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Vulnerability analysis aimed at the safeguard of the Ererouyk basilica in Armenia

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Abstract

The basilica of Ererouyk have recently attracted the attention of the Armenian government, which has decided to promote its preservation by commissioning the National University of Architecture and Construction of Armenia to coordinate a group of Italian and Armenian experts. Built in the sixth century, the three-nave basilica of Ererouyk is unique in Armenia for its size, importance, and typology. For this reason, it has interested many scholars since the late 19th century. In this work, the path followed to know in an accurate way the structural response and to evaluate the vulnerability will be described. The first phase of the study consisted in an in-depth analysis of the damages and restoration interventions that the basilica has undergone during its history. Subsequently, the identification of the material properties both using results of tests performed on the basilica material and referring to literature data was performed. Then the seismic input was defined, following Armenian standards. Aware of the huge uncertainties inherent in the behavior of a sack masonry building that has undergone changes over the centuries, it was decided to perform the structural analysis using methods/models of increasing complexity, from linear kinematic approach to nonlinear time history analyses using three-dimensional finite element model with non-linear properties of the masonry. The systematization of all the information collected has allowed giving a complete and exhaustive picture of the vulnerability of the structure, highlighting the necessity to intervene for the improvement of its structural behavior towards seismic action.

Keywords: cultural heritage; non linear time history analyses; seismic assessment of ancient structures; masonry structures

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1. Introduction

The object of this work is the study of the seismic vulnerability of a historic masonry building belonging to the Armenian cultural heritage: the basilica of Ererouyk. It is one of the oldest and rarest examples of the paleochristian Armenian architectural heritage. The site is located near Anipemza, a small village in the province of Shirak, 50 km from the capital Yerevan. The area is located on a plateau, bordered to the west by the Akhurian River, which creates a natural and political barrier with the Turkish state and it is characterized by a quite high seismic activity.

The stimulus for this work was the resolution signed in 2020 by the prime Minister of the Armenian Government, which decided to support the design of a preservation project for the basilica. The National University of Architecture and Construction of Armenia, contracted to coordinate all the needed activities, involved Politecnico di Milano, in particular for the seismic assessment of the basilica. Due to the lack of an Armenian Code on the seismic assessment of existing buildings, the Italian Guidelines (2006) were adopted. In the following, the methodology used and the results obtained are described.

2. Methodology

According to the Italian Guidelines (2006), the first part of the study consisted in a deep work of knowledge of the basilica and the following selection of the analysis methods to be used for an accurate seismic assessment.

2.1. The basilica of Ererouyk: past and current state

The basilica, although today it appears partially ruined, is imposing for its dimension (rectangular shape of 30x40 m), unusual in the Armenian panorama and extraordinary for its unique typology that makes of it one of the most important monuments of early Christian Armenia (Fig. 1a).

It is possible to date the first construction of the basilica to sixth century, even if it is known that successive interventions took place at least until the tenth century. It has a plan elongated from the west to the east , with a central and two lateral smaller naves, separated by two rows of cruciform pillars, now disappeared (Fig. 1b). It was covered by a wooden roof with ceramic tiles and did not have a dome. Along its north, west and south facades it had galleries opened onto the outside by a colonnaded arcade which have disappeared long time ago, due to their scarce connection to the main structure. The apse is inscribed in the Eastern facade and flanked by two double storied vaulted sacristies. Most peculiar is that the north-eastern room has a higher inclined vault, which exceeds the height of the exterior walls and gives some insight to the roofing system of the building. Of the two towers that flanked the western façade only the northern is preserved.

The basilica was built directly on the bedrock; the six steps stylobate has only an aesthetic function. The material employed in the construction of the basilica is the yellowish tuff, a local stone that characterized most of the Armenian buildings. The used construction technique is typical of Armenian historical architecture and it is called *midis*, it derives from the Roman opus caementicium and it is similar to Italian three-layer masonry known as *sacco italiano*: it involves the construction - often dry - of two external faces of large rectangular stones, which are worked on the exposed face and roughly cut towards the internal one in order to facilitate gripping with the mortar. The inner part between the two vestments is filled with mortar and various aggregates. In the basilica the midis thickness is almost constant around 110-120 cm, with the external blocks varying in size around 30 cm. In addition, the external stone blocks have engravings which embellish the façade and give testimony of various historical events.

