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Pushover Analysis of Historical Elti Hatun Mosque

L. Mangia[1], B. Ghisaasi[2], E. Sayın[3], O. Onat[4], P. B. Lourenço[5]

[1]Department of Civil Engineering, Minho University, Guimaraes, Portugal
[2]Department of Civil Engineering, Minho University, Guimaraes, Portugal, bahmanghiassi@civil.uminho.pt
[3]Department of Civil Engineering, Fırat University, Elazığ, Turkey, esayin@firat.edu.tr
[4]Department of Civil Engineering, Tunceli University, Tunceli, Turkey, onuronat@tunceli.edu.tr
[5]Department of Civil Engineering, Minho University, Guimaraes, Portugal, pbl@civil.uminho.pt

Abstract

Historical structures, being an important part of cultural heritage, have shown extreme vulnerability to seismic actions. A clear understanding of the performance of them is thus of critical importance for taking preventive actions. This paper presents a case study related to pushover analysis of a historical masonry structure located in Tunceli, Turkey. The evaluated monument is Elti Hatun Mosque located in the seismic zone 2 according to seismic zone map of Turkey. The mosque is modeled and analyzed with Diana finite element software on the base of real dimensions measured on site. Material properties are obtained from literature on the base of similar studies. The results are presented as pushover curves, crack distribution and failure modes. The results show that the safety level of the structure is acceptable at its current condition.

Keywords: *historical heritage; mosque; pushover analysis; finite element method; seismic performance*.

1. Introduction

Historical mosques are one of the most important eyewitness of the local history of the urban areas where constructed. All historical constructions are thus expected to withstand external activities such as seismic actions. The observed vulnerability of historical structures in the past earthquakes, has indicated the need for seismic performance evaluation and protection of these structures.

Several studies can thus be found in the literature on seismic behavior simulation of historical structures suing finite element (FE) approaches. Lourenço et al. (2007) presented structural safety assessment of a historical structure called as Monastery Jeronimos in Lisbon, Portugal. In the paper, they emphasized that the results obtained from numerical analysis in historical structures are usually important to understand the structural behavior. Koçak and Köksal (2010) studied seismic behavior of Little Haggia Sophia to determine causes of damage under any type of seismicity. For this purpose, in-situ test and finite element analysis were performed. It was reported that brick and mortar connection is extremely loose and possible damage can occur due to support movement under any seismic event over İstanbul. İlerisoy and Soyluk (2012) assessed earthquake performance of historical Şehzade Mehmet Mosque in Istanbul. For the dynamic analyses of the mosque, the time history method was preferred, and two shallow earthquake (Düzce, Kocaeli) acceleration records were used. The results show that the structure can experience major damage under the selected earthquake records. Çakır et al. (2014) studied performance of historical Ishan Church in Artvin, Turkey. In this study, local and global crack propagations and weak areas of the church were investigated by static and dynamic analysis. It was reported that sensitive part of the structure are transition zones and free end of roof part of the structure. Ceroni et al. (2012) studied seismic vulnerability of historical masonry buildings by means of nonlinear static analysis. Before this analysis, many pre-studies were performed around this historical monument including material survey and dynamic in-situ tests. It was reported that after dynamic identification and robust finite element simulation, soil identification is necessary to assess an advanced estimation. Asteris et al. (2014) assessed three different historical masonry structures to determine seismic vulnerability located in three different countries (Greece, Portugal and Cyprus). Seismic vulnerability reduction graph was proposed by them to determine the damage state after intervention. This graph was proposed to help civil authorities to choose vulnerability of the structures. Lança et al. (2015) studied structural response of upper choir of the six similar ribbed vault of historical Santa Maria Belem Church. It was reported that the analysis results remain acceptable limits under simplified assumptions. Aslan and Şahin (2016) studied different seismic response of Süleymaniye Mosque under different earthquake records. For this purpose, Kobe, Norgride and Düzce earthquake records were used at time history analysis. Maximum principal stresses were occurred along longitudinal direction for all records. However, maximum principal stresses were obtained in transversal direction while performing analysis with Kobe record. It was emphasized that maximum principal tensile stress occurred at vault and arch system due to heavy dead load.

This study presents seismic performance evaluation of historical Elti Hatun Mosque by performing nonlinear static analysis. For this purpose, finite element model of the structure is produced with the FE package Diana (2010).

