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Structural Vulnerability Assessment of Historical Buildings in Turkey

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Abstract

Structural Vulnerability assessment of historical buildings is very important to carry them to the future. Turkey is a rich country in terms of historic masterships mostly from Ottoman Empire, such as mosques, bathhouses, churches and aqueducts. Especially mosques are the common historical structures in turkey. Therefore, in the present study, structural vulnerability assessment of historical mosques in Turkey was carried out. One of the existing ones is considered as a sample building and structural vulnerability assessment was carried out on this building. The sample building was selected as Konak Mosque located in Izmir, Turkey. The mosque was structurally investigated through advanced approaches. The mosque, constructed in 1755 by Ottoman at very central location close by the clock tower, is little one decorated with blue tiles. The mosque is also nearby a historical bazaar where the main historical business stream line is located. Konak Mosque is one of these new styles in that age. It can be named as a signature historical building representing Islamic minimalist oriented architecture with its unique octagonal plan. In the present study, the building was modelled by using the Finite Element Modelling (FEM) software, SAP2000. Time history analyses were carried out using 10 different ground motion data. Displacements, base shear and stress values were interpreted and the results were displayed graphically and discussed. For probabilistic seismic risk assessment, fragility analyses were also carried out and the fragility curve and surface were sketched for the mosque. Saddle point was determined on the fragility surface.

Keywords: Historical Masonry Buildings; Konak Mosque; Time History Analysis; Probabilistic Seismic Risk Assessment.

1. Introduction

Turkey, with thousand years of history, is a place of significant cultural wealth and heritage. This heritage is carrying the thousand years of cultural wealth and heritage from past to present. They are also unique reflections of identity, which stands as a significant and strong link between the past and the present. Therefore, preservation of these buildings is very important and necessary. However, preservation of the historic structures is a complex process including, structural, architectural, and historical preservation components. In structural component, historical buildings have been investigated through various modern techniques to have accurate results. Accurate analysis approaches bring accurate results in the analyses. In the analysis of historical buildings, definition of material components and formation of the buildings is very important.

Historical buildings in Turkey are generally made of stone or masonry from Greek and Ottoman periods. Masonry is constituted by interconnecting the masonry units with or without mortar. Most common masonry units are brick, stone and adobe. In addition, wooden material was also used for various purposes in the historic masonry structures. The masonry has low tensile strength while its compressive strength is high. Because of that, masonry structures are very vulnerable under tensile stress. To determine the material properties of the existing masonry structures, there are various assessment approaches. These approached can be classified as destructive, non- destructive and in-situ test

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methods. For simplification, masonry material is generally assumed as a unit body. In some cases, such simplifications may result with inaccurate behavior and therefore, assumptions in the analysis are very important to define the structural behavior accurately.

In historical masonry structures, main parts are walls, domes, arches, vaults and pillars. The other components can be aligned as buttresses, ties, piers, drum and weighting towers. The main damage reasons of masonry structures are earthquake and soil settlement. Earthquake is more important because the soil condition has reached equilibrium since the structure was constructed a long time ago. There are many damage patterns for historic masonry structures such as out of plane rapture, cracks due to tensile stresses greater than tensile strength of masonry, corner and junction damages, radial cracks on domes, moving the abutments of the arches and vaults, frost effect and rapture and buckling of the ties.

Structural performances of historical buildings are in variety with their geometry and defined material properties. Therefore, when modeling historical buildings, defining the material properties and geometrical shapes of the buildings are the critical steps in the procedure. Historical buildings have low ductility. They may have severe damages during the severe earthquakes. Many historical buildings are located in high seismic zone in Turkey [1]. In case of any possible future earthquakes, these existing historical buildings may suffer substantial or heavy damages. Due to this fact, these buildings must be preserved for the next generation. They bring us historical concept about sociological, economic and political perspective from the past up to now. Historical buildings were built based on the masters` knowledge and experience without design standards or scientific studies [2].

