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# SEISMIC PERFORMANCE EVALUATION OF HISTORICAL CASE STUDY OF ARMENIAN ARCHITECTURE TEKOR CHURCH

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A b s t r a c t

Masonry churches, which are one of the cultural heritages, show the historical background, cultural and religious characteristics of the cities and material properties. Churches in the earthquake zone, which are different from each other in terms of typology and have a special importance, are at risk. The aim of this study is to examine the earthquake behavior of a church sample in Turkey and to provide a guide for structures with similar typology. The building was modeled and subjected to dynamic loads using macro modeling technique. Free vibration mode shapes were determined by modal analysis, and it was determined that these modes were mainly in the form of translation of the upper part of the structure. In the time history analysis, the stress and deformation values were determined. It has been observed that the stresses take high values at the supports and top of the main columns and in the arches connecting these columns to the side walls. It was concluded that the deformations reached their maximum values at the apex of the triangular gable walls in the upper part of the building. The results obtained are consistent with the damage the church received in past earthquakes.

Keywords: cultural heritage, damage, FEM models, historical construction, masonry church, seismic vulnerability

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## 1. INTRODUCTION

Generally, strong earthquakes cause significant damage and destruction. Especially ancient masonry structures, which are one of the cultural heritage, are vulnerable to earthquakes effects (Cescatti et al., 2020; Penna et al., 2019; Valente, Barbieri, & Biolzi, 2017). Cultural heritages of Mediterranean countries, such as Turkey, located in the earthquake zone are at risk. Due to reasons such as aging processes, vandalism and environmental factors, this risk increases in masonry buildings with historical importance.

Studies show that masonry walls, connections between walls, number and position of columns, problems in vertical and horizontal connections in plan typology reduce the strength during earthquakes (Alessandra Marotta, Sorrentino, Liberatore, & Ingham, 2017; Sorrentino et al., 2017). The fact that monumental masonry structures are generally built by considering only static loads and ignoring earthquake loads causes damage to cultural heritage by earthquakes (Orlando, Betti, & Spinelli, 2020); (Betti, Galano, & Lourenço, 2021). For this reason, seismic analysis of structures will be an example for other typologies. Due to structural systems, it is necessary to examine the resistance of ancient churches under earthquake load. Masonry churches, one of the heritage buildings, are in complex structures and these structures have a high vulnerability. Detection of the damage, the effect of the earthquake on the structure and cracks by analysis not only protects people, but also conserve historical structures. In this context, this paper focuses on masonry churches to determine and analyze the risks of heritage typologies.

So far, many studies have been carried out to assess the damage and vulnerability of historic masonry churches subjected to earthquake loads and definition of the future seismic loads and design of proper retrofitting solution (Casapulla, Celano, Rainieri, Fabbrocino, & Ceroni, 2021; Casapulla et al., 2019; Cattari, Lagomarsino, Bosiljkov, & D'Ayala, 2015; Criber, Brando, & De Matteis, 2015; Lang & Bachmann, 2003; Parisi, Shesi, & Papa, 2018; Penna et al., 2019; N. Ruggieri, 2021; Salzano, Casapulla, Ceroni, & Prota, 2020; Sánchez-Aparicio et al., 2021; Sánchez-Aparicio, Riveiro, González-Aguilera, & Ramos, 2014; Tiberti & Milani, 2017).

Studies aim to determine the statistical correlations or to determine the collapse mechanisms of historical churches in different or in the same region according to their typologies (Clementi, Ferrante, Giordano, Dubois, & Lenci, 2020; Fabbrocino, Vaiano, Formisano, & D'Amato, 2019; A. Marotta, Sorrentino, Liberatore, & Ingham, 2016; Porto, Silva, Costa, & Modena, 2012; Rodriguez, Vasconcelos, & Lourenço, 2021). There are parametric studies in which both seismic analysis is performed and damages are determined and macro seismic intensity is performed (S. Ruggieri, Tosto, Rosati, Uva, & Ferro, 2020);(Betti et al., 2021; Morici, Canuti, Dall'Asta, & Leoni, 2020).

