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De-propping Analysis of Izmir Adnan Menderes Airport New Domestic Terminal Barrel Vault Roof with Structural Health Monitoring System

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Abstract

Izmir Adnan Menderes Airport New Domestic Terminal Roof has been designed and built in single layer barrel vault form having free span length of 72 m. The structure has been reinforced by 7 tension rods to provide arching effect. Roofing structure is composed of two types of uniform box profiles having dimensions of 400×600×14 mm and 400×600×16 mm. The single layer geometry of the roof has tendency to deflect if it is not supported properly with temporary props which need to be located in proper positions and having sufficient capacity to carry loads acting on it. Therefore, temporary supporting steel props were used in order to provide appropriate and stable conditions during installation works.

All propping and de-propping sequences are determined based on structural analysis performed for temporary supporting systems during installation in order not to subject to excessive deformations and overstresses. The Structural Health Monitoring System (SHMS) is used in order to follow up general structural behavior of the roofing structure both during installation stages and also for long term structural performance of the roof. SHMS system is also used very beneficially during de-propping stages of the installation works. As the temporary props are removed, neighboring props receive higher loads and arching effect on roofing structure starts to be active. Temporary props are removed sensitively as per the data obtained from SHMS by measuring loads acting on tension rods in barrel vault roof, which is a good indication of the arching effect. General SHMS system applied on the roofing structure and particularly its benefits during the de-propping operations of the temporary supports will be explained within the scope of the study. The main goal of the study is to present the implementation of the data obtained from the SHMS on real civil engineering practice.

Keywords: Structural Health Monitoring, structural analysis and design, de-propping, installation.

1. Introduction

Polarkon Metal Structures Co. (Polarkon) is a design & build company that specializes on space frame and conventional steel structures having long clear span lengths. After its establishment in 1995, several critical structures have been completed successfully with special engineering solutions. Polarkon developed its own structural health monitoring system in order to monitor critical structures it has designed and built. SHMS used in Izmir Airport Domestic Terminal Building is also an in-house monitoring system developed by Polarkon Engineers under the supervision and consultancy of Prof. Dr.

Ahmet Türer from the Civil Engineering Department of the Middle East Technical University, Ankara, Turkey.

In parallel with the growing demand for airlines passenger transportation, numerous new airport terminals have been constructed, and many existing terminals have been renovated throughout Turkey over the past decade. This study primarily focuses on barrel vault roof of new domestic terminal building in Izmir Airport, which stands as the second-largest domestic terminal building in Turkey after Istanbul Grand Airport. Polarkon was responsible for undertaking the structural design of steelwork which include developing all structural details and their calculations, shop drawings, and executing fabrication and installation of the barrel vault roof. Total duration for fabrication and installation took approximately eight months. However, the entire project spanned more than a year, starting from structural detailing to completion of the finishing works. A real time long term Structural Health Monitoring System (SHMS) was also designed and applied by Polarkon in order to follow up structural performance of the barrel vault roof.

The single layer barrel vault roof was installed with temporary supports having sufficient capacity to prevent excessive deflection of the roof structure during installation period. All propping and de-propping sequences were determined based on structural analysis performed for temporary supporting systems. Specifically, de-propping analysis and its investigation with the aid of SHMS are explained within the scope of current study. As the temporary supports are removed consecutively during installation progress, the gradual increase of the tensile load acting on rods is presented based on the data obtained from SHMS.

2. General Information for Barrel Vault Roof

Barrel vault steel roof has single layer lattice shell architectural geometry with plan dimensions of 75 m by 201 m. The overall structural stability of the system having a critical span length of 72 m is provided by four funnel structures and seven tension rod systems placed in between funnels. Roofing structure is supported on reinforced concrete beam in each six meter in longitudinal directions in addition to funnel connection supports. Single layer roofing structure is designed by uniform 400×600 mm box profiles. Unique bolt connection detail is developed for connections for the purpose of hidden connection requirement which comes from architectural constraints. Total number of members and connection are 1752 and 829, respectively. The general perspective and sectional views are presented in Figure 1.