2. Local Seismicity

Elti Hatun Mosque is located in Tunceli province Mazgirt town. This town is very close to intersection point of North Anatolian Fault (NAF) and East Anatolian Fault (EAF). Half of the Tunceli territory is located in primer earthquake prone region (North side) and other half of the Tunceli province is located in seconder earthquake prone territory (South side). Seismicity of Tunceli province can be seen in Figure 1 ~~below~~.

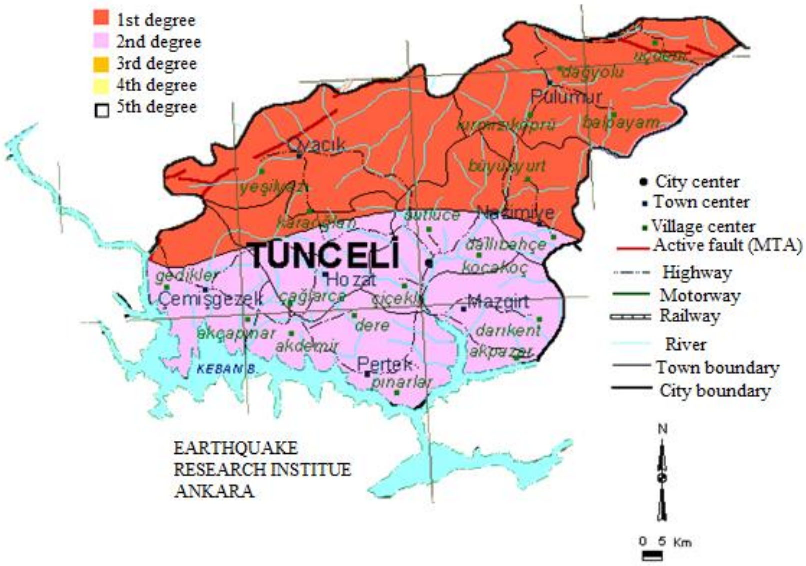


Figure 1: Tunceli earthquake risk map (AFAD, 2015)

3. Elti Hatun Mosque

Elti Hatun mosque is one of the most important historical monuments of Artuklu era around east part of the Turkey. Elti Hatun Mosque was constructed in 1252 by Artuklu emperor Uzun Hasan for his sister Elti Hatun. This mosque was composed of many vaults and arch systems. During the construction phase of the mosque, Horasan mortar was used. Horasan mortar is composed of lime and brick powder. The mosque was restored in the end of July in 2014. Figure 2 show~~s~~ the views of Elti Hatun Mosque after restoration.

Figure 2: Outside and inside of the Elti Hatun Mosque

4. Finite Element Model

The geometrical dimensions of the mosque were determined by on site measurements. A three-dimensional finite element model of the mosque was generated by FE software Diana (2015). The material properties were selected from the similar literature.

4.1 Developing of Finite Element (FE) Model

A three-dimensional finite element model of the mosque was constructed with solid TE12L tetrahedron elements, see Figure 3. This element is a four noded and three sided isoparametric solid tetrahedron element, see Figure 4. The FE model consisted of 530,042 nodes and 232,264 elements. All the nodes at the base were fixed against displacements in all directions.

