XI International Conference on Textile Composites and Inflatable Structures
STRUCTURAL MEMBRANES 2023
C. Lázaro, R.Rossi and R. Wüchner (Eds)

DESIGNING A LARGE SPAN STRUCTURES UNDER SEISMIC LOADING – A CASE STUDY

STRUCTURAL MEMBRANES 2023

DR. FEVZİ DANSIK[*], DR. MELTEM SAHIN[†] AND NECATI C. SAMAT[††]

[*] Managing Partner at AG Tensioned Structures
Cihangir District Sehit Piyade Er Yavuz Bahar Street No:4/2/1
Mirabbo Industry Area Avcilar / Istanbul - TURKIYE
fevzidansik@asma-germe.com

[†] Lecturer at Mimar Sinan Fine Art University (MSGU)
Facutly of Architecture, Meclisi Mebusan Street Findikli Istanbul - TURKIYE
meltem.sahin@msgsu.edu.tr

[††] Project Manager at AG Tensioned Structures
Cihangir District, Sehit Piyade Er Yavuz Bahar Street No:4/2/1
Mirabbo Industry Area Avcilar / Istanbul - TURKIYE
caglarsamat@asma-germe.com

Key words: Acoustic, Amphitheatre, Case Study, Double Layer, Earthquake Resistant, Large Span, Lightweight System, Structural Membrane.

Summary. Structural membranes have become a frequently preferred system type in long span structures such as amphitheatres, stadiums, performance centres, sport halls, with their ability to cover long distances by lighter solutions. The membrane material, which is the main component of the lightweight structures including membranes and has sufficient strength together with stretching, has very low weight of around 1 kg per sqm compared with the conventional load bearing materials. This is very important feature, both aesthetically and economically. Its light weight does not only provide an economical solution, but also allows to have better structural performance under seismic loads. Besides its lightness, another advantage of membrane-covered structures such as the amphitheatre is acoustic performance, which is an important one for the structure to meet serviceability requirements.

In this paper, the amphitheatre in Hasan Kalyoncu University in Gaziantep - Turkiye was chosen as a case study to show the design process of the membrane roof covering system supported by steel trusses under severe earthquake threats. This amphitheatre had some challenging features with its 94 m wide span arch and 5000 sqm covered area. It suffered three major earthquakes measuring: the first one 7.7 Mw (Richter Scale), 11 minute later second one 6.6 Mw and the third one after 9 hours (Mw) on the 6th of February 2023. The amphitheatre is only 50 km south of one of the epicentres of the largest earthquake. There were nearly 6.000 aftershocks within 10 days of the first earthquake. It is a relieve to see that the structure has not

been affected. It was a relieve to see that there was no damage on the amphitheatre. However, the distraction effected 11 major cities, nearly 2 million people had to be relocated and more sadly around 45.000 people died. The devastation was catastrophic.

1 INTRODUCTION

The aim of this paper is to show the design, analysis, material selection, manufacturing and the installation process of large span structure with tensioned membranes and evaluate of the gains in a proper design and application under severe earthquake threats. The amphitheatre in Hasan Kalyoncu University in Gaziantep - Turkiye was chosen as a case study to show the design process of the membrane roof covering system supported by steel trusses under severe earthquake threats. The amphitheatre was completed in 2019. This amphitheatre had some challenging features with its 94 m wide span arch, covering 5000 sqm area and the last but not the least area and located close 63 km to the fault East Anatolian Fault which is one of the major faults of the world.

The tensioned membrane systems have started to become a new trend in structural engineering as aesthetic and lightweight construction systems for both architects and engineers. It is preferred by architects who do not like to see large cross-section structural systems with its ability to pass large openings by using very light materials, while its lightness features also ensure that it is economical sections.

The lightness is not only important for these reasons. At the same time, the membrane cover, which has a weight of around 1 kg per square meter, helps to reduce the earthquake loads that will act to the structure and to prevent the structure from being damaged under an earthquake.