In a study, masonry churches with three naves were classified according to typological, structural and architectural features and the damages caused by the earthquake were analyzed visually (Matteis, Criber, & Brando, 2016). In a study, overturning of façade of single-nave churches was examined in under seismic loading (Felice, Fugger, & Gobbin, 2021). According to a research (Milani & Valente, 2015), seven masonry churches severely damaged in an earthquake sequence were analyzed by means of non-linear dynamic simulations. It shows the results of collapse acceleration and behavior factor in the study. Zizi, Corlito, Lourenço, and De Matteis (2021) have evaluated the Damage Limit State for Artistic Asset on a regional scale, which is affected by seismic hazards, emphasizing the importance of medieval masonry churches. Seismic vulnerability assessment historic churches in a paper characterized by a specific building typology (Fazzi, Galassi, Misseri, & Rovero, 2021). It has been adopted in approaches based on decomposition of churches into macroelements (Lagomarsino, Cattari, Ottonelli, & Giovinazzi, 2019). Sferrazza Papa, Tateo, Parisi, and Casolo (2020) investigated the seismic response of the reinforced concrete and wooden roof of a church. There is a study examining the effect of churches from landslides (Ferrero, Cambiaggi, Vecchiattini, & Calderini, 2020). All these studies emphasize the cultural heritage preservation of ancient masonry churches and the necessity of seismic damage assessments.

Roca, Cervera, Pelà, Clemente, and Chiumenti (2013), Mallorca Cathedral, an FE code was developed specifically for a large historical building to investigate mechanical damage and long-term deformation. It was analyzed under earthquake load and cracks were detected in the tensile damage and realistic collapse was determined. Argiento, Celano, Ceroni, and Casapulla (2020) made parametric nonlinear static analysis of a sample masonry church. As a result of the analyzes carried out with the approach of finite elements and discrete macro element models, simple iron-framed masonry panels suggestion was made. Matteis, Corlito, Guadagnuolo, and Tafuro (2020) analyzed churches' seismicity to validate the possibility of churches to propose appropriate response strategies to reduce structural reinforcement and seismic risk. Several publications have compared seismic analysis methods such as linear and FEM pushover analysis and FEM nonlinear dynamic analysis. (Endo, Pelà, Roca, da Porto, & Modena, 2015; Monaco, Bergamasco, & Betti, 2018).

Betti et al. (2021) emphasizes that the regional studies are not sufficient and that if there is a monumental structure, non-linear analysis should be made of a single structure. In this context, Betti et al. (2021) based on the statement that a monumental building should be studied single, this study focuses on a monumental building. It is aimed to evaluate a church in Kars in Eastern

Anatolia, which reflects the architectural identity of the city with its typological and structural features. Within the scope of the study, seismic performance evaluation was made on the sample church. This work is important in that it focuses on a special and unique church. In addition, this study exemplifies the earthquake resistance of three-nave church typologies.

## 2. DESCRIPTION OF THE CHURCH

### 2.1. Architectural properties

The remains of the fifth century church (Toramanyan, 1911) are located on the hillside in the district of Tekor. According to the information obtained from the official website of the Governor's Office, it is written in the inscription found at the northern entrance of the building that "this martyrdom of Saint Sargis" is mentioned. The mention of these people shows that the construction of the church was in the 480s. This script is the oldest known Armenian and is written from the bottom up. The building was restored by the Bagratids (URL-1).

In Armenian architecture, it is accepted as the first domed structure of the Tekor Surp Sergius Church together with the Etchmiadzin Cathedral (Donabédian, 2007). As in the domed basilica type plan typologies, the middle part of the church is covered with a dome on the inside and a cone on the outside. The church consists of two side naves separated by two columns on the right and left of a main nave (Figure 1a).

There are four independent columns on which the load of the dome is transferred, arches with the width of columns extend to the entrance wall in the west and the apse wall in the east. These columns are connected to the north and south walls with thinner section arches on the horizontal axis. These columns and arches separate the main nave and the side naves. The side naves are covered with vaults extending in the east-west direction. The middle sections of the side naves are covered with barrel vaults in the longitudinal direction up to the bottom of the dome. There are two long rooms on both sides of the apse on the east side of the church. Next to the northern room, there is a semi-circular baptismal font carved into the outer wall (Figure 1b).

There are two doors on the north façade of the church, and one on each on the west and south façades. It is emphasized by a pediment with horseshoe arches on two built-in columns next to the columned doors. The lintel passing over the arches surrounding the doors forms a horizontal dividing facade element. Four columns on both sides of the doors on the north façade and six columns on the west and south façades extend to the horizontal lintel. There are two embrasure windows on the facades of the church (Figure 1c-d).