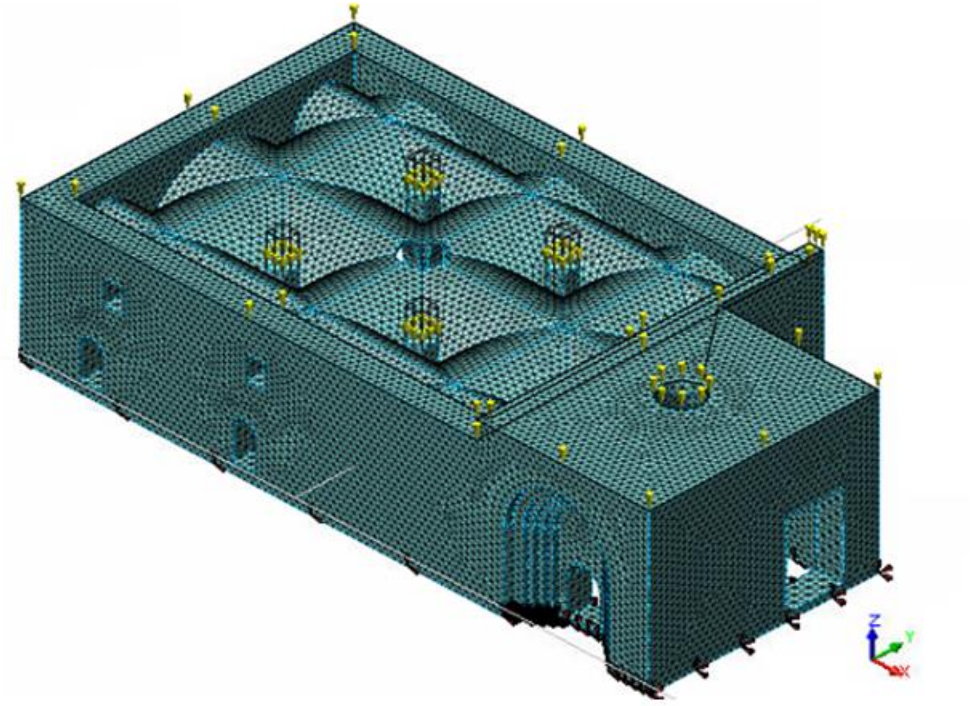


Figure 3: FE model of Elti Hatun Mosque

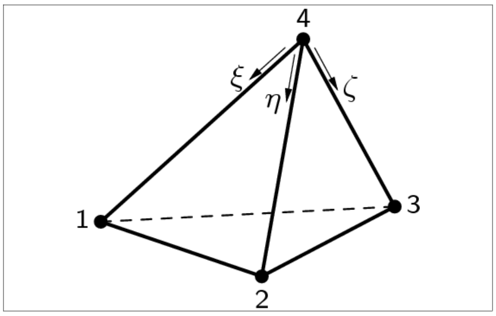


Figure 4: TE12L isoparametric tetrahedron element

The model was developed following a macro modelling strategy assuming the masonry as a continuum material. After developing the finite element model, the structure's self-weight and dead loads from the upper roof were applied as materials density and structural load, respectively. The dead load of roof includes the external contemporary roof composed of galvanized thin steel. This roof was placed after restoration of the mosque to protect the mosque's historical texture against severe climatic condition especially snow load. This galvanized thin steel is supported by wooden elements. The total load of this supplementary part was distributed over the vault and arch system as a dead load.

4.2 Material Properties

Only one material type was used for this mosque, see Table 1. The total strain rotating crack model was used for simulating the nonlinear behavior of masonry. This mosque is composed of dense basalt stones. That is why density of masonry element is kept high. Restoration of the mosque was completed by the end of July 2014. A 0.15 MPa tensile strength was adopted for masonry. The adopted material properties are given in Table 1. The compressive strength of masonry is adopted 3.0 according to sensitivity analysis of Lança et al. (2015)

Table 1. Linear and nonlinear properties of the FE model.

Young's Modulus (MPa)	Density (kg/m^3)	Poisson's Ratio	Compressive Strength (f_c, MPa)	Mode-I Fracture Energy (G_{FI}, N/mm)	Mode-II Fracture Energy (G_{FII}, N/mm)	Tensile Strength (f_t, MPa)
1500	2200	0.2	3.0	16.26	0.029	0.15

5. Analysis and discussion of Results

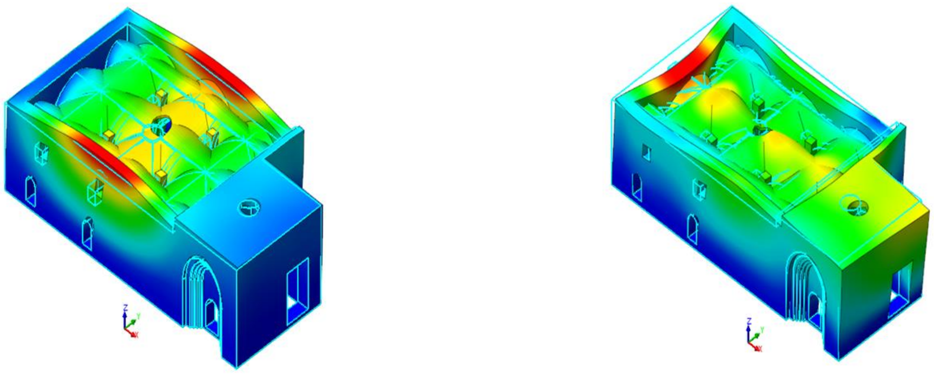
A linear elastic and Eigen value analysis were initially performed on the developed model if the structure. The nonlinear analysis was then performed in two stages by performing a pushover analysis based on uniform distribution of the mass. In the first stage, the nonlinear behavior of the structure under its self-weight is assessed. Then, pushover analyses along the structure's principal directions are performed assuming both material and geometrical nonlinearities.

