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THE CHALLENGES AND ADVANTAGES OF MACRO MODELING IN ANSYS SOFTWARE FOR SEISMIC VULNERABILITY ASSESSMENT OF HISTORIC MASONRY STRUCTURES

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Abstract

This study aims at creating an advancement guideline for a software which can be used for seismic vulnerability assessment of historic masonry structures by revealing the results of an experience related to the macro modeling of a historic masonry building. The case study structure is Bergama Bedesten (15th-16th centuries) located in Bergama, İzmir, Turkey. ANSYS software is used for the Finite Element Modeling of the structure. The seismicity at its location is determined and the structural response under lateral loads is obtained together with the dynamic characteristics. Mesh design, component creation according to the used material change in structural elements, contact surface identification, the arrangement of the stress scales, and result interpretation are realized. For these stages, the challenges are discussed with the solutions. The advantageous aspects of the software are explained. For the challenges, in mesh design, the ineffectiveness of cartesian method for some elements was detected and tetrahedrons method was chosen. In contact surface identification, the overlapping portions of structural components could not be detected by the software exactly, so the manual surface separation was realized. In the stress level interpretation, the lack of assignment for material limit strength values to the analysis scale was experienced and the addition of limit values was carried out. The scale also needs manual arrangement for the increase of interval numbers of stress values to emphasize vulnerable zones. This flexibility of scale to be arranged can be seen as an advantage, as well. The 3d section and axonometric view creation provide the presentation of stress changes at inner and outer surfaces of the structure which is another positive side.

Keywords: Macro modeling, masonry structures, modeling strategies, seismic vulnerability.

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1 INTRODUCTION

The historic masonry structures are vulnerable to seismic loading and their seismic vulnerability assessment varies from simplified to advanced methods such as risk index classification by visual observation [1][2] to numerical modeling for detailed structural behavior determination [3][4]. The combination of these two approaches [5] can be preferred, as well. Modeling of the masonry structural systems is a demanding task and there are different methods chosen according to the structural characteristics of the buildings. For example, historic masonry buildings with a box behavior (e.g. palaces, caravanserais etc.) buildings analyzable by independent macro elements (e.g. churches, mosques etc.) buildings characterized by monodimensional masonry elements (e.g. towers, minarets etc.) and massive structures prevailing local failure of masonry (e.g. fortresses, city walls etc.) may require different approaches such as macro block modeling, discrete element modeling, structural elements modeling and continuous constitutive law modeling for in detail seismic vulnerability assessment investigation [6]. However, the most inclusive choice for differently characterized masonry structures is Finite Element Modeling. It presents micro, simplified-micro, and macro modeling choices changing the detail level in the model. Macro modeling provides the opportunity to assess global structural behavior of monumental scale buildings under seismic loading. In this approach, brick, stone etc. materials put together with mortar are admitted as composite media, so the structural components can be modeled as total elements decreasing the detail and burden during analysis phase [7].

Different analysis softwares are used for seismic vulnerability assessment of historic masonry structures. Each presents a variety of tools for macro modeling and analysis phases. Zucca et al. tried to assess the seismic vulnerability of Santa Maria Novella Basilica in Florence by the macro modeling of the structure in Midas Gen and performing response spectrum analysis defining stress fields in structural components [8]. The study carried out by Ravichandran et al. compared five alternative modeling approaches four produced in ANSYS and one generated in SAP2000. The case study is a small-scale masonry house. The focus is on the suggestion of a FE macro modeling approach to reduce computational effort [9]. Hovaidae et al. generated the macro model of Arge-Tabriz monument in ABAQUS software. By the use of region-specified simulated ground motion records, the probable failures that will be caused by possible earthquakes were determined in the structure [10]. Tomar et al. investigated the seismic vulnerability of a historical brick masonry structure by macro modeling approach benefiting from ANSYS software. As a result, some structural elements were found overly stressed caused by out-of-plane movement and in-plane shear. Retrofitting strategies were suggested for the necessary portions of the structure [11]. Uzdil et al. benefited from linear, nonlinear, and kinematic limit analysis approaches to analyze both the global structural behavior under seismic loading and to assess out of plane behavior of masonry facade walls as local failure caused by earthquakes. The overall seismic vulnerability of the structure was determined considering the limit values stated in building codes by the use of macro model generated in Midas Gen while overturning, vertical and lateral bending mechanisms were detected by the local analysis [12].

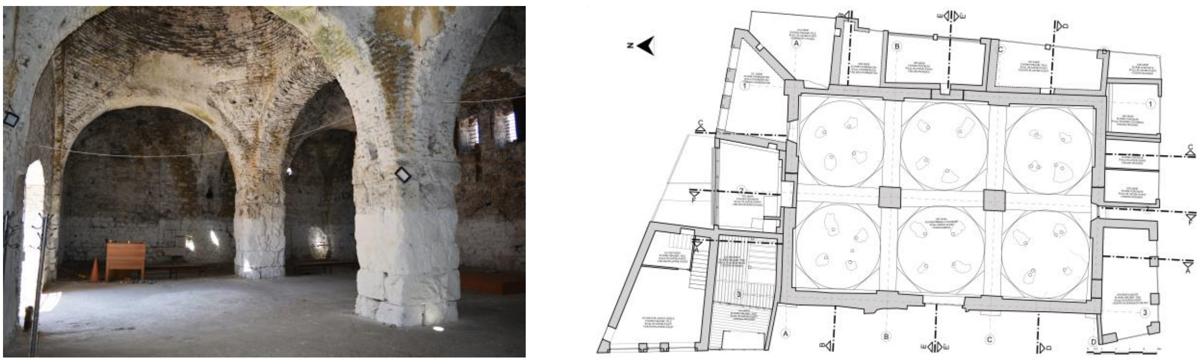
The most time-efficient approach decreasing modeling and result interpretation time can be designed by the development of these softwares. However, the presented studies in the literature do not mention about the modeling and analysis process with the experienced challenges and benefited advantages. Instead of this, the selected parameters in macro modeling process and the results of the carried out seismic vulnerability assessment work are stated only. So, this study aims at explaining the process of macro modeling and analysis stages for seismic vulnerability assessment of a historic masonry structure with their challenging and advantageous sides to emphasize the required advances in the used ANSYS software for a more efficient working environment.

2 METHODOLOGY

Within the study, a historic masonry monumental building Bergama *Bedesten* was modeled in ANSYS software by macro modeling approach and Finite Element Method to assess its seismic vulnerability. It is a 15^{th}-16^{th} century structure located in Bergama, İzmir Turkey (Figure 1).