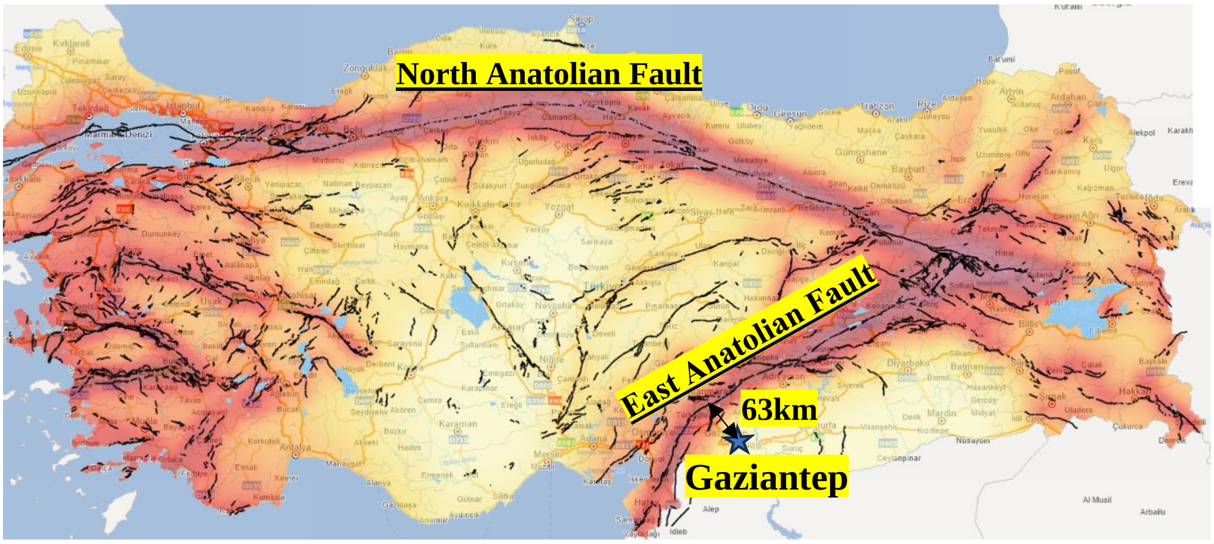


Figure 1: Turkiye earthquake hazard zones map and location of Gaziantep [1]

The amphitheatre in Hasan Kalyoncu University is in the city of Gaziantep located in South-East of Turkiye. This region is classified as the 3rd degree Earthquake Hazard Danger Zone, Figure 1 [1]. It suffered three major earthquakes measuring: The first one 7.7 Mw (Richter Scale), 11 minute later second one 6.6 Mw and the third one after 9 hours (Mw) on the 6th of

February 2023, Figure 2, [2]. The amphitheatre is only 50 km south of one of the epicentres of the largest earthquake.

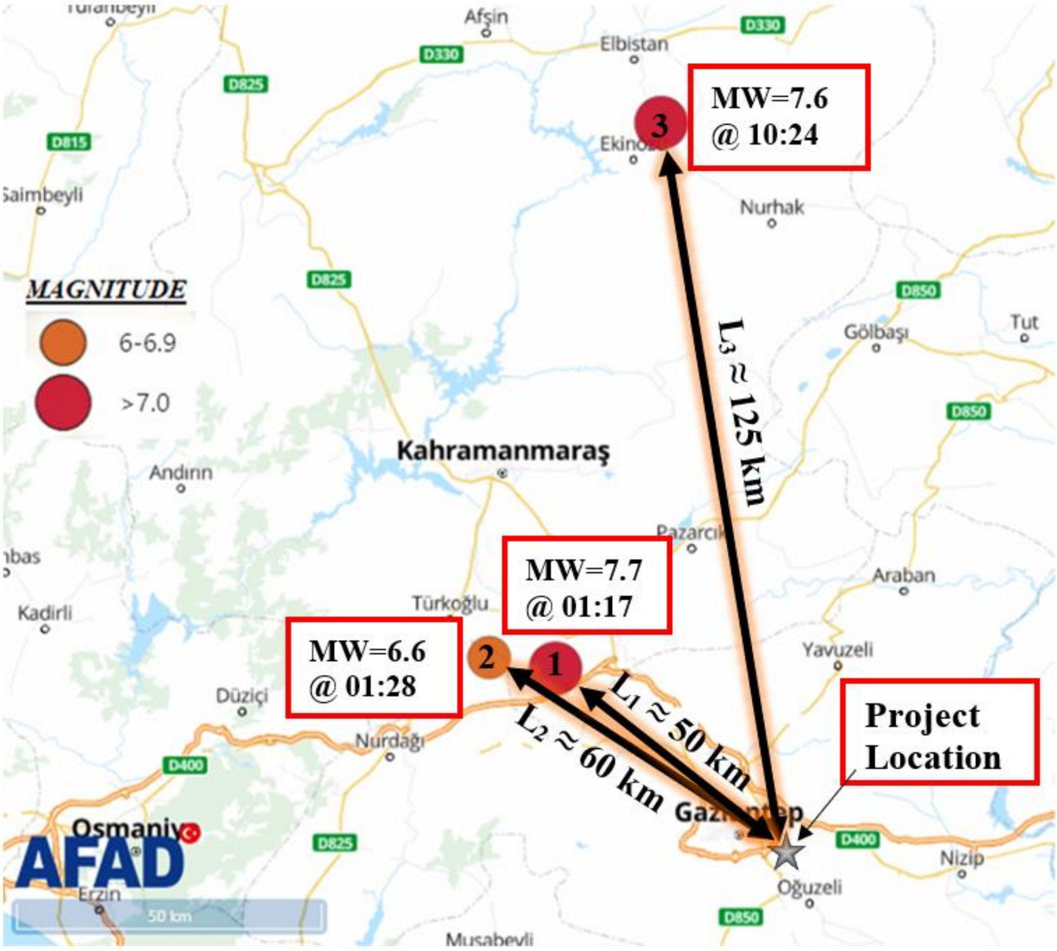


Figure 2: Earthquakes locations, time and distances to project location [2]