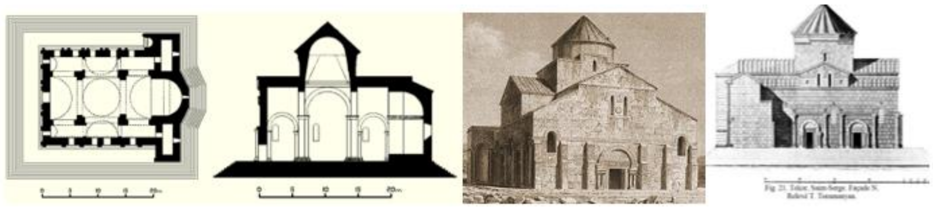


Fig. 1.Tekor Church: a)Plan b)Section c)View in the 1840s d)View of Church (Toramanyan, 1911)

Kazaryan (2011) states that in the early Christian churches, as in the Tekor church, the dividers of the walls with vertical and horizontal elements are a typical example in the Ancient order, and the various patterns of Armenian masters were developed in the West and East and their examples were multiplied(Kazaryan, 2011). Romanazzi (2009) stated that the geometric connection between the columns and the dome is the only example that remains of its primitive form and said that Tekor Church is unique in terms of plan typology among the longitudinal churches. In the gavit covering system that emerged between the 11th and 13th centuries, the drum doesn't exist, the cornice has very often a square plan and the transition between the square and the octagon is above it. If compared both with these gavits and with Seljuk examples, the strange aspect of the solution at Tekor is the greater height of the inclined surfaces.

## 2.2. Damage and Deformation

Damaged after the 1912 earthquake (Figure 2a-b), the church was almost completely destroyed in the 20th century (Romanazzi, 2009). As can be seen in the figure 2b, the damage of the earthquake in 1912, the roof and the south facade of the church, whose dome collapsed due to the earthquake, were destroyed.

Another earthquake in 1936 caused an unknown damage to the building. In addition, the fact that the building materials were removed reveals that it was the result of vandalism as well as the earthquake (URL-1). The church in the 1980s is included in the figure 2c. The current state of the church and the remains can be seen in the figure 2d.

Fig. 2. Damage and deformation: a)Before earthquake in 1912 b)after earthquake in 1912 c)1980s (URL-2, 2000) d) Remains (URL-2, 2000)

## 3. MATERIAL AND METHOD

To analyze large-scale historical buildings in computer environment via a software using the FEM, the 3D model is created in the simplest form. Since the structure is very large in general, the modeling method chosen in the analysis of such historical buildings is the macro modeling method. The analyzes executed with this modeling technique, in which the main masonry unit forming the structure is handled with mortar, gives sufficiently detailed results about the behavior of the structure and the structural stresses under static and dynamic loads (Şeker & Büyükgüner, 2021). In this study, analyses have been executed using (ANSYS, 2019) program, which also uses the finite element method.

The Finite Element Analysis (FEA) is the simulation of any given physical phenomenon using a numerical technique called Finite Element Method (FEM). Civil Engineers use this method to simulate structure’s real behavior faster while saving on expenses. For a computer to simulate, numerical techniques have been developed over the last few decades and one of these is the Finite Element Analysis. After this, relevant quantities of a structure (like stresses, strains, etc.) are computed to estimate the structural behavior under the given load. this technique is used as the basis for modern simulation software’s and helps engineers to find weak spots, areas of tension, etc. in the designs. The results of a simulation-based on the FEA method are usually depicted via a color scale that shows the distribution over the structure. In these analyses, 3D finite element model of the structure is used. Relevant material properties and boundary conditions are assigned to the parts of the structure. Under these conditions, the analyses are executed, and results are obtained (URL-3, 2021).

To perform the analyses of the church using ANSYS, the three-dimensional model was created according to the drawings of the church. The church was assumed to be constrained fixed at the base, and stone masonry material property was assigned to the model. FEM consists of 114575 node points and 27936 solid elements in the ANSYS. The Solid 186 element used for analysis has 20 node points and each node has 3 (in each direction) translational freedom (ANSYS, 2019). The 3D model of the building is presented in Figure 3b. At first, modal analyses were performed to get the main modes of the church using linear elastic material properties. These mod shapes give an opinion for the deformation shapes of the church under lateral loads. After this analysis, nonlinear material model was used for time history analysis under a strong earthquake occurred at the region. The stress and deformation values obtained from the analyses are presented as a color scale in the model.