Figure 1. Exterior view of Bergama *Bedesten*

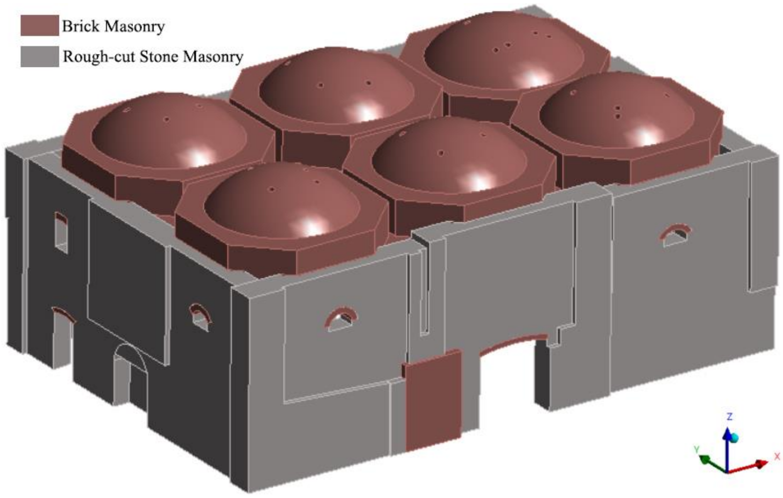
During the modeling phase, firstly the structural components and their material usage were considered. The main structural components are constituted by domes, drums, plane triangles, arches, pillars and load-bearing walls. Domes and arches are fully out of brick, while in drums and walls the alternating use of rough-cut stone and brick is visible. However, in the walls, the ratio of stone is higher than brick. So, rough-cut stone masonry parameters were chosen for these components. In the drums, the brick ratio is higher. So, brick masonry assignment was realized for these ones. The pillars are totally rough-cut stone masonry. At the door and window openings, brick arches; and at the two door openings, rough-cut stone masonry arches can be observed (Figure 2).



(a) (b)

Figure 2. Inside view of Bergama *Bedesten* showing main structural components and material usage (a), reflected ceiling plan view (b)

In the following Figure 3, the structural components that brick masonry or rough-cut stone masonry assigned can be seen in the macro model of the structure with the parameter values. Material parameters were taken from the guideline ''Management of Earthquake Risks for Historical Buildings'' [13].



Masonry Type / Parameters	Brick Masonry	Rough-cut Stone Masonry
Compressive Strength f_m (MPa)	1.8	1.1
Shear Strength τ_0 (kPa)	60	35
Modulus of Elasticity E (MPa)	1800	1020
Shear Modulus G (MPa)	300	170
Unit Weight w (kN/m^3)	18	20

Figure 3. Assigned materials to the structural components of Bergama *Bedesten* with their parameter values

The control of contact surfaces between different components was carried out and required corrections were made for the overlapping areas. A typical example is shown in Figure 4.

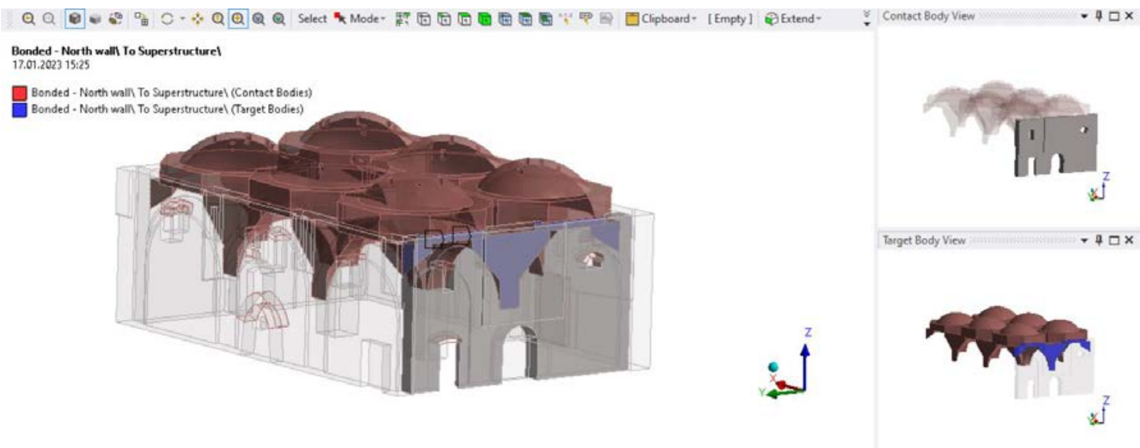
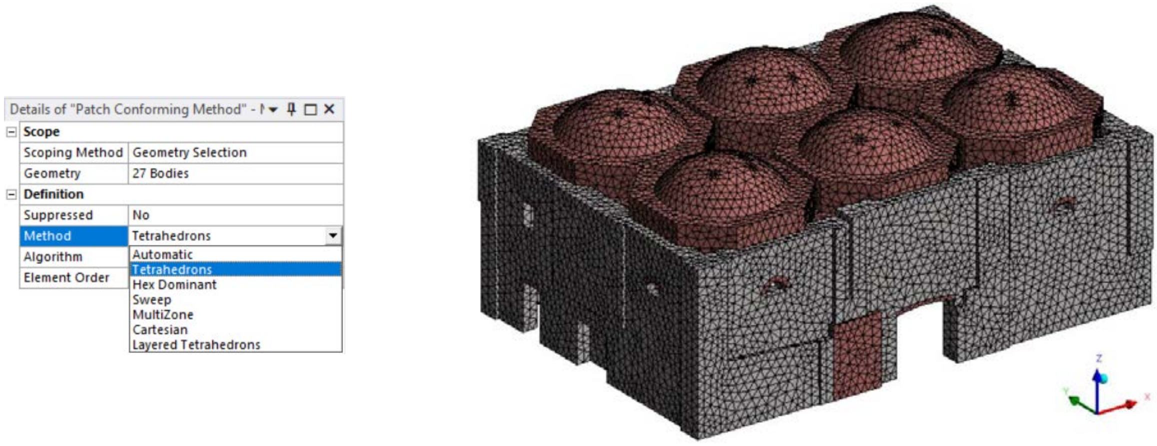


Figure 4. A contact surface example between the north wall and superstructure components

After the completion of component modeling considering material differences and contact surface identification, the finite element mesh design phase was realized. ANSYS presents different meshing styles like tetrahedrons, hex dominant, sweep, multizone, cartesian and layered tetrahedrons (Figure 5a). For the varying structural components, the most suitable mesh pattern was determined as the tetrahedrons and by the use of 0.4 m. average sizing, the meshing application was carried out as can be seen in Figure 5b. At the locations that the geometry changes within small distance, use of lower sizing was considered.