There were nearly 6.000 aftershocks within 10 days of the first earthquake, Figure 3. It is a relieve to see that the structure has not been affected. However, the distraction affected 11 major cities, nearly 2 million people had to be relocated and more sadly 45.089 people died [3]. The devastation was catastrophic.

These are followed by earthquakes with a magnitude of around 4.0 in this period and afterwards. The earthquakes, whose epicentres were Kahramanmaras and Elbistan, affected 11 provinces, including Gaziantep, 77 km from the epicentre. The social impact cannot be counted however according to the latest official information, 45.089 people have lost their lives. 1.971.589 people have been evacuated from Kahramanmaras, Gaziantep, Sanliurfa, Diyarbakir, Adana, Adiyaman, Osmaniye, Hatay, Kilis, Malatya and Elazig and registered by applying to the governorships and district governorships in the provinces at destination [3].

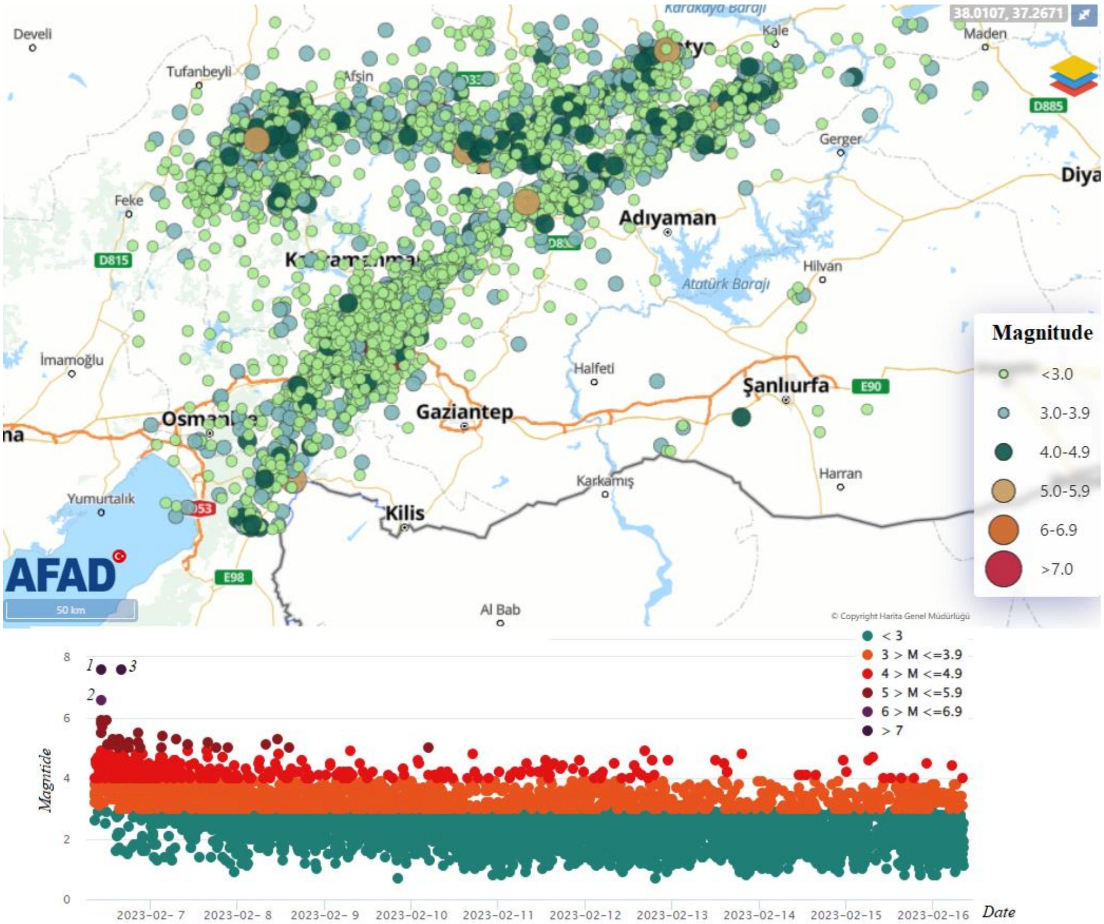


Figure 3: Earthquakes locations, time and distances

2 STUCTURAL SYSTEMS

Gaziantep is a traditional city that has hosted many different cultures and ethnic groups for centuries. It is a city with an architectural texture. Its location, its connection with Silk Road and Aleppo, and being on the trade route made the city an important centre in the past. Different morphological structures have been formed because of cultural, social and commercial life in the city. This differentiation, which is in the cities like Gaziantep where the concept of privacy is at the forefront, affects the residential and public structures of the city. It allows us to compare and understand the interaction of architecture and socio-culture [4]. The amphitheatre is very different from the morphological architectural texture in the ways of both material and form.