We don't have any testimonies of what happened to the basilica since then up to the 19th centuries when it was "discovered" by the scholars. In the first pictures of Ererouyk, the situation was not so different from today: the basilica didn't have the roof and the south western tower was gradually collapsing until its complete disappearance. Apart from that, in the last hundred years, before the earthquake that struck Armenia in 1988, only little damage has been recorded, concerning mainly the collapse of some blocks. The earthquake had a strong impact on the north western tower pushing its walls dangerously out of plomb, and on the south eastern sacristy, where big cracks were opened. The collapse of few stones was registered in the top of the basin of the apse and again on the top of the longitudinal walls, mainly on the northern façade where nearly one row of ashlars was lost.

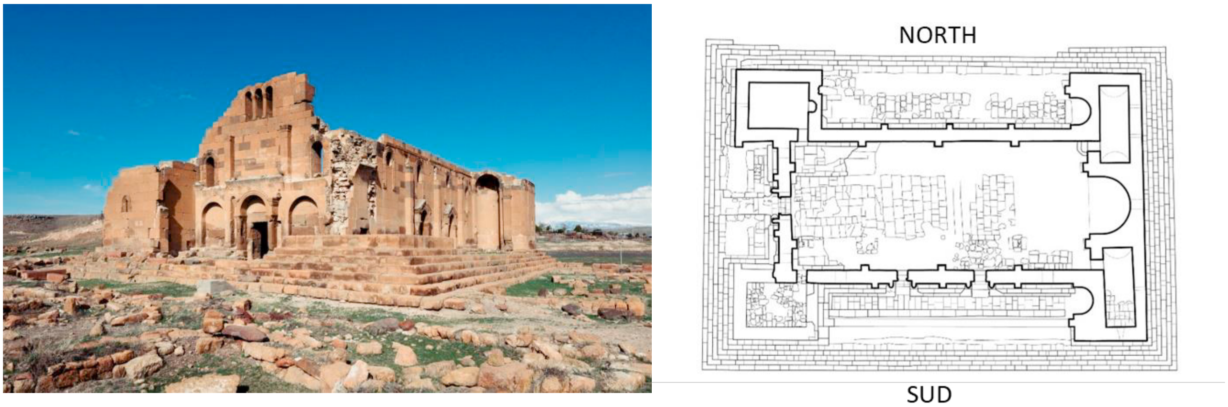

Fig. 1. The basilica of Ererouyk today.

Since 1928, a number of restoration projects was developed, even if only a part of them implemented. Moreover, several campaigns of survey have been implemented during the last 15 years, using total stations, photogrammetry, laser scanner and images taken by a drone. All the documentation concerning studies, surveys and interventions realized during the time has been collected from the available sources (Alberga and Demetri 2018, Donabédian et al. 2014, Montevecchi et al. 2012, Getty-Grant-Program 1988), confronted and visualized through an accurate 3D model that put together the actual crack pattern, the collapses underwent in the past and the interventions realized (Fig. 2). This has been used as a reference for this work.

Today, the main general problems are: i) the widespread rising damp in the masonry walls, that affects 1-1.5 meters of the masonry from the basement as well as from the top; ii) the presence of cracks suggesting the risk of overturning mechanisms under horizontal forces; iii) diffuse surface cracks not related to macroscopic movements. Moreover, there are specific elements that in case of earthquake could fail: i) the pilasters that adorn the various prospects as well as the entire sculptural-decorative apparatus of the west façade, being barely leaning against the façades; ii) the tympanum of the west façade, arising from the top line of the monument and being weakened by the presence of a three-light window; iii) the masonry corner toothing of the west and south façade, partially destroyed during the collapse of the of the south tower.