In this study, to understand the structural behavior of historical mosques in Turkey, a sample historical mosque was selected for investigation. Konak Mosque, located in Western Turkey, Izmir, from Ottoman period was selected. The building was modeled by using the Finite Element Modeling (FEM) software, SAP2000. As a part of Structural vulnerability assessment of Konak Mosque, time history analyses were carried out using 10 different ground motion data on the FEM models. Displacements, base shear and stress values were interpreted and the results were displayed graphically and discussed. For probabilistic seismic risk assessment, fragility analyses were also carried out and the fragility curve and surface were sketched for the mosque.

2. Structural Analysis of Historical Buildings

The masonry structure has high compressive strength and low tensile stress. This property is so important that the structural form of masonry constructions is based on compressive forces. The masonry material is so brittle. Sudden failure occurs in tension loading. Fracture energy is the absorbed energy until the failure time. It can be determined calculating the area under stress-strain diagram as seen in Figure 1. [3, 4].

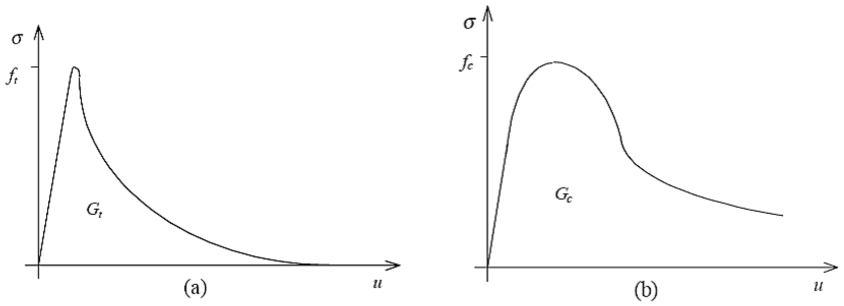

Figure 1. Typical behavior of quasi-fragile materials under uniaxial loading and definition of the fracture energy a) tension loading b) compression loading [3]

Overall strength of masonry is mostly affected by the bind strength at the unit-mortar interface [4]. Generally, the weakest contact in masonry assemblages is the bond between unit and mortar [5]. The Perpendicular forces to the mortar-unit joint are resisted by the tensile bind strength where the parallel forces to the mortar-unit joint are resisted by the shear bind strength of masonry [6]. Tensile failure or shear failure can occur at the unit–mortar interface [5]. Amount of the binding material, easily processing due to water content and penetrating of mortar to the surface of units enhance the binding strength [6].

Strength of stone masonry depends on the material properties and bond type of units. The stone is massive and stiff. Type and thickness of mortar is more effective on the compressive strength of stone masonry than stone units. The strength of stone does not much effect to stone masonry. The joint behavior of unit and mortar determines the strength of stone masonry. If the mortar strength is weaker than units, masonry strength primarily depends on the strength of mortar. The shear strength of the stone masonry is approximately 25% of the compressive strength [6]. Different types of stone masonry are shown in Figure 2 [7].

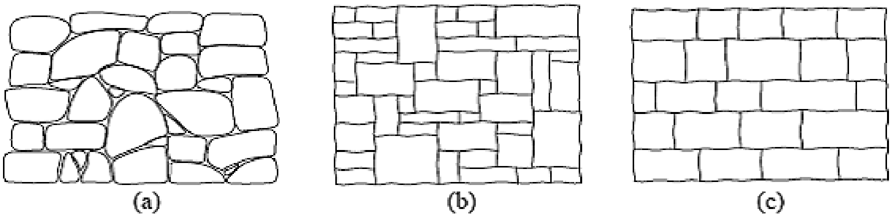

Figure 2. Different types of masonry: a) rubble masonry, b) ashlar masonry, c) coursed ashlas masonry [7]

3. Seismicity of Area and its Characteristics

Izmir, located in the Aegean region, is the third largest city of Turkey, neighboring the Aegean Sea. Izmir is located in a highly active seismic region in Turkey. Earthquakes in the Aegean Graben System and the Aegean Trench dominate the seismicity of the region. The tectonic setting in the region is complex and unexpected large earthquakes can occur in this region, potentially leading to losses and severe damages. There have been several destructive earthquakes throughout history. Records indicate that large earthquakes occur frequently in Izmir, the latest in 1778. Main Highlights of the Earthquakes and related fault zones in Izmir Region is shown in Figure 3 [8-10].