The amphitheatre belongs to Hasan Kalyoncu University was designed to serve the university for the ceremonies and performances. The capacity of the amphitheatre is 3000 spectators. It consists of two parts in plan. One is the audience part designed in the shape of oyster which the client insisted in this form, and the other one is the long and narrow part. The second part serves as both the entrance and the stage. The old design of the project is shown in Figure 4.

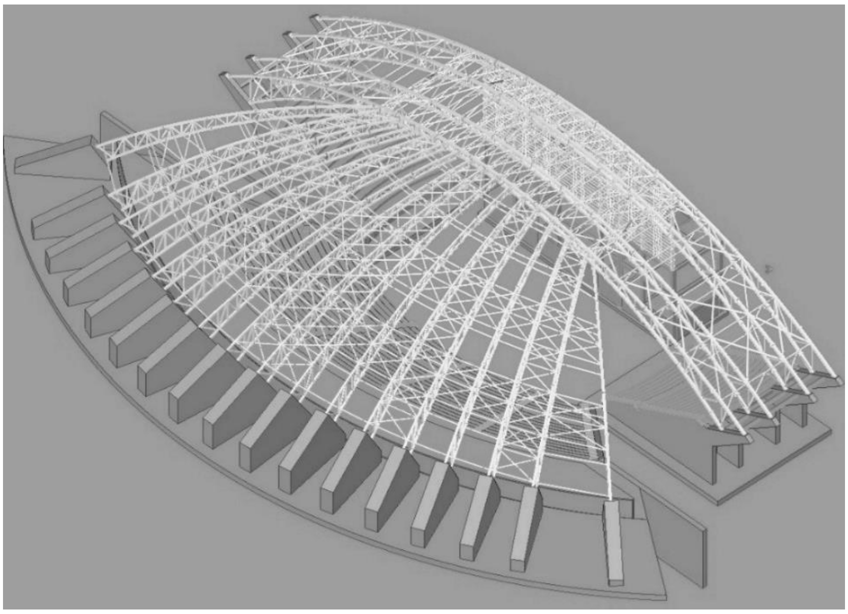


Figure 4: Perspective view of the old design

Although the first design is sufficient in terms of structural strength, it is not suitable for the tensioned membrane in terms of architectural aspects. Additionally, it has been predicted that the structural system can be solved more appropriately in terms of cost. In the old design, the structural system had been determined using linear analysis method with SAP2000 program. For the membrane material any pretension was not taken into calculations, the tensioned membrane material had been taken into calculations only with its weight in the analysis.

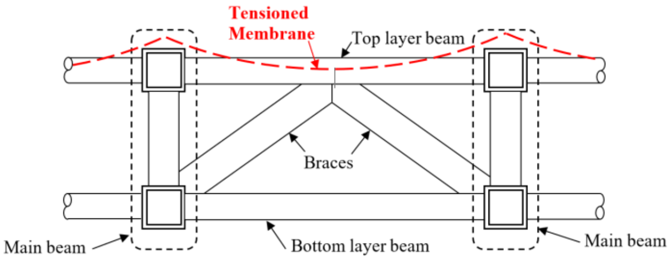


Figure 5: Typical section of structural system for the old design

The typical section of structural system for old design is shown in Figure 5. In this section, it is clearly seen that in the old design, the membrane will clash with the top layer beam when the tensioned membrane has equilibrium form with tension forces. Therefore, the need to revise the design has arisen, taking into account the criteria of economy, architecture and applicability. The design of typical section of structural system is revised as shown in Figure 6. In this way, it is aimed to prevent the tensioned membrane from clashing with the top layer beam and to form a triangular truss beam in terms of structural behaviour. The general view of the revised new design of the structure is shown in Figure 7.