The physical and mechanical properties of masonry material was taken from literature (TYDRYK, 2017). According to this code, the elastic modulus of the masonry is 1500 MPa, the poisson rate is 0.18 and the specific bulk density is 1580. Tensile strength for stone masonry is 0.35 MPa and for compressive strength is 3.5 MPa, limited damage is 0.003, controlled damage is 0.007, and prevention of collapse is 0.01.

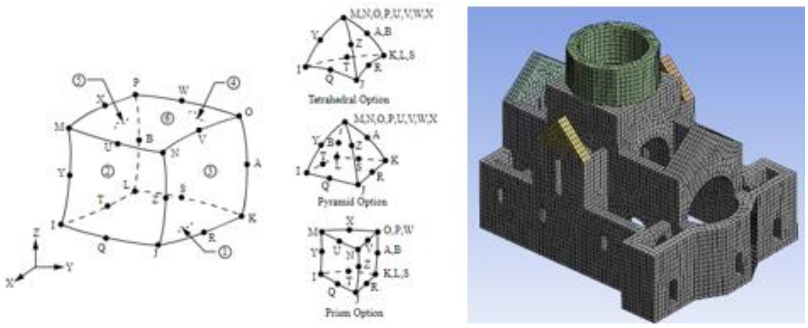
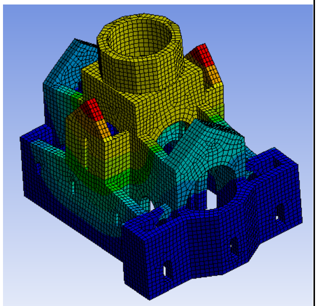
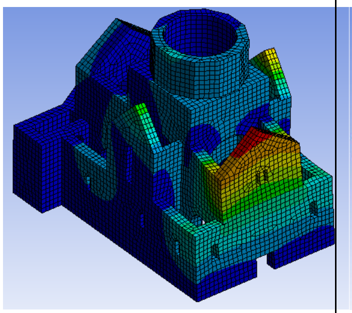
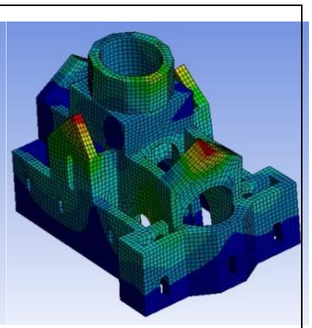
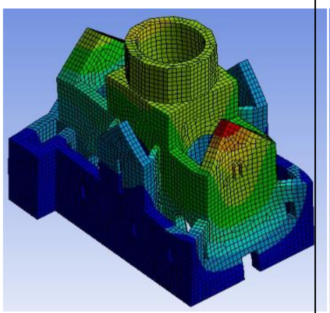
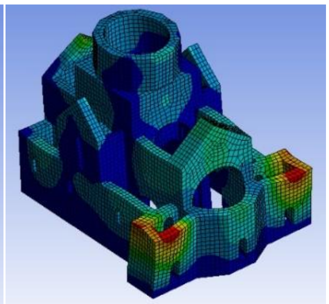
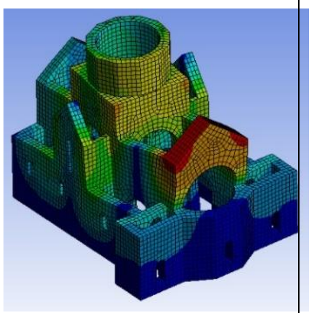


Fig. 3. a) Solid 186 (SOLID186) b) Finite element model of the church

## 4. MODAL ANALYSIS

First mode emerges as a translation in the transverse direction of the church, and the displacements take high values on the triangular gable walls on the upper elevations of the church and the arch system carrying the dome. Mode-2 is formed as a translation in the longitudinal direction and large displacement values occur on the triangular gable walls in this direction. Mode-4 appears to be the torsion mode of the structure. In this mode, the arch system carrying the main dome in the middle of the church and the pulley carrying the dome are subject to torsion. The Mode-12 includes the out-of-plane movements of the triangular gable walls on the north, south and west facades, and the Mode-19 also includes the out-of-plane movements of the inner walls along with the east-west translational movements of the triangular gable walls on the north, south and west facades. Mode-33 includes a local out-of-plane translation of the apse side walls (Table 1).