(a) (b)

Figure 5. Mesh types in ANSYS (a), tetrahedrons mesh design in Bergama *Bedesten* (b)

The modal analysis was performed on the structure to determine the natural mode frequencies in x and y-directions to be used in seismic analyses. The seismic vulnerability of the structure was determined by single-mode equivalent earthquake load analysis. It could be possible since the mass participation ratio was high at the first translational modes in both directions. The horizontal elastic acceleration design spectrum at the location of Bergama *Bedesten* is used. The acceleration is obtained from the interactive seismic hazard maps web application of Turkey Disaster and Emergency Management Authority [14]. The derived horizontal acceleration using the first two mode frequencies and horizontal elastic design spectrum knowledge [15] was applied on the structure for x and y-directions as seismic loading, one by one. The gained maximum principal stress values as a result of the analysis showed the seismically vulnerable parts of the structure. The zones exceeding limit tensile strength values for each material type were assessed as vulnerable locations. These locations were compared with the parts of the structure that have failure, deterioration or alteration to detect whether they overlap or not (Figure 6). This step revealed intervention priority for the locations that have failure, deterioration or alteration and seismically vulnerable.

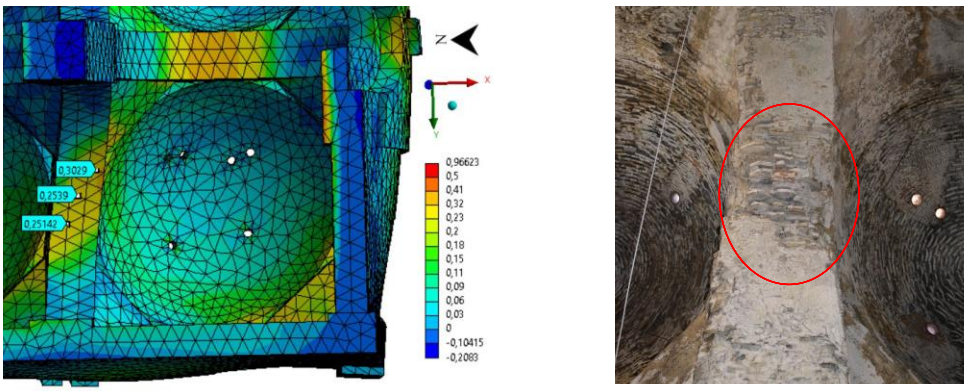


Figure 6. Comparison of maximum principal stress results with the current failures, deteriorations or alterations; a detected vulnerable arch example with section diminishment

The criticism of the carried out work is made for different stages of the study with the challenging and advantageous aspects of the software. In accordance with this, some recommendations for macro modeling in ANSYS and for the development of the software are stated.

3 CHALLENGES OF THE SOFTWARE

In this part, the results of the macro modeling process and seismic vulnerability assessment analysis phase are expressed with the encountered errors and they are discussed with the possible solutions.

For the challenges, in mesh design, the ineffectiveness of the cartesian method for thin and curvilinear elements was detected and the tetrahedrons method which has more potential to create curvilinear volumes was chosen. The dome surfaces and arches with thinner sections and curvilinear form have failed parts with cartesian method and 0.2 m. size meshing while the masonry orthogonal walls are well generated with this method (Figure 7).

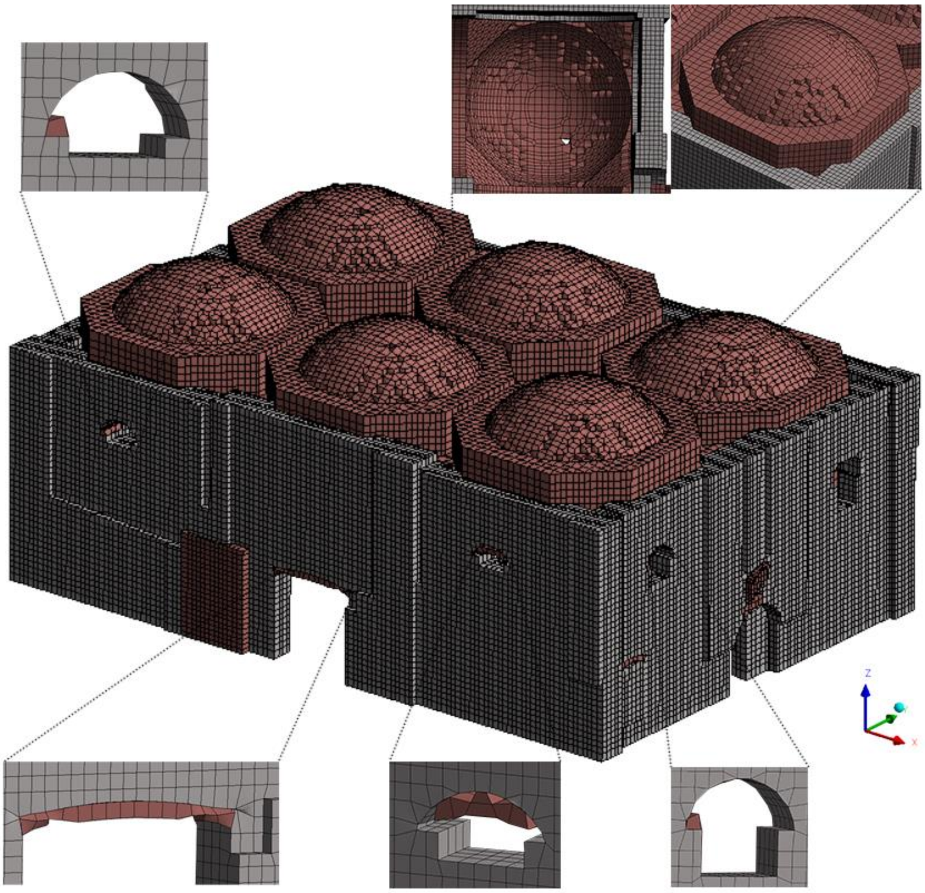


Figure 7. Cartesian meshing in Bergama *Bedesten* and failed components

Although the cartesian mesh is workable in generating orthogonal geometries with 0.2 m. mesh sizing, it is dense and overdetailed mesh unit for the desired numerical analysis of this monumental structure to assess its overall structural behavior. Besides, errors occur during the analysis phase. The deficiencies are seen for the wall details at higher mesh sizes (0.4 m.) for cartesian method, so it is not a suitable mesh type for walls with different projections as seen at the thickened portions of the walls corresponding to load-bearing arches inside. However, tetrahedrons method with 0.4 m. sizing generates the correct geometry of the perpendicular projections from the wall (Figure 8).