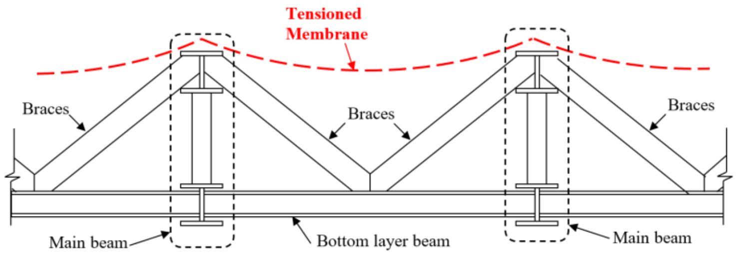


Figure 6: Typical section of structural system for the new design

The general view of the revised new design of the structure is shown in Figure 7.

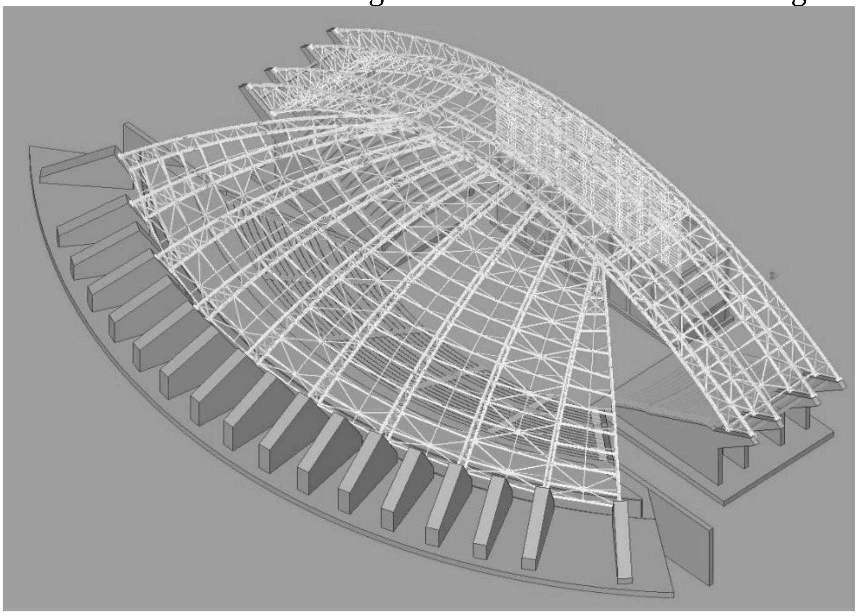


Figure 7: Perspective view of the new design

3 DESIGN CRITERIA

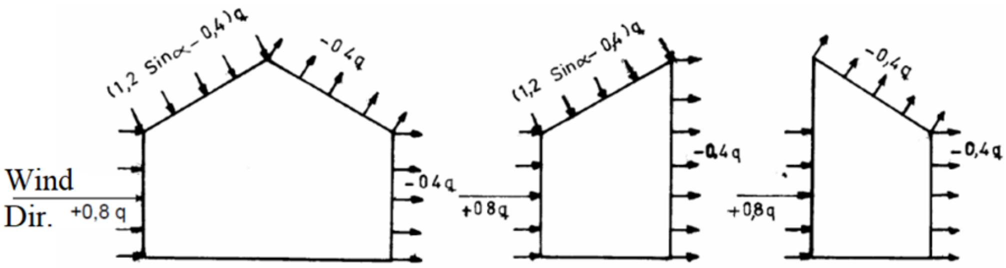
The amphitheatre structure consists of steel half dome roof, reinforced concrete tribune, stage, backstage and rooms under the tribune. Steel roof elements are designed with fixed support separately from reinforced concrete in the SAP2000 program, and the elements are modelled as bar elements. The codes and standards have been considered in the design are TS498 [5], TEC2007 [6] and TSC2018 [7]. According to codes the loads acting on the structure is listed below:

- Dead Load: Expresses the own weight of the structural system elements. It has been calculated by the program depending on the divisions and unit weights of the units in the analysis model.
- Additional Dead Load: Additional dead load values are given below:
  - Roof cladding = 0.2 kN/m²
  - Insulation = 0.1 kN/m²

- Lighting = 0.5 kN/m^2
- Chandelier = 15 kN (Point load)

- Roof Live Load: The roof live load has been taken into account as 0.5 kN/m^2
- Wind Load: Wind loads have been calculated compliant with TS498 as shown in Figure 8.

Height h	0 m	8 m	20 m	100 m
Peak Velocity Pressure	50 Kg/m^2	80 Kg/m^2	110 Kg/m^2	130 Kg/m^2



Height of strucure .... h (m) : **27.30** **m**

Peak Velocity Pressure..........q_w(kg/m^2) : **110** **Kg/m^2**

Figure 8: Wind load parameters

- Snow load: The snow load value for Gaziantep's region and altitude is 1.30 kN/m^2 according to TS498.
- Temperature Load: Due to temperature changes, ±30°C loading was applied to the structural elements. The coefficient of thermal elongation, A = 1.170E-05 is assumed.