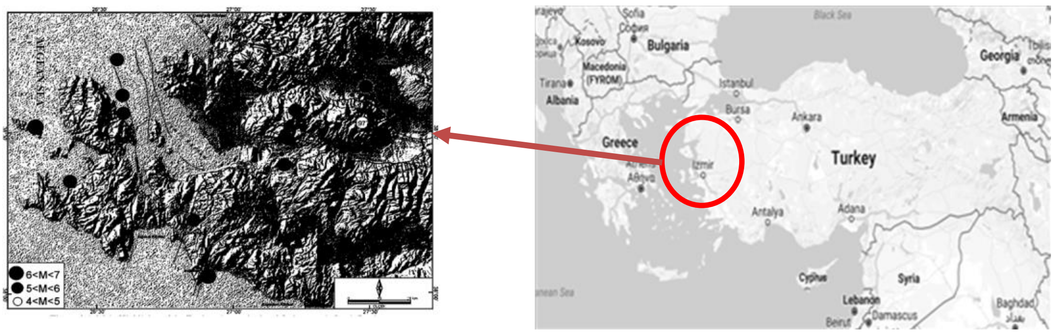

Figure 3. Map of Izmir Region, Turkey with major earthquakes [8]

Considering its location and urban features, the city of Izmir, a port, has come to be one of the leading symbols of cultural and historical heritage. There are many historical buildings in Izmir historical down town as bordered in Figure 4 [11]. These buildings are liable to have sustained multiple damages throughout the years from the earthquakes, and effective structural countermeasures should be taken to carry them to future. The cultural and historical richness of the city brought fourth various historical buildings, with the mosques from the Ottoman period having a great importance. These historical buildings give a particular texture to the city. Like other parts of Turkey, Izmir and its historical structures have a high seismic risk, making it possible for these buildings to suffer heavy damage if exposed to an earthquake. It is, therefore, extremely valuable to determine the structural behavior as well as the seismic safety of these historical structures. Thus far, the policies pertaining to the conservation of these historical structures have been inadequate. Existing structural studies have focused on residential buildings in the city of Izmir, with no significant studies evaluating historical structures at a regional scale. It is understood that the process of evaluating the behavior of historical structures is primarily different from that of residential buildings.

Figure 4. Historical Downtown of Izmir, Turkey

4. Structural Vulnerability Analysis of Konak Mosque

In the present study, to determine the structural vulnerability of historical buildings, one of the sample historical building was selected and investigated. The selected building is Konak Mosque. The Konak Mosque is one of these important historical buildings in Izmir, Turkey. The mosque was constructed in 1755 and located at the Konak Square in the heart of the city next to the Governor's Mansion and the Izmir Clock Tower, is a little one decorated with blue tiles. The region was very important for the city due to the harbor. With the harbor, a window to the World, city became the touch point of the West and East. Western business models met with Eastern culture. With the influence of the Western investigators and visitors, the city had the all new styles including the architectural elements for that age. Konak Mosque can be named as a signature historical building representing Islamic minimalist oriented architecture with its unique orthogonal plan [12].

In the historical perspective, the Konak Mosque has gone through various restorations. The first one was at during the 1st World War and it was again restored in 1964. The mosque has a main area of square shape in the plan view. The main area is covered by a main dome having a height of 3.65 m. The main dome was covered with lead by external part. The mosque has a minaret having height of 15.04 m made of ashlars [12]. The plan view and general view of Konak Mosque are shown in Figure 5.

