To solve this problem, Sarhosis et al. proposed a manual limit analysis method which a fast evaluates the failure mechanisms of towers/pagodas [8].

In this case, the paper chose a historical Chinese masonry pagoda – Huqiu pagoda as a case study. Doing a serious simulation analysis in Abaqus software with CDP model, and also a manual limit analysis. Comparing the two results, a more complete assessment of the vulnerability of Huqiu pagoda can be provided.

2 Description of Huqiu pagoda

Huqiu pagoda (Fig. 1), located in Suzhou, Jiangsu, China, is a critical cultural relic protection unit in China. It is an octagonal masonry pagoda with a first-floor plane that is 13.81m from north to south and 13.64m from east to west (Fig. 2). The interior of the pagoda consists of 7 floors with a total of 48.2 meters. In terms of facade modeling, it shrinks layer by layer from bottom to top, and the closer to the top, the greater the degree of shrinkage. Huqiu pagoda was first built in 959 AD and completed in 961. Except for a small amount of timber used in the eaves and some non-structural parts, the entire pagoda body is basically made of bricks. The pagoda body consists of three parts: the outer walls, the corridor (for sightseeing and walking), and the inner walls. The stairs connecting each floor are located in the corridor. The design effect of each facade of the outer wall is basically the same, with a door in the middle and a walkway leading to the corridor, and windows on both sides of the door. The plane structure of the inner walls is still octagonal, with doors and aisles facing east, west, north, south, and four directions. The aisle leads to the central room of the pagoda [9,10].

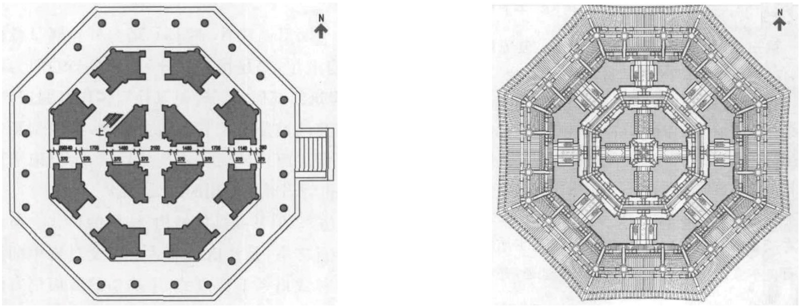
(a) Location

(b) Current situation

(c) Restoration drawing of the east facade

Fig. 1. Huqiu pagoda [9,10].

In the past, Huqiu pagoda experienced many fires, almost all the timber eaves were destroyed, and only the masonry parts of the existing structure remained. Another critical damage to the Huqiu pagoda is that the whole pagoda body is inclined to the northeast. As of 2010, the angle of the center line of the pagoda body from the plumb line was measured to be 3°59′, which is more than 8 meters away from the center. According to the current situation and analysis of preliminary survey data, the reason for the inclination is the uneven settlement of the foundation.



(a) First floor (b) First floor bottom view

Fig. 2. Plans of Huqiu pagoda [9,10].

3 Finite element simulation by Abaqus

3.1 Material and simulation model

In order to study the failure mechanism of Huqiu pagoda under the action of horizontal seismic load and the law of damage diffusion in the structure, this paper uses the common commercial finite element software Abaqus to carry out pushover and nonlinear dynamic analyses on the pagoda.

It is necessary to define the material properties of the historical masonry pagoda first. They are specific weight, elastic modulus, Poisson's ratio, etc. Since the Huqiu pagoda is currently a historical heritage building in China, it cannot be tested on-site. Referring to [11] and the historical Chinese masonry pagodas researched by authors in the past, the material parameters used in the numerical simulation in this paper are shown in Table 1.

Table 1. Mechanical properties.

Young's Modulus	Specific Weight	Compression Strength	Tensile Strength	Tensile Fracture Energy
1600 MPa	18 kN/m^3	1.5 MPa	0.05 MPa	0.007 N/mm

Table 2. Parameters of CDP model in Abaqus.