4 CALCULATION of EARTHQUAKE FORCES

The earthquake forces are basically calculated as the horizontal force acting on the centroid of the system, which is the ratio of the weight of the structure and live loads by equation (5). The weight of the system is the main factor for the horizontal force since the live loads are defined by the location and the function of the structure. The less the weight, the less the horizontal force. The ratio is calculated by considering the period of the structure, the soil conditions and ductility which is referred as structural behaviour factor. The ductility of the structure is the main factor to reduce the design horizontal loading.

The earthquake forces have been calculated compliant with mode superposition method in TEC2007. In the mode superposition method, maximum internal forces and displacements are determined by the statistical combination of maximum contributions obtained from each of the sufficient number of natural vibration modes considered. According to TEC2007 the seismic design parameters as shown below:

Building importance factor (I) : The building importance factor has been given as 1.2 for the theatre and concert halls structures in the TEC 2007.

Zone of the structure in the seismic hazard map : As shown in the Figure 1, the structure is located in the 3rd degree earthquake hazard zone in the earthquake hazard map.

Effective ground acceleration coefficient, A_0 : For the 3rd zone the effective ground acceleration coefficient (A_0) is given as 0.2 in TEC2007.

Local site class : The local site class is Z2.

Spectrum characteristic periods, T_A,T_B: According to TEC2007 for Z2 local site class soils the spectrum characteristics periods T_A and T_B are 0.15 and 0.40, respectively.

Structural system behaviour factor, R : For the nominal ductility level and the buildings in which seismic loads are fully resisted by centrally braced frames the structural system behaviour factors (R) is given as 4.0 in TEC2007 which is the case for our case study.

The spectrum coefficient, S(T) : The spectrum coefficient S(T), shall be determined as shown in Figure 9 depending on the local site conditions and the building natural period, T.

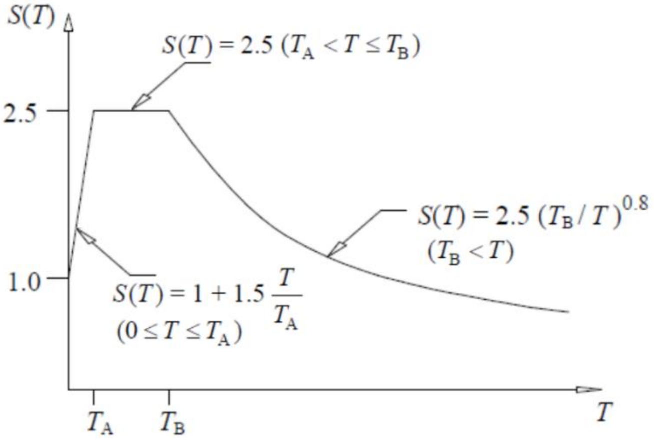


Figure 9: The spectrum

Spectral Acceleration Coefficient A(T) : The Spectral Acceleration Coefficient A(T) which is considered as the basis for the determination of seismic loads and it is shown in equation (1)

$$A(T) = A_0 \, I \, S(T) \tag{1}$$

Elastic Spectral Acceleration, $S_{ae}(T)$: The elastic spectral acceleration which is the ordinate of Elastic Acceleration Spectrum defined for 5 % damped rate is derived by multiplying Spectral Acceleration Coefficient with gravity, g as shown in equation (2)

$$S_{ae}(T) = A(T) \, g \tag{2}$$

Seismic Load Reduction Factor, $R_a(T)$: The seismic load reduction factor is shown below depending on structural system behaviour factor, R and the natural vibration period T and it is shown in equation (3).

$$\begin{aligned} R_a(T) &= 1.5 + (R - 1.5)\frac{T}{T_A} && (0 \leq T \leq T_A) \\ R_a(T) &= R && (T_A < T) \end{aligned} \tag{3}$$

Reduced Acceleration Spectrum $S_{aR}(T_n)$: The reduced acceleration spectrum ordinate has been taken into account in any nth vibration mode is determined by equation (4):

$$S_{aR}(T_n) = \frac{S_{ae}(T_n)}{R_a(T_n)} \tag{4}$$

The graphic for the calculated the spectrum coefficient S(T) and the reduced acceleration spectrum $S_{aR}(T_n)$ are shown in the Figure 10.