Table 1. Shapes, periods, and mass participation factors of effective modes of church

| | | |
|---|---|---|
|  |  |  |
| **Mod 1** | **Mod 12** | **Mod 19** |
| T=0.30sn | T= 0.10sn | T= 0.087sn |
| MPR in trans. direction:53% | MPR in trans. direction:8% | MPR in trans. direction:8 % |
| MPR in long. direction:0% | MPR in long. direction:0% | MPR in long. direction:0% |
|  |  |  |
| **Mod 2** | **Mod 33** | **Mod 4** |
| T= 0.30sn | T= 0.06sn | T= 0.14sn |
| MPR in trans. direction:0% | MPR in trans. direction:0% | MPR in trans. direction:4,3% |
| MPR in long direction:54,8% | MPR in long. direction:6,4% | MPR in trans. direction:0% |

## 5. SEISMIC ANALYSISES

The seismic analyzes within the scope of the study were carried out by using the acceleration records of an earthquake with a magnitude of Mw 6.6 on the Richter scale on 13 March 1992 at 19:18 local time in the southeast of Erzincan province in Turkey. In this earthquake, 653 people died, 6702 buildings were damaged or destroyed.

The earthquake did not cause a significant faulting on the surface due to the depth of the epicenter and very thick loose sedimentation in the basin. Fractures are usually discontinuous, several hundred meters long and developed as secondary settlement fractures caused by seismic shaking (Demirtaş, 2019).

### 5.1. NS Direction

The time history analysis was executed under the Erzincan earthquake's north-south direction acceleration record. It is seen that the equivalent (von mises) stresses have high values at the arch system connecting the main columns to the sidewalls, the support points of the arch system carrying the main dome, and the arch at the apse. The maximum value is 2.72 MPa, which is higher than the safety stress value Table 2a.

The distribution of displacements obtained in the same analysis is given in Table 2b. It is seen that the deformations that occur in the form of translation and get their maximum values at the top of the triangular gable walls of the north-south facade. High deformation values are also observed in the main dome and the arch system in the middle part that carries it. The maximum value is 77.83 mm.

The distribution of plastic strains obtained because of acceleration loading in the north-south direction is given in Table 2c. Plastic deformations take high values at the support points of the main columns and at the top of these columns. Plastic deformations do not occur in other regions.

### 5.2. EW Direction

The distribution of the equivalent stresses occurred under the east-west acceleration record of the Erzincan earthquake is given Table 2d. It is seen that the stresses take high values at the supports of main columns and at the arch support points of the arches connected to these columns. The maximum value is 2.40 MPa.

The distribution of the deformations occurred in the analysis in this direction is given in Table 2e. Deformations take high values at the upper points of the triangular gable walls. Again, it is seen that the deformations are intensified at the arch system and part carrying the main dome. The maximum value is 50 mm.

The distribution of equivalent plastic strains is shown in Table 2f. Plastic strains are concentrated on the walls of the apse part and at the support points of the main columns, but do not occur in other parts of the church.

In the strength evaluation, the maximum stresses formed should not exceed the allowable stress value of the deformation evaluation; the ratio of the maximum deformation to the maximum height of the structure should not exceed a certain value (TYDRYK, 2017). The Earthquake Risk Management Guide for Historic Buildings defines the limits for the maximum deformation ratio allowable for varying performance levels in the context of dynamic effects.

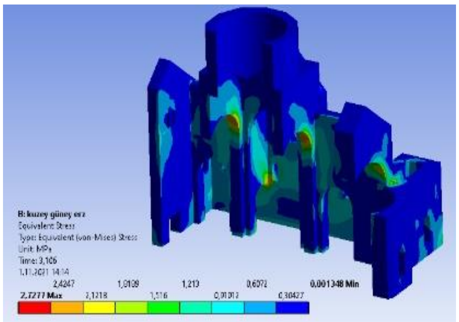
The performance levels given in TYDRYK are defined as follows:

1. Limited Damage: In this damage level, limited nonlinear behavior (damage) occurs in the load-carrying system elements of the building.
2. Controlled Damage: In this damage level, the damage only occurs in repairable load-carrying system elements of the building.
3. Prevention of Collapse: In this damage level, severe damage occurs in the load-carrying system elements of the building, and the building is about to collapse partially or completely, but the collapse is prevented.

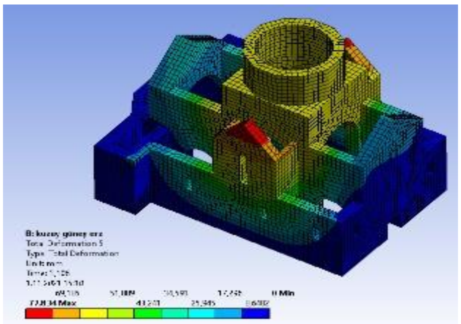
The deformation ratio in historical buildings is the ratio of the difference in horizontal deformations at different levels to the height difference. Because the foundation of the building is fixed at the ground, the deformations in this plane are zero. Therefore, the height and deformation differences between the top and bottom points of the structure are considered in the study.