2.2. Material properties

The characterization of the material mechanical behavior is a fundamental step in the seismic assessment of a structure. Unfortunately, in the case of the basilica, available experimental results were limited to simple compression tests on tuff and mortar samples (Hatsagortsyan 1959, Zadoyan 2006). They allowed to define a low, mean and high compression strength of tuff ($f_{c,tuff}$= 9.1 -11.6 - 14.1 MPa) and mortar ($f_{c,mor}$= 1.3 -1.8 - 2.3 MPa), but no data were available on the *midis* mechanical behaviour. Consequently, it was decided to enrich this information with literature results, combining the data collected on *midis* by Shaginyan et al. (1950) with an extensive experimental work conducted by Italian authors (Calderoli et al. 2009, Bernardini et al. 1984) to characterize the mechanical behavior of Italian tuff and three-layer tuff stone masonry, widely used in the historic buildings in southern Italy. Starting from $f_{c,tuff}$ and $f_{c,mor}$, the compression strength of the *midis* ($f_{c,mid} = f_{c,tuff}^{0.75} f_{c,mor}^{0.25}$) was defined using the equation proposed in Faella et al. (1993), and from this the Young's modulus (E_{mid}=600 $f_{c,mid}$) according to Guadagnolo et al. (2020). Finally, taking into account the variability of tuff and mortar compression strength, three classes of midis were adopted, with low, mean and high Young's modulus and compression strength ($f_{c,mid}$ =1.7 - 2.2- 2.7 MPa, E = 1020 - 1320 - 1620 MPa).). For each of them, two values of tensile strength ($f_{t,mid}$) were assumed, equal to the 10% and 20% of $f_{c,mid}$. The definition of these parameters allowed to set-up a finite element model able to describe not only the material elastic behaviour, but also the non-linear response, once the peak of resistance is exceeded. In particular, the concrete damage model (Lee and Fenves, 1998) available in the finite element commercial code Midas Gen (v. 2021, MIDAS Information Technology Co., Ltd.) was used: it allows to control the compression and tensile behaviour by directly assigning the stress-strain curves, reproducing the asymmetric fragile behaviour typical of the masonry and the loss of stiffness in the event of a cyclic load.

Fig. 2. 3D model of the basilica with indication of the degraded parts and the restored.

2.3. Seismic action

The seismic action for the vulnerability assessment of the basilica of Ererouyk was defined according to the Armenian seismic code (2020): the horizontal and vertical elastic spectra with 10% probability of exceedance in 50 years for the Ererouyk site are reported in Fig. 3 (left)

Aiming to study the non-linear behavior of the structure under seismic action, ground acceleration time-histories, considering three accelerograms simultaneously acting in two orthogonal horizontal and in vertical directions, were also used to describe the seismic motion. In particular, three sets of earthquake ground motions selected and spectrally matched using the program “Select and Match”, developed by Roberto Paolucci, Arsalan Bazrafshan, Ali Guney Ozcebe, Chiara Smerzini and Andrea Barri (Politecnico di Milano) were adopted (Fig. 3 right).

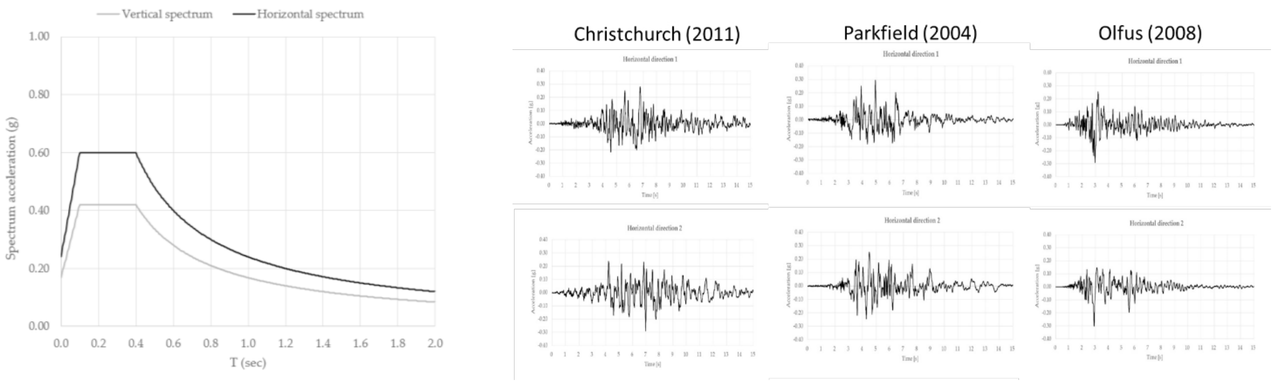

Fig. 3. Horizontal and vertical elastic spectra of Ererouyk site (left); horizontal components of spectrum-compatible earthquake ground motions for non-linear time history analyses (right).

2.4. Analyses

Aware of the huge uncertainties inherent in the behaviour of a sack masonry building that has undergone changes over the centuries, it was decided to perform the structural analysis using methods/models of increasing complexity described here in order:

1) linear kinematic approach, based on the identification of macro-elements (rigid body) and related collapse mechanisms

2) three-dimensional finite element (3D FE) model with elastic-linear properties of the masonry for the study of dynamic properties of the structure (modal analysis)

3) three-dimensional finite element model with nonlinear properties of the masonry (Section 2.2), for the study of seismic response over time (nonlinear time-history analyses).