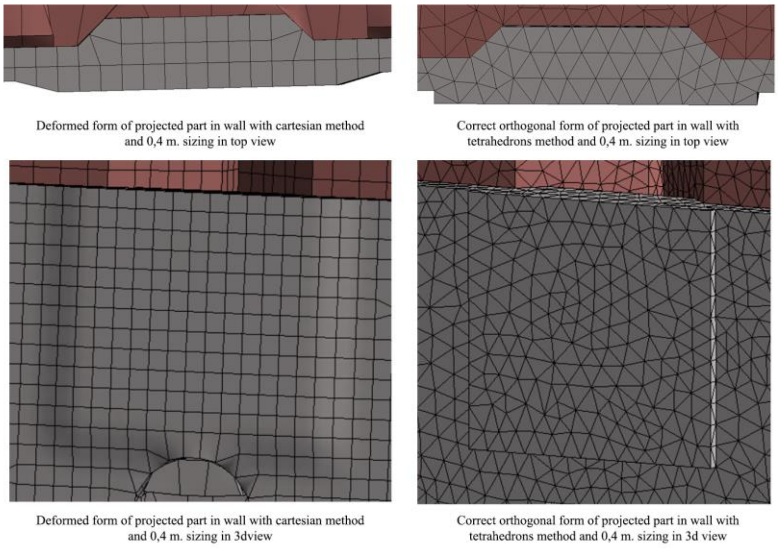


Figure 8. Deformed and correct forms of projected parts in walls with cartesian and tetrahedrons methods

As a result, the ineffectiveness of the cartesian method was detected because of section thickness and curvilinear geometry properties of the components. The tetrahedrons method with 0.4 m. sizing provided the desired geometry generations, so it is preferred for the meshing of the overall structure. In modal analysis phase, the mesh size lower than 0.4 m. did not work which is another reason to choose the assigned mesh size and type and it proves the invalid situation for smaller mesh sizes than 0.4 m. at this scale monumental structures (Figure 9).

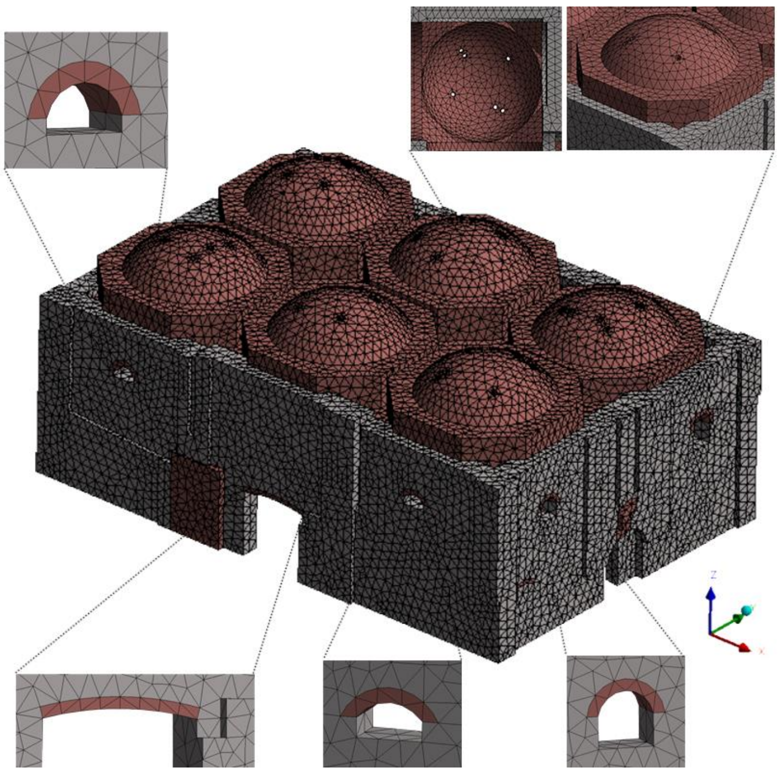


Figure 9. Tetrahedrons meshing in Bergama *Bedesten*

For contact surface identification stage, the overlapping portions of different structural components could not be detected by the software directly, so the manual surface separation by the use of line tool was realized. The overlapping surfaces of superstructure and walls, the overlapped parts of the walls with each other, and contact surfaces between brick arches of windows, doors and rough-cut stone masonry walls were defined (Figure 10).