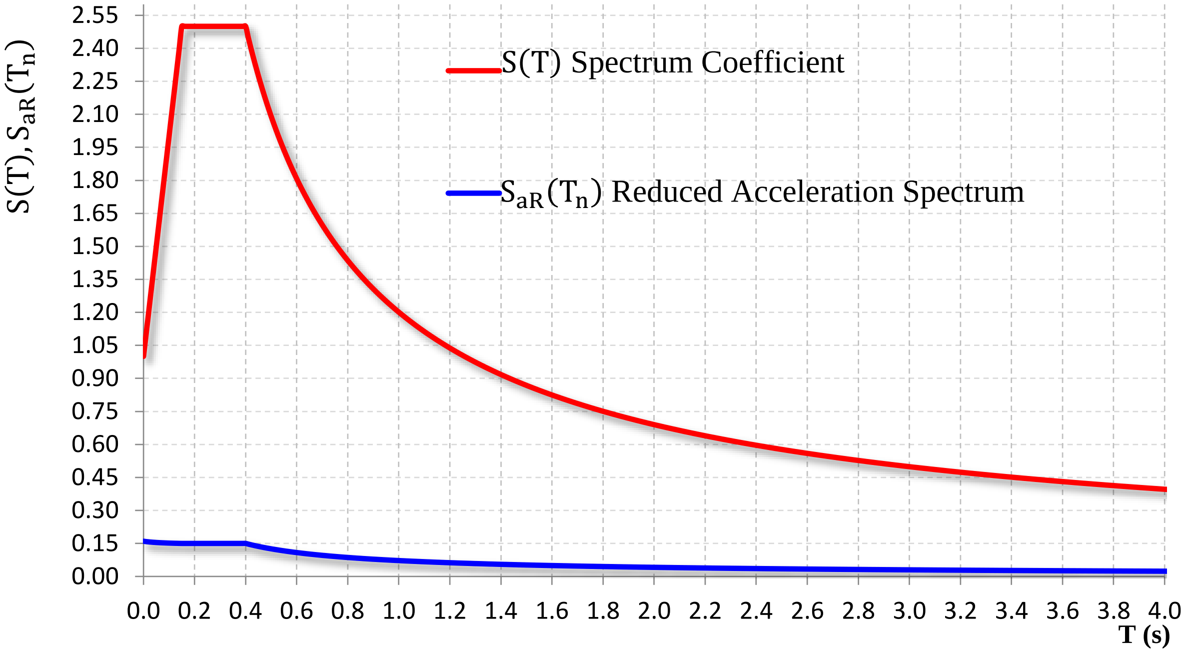


Figure 10: The response spectrum and reduced seismic response coefficient.

The first mode of the structure is calculated as 0.40 s which corresponds the maximum spectrum in the graphic in Figure 8.

Total base shear, V_t, acting on the entire building in the earthquake direction considered shall be determined by equation (5).

$$V_t = \frac{WA(T_1)}{R_a(T_1)} > 0.10\, A_0 I\, W \tag{5}$$

Here, T_1 is the first natural vibration period of the building and W which is determined by equation (6) is the total building weight.

$$W = \sum_{i=1}^{N} g_i + nq_i \tag{6}$$

Here, n represents the live load participation factor and for the considered structure its value is 0.3, g represents the dead loads; q represents the live loads; N represents the total floor number. For the amphitheatre structure, the total dead load is g = 4218 kN, the total snow load is 6315 kN and the total roof live load 2757 kN. Hence using equation (6) the building weight W can be calculated as W = 4218 kN + 0.3*(6315 kN + 2757 kN) = 6940 kN. Multiplying by total building weight W and reduced acceleration spectrum value, $S_{aR}(T_n)$ corresponds to the total base shear forces of earthquake loading V_t. The first natural vibration period T_1 is 0.4 s, hence the reduced acceleration spectrum value, $S_{aR}(T_n)$ calculate as 0.15. The total base shear force of the earthquake loading, V_t equals to 6940 kN * 0.15 = 1041 kN. Since the first natural vibration periods in x and y direction of the structure correspond the maximum spectrum values in the graphic in Figure 10. Therefore, the same value is obtained for the total base shear in the x and y directions as 1041 kN.

5 LOAD COMBINATIONS

The design of structural elements has been done allowable strength design (ASD) procedure in TSC2018. Hence the load combinations have been determined compliant with TSC2018 as shown below:

Load Combinations

- 1.0 D
- 1.0 D + 1.0 L
- 1.0 D + 1.0 S
- 1.0 D + 0.75 L + 0.75 S
- 1.0 D + 1.0 W
- **1.0 D + 0.7 E**
- 1.0 D + 0.75 L + 0.75 S + 0.75 W
- 0.6 D + 1.0 W
- **0.6 D + 1.0 E**
- 0.6 D + 1.0 T

Load Cases

- D : Dead Load
- L : Live Load
- W : Wind Load
- S : Snow Load
- E : Earthquake Load
- T : Temperature Load

6 RESULTS

The first, the structural membrane part is analysed by using EASY. Then, the structural steel is imposed with the resulting tensioned membrane reaction. Finally, the structural system is analysed with the calculated earthquake force by using SAP2000.