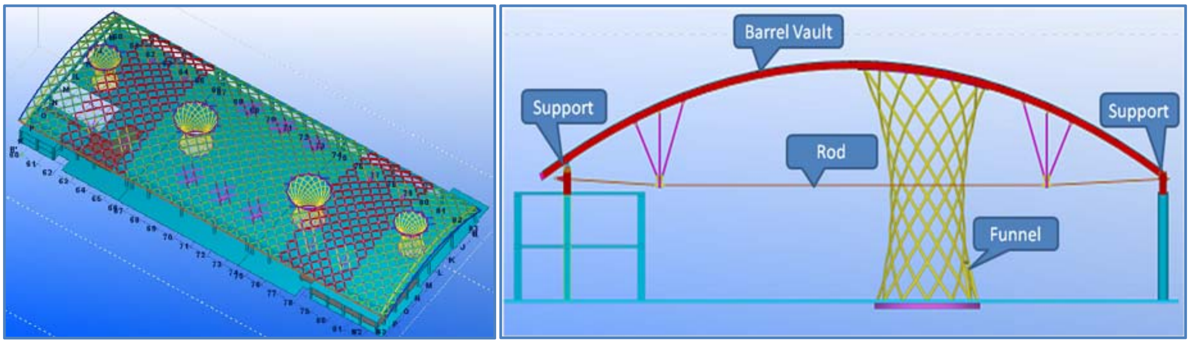

Figure 1: Perspective and sectional views of barrel vault roof

2.1. Typical Connection Detail

The typical connection detail is the most repetitive connection which exists in the intersection joint of four rectangular box sections. Bolt connection alternative is preferred which results in more precise geometry and more reliable connection mechanism. However, architectural constraints prohibited the use of visible bolted connections visible to people inside the airport. Due to lack of enough space inside the rectangular boxes to create moment arm in between outermost bolts, limited connection capacity can be obtained using conventional end plate connection. Therefore, special connection detail is developed by Polarkon's engineers and applied from inside the rectangular box sections. A cross member is inserted in between end plates which contribute to an additional 60% bending moment capacity as compared to equivalent connection detail in the absence of cross members. General geometry of the connection is illustrated in Figure 2. An access window is opened at the top chord of rectangular box section in order to connect and tighten the bolts at connection. A cover plate is welded on top of access windows at site to preserve structural performance of connecting members.

Figure 2: Typical connection detail

2.2. Installation of Barrel Vault Roof

Single layer geometry of the barrel vault roof has a tendency to deform during installation which creates additional problems to obtain precise barrel vault geometry. The structural system can start to contribute carrying vertical loads after reaching full arch geometry at initial stages of installation. Since a slice of arch roof having a length of 72 m cannot be lifted up with a mobile crane in a single operation due to site conditions, stability problem exists until reaching both supports in longitudinal axis. Although the first arch slice starts to carry primary vertical loads, its capacity still is not sufficient to carry its total own weight in the absence of tension rod members. Therefore, propping system is required during all installation stages. Furthermore, minimum tolerances used in fabrication is the another source of difficulty during bolting and positioning of members. In order to overcome installation problems listed above, a space frame scaffolding system is designed below the roofing structure as shown in Figure 3.