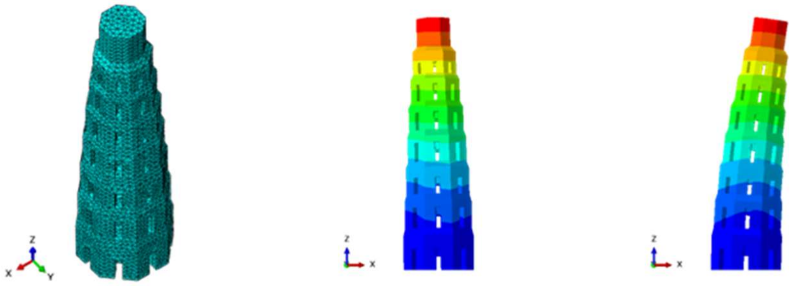
Dilatancy Angle	Eccentricity	fb0/fc0	Viscosity Parameter
10°	0.1	1.16	0.0001

The Abaqus numerical simulation refers to the CDP model, which has been skillfully used in the damage simulation of masonry structures. The CDP parameters used in this simulation (Table 2) refer to the following literature [12-14]. Since the materials used in ancient Chinese masonry structures usually have poor performance, the author tends to choose a lower viscosity parameter (0.0001) to ensure the accuracy of the simulation results and prevent overestimation.

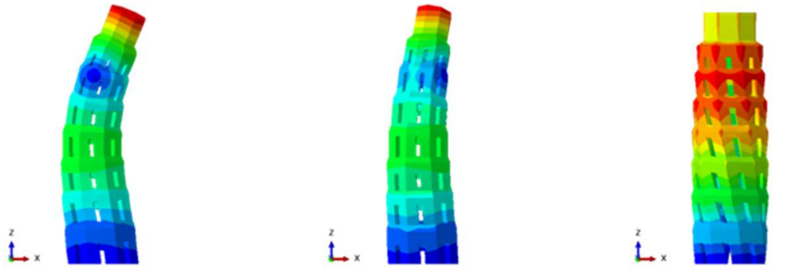
The model of the masonry pagoda was first built in the software AutoCAD. In order to facilitate modeling and reduce analysis costs, the authors simplified the model. The eaves, stairs, and other parts which will not influence the structure were ignored, the research just contains the outer walls, inner walls, central rooms, and openings. The Huqiu pagoda was discretized into 53420 solid elements (Fig. 3 (a)) in the Abaqus environment for the following simulation analyses.

3.2 Modal analysis

The first four vibrational modes of Huqiu pagoda are translated along the X and Y direction, while the fifth vibrational mode is rotation mode with 3.5361 Hz (Fig. 3).



(a) Discretization of the pagoda in Abaqus (b) 1st mode: 0.9782 Hz (c) 2nd mode: 0.9782 Hz

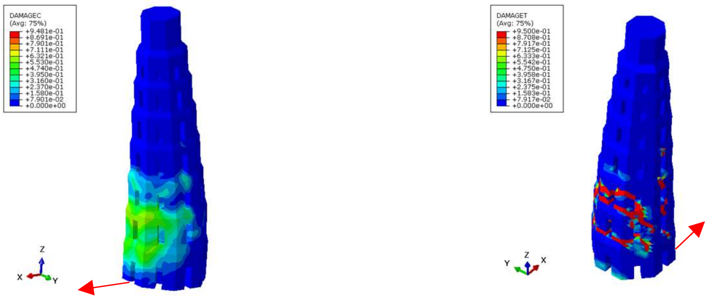


(d) 3rd mode: 3.4331 Hz (e) 4th mode: 3.4333 Hz (f) 5th mode: 3.5361 Hz

Fig. 3. Different vibration modes in numerical simulations of Huqiu south pagoda.

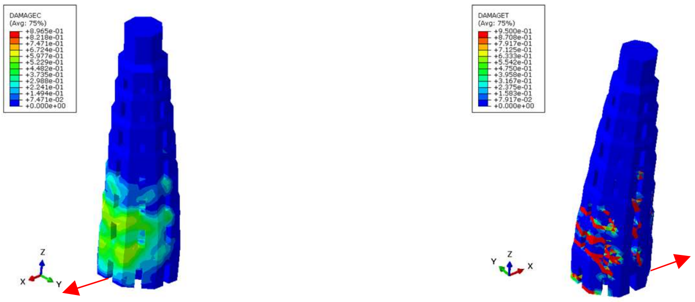
3.3 Pushover analyses

Because in the modeling process, the Huqiu pagoda has been simplified to a certain extent, and it is completely symmetrical in the positive and negative four directions of X and Y. In this case, the research only chose the X+ direction for pushover analysis with G1 and G2 loading conditions, and the capacity curve a_g/g – Displacement was shown.