5.1 Eigen Value Analysis

Eigen value analysis was performed on the model to see the mode shapes and mode frequencies. The total weight of the structure was obtained as 19979.6 kN. The first five mode frequencies and periods are given in Table 2. 75 % participation is reached end of 30th mode. First and fourth modes can be seen in Figure 5.

Table 2. Mode shapes and frequencies of the FE model.

Mode Number	Mode Frequencies (Hz)	Period (s)
1	6.76	0.148
2	8.78	0.114
3	9.11	0.110
4	10.0	0.099
5	11.3	0.088



a)First mode of model b)Fourth mode of model

Figure 5. First and fourth mode of numeric model

5.2 Nonlinear Static Analysis

Nonlinear analysis was performed on the model in two directions proportional to the total mass of the structure. Lateral push was applied in transversal (y-direction) and longitudinal (x-direction) directions. Three nodes were considered to plot the pushover curves, see Figure 6.

The obtained force-displacement curves of the structure are presented in Figure 7 and Figure 8 respectively. It can be observed that, in longitudinal (x-direction) direction, the displacements were nearly the same at the center of the vault and at the corner of structure. But, the roof displacement belong to top of the main entrance of the structure is more than that. The reason for this is vault and arch system that belong to the main pray room showed superior behavior due to the existence of four pillars and the thick wall system. The main gate of the mosque works as a support system for grand pray room of the mosque. This support mechanism shows resistivity against longitudinal lateral pushover loading. Vault and arch system showed weaker behavior during the pushover analysis due to the larger displacements than node 2 and node 3. For this reason, transversal displacement of the node 1 is nearly 2.5 times bigger than node 2 and node 3 as seen in Figure 8. Deformation of the model at peak displacement can be seen in Figure 9 for both directions. The structure shows a safety factor of 0.65 and 0.32 in longitudinal and transversal directions, respectively.