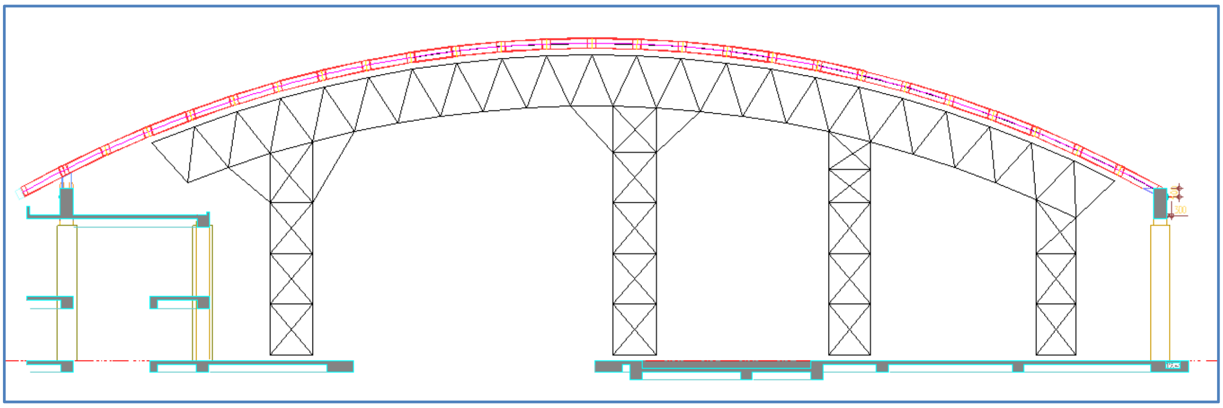

Figure 3: Typical sectional view space frame scaffolding and barrel vault roof

The roofing structure installation proceeds on temporary prop systems beyond space frame scaffolding. Single prop systems were used in between funnels whereas additional surrounding space frame systems were installed for funnel regions (Figure 4).

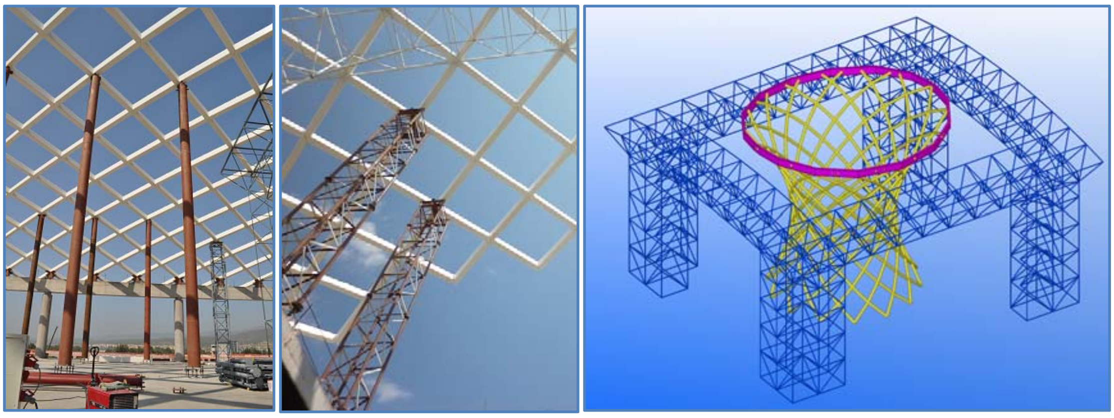

Figure 4: Propping system used in between funnels (single props) and in the periphery of funnels (space frame)

2.3. Tension Rods

Tension rods are the most critical structural elements of the barrel vault roofing system which have no redundancy against any means of failure. Tension rods are used to activate arch effect in the region in between funnels where reinforced concrete substructure is not sufficient to develop lateral forces to create required arch effect by itself. Seven solid tension rod systems are used having a diameter of 85 mm, which has identical elastic modulus with conventional steel. Typical tension rod system implementation is shown in Figure 5. Tension rods system composed of members having approximately 10 m lengths are connected to each other by appropriate couplers and turnbuckles. All tension rods are pre-tensioned by 45 tons with special hydraulic jacks as presented in Figure 5 in order to activate proper working mechanism in between tension rods and barrel vault roof.

Figure 5: Typical tension rod system in the project and pretension application

2.4. Structural Health Monitoring System (SHMS)

A real time, long term, SHMS has also been designed and applied by Polarkon in order to follow up structural performance of the barrel vault roof. To address this issue, pancake-type load cells are installed on the tension rod system to continuously measure the axial loads acting on tension rods at 15-minute intervals. Data acquisition unit located at site, collect data from load cells and transmit it to data base in central server through internet connection. The relevant data is retrieved from the server database with web-based software to present the information for the users in required format, such as user defined tables and graphs. The basic idea behind SHMS implementation can be outlined as follows;

i. Evaluation of the barrel vault roof as a critical structure, attributed to its single-layer lattice shell geometry and a critical span length of 72 meters.
ii. Comparison between theoretical values and on-site measurements to validate the precision of fabrication and installation processes.
iii. Assessment of the impact of cladding installation and the de-propping of temporary support systems on the structure's stability.

iv. Verification of the operational efficiency of specialized connection details developed for this project.
v. Examination of the long-term structural behavior trends of the barrel roof for ongoing monitoring purposes.
vi. Analysis of the potential permanent effects of catastrophic events on the barrel vault roof through comparative analysis of data collected before and after such events.
vii. Implementation of an early warning system through software to promptly identify any potential failures resulting from severe loading or unexpected events.