For limiting the computational effort, the 3D FE model geometry was simplified, including only the vertical surfaces, while vaults and domes were replaced with loads representing the corresponding weights; moreover, small openings were disregarded and a general regularization of surfaces were performed. The model is composed by 1630 plate elements.

3. Results

In the following, some of results obtained applying different methods for structural analysis are summarized. In particular, attention is focused on recognizing local and global mechanisms that can be activated under seismic action. Moreover, notwithstanding all the analyses were performed considering different material models (low, medium and high resistance, Section 2.2), only the results obtained with mean values (E = 1320 MPa, $f_{c,mid}$= 2.2 MPA, $f_{t,mid}$ = 0.22 MPa) are shown here.

3.1. Analysis with linear kinematic approach

Following the linear kinematic approach (Italian Guidelines. 2006), sixteen potential mechanisms were considered (Fig. 4), according to the local weakness identified evaluating the state of preservation of the basilica. Once calculated the collapse acceleration that activates the mechanisms (a^*_0), the comparison with the acceleration expected at the site for a return period of 475 years (a), highlighted that only two of them (CM_WO-1 and CM_WO-2) were safe (a^*_0/a >1). Among the others, the most dangerous ones (a^*_0/a < 0.4) were those activating the overturning mechanism of the façade (SM_WO-3), of the decorative parts (SM_WO-4 and SM_WO-6), and of the north pastophorion barrel vault wall (SM_WO-5).

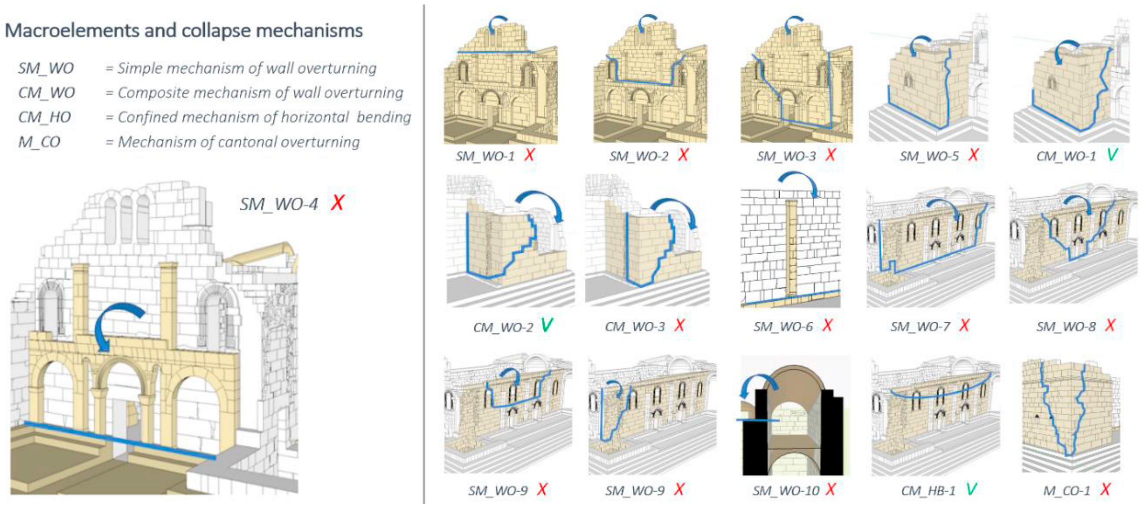

Fig. 4. Collapse mechanisms evaluated using the linear kinematic analysis. Red X means that the mechanism is not verified, green V means it is verified.

3.2. Modal and non linear dynamic analyses

The modal analysis results indicate that more than 80% of participating mass in x direction and y direction refers to vibration modes having periods between 0.06 s and 0.33 s: it means that the structure is prone to the maximum spectral amplification in its horizontal direction. The behaviour in z direction is different: the most of the mass has a period of vibration around 0.04 s, well below the plateau of the spectrum. The shapes of the vibration modes show that the dynamic behaviour of the structure is strongly influenced by the out-of-plane motions of the walls along the north and south sides, as well as those of the upper part of the facade and the northern sacristy (Fig. 5).