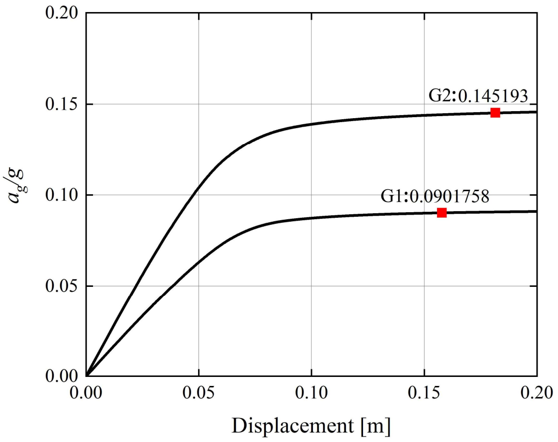
Compressive damage Tensile damage

(a) Damage－G1



Compressive damage Tensile damage

(b) Damage－G2



(c) Capacity curve

Fig. 4. Pushover analysis results of Huqiu pagoda, load direction: X+.

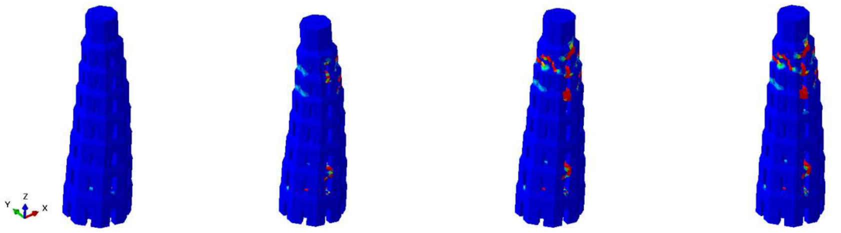
In Fig. 4 (a) and (b), damage overturning with diagonal cracks can be observed on the first and second floors. At the same time, cracks along the center line of the pagoda appeared on the facade perpendicular to the direction of the seismic load, but the cracks only existed on the first to third floors and did not extend to the top. Since the internal central rooms exist in the total center part of the pagoda body, their influence on the thickness of the facade wall in all directions is the same. It can be seen from Fig. 4 (c) that the damage of Huqiu pagoda is similar under the G1 and G2 loading conditions applied along the X+ direction, but the ultimate load under the G2 loading condition is higher (about 0.145).

3.4 Non-linear dynamic analyses

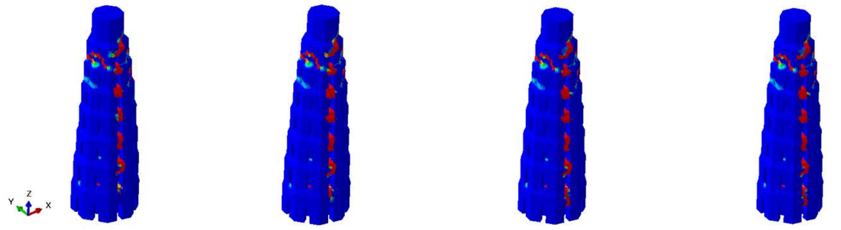
The spectrum-compatible accelerogram applied in Huqiu pagoda for non-linear dynamic analysis is generated from a real accelerogram at disposal, which is a ground motion recorded during the 2008 earthquake by Wolong Wenchuan station (provided by Yangzhou Univerisity). The seismic wave was computed from the elastic spectrum provided by the Chinese Building Code [15] by using the SeismoArtif software [16] and has been filtered by the SeismoSignal software [17].

Because of the symmetry of the Huqiu pagoda, the non-linear dynamic analyses were only performed along the X+ direction. In Fig. 5, the first damage appeared on the two facades perpendicular to the Y-axis around 5.059 s. With the passage of time, the two cracks extended into one crack that penetrated from top to bottom. In the part above the sixth floor, the crack develops in a Y-shape towards both sides of the facade. After 6.8 s, the crack width increased, but no longitudinal development trend was observed.