The height of the structure in this study is 20.95 m. Therefore, the maximum deformation limits according to TYDRYK are 62,85 mm for limited damage, 146,65 mm for controlled damage, and 209,5 mm for prevention of collapse.

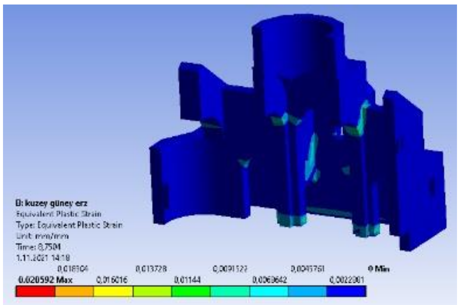
Table 2. Seismic analyses of church using the earthquake records



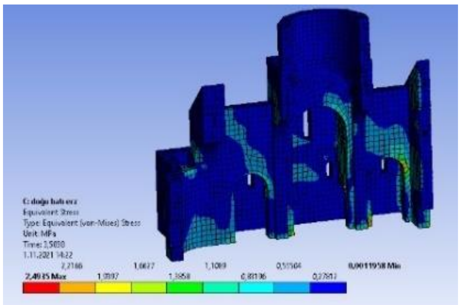
a)Equivalent stress



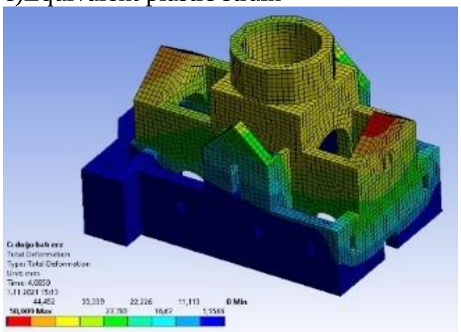
b)Total deformation



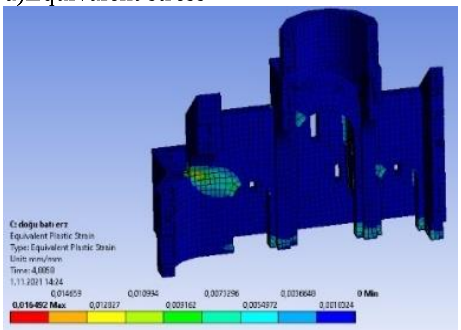
c)Equivalent plastic strain



d)Equivalent stress



e) Total deformation



f) Equivalent plastic strain

The distribution of equivalent plastic strains is shown in Table 2f. Plastic strains are concentrated on the walls of the apse part and at the support points of the main columns, but do not occur in other parts of the church.

In the strength evaluation, the maximum stresses formed should not exceed the allowable stress value of the deformation evaluation; the ratio of the maximum deformation to the maximum height of the structure should not exceed a certain value (TYDRYK, 2017). The Earthquake Risk Management Guide for Historic Buildings defines the limits for the maximum deformation ratio allowable for varying performance levels in the context of dynamic effects.

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## 6. RESULTS

Anatolian geography, which has hosted to many civilizations, also contains structural structures belonging to different religions as a requirement of this feature. In this study, the church of Digor, one of these historical structures, was evaluated under the influence of seismic loads. The structure, which was modeled as a 3D model at the first stage, was subjected to time history analysis under the 1992 Erzincan earthquake acceleration records. As a result of the analyzes, it has been determined that the stresses in the support and top points of the main columns and the arch systems connecting these columns to walls at each sides have high values. In terms of deformations, it has been determined that gable walls at the lowest elevations of the church and arch system carrying the main dome and its pulley are the parts to be demolished. Plastic deformations, which are the results of nonlinear time history analysis, are concentrated at the support points of the main arch system, the base points of the main columns and at the apse. These results show the areas where the structure is likely to be damaged in a possible earthquake. The results obtained are in harmony with the parts of the building that were destroyed in the earthquake. In this case, it has been determined that this kind of modeling and analysis gives very realistic results in terms of detecting the real damages that will occur in such structures under the effect of earthquakes. It is aimed that the results obtained will guide the restoration works to be carried out in the future.

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