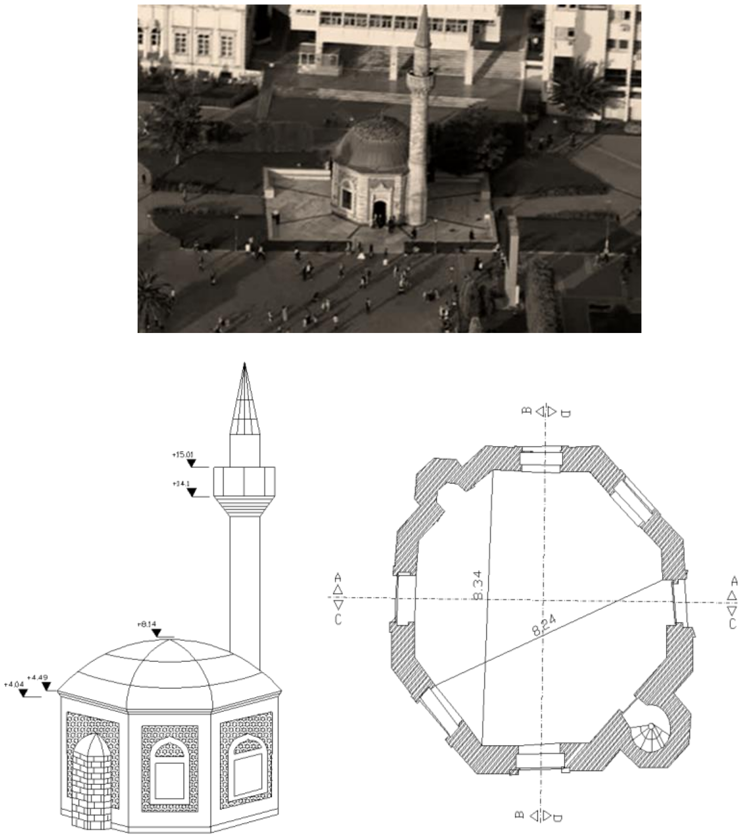

Figure 5. The mosque's plan view and general view

Generally, historical masonry buildings have complex geometry that gives the difficulty in the modeling for the analysis. Therefore, it is necessary to make some idealizations and assumptions when preparing the analysis models. In the present study, the three-dimensional analysis model was developed using the architectural plans and sections of the building, which was created via AutoCAD [13]. Then, three-dimensional model of the building was integrated in SAP2000 software [14]. For the analysis, in the modeling process, assumptions and simplifications were made to keep the number of the finite elements of model limited to avoid geometric complexity of the structure.

The building was analyzed under self-weigh and 10 different selected earthquakes. In modeling, two types of elements were used. The external masonry walls were modeled by three-dimensional solid elements, while two-dimensional shell elements were used for modeling the domes and minarets. Generally, it is not easy to determine reasonable number of finite elements to obtain response of the structural system with rational accuracy. In this study, approximately, 2,500 solid elements, 1,500 shell elements were used for constituting the structural analysis model of the mosque.

The mosque was assumed to be made of stone material and ceiling materials. In fact, the body walls consist of three major materials; three courses brick, one course stone and in between mortar. The main dome is made of brick. However, because of the complexity of the structure and lack of the sufficient data, the structure were assumed to be composed of a single material having the same modulus of elasticity, unit weight and poisson's ratio. Stone material has an elastic modulus E = 3000 MPa, a unit volume weight γ = 16.61 kN/m^3 and Poison's ratio υ = 0.2 and ceiling material has an elastic modulus E = 13,000 MPa, a unit volume weight γ = 2.2 kN/m^3 and Poison's ratio υ = 0.16. These values were determined by literature survey. Three-dimensional structural model was developed by using SAP2000 structural analysis software [14, 15]. Structural model for the analysis is shown Figure 6.