3. De-propping

The installation of the barrel vault roof was carried out on temporary supports due to the sensitivity of the single layer geometry of the roof against deflection. Additional space frame scaffolding system was also used around funnel structures due to the delay in installation of funnels which was undertaken by another subcontractor. Total 54 single props and 6 space frame scaffolding system were used during the entire installation period of the project which is also presented in plan view in Figure 6. Single props are designated with numbers from 1 to 54 whereas space frame scaffolding systems are indicated with SF1 to SF6. The props designed with circular pipes are shown with circles in Figure 6. The rectangles refer to the tower type of temporary support.

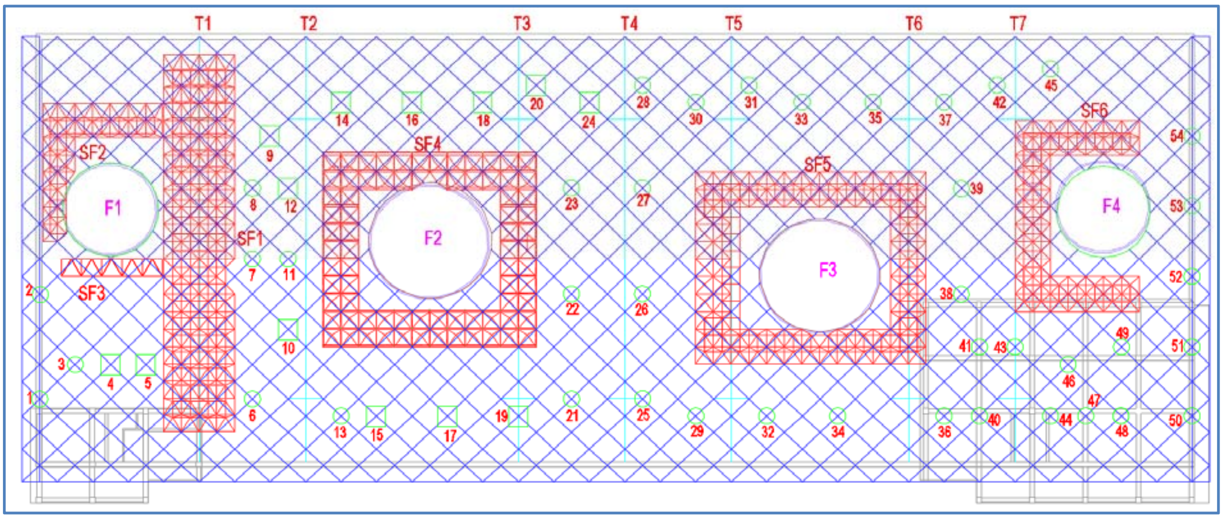

Figure 6: Prop layout of the roofing structure

De-propping stages for a typical circular prop is shown in Figure 7.

Figure 7: De-propping of typical circular prop

The de-propping analysis is carried out in two phases. The structural analysis is conducted through the analysis software for each prop removal stage in the first phase. On the other hand, the tensile loads acting on tension rods are measured with the load cells installed on tension rods at site in the second phase. As per the de-propping scenario, deflection in roof, compressive load acting on neighboring props and point load acting on concrete slab are calculated during Phase 1. All these parameters are studied in detail during the computer analysis conducted in Phase 1. The de-propping scenario is altered if any of the parameters mentioned above exceed the predefined limits. The maximum deflection of the roof during de-propping stages is provided below obtained from structural analysis results on computer. As expected, the maximum deflection increases as the props are removed.