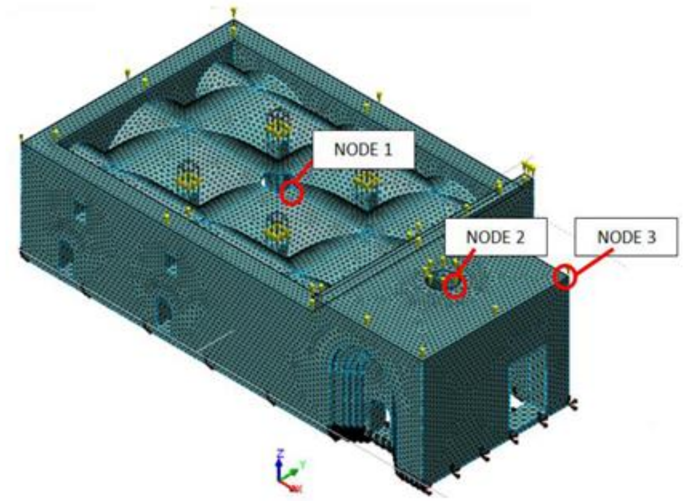


Figure 6. Considered nodes for pushover analysis

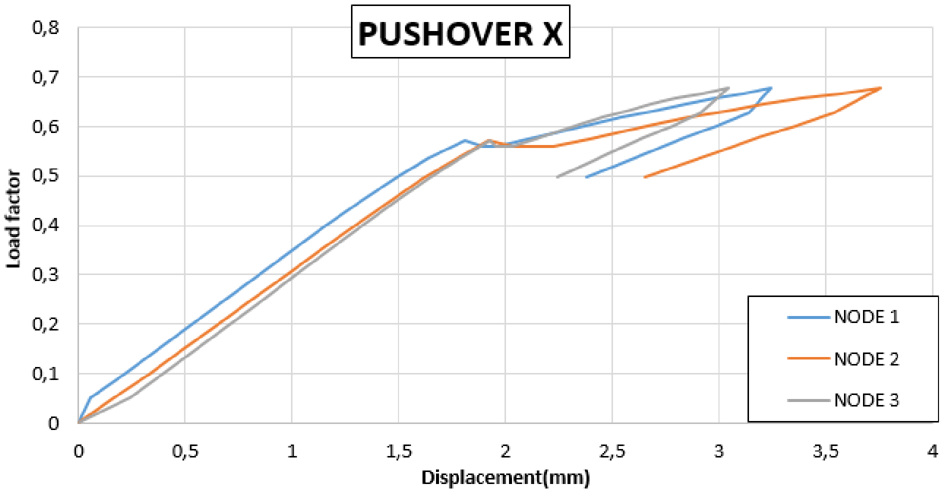


Figure 7. Force – Displacement curve in longitudinal direction

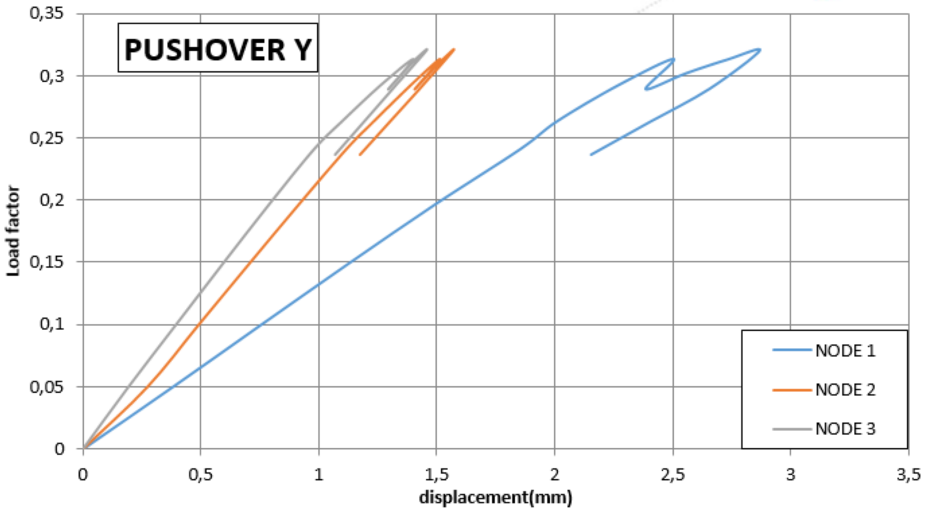
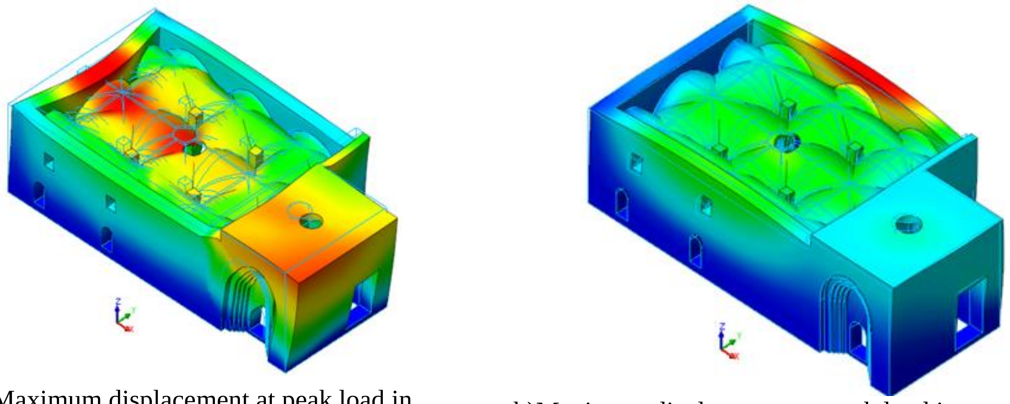


Figure 8. Force – Displacement curve in transversal direction



a)Maximum displacement at peak load in longitudinal direction

b)Maximum displacement at peak load in transversal direction

Figure 9. Deformed shape of the model for both directions.