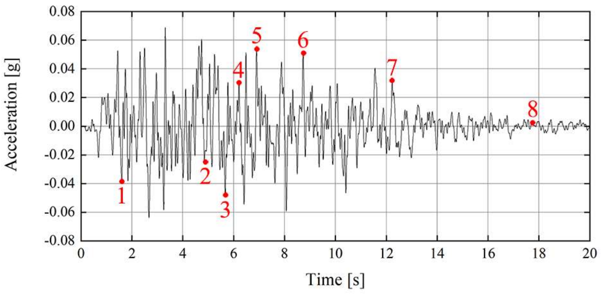
Direction	PGA [g]	Scale Factor [–]	Scaled PGA [g]
X+	0.35	0.2	0.07



Point 1: 2.367 s | Point 2: 5.059 s | Point 3: 5.662 s | Point 4: 5.945 s



Point 5: 6.549 s | Point 6: 8.412 s | Point 7: 12.370 s | Point 8: 17.820 s

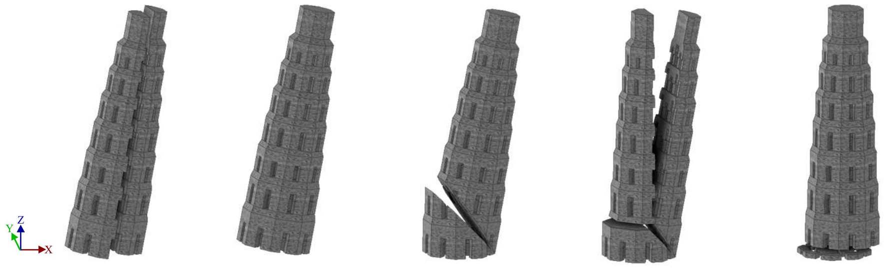


Accelerogram

Fig. 5. Tension damage evolution during NLDA of Huqiu pagoda by X+ direction.

4 Manual limit analysis

According to the data [18,19], along the X+ direction with G1 and G2 load distribution, five failure mechanisms for manual limit analysis are considered (Fig. 6). The inclined planes of mechanisms n.3 and n.4 have been posed with an inclination of 30°, 45° or 60° to the horizontal plane. Both G1 and G2 distributions for the horizontal inertia loads have been applied. It is worth noting that a Mohr-Coulomb failure criterion has been used in mechanism n.5 calculation; the friction angle has been taken equal to 30° following what is stated in [20].



Mechanism n.1: vertical splitting in two parts

Mechanism n.2: base rocking

Mechanism n.3: overturning with diagonal cracks ("a la Heyman")

Mechanism n.4: a combination of splitting and diagonal overturning

Mechanism n.5: base sliding

Fig. 6. Manual limit analysis of Huqiu pagoda in X+ direction.

The results of the manual limit analysis are presented in Table 3. Among them, the vertical splitting in two parts (Mechanism n.1) is the easiest to appear, and the collapse acceleration under G1 and G2 loads are 0.091 g and 0.124 g, respectively. The simulation analysis results of sections 3.2 and section 3.4 are closer to mechanism n.4. Such results may be due to the different material parameters used by the two analytical methods. In mechanism n.4, when the damaged plane is positioned at 30°, the collapse acceleration is the lowest, and the error rate with the Abaqus pushover simulation results is about 26.7%. According to the rules, when the angle of the masonry damage plane is lower (less than 30°), the resulting collapse acceleration will be smaller, and the error rate will be lower. From an engineering point of view, this is acceptable.

Table 3. Manual limit analysis of Huqiu pagoda in X+ direction.

Mechanism	Inclination Angle [°]	Collapse Acceleration G1 [g]	Error Rate [%]	Collapse Acceleration G2 [g]	Error rate [%]
#1	/	**0.091**		**0.124**	
#2	/	0.233		0.298	
#3	30	0.188		0.254	
	45	0.167		0.224	
	60	0.144		0.184	
#4	30	**0.123**	**26.69**	**0.198**	**26.67**
	45	0.130		0.217	
	60	0.157		0.337	
#5	/	0.527		0.527	

5 Conclusion

The paper selected a historical masonry pagoda – Huqiu pagoda to analyse the vulnerability. A serious of finite element simulation analyses (pushover analysis and dynamic analysis) and manual limit analysis were done. The results show that Huqiu pagoda is affected by horizontal loads, and a vertical crack will appear, activating the ultimate bending at the bottom. The weak links of the pagodas are mainly reflected in the central room. Cracks on the surface are common in the openings. The results of the manual limit analysis corroborate the results of the numerical simulation.

In future research, the authors will conduct further research on masonry pagodas/towers with different plan structures and heights and even masonry aggregates. Attempts to further eliminate error rates between numerical simulations, manual limit analyses, and collapse accelerations of masonry buildings under the influence of real seismic loads.