It was interesting to see that the main effect for the element design is not the load combination with the earthquake forces despite the structural period corresponds to the maximum spectrum value. The dominant effects the load combination with temperature. This is due to the arch spanning 94 m and the arch length is 110 m.

The weight of the new structural system was calculated as 572 tons. The weight of the old project was 753 tons. This means that there is a decrease nearly 32%.

The total base shear forces of earthquake loading, V_t equals of the new system is 1041 kN. This horizontal force was 1230 kN. This means that there is a decrease nearly 19%.

The effects of the significant decreases above can be outlined as follows:

- The horizontal forces due to the earthquake are decreased.
- The cost of the material supply is decreased.
- The crane capacities for the installation are decreased and hence the cost.
- The fabrication time is decreased and hence the cost. Time is money.
- The environmental impact is decreased.

Table 1: The weights of the old and new design.

	Old Design	**New Design**
Profiles	517 tons	423 tons
Plates	227 tons	131 tons
Secondary Steel	9 tons (*)	9 tons
Total	753 tons	572 tons

(*) This was not considered in the old design. Hence, this amount is assumed to be the same as the new.

The ratio the dead load to the total life load can be considered as a parameter of the effectiveness the structural system. Let this ratio be referred as 'Effectives Ratio' and denoted with 'ER' in the context of this study:

$$ER = D / (0.75\ L + 0.75\ S + 0.75\ W)$$

The dead load of the structure is 572.000 kg / 5.000 m2 = 150.6 kg/m^2.

$$ER_{old} = 150.6 / (0.75x50 + 0.75x130 + 0.75x\ 100) = 0.717 < 1$$

The dead load of the structure is 572.000 kg / 5.000 m2 = 114.4 kg/m^2.

$$ER_{new} = 114.4 / (0.75x50 + 0.75x130 + 0.75x\ 100) = 0.544 < 1$$

The interpretation of the above is that only %54.4 of the structural elements are carrying their self-weight for the new design. On the other hand, 71.7% of the structural elements are carrying their self-weight for the old design.

It should be noted that that the amount of the secondary steel is 1.8 kg/m^2 which is considerably lower than most of the covering material available in the market. The membrane material has sufficient strength together with stretching to span longer distance without need for additional support while covering the structure.

Figure 11: HKU Amphitheatre Gaziantep – TURKIYE

12 CONCLUSIONS

Structural membranes have become a frequently preferred system type in long span structures such as amphitheatres, stadiums, performance centres, sport halls, with their ability to cover long distances by lighter solutions. Their performance under the earthquake was investigated a case study for the amphitheatre in Hasan Kalyoncu University in Gaziantep - Turkiye which suffered major earthquakes without any damage.

This case study demonstrates that the long span structure with structural membranes under earthquake effects can perform quite well and stand still. This is only possible with proper design codes and well understanding of the behaviour of the structural components.

It has also been possible to illustrate that optimum solution can be obtained by material behaviour and making small changes on the configuration of the structural elements. This has been done by comparing the existing design and the once developed by the authors.

The gain was significant for the structural system but the lost was catastrophic for our nation. The healing of the nation will take many years to come.

This paper is dedicated all the souls lost, psychologically and physically injured people in the earthquake on the 6th of February 2023.

REFERENCES

[1] Earthquake Zones Map., 1996., Settlement Government of Republic of Turkey.

[2] https://deprem.afad.gov.tr/event-catalog , website, visited on 2023-06-22.

[3] Press Bulletin, 01.03.2023, About the Earthquake in Kahramanmaras – 36, https://en.afad.gov.tr/press-bulletin-36-about-the-earthquake-in-kahramanmaras

[4] Gurbuz Yıldırım, E., & Cagdas, G., (2018), “Space Syntax Analysis of Traditional Architectural Pattern of Gaziantep in a Socio-Cultural Context, Gaziantep University Journal of Social Sciences, 17 (2), 508-532, Submission Date: 24-10-2017, Acceptance Date: 26-03-2018.

[5] TS498 – 1987. Design Loads for Buildings

[6] TEC2007 - Specification For Structures To Be Built In Disaster Areas, 2007, Ministry of Public Works and Settlement Government of Republic of Turkey, Turkish Earthquake Code 2007.

[7] TSC2008 - Design, Calculation and Construction Principles Of Steel Structures, 2018, Ministry of Public Works and Settlement Government of Republic of Turkey.