The nonlinear analysis under the self-weight of the structure is performed to investigate its safety factor under vertical loads. The obtained pushover curves are presented in Figure 10.

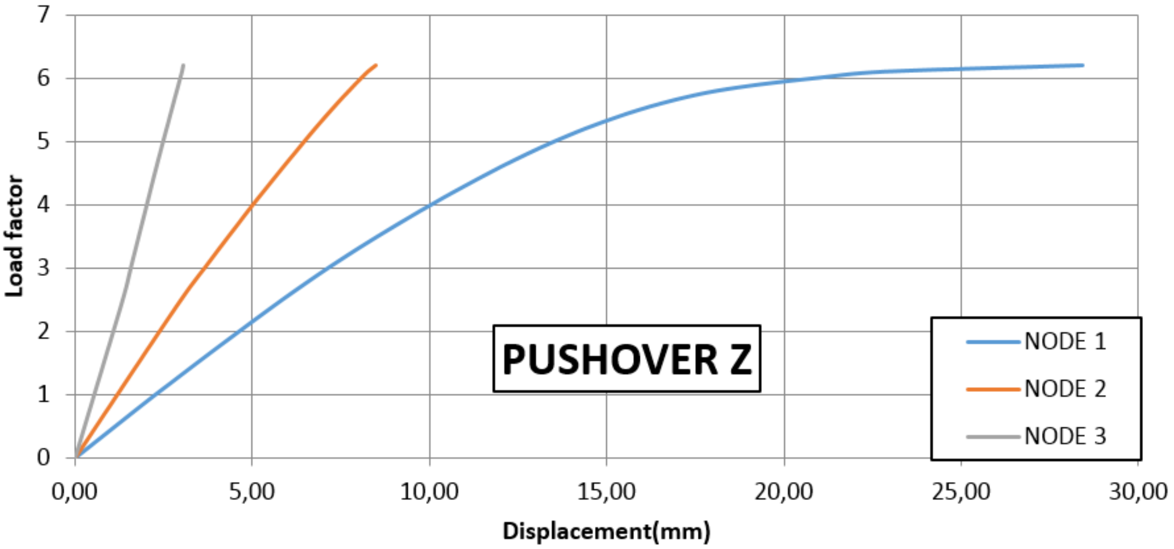


Figure 10. Force – Displacement curve in transversal direction

As seen from Figure 10, the failure under vertical loads occur at the central point of the arches (node 1). Except for node 1, the pushover curves remain elastic due to existence of perimeter thick rigid walls. The structure is sensitive to vertical loads at node 1 due to a missing column at the center of the main pray room. Stress distribution can be seen in Figure 11. The safety factor of the structure under its self-weight is around 6.0 which is a relatively high value and in acceptable range.

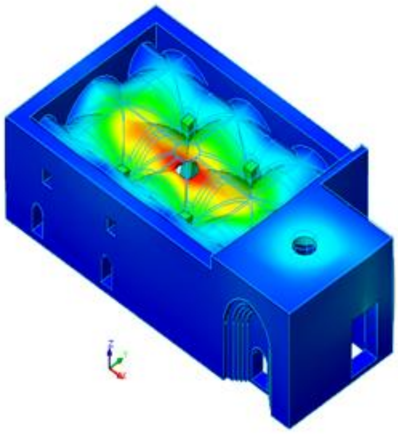


Figure 11. Stress distribution of model at peak vertical load step

6. Conclusions

The seismic performance of Elti Hatun Mosque was investigated in this study by performing nonlinear static analysis. A three-dimensional finite element model of the structure, with original dimensions measured on site, was generated with Diana FE software package (2015). Pushover analysis was performed for transversal, longitudinal and vertical directions to investigate the nonlinear behavior of the structure. Macro modeling strategy was adopted to model masonry elements. The results showed that the structure is two times weaker in the transversal direction than longitudinal direction, as expected. One of the most important reason for this is the main gate of the structure which works as a rigid support system in the longitudinal direction. Vertical pushover analysis was performed to investigate the safety factor of the mosque under its self-weight. The results showed acceptable performance of the structure in all directions. However, the presented results are only a prediction of the behavior due to several uncertainties about the material properties. This study should thus be extended with dynamic identification of the structure which is still in progress.

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