Acknowledgments

The work has been supported by the Chinese Scholarship Council CSC (award to Peixuan Wang for 4 years of Ph.D. study abroad at the Technical University of Milan, Italy).

References

1. Si, J.H., Li, K., Lu, J.L., Chen, C., Li, & J.Y. Numerical analysis of seismic damage of masonry pagoda structure in Chongshou temple. Journal of Xi'an University of Technology, 34(02), 153–158 (2018). [In Chinese]
2. Liu, Y. Study on the Damage Characteristics of the Longhu Pagoda in the Wenchuan Earthquake. Master Thesis, Yangzhou University (2012).
3. Peng, B. Graphic Simulation Technology of Collapse Response of Masonry Structure. Journal of Tongji University, 10, (2004).
4. Samarasinghe, W., Page, A.W., & Hendry, A.W. Behaviour of Brick Masonry Shear Wall. The Structure Engineering, 59B(03), 42–48 (1981).
5. Milani, G., Lourenco, P.B., & Tralli, A. Homogenised Limit Analysis of Masonry Walls, Part I: Failure Surfaces. Computers and Structures, 84(3–4), 166–180 (2006).
6. Reccia, E., Cazzani, A., & Cecchi, A. FEM-DEM Modeling for Out-of-plane Loaded Masonry Panels: A Limit Analysis Approach. The Open Civil Engineering Journal, 6(1), 231–238 (2012).
7. Milani, G., Lourenço, P., & Tralli, A. 3D Homogenized Limit Analysis of Masonry Buildings under Horizontal Loads. Engineering Structures, 29(11), 3134–3148 (2007).
8. Sarhosis, V., Milani, G., Formisano, A., & Fabbrocino, F. Evaluation of different approaches for the estimation of the seismic vulnerability of masonry towers. In Bulletin of Earthquake Engineering (Vol. 16, Issue 3). Springer Netherlands (2018).
9. Zhang, Y. Research on Restoration of Yunyan (Huqiu) pagoda in Suzhou. Architectural History, (2), 34–47 (2009). [In Chinese]
10. Hu, Y.X. Research on Modal Parameter Identification of Ancient Masonry Pagoda Based on Environmental Dynamic Test. Master Thesis, Yangzhou University (2012). [In Chinese]
11. GB 5003-2001. GB 5003-2001 Code for Design of Masonry Structures (2001). [In Chinese]

12. Habieb, A.B., Milani, G., Tavio, T., and Milani, F., Low Cost Frictional Seismic Base-Isolation of Residential New Masonry Buildings in Developing Countries: A Small Masonry House Case Study. The Open Civil Engineering Journal, 11 (1), 1026–1035 (2018).
13. Wang, P.X., Scacco, J., Milani, G., & Li, S.C. Seismic vulnerability evaluation of longhu pagoda, Sichuan, PRC. Proceedings of the International Conference on Structural Dynamic, EURODYN, 2, 4226–4242 (2020).
14. De Iasio, A., Wang, P.X., Scacco, J., Milani, G., & Li, S.C. Longhu pagoda: Advanced numerical investigations for assessing performance at failure under horizontal loads. Engineering Structures, 244(February), 112715 (2021).
15. GB 50011: GB 50011 Code for Seismic Design of Buildings, PRC, （2016). [In Chinese]
16. SeismoArtif User Guide, © 2002-2020 Seismosoft Ltd.
17. SeismoSignal User Guide, © 2002-2020 Seismosoft Ltd.
18. Sarhosis, V., Milani, G., Formisano, A., & Fabbrocino, F. Evaluation of different approaches for the estimation of the seismic vulnerability of masonry towers. In Bulletin of Earthquake Engineering (Vol. 16, Issue 3). Springer Netherlands (2018).
19. Milani G. Fast Vulnerability Evaluation of Masonry Towers by Means of an Interactive and Adaptive 3D Kinematic Limit Analysis with Pre-assigned Failure Mechanisms. International Journal of Architectural Heritage, 13, 941–62 (2019).
20. Acito M, Chesi C, & Milani G, Torri S. Collapse analysis of the Clock and Fortified towers of Finale Emilia, Italy, after the 2012 Emilia Romagna seismic sequence: Lesson learned and reconstruction hypotheses. Construction and Building Materials, 115, 193–213 (2016).