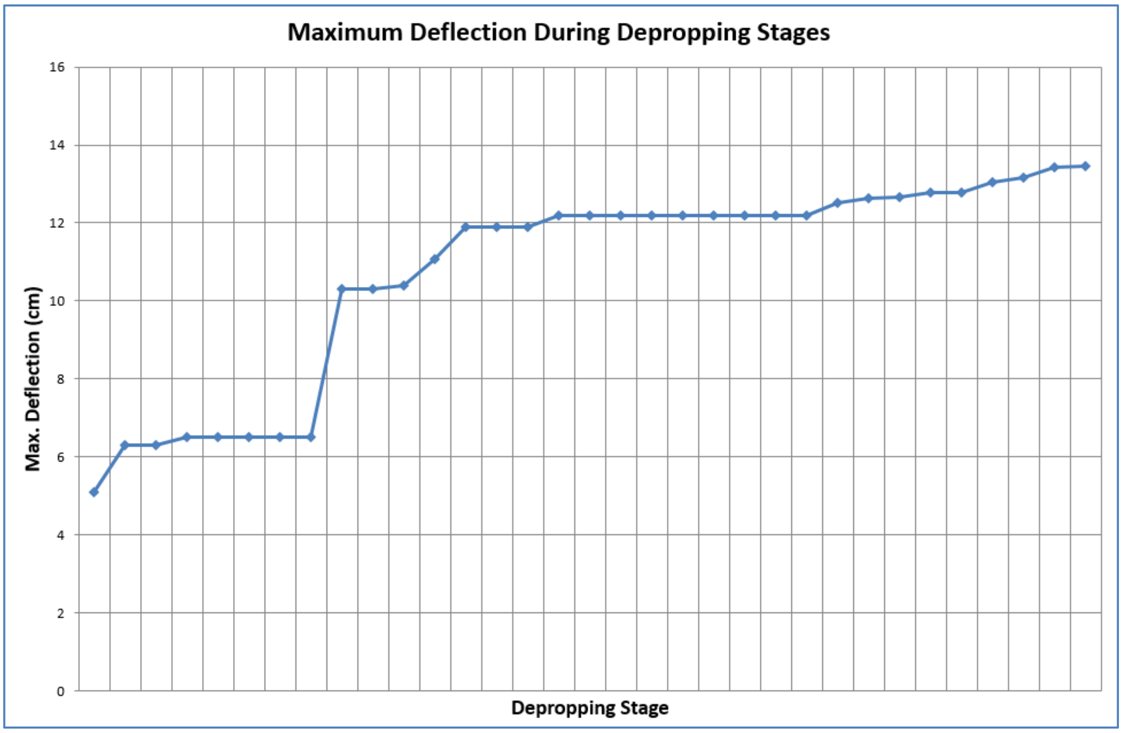

Figure 8: Maximum deflection results obtained from structural analysis results (without cladding)

The tensile load acting on tension rods are also measured at site with load cells which are collected by the SHMS. Tensile load acting on tension rods is an important indicator for the development of the arching effect which is the required structural behavior expected from the barrel vault roof geometry as per the structural design consideration. In a simplified approach, a force couple is expected to be developed between the main structural members in roof and tension rods. This coupling can effectively resist significant bending moments arising from gravitational loads acting on the roofing structure. Compressive force acting on the main roof members and the tensile force acting on tension rods create resisting bending moment due to the long force couple distance. Slender structural members can be designed with the aid of the related arching affect generated by tension rods. Load cells are installed on tension rods T2, T3, T4, T5 and T6 referring to the notation provided in Figure 6 at the first stages of the work. Tensile load acting on T2 is measured during all the de-propping stages, which is presented in Figure 9. As seen on the graph, tensile force acting on T2 is not changed within the first stages of de-propping works due to 45 tons initial pretension force. In other words, removal of a few props at the first stages do not generate tensile load on the T2 exceeding pretension load. As additional props are removed, causing an increase in tensile force on the tension rod, the tensile force starts to increase. It is also observed from the below graph that the tensile load increases very slightly during the latest stage of de-propping work, i.e. after 85 tons tensile load. This is primarily due to the removal of props, located far from T2 with minimal impact.