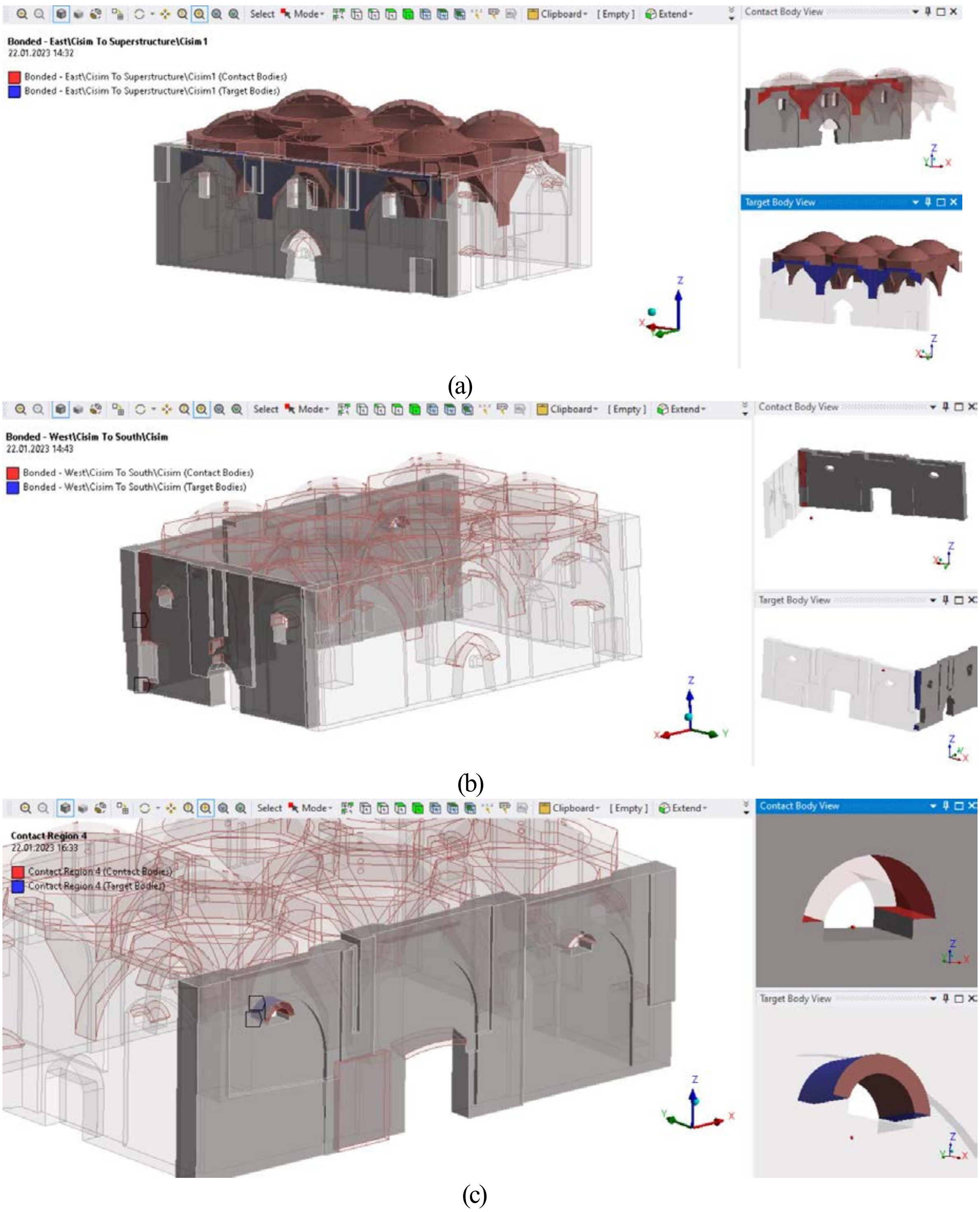


Figure 10. Different overlapping surface types; (a) between wall and superstructure, (b) between two walls, (c) between window/door arch and wall

As an example for the manual surface separation requirement in the software, the east wall and superstructure components can be shown. In the Figure 11, the situation of contact surfaces in both east wall and superstructure defined automatically by the software is seen. These contact areas are more than the overlapping portions and they are nearly the whole surface of each component although they do not touch to each other.

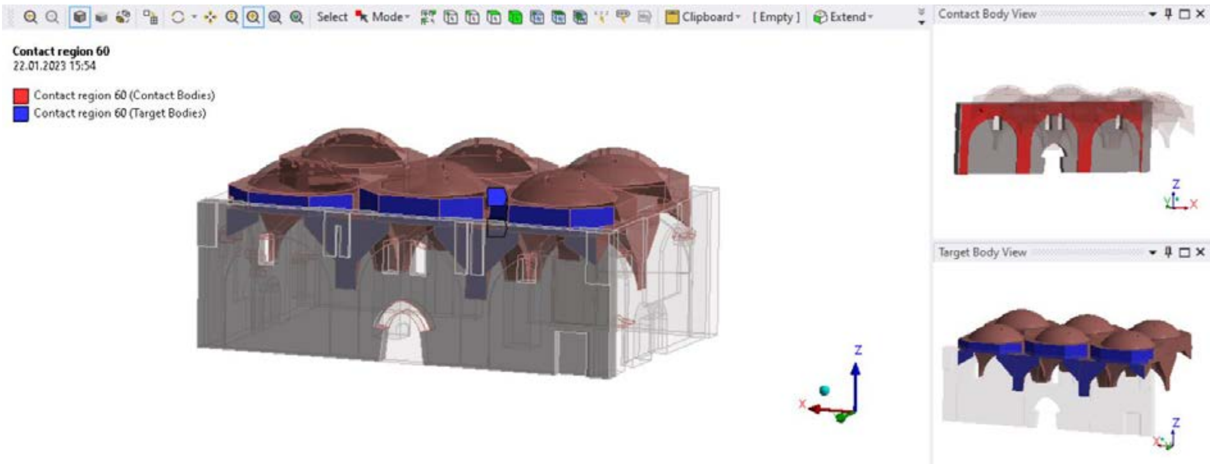
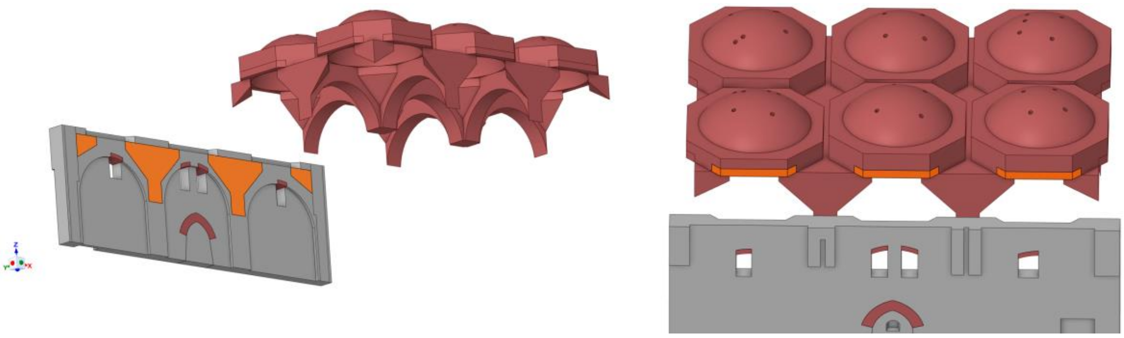


Figure 11. Wrong detection of contact areas in software for east wall and superstructure

Because the software could not detect the overlapping portions automatically, manual surface separation was realized by drawing the overlapping part borders with line tool at the related surfaces, and correct contact areas were generated (Figure 12).



(a) (b)

Figure 12. Manual identification of contact areas by drawing the borders of overlapping areas in each component, as example; for east wall (a) and superstructure (b)

For the detection of the parts in the structure that have seismic vulnerability risk, the maximum principal stress values as the result of single-mode equivalent earthquake load analysis applying the horizontal acceleration on x and y- directions to the structure were examined for whether they exceed the limit tensile strength values for materials or not. However, in the scale automatically created by the software, the limit tensile strength values for materials are not included. So, manual addition of these values to the analysis scale was realized as 0.11 MPa for rough-cut stone masonry and 0.18 MPa for brick masonry (Figure 13).