Moving to nonlinear time-history analyses, the results in terms of displacement clearly show that five different mechanisms of movement are activated (Fig. 6): the out-of-plane oscillation of the tympanum of the main façade (mechanism A), the out-of-plane oscillation of the long façades (mechanism B), the overturning of the corner between the west and south fronts, helped by the fact that there is no beneficial effect of the tower as it happens in the opposite site corner (mechanism C); the strong thrust of the long south and north façade exerting on the perpendicular pastophorion façade (mechanism D); the overturning of the cantonals of the pastophoria (mechanism E).

The largest displacements are reached for mechanisms A, B and C with values of about 60 mm, 30 mm and 50 mm, respectively, for a maximum drift of 0.5%. Clearly, these values are even worst in case low values of material properties are considered (Section 2.2), showing a global vulnerability of the structure. This is also confirmed when stresses are checked. Indeed, while the compression strength is never reached (stresses always remain under the limit value of 2.2 MPa, assuming a maximum value of 1.86), tensile stresses, instead, reach their limit value in several parts of the masonry, according to the activation of the mechanisms cited above. This is shown in Fig. 7, where the displacements in horizontal directions and the compressive and tensile stresses in vertical direction, reached under the action of Parkfield earthquake, are reported.

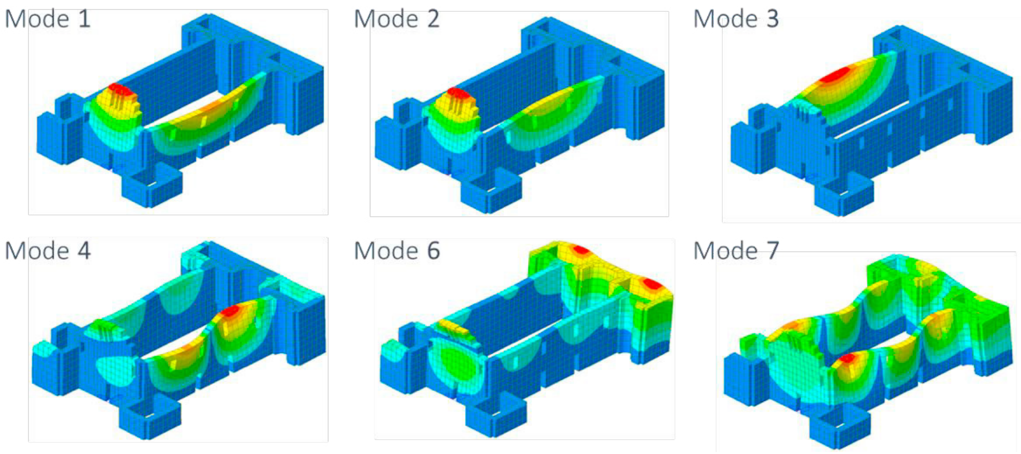

Fig. 5. First vibration modes of the basilica.

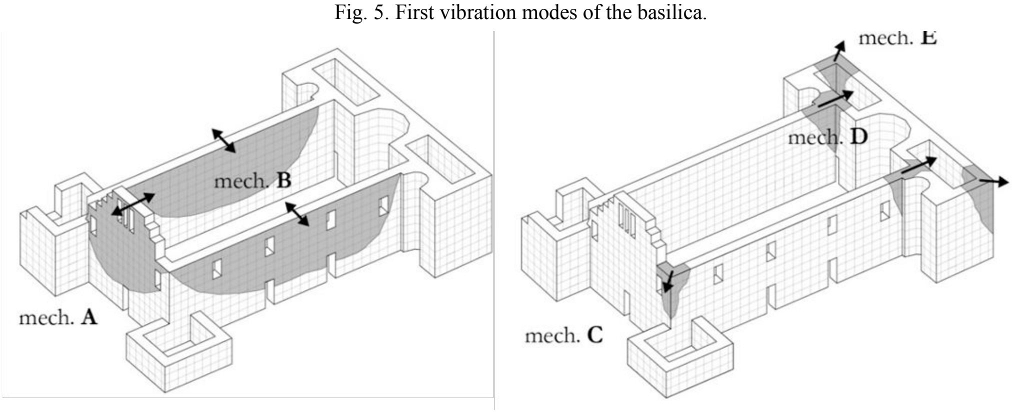

Fig. 6. Mechanisms activated by seismic action during nonlinear time-history analyses.