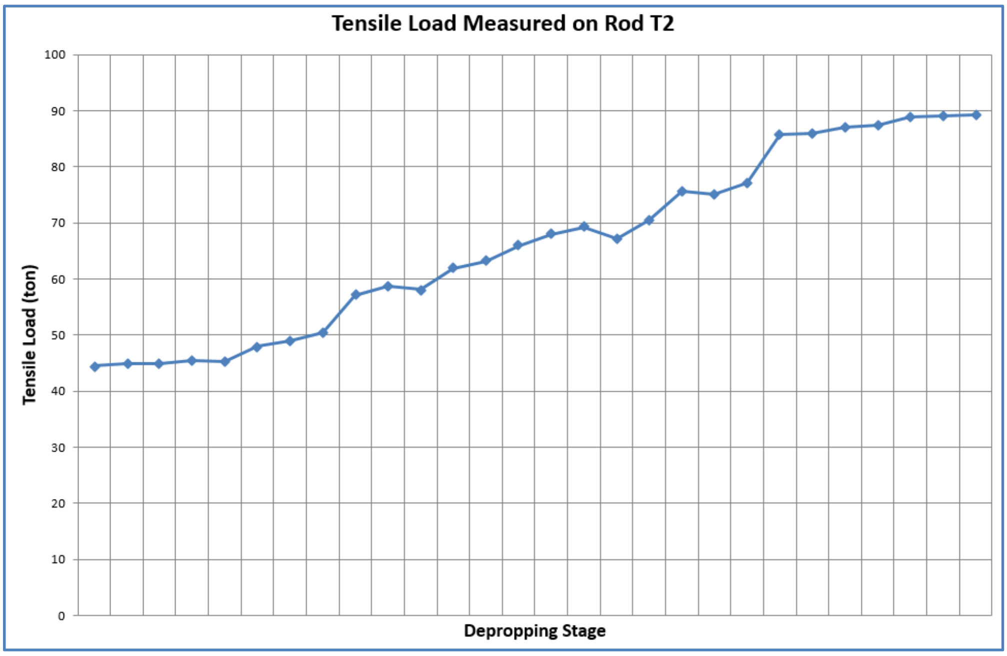

Figure 9: Variation of tensile loads acting on T2 during de-propping stages (without roof cladding)

After the completion of the structural steel and the cladding installation works, a comparison has been made between results obtained from the measurements at site and the theoretical structural analysis, presented in Figure 10.

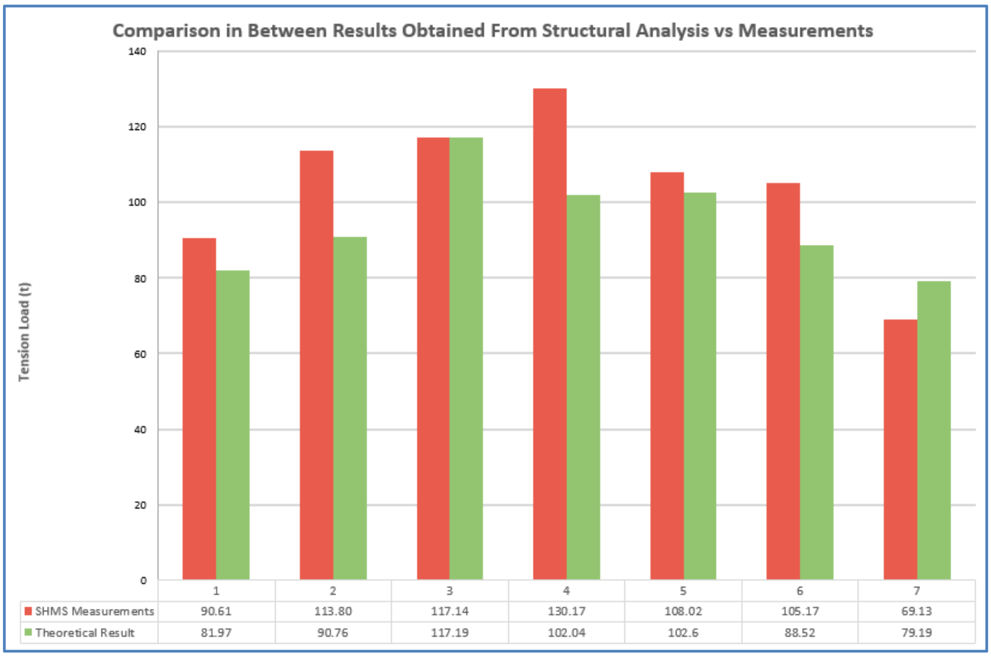

Figure 10: Comparison in between results obtained from SHMS and theoretical results (with roof cladding)

As seen in Figure 10, results obtained from both studies are fairly consistent. The reasons due to minor differences between both results can be summarized as follows;

i. The cladding loads considered in the structural analysis is slightly different than the actual values, especially due to the randomly distributed glass skylight create and the non-uniform cladding load (that is considered uniform in structural analysis)

ii. The internal temperature of the tension rods is different for seven rods which are far from each other and some tension rods are exposed to direct sunlight due to partial glazing on the roof
iii. The installation of tension rods and the de-propping of temporary supports one by one result in a noticeable variation in load redistribution, compared to the ideal conditions modelled in the structural analysis model.
iv. The tolerances on the reinforced concrete structure is also another reason for the variation in tension loads.