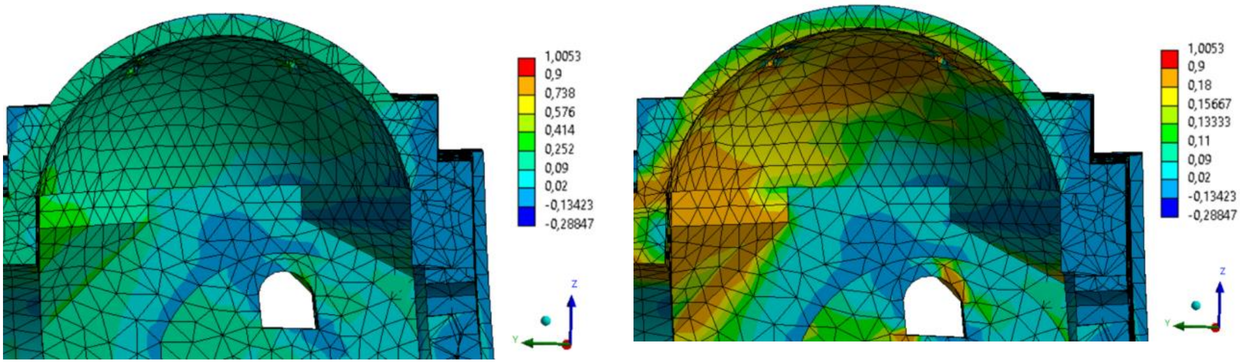


Figure 13. Addition of 0.11 MPa and 0.18 MPa values to the scale, example; maximum principal stress scale under y-direction earthquake loading in the southwestern dome

In addition, at the locations where the stress concentration spread, the exact risky areas could not be deciphered through only addition of the limit strength values. So, by the decrease of stress level intervals and the increase of contour numbers, the vulnerable zones became more identifiable and distinguishable from the remaining (Figure 14).

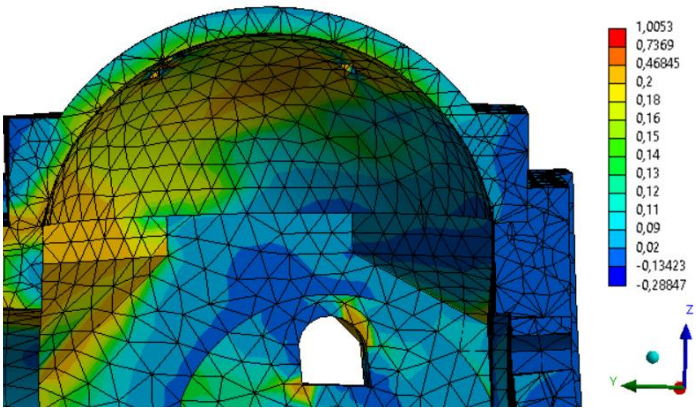
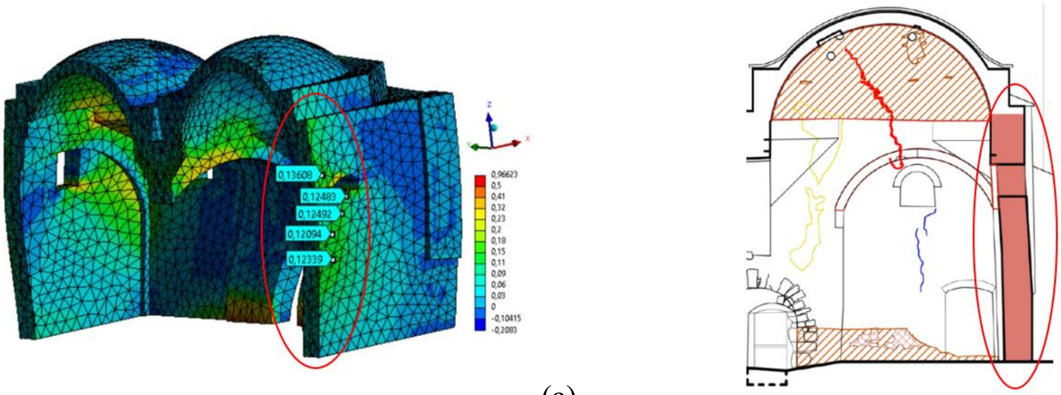


Figure 14. Increased contour numbers emphasizing exactly vulnerable zones in a more sensitive way in southwestern dome for maximum principal stress under y-direction earthquake loading

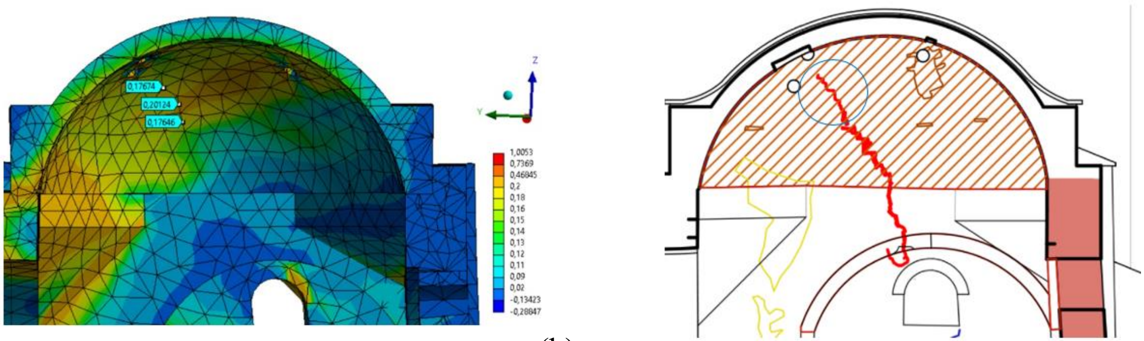
4 ADVANTAGES OF THE SOFTWARE

In this part, the advantageous sides of the software for interpretation of seismic vulnerability assessment results are discussed with the benefited qualities of ANSYS to be directive for further similar structural analysis studies.

As expressed in the previous section, by the control of limit tensile strength values of the materials, the vulnerable zones were tried to be determined. As a further step, whether the portions of the structure that have structural damage or alteration are in vulnerable zones or not was also investigated. At this stage, the increased interval numbers in the scale became effective to detect the overlapping zones. By the addition of stress labels on these zones, the stress levels at the crack traces, at overturned part of the west wall and at other structurally damaged parts, the exact stress levels were made visible numerically on the visuals (Figure 15).



(a)



(b)

Figure 15. Detection of overlapped parts for vulnerable zones and structurally damaged areas at overturned west wall (a) and crack in southwestern dome (b) by increase of contour numbers and label tool

This is the advantageous aspect of the software to make the user able to emphasize the vulnerable portions by the production of desired number of contours and label tool providing also the sensitive detection of completely overlapping portions for vulnerable zones and structural damage areas. The same quality is effective for the altered portions to see which part of the structural element is vulnerable by what level of maximum principal stress. In the Figure 16, the alteration of west main entrance door arch profile and its vulnerable zone can be seen for comparison.