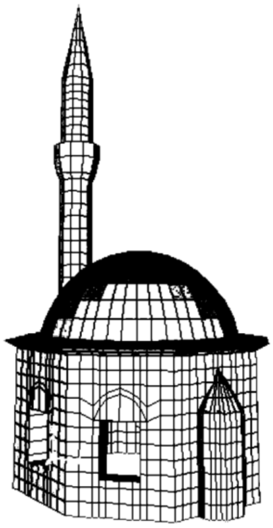

Figure 6. Structural finite element model of Konak Mosque

To determine the structural behavior of Konak Mosque, time history analyses were carried out by using 10 different ground motion records on the Konak Mosque's Finite Element models. Various structural analyses were carried out under self-weight and earthquake loads. Time history analyses are most reliable analysis type in the structural assessment approaches. For time history analyses, ground motion data were provided from Pacific Earthquake Engineering Research Center (PEER) [16]. Selected ground motion records for the dynamic analysis of the historical buildings are given in Table 1.

Table 1. The ground motion records used in the Analyses

No	Earthquake	Date	Moment Magnitude (Mw)	Ground Velocity (cm/s)	Ground Acceleration (g)	Distance (km)	Type
1	AZF315	25/02/1980	4.9	2.6	0.066	12.1	lateral slip
2	G01320	24/04/1984	6.2	2.9	0.098	16.2	lateral slip
3	G01320	06/08/1979	5.7	8.3	0.132	9.3	lateral slip
4	GRN180	28/06/1992	7.3	14.1	0.041	141.6	lateral slip
5	ABY090	28/06/1992	7.3	20	0.146	69.2	lateral slip
6	SIL000	28/06/1992	7.3	3.8	0.05	51.7	lateral slip
7	29P000	28/06/1992	7.3	3.7	0.08	42.2	lateral slip
8	G01090	18/10/1989	6.9	33.9	0.473	11.2	Oblique
9	SGI360	18/10/1989	6.9	8.4	0.06	30.6	Oblique
10	MCH000	18/10/1989	6.9	3.5	0.073	44.8	Oblique

SAP 2000 software was used for time history analyses to determine the structural behavior of the historical building. 12 mode values were considered in the dynamic time history analyses. Displacements, stresses and base shear values were interpreted and the results were displayed graphically and discussed. The values of the displacement stress and base shear obtained from Konak Mosque is given in Figure 7. In Figure 7, displacements, stress and base shear values obtained for selected earthquake data. The increase and decrease are given in numbers in the Figure 8. to describe the demand. Demand line is giving us linear proportion in the graphs.

With probabilistic seismic risk analysis, the rate of probability of exceeding is defined with various ground-motion levels at for a site [17]. Fragility curves represent the probability of structural damage due to earthquakes as a function of ground motion indices [18-20].

In this study, time history analysis results were used to carry out fragility analysis. Fragility curves were sketched by using values which were obtained as exceedance probability corresponding to each displacement value. Exceedance probability values of Konak Mosque were obtained for selected earthquake ground motion values. The fragility curve is shown Figure 8. In Figure 8, the demand was determined at around 42% line. In Figure 9, fragility is given in a surface distribution and with this surface graph, probability of exceedance can be defined for various drift values. In Figure 9, saddle point is determined for the obtained values.