4. Conclusions

The proposed path of knowledge and analysis has allowed to reach a deep awareness of the vulnerability of the basilica of Ererouyk, considering both local mechanisms and global response. This study provides the basis for the design of a conservative intervention capable of preserving the basilica in all its authenticity, limiting re-integartion and replacements. In fact, the results of the linear kinematic analyses allow defining the specific points where to apply local interventions, such as chains or steel bars; on the other hand, the nonlinear time-history analyses also suggest proceeding with an overall improvement of the masonry strength, which could be achieved through mortar injections. A critical point seems to be the corner between the west and south facades, where the absence of the south tower allows high movements. In this case, it seems that the introduction of new elements, such as buttresses, may be the most effective way to limit such movements, but its impact on the figure of the basilica must be carefully evaluated.

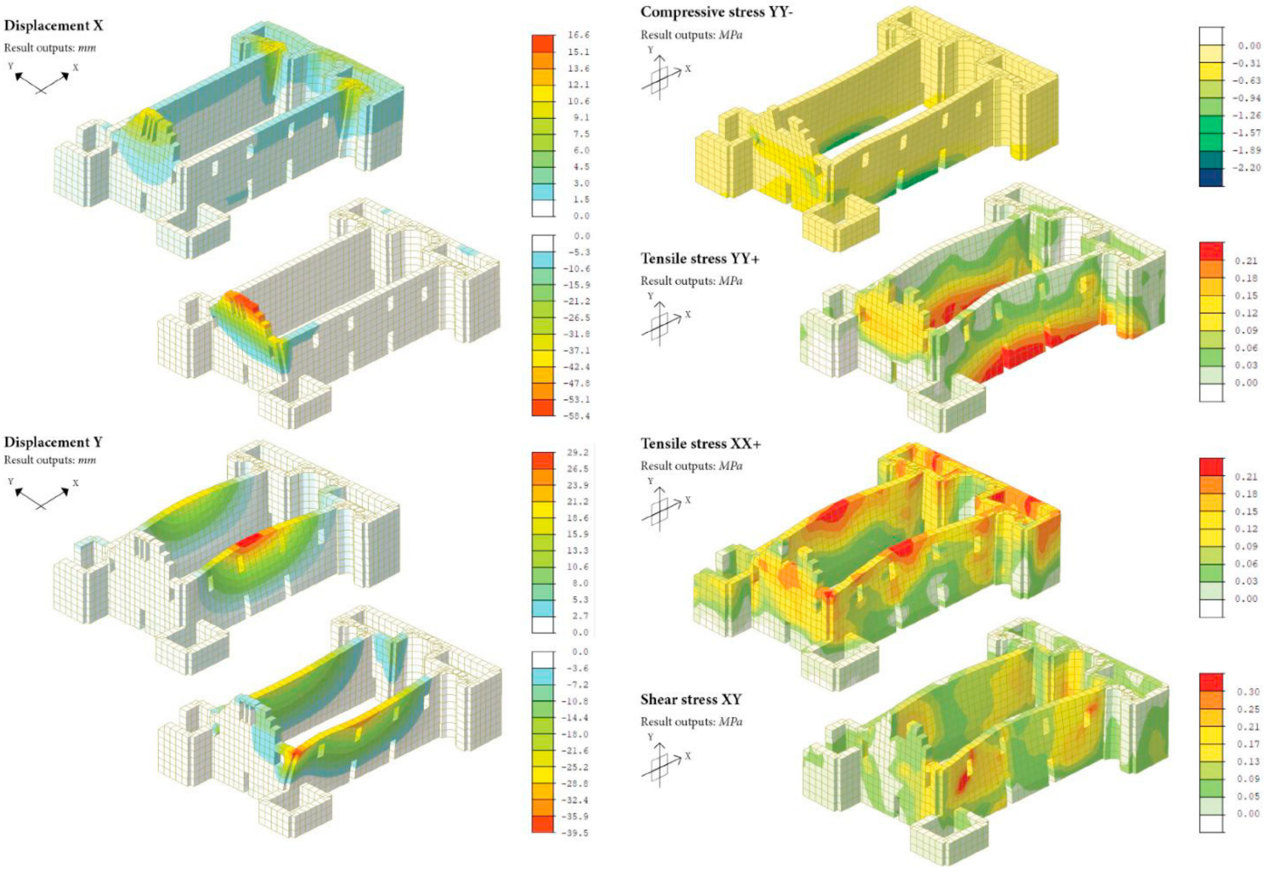

Fig. 7. Parkfield earthquake: maximum displacements reached in direction X at the top and direction Y at the bottom (left); maximum compressive at the top, tensile in the middle and shear stress at the bottom (right).

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