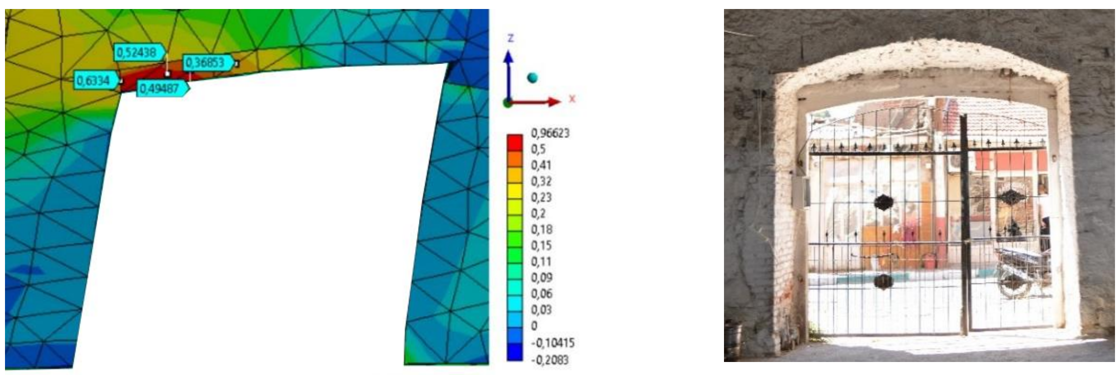


Figure 16. Maximum principal stress levels indicating vulnerable zone in altered west entrance door arch

In the study, all analysis results are shown in roof plan, ceiling plan, 3d section and axonometric views from different angles. This different view creation application allowed to show all the vulnerable zones of the structure located at different parts and the stress changes at inner and outer surfaces of the components were revealed (Figure 17).

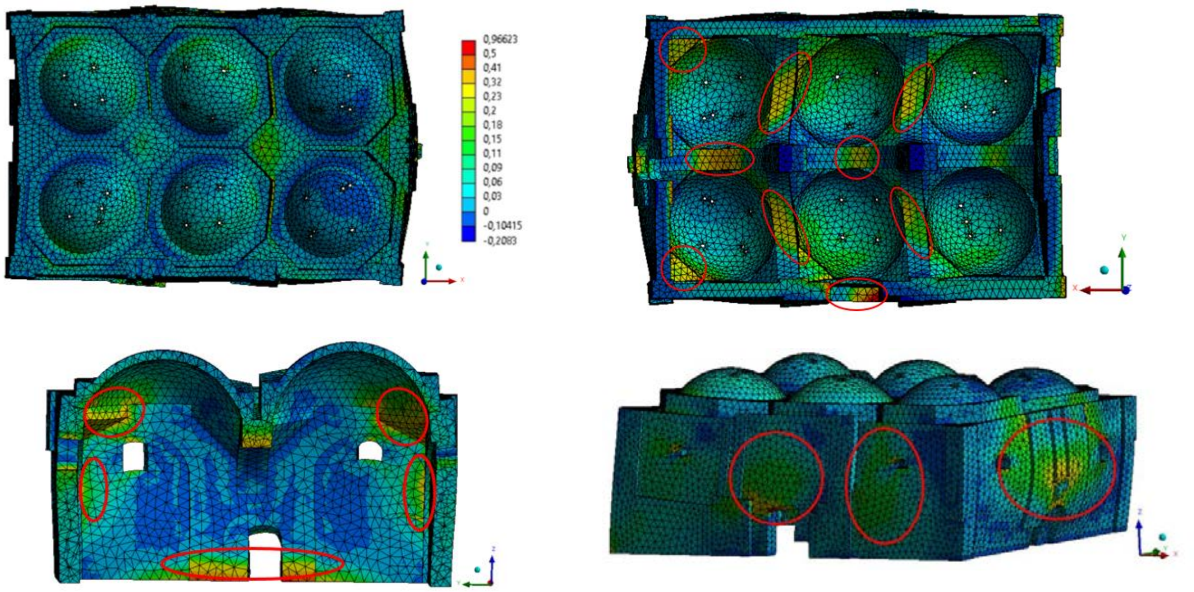


Figure 17. Maximum principal stress level changes and marked vulnerable zones by the application of x-direction earthquake loading shown in different view examples

Through the animations, the stress increase scene-by-scene creates a more perceivable presentation of stress-densified areas in the structure. This is helpful to emphasize the vulnerable zones in a more realistic way (Figure 18).

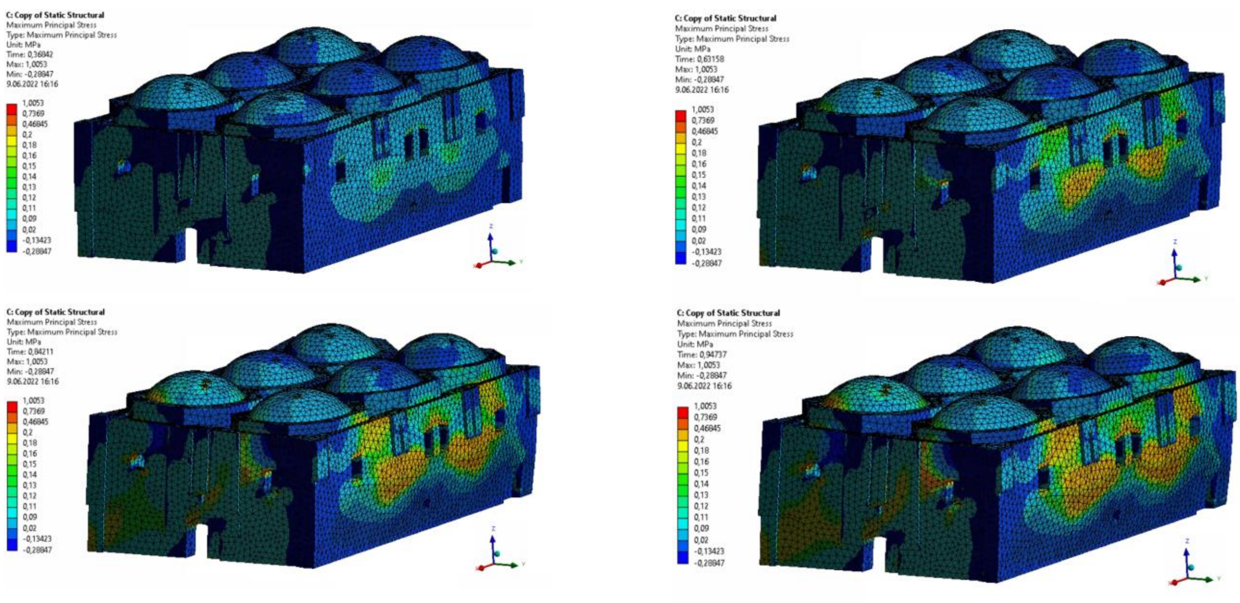


Figure 18. Maximum principal stress level changes by the application of y-direction earthquake loading shown in a 3d view scene by scene

Through 3d section animations, the stress changes presented in interior structural components such as arches, transition zone and domes create a powerful representation of the load-pattern change because of the applied seismic loading, too (Figure 19).