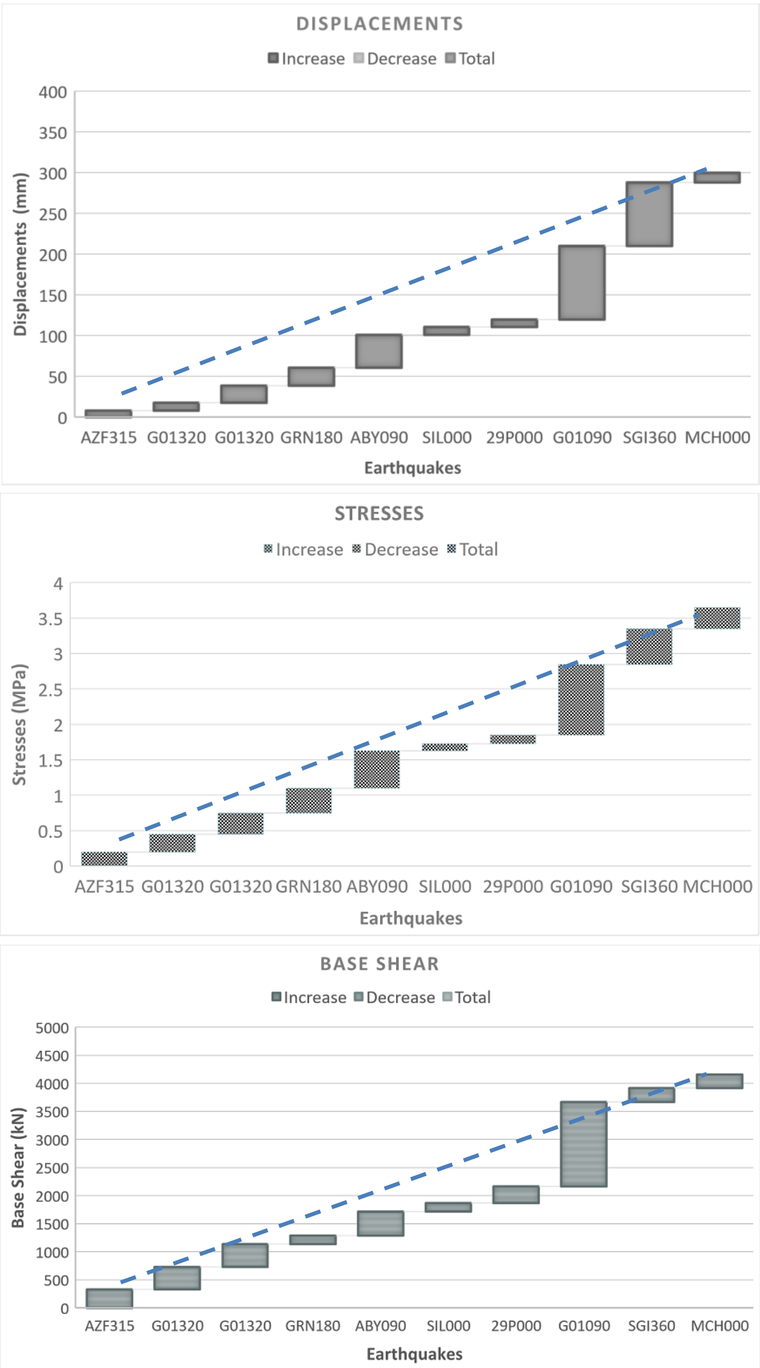

Figure 7. Displacement, Stress and Base Shear values of Konak Mosque

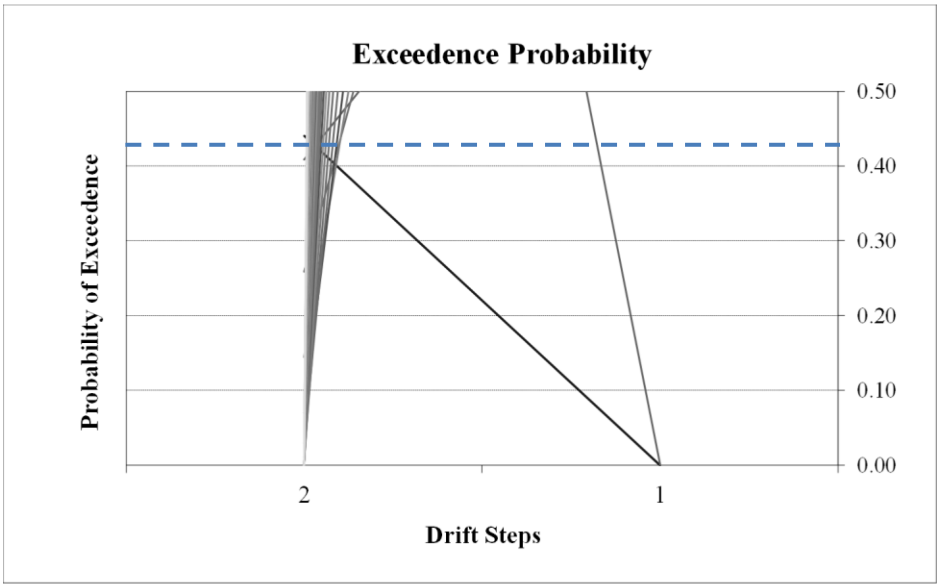

Figure 8. Fragility curve of Konak Mosque

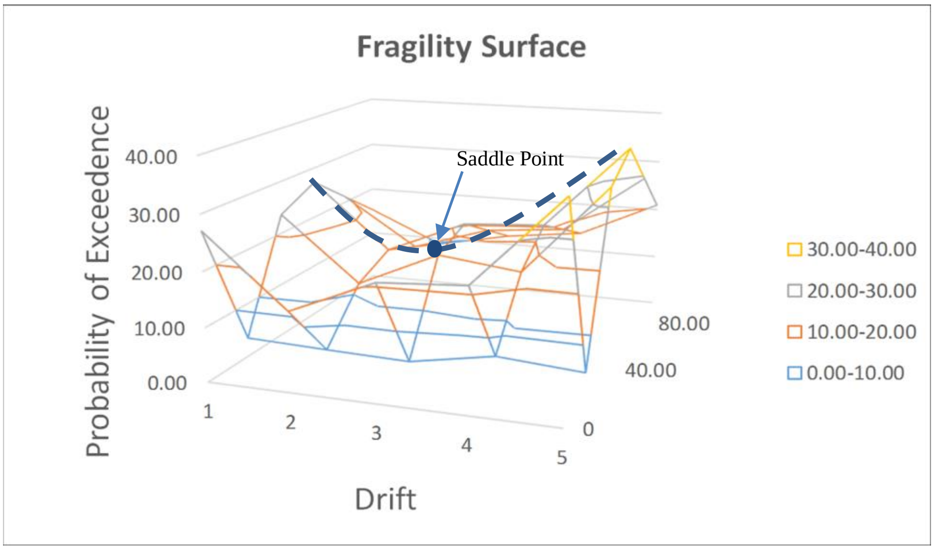

Figure 9. Fragility surface for Konak Mosque

5. Conclusions

In this study, structural assessment of Konak Mosque was discussed with detailed structural assessment approach. The historical building was modelled and analyzed through time history analyses under 10 different ground motion data using SAP2000 Finite Element Analysis software. The dynamic analyses were performed with-10 ground motion data to the historical mosque building. Three-dimensional FEM model was prepared for the analysis. The historical structures generally have very complex geometry. It is very difficult to reflect all geometrical shape. Therefore, simplifications were applied when preparing the structural model. Structural vulnerability of the structure was determined using a reasonable number of finite elements.

In the study, time history analysis and fragility analysis were carried out. As a result, the highest displacement, stress and base shear values occurred at Loma Prieta [G01090] earthquake, and the lowest displacement, stress and base shear values were occurred at Anza [AZF315] earthquake. Fragility analysis was carried out as a part of probabilistic risk assessment. Displacement exceedance probability values were determined by using time history analysis results, and accordingly fragility curves were sketched in two dimension and surface graph. Graphics were drawn by using exceedance probability corresponding to each displacement values. Fragility curve and surface were depicted. Saddle point was also determined as the optimum point.

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