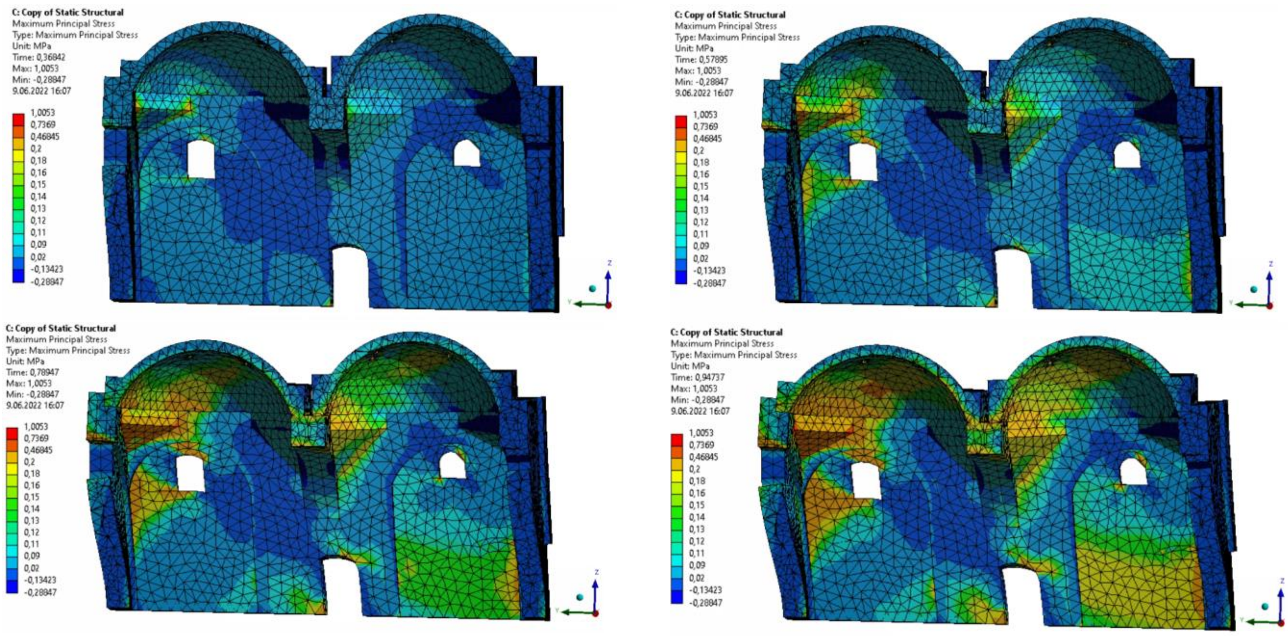


Figure 19. Maximum principal stress level changes by the application of y-direction earthquake loading shown in a 3d section view scene by scene

5 CONCLUSIONS AND RECOMMENDATIONS

The macro modeling of historic masonry structures by finite element method requires the combination of different work phases in ANSYS software such as component creation according to material usage change, meshing and contact surface identification. After these phases are realized, the analysis stage is carried out covering modal analysis and single-mode equivalent earthquake load analysis in this study. The macro modeling of Bergama *Bedesten* became the example case study to experience and reveal the challenging and advantageous aspects of the ANSYS software for macro modeling and seismic vulnerability assessment of historic masonry structures.

As a result, the following recommendations can be made for macro modeling in ANSYS and for the development of the software:

1- In mesh design, the tetrahedrons method has more potential to generate thin and curvilinear geometries compared to cartesian method with an efficient mesh size for the global structural behavior assessment of monumental masonry buildings. Therefore, either the use of this method in the overall structure can be preferred for the buildings accommodating this kind of curvilinear geometries with thin section, or the use of different mesh styles can be considered for differently characterized geometries. However, the second choice can lead to the requirement of further adjustments for the compatibility of different mesh types.

2- The contact surface identification between different components may not be created by the software automatically. The manual identification of these areas is time consuming. So, the improvement of the software for this stage can be beneficial decreasing the work time for macro modeling.

3- The automatic assignment of the material limit tensile strengths to the analysis scale was not carried out by the software. After the manual addition of the limit values, the scale still needs adjustments for the contour intervals and increase of their numbers is required to emphasize the exact locations of the vulnerable parts. These automatic inclusion of limit values for materials to the analysis scale and increase of contour numbers with lower intervals between them around limit value levels can be realized by the software automatically. It leads to the decrease in analysis result deciphering time and creation of effective visuals representing the vulnerable zones.

As the aspects of the software that should be conserved and maybe improved more can be listed as followed:

1- The label tool allowing the numerical representation of stress values on the visuals which provides the comparison between structural damage areas and vulnerable zone stress levels exceeding the limit tensile strength values by maximum principal stress analysis results is a useful quality for the software. This tool is also effective to determine the vulnerable zones at the altered structural components increasing intervention priority for the related parts.

2- The different view generation as roof plan, ceiling plan, 3d section or axonometric views creates the opportunity to represent all vulnerable zones at inner and outer surfaces of the structure which is valuable for interpretation and presentation stages.

3- Thanks to the animations, scene-by-scene stress level changes can be visible to the user showing the effect of seismic loading on the structure and vulnerability increase in the different components. Because in different views like 3d sections, this quality is active, too, it is possible to see the horizontal acceleration effect on internal structural components like arches, domes etc. in a dynamic representation environment. This quality creates an impressive presentation tool for the analysis results.

4- The software allows solid modeling and the introduction of detailed material models. The solid elements allow better representation of geometrically irregular masonry components. It would not be that successful with shell or frame elements.

In conclusion, ANSYS software provides a useful computer environment for seismic vulnerability assessment of historic masonry structures with beneficial sides in analysis result interpretation and presentation stages. It can be further improved by the expressed recommendations for a more time-efficient use in macro modeling and in generation of analysis visuals showing vulnerable zones.

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