4. Evaluation of Long Term SHMS Results

SHMS continues to collate online data after the completion of steelwork installation. The variation of the tensile force acting on tension rods is presented in Figure 11 for eight-day period after the completion of the cladding works. It is observed from the below graph that the tensile load varies similar to sinusoidal waves during each day interval due to temperature variations within a day.

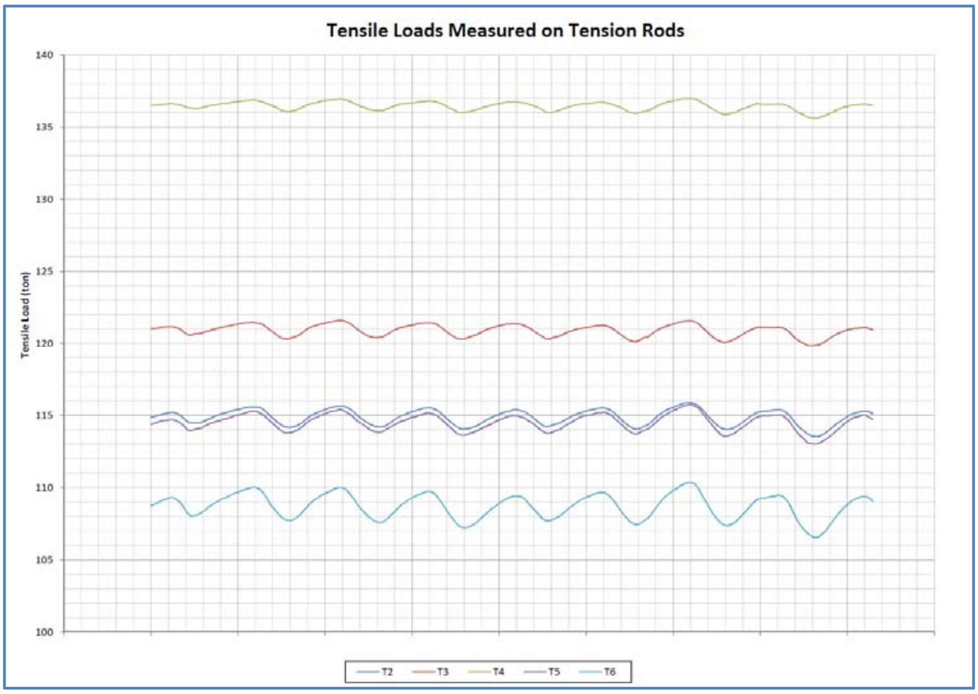

Figure 11: Tensile loads variation on tension rods

A closer look of tensile load versus temperature variation is also presented in Figure 12 by reducing upper and lower limits, amplifying the variations. It is clear that the tensile force acting on the tension rod is inversely proportional with the temperature. As the temperature increases tension load decreases and on the contrary, as the temperature decreases, tension load increases. Although the changes in tensile load are less than 2% compared to its original load value, temperature variation is also very low due to the climatic environment of airport terminal. As seen from the axis on the right-hand side, temperature variation does not exceed 3°C which means higher temperature variation might create non-negligible effect on tension rods. Long-term variation of the tensile forces acting on the rods is also presented in Figure 13 based on approximately three-year intervals. Approximately 5% fluctuation is observed in tensile forces due to seasonal variation of temperature between summer and winter. It is also worth noting an intriguing peak, indicated by the red circle on the graph, where there is a sharp increase in tensile forces (approximately 8%). It was cross-checked with the weather records for the relevant territory, and it was discovered that there was a snowfall on that specific date, which happened to be the only snowy day in Izmir City throughout the three-year recorded period. This is also an important indicator, illustrating the proper functioning of the SHMS. Furthermore, stationary horizontal behavior of tensile loads with relatively minor fluctuations during three-year period gives at least a general information about stability of structural performance of the roofing structure. Even minor changes in the design loads and structural system can be noticed from the data collected by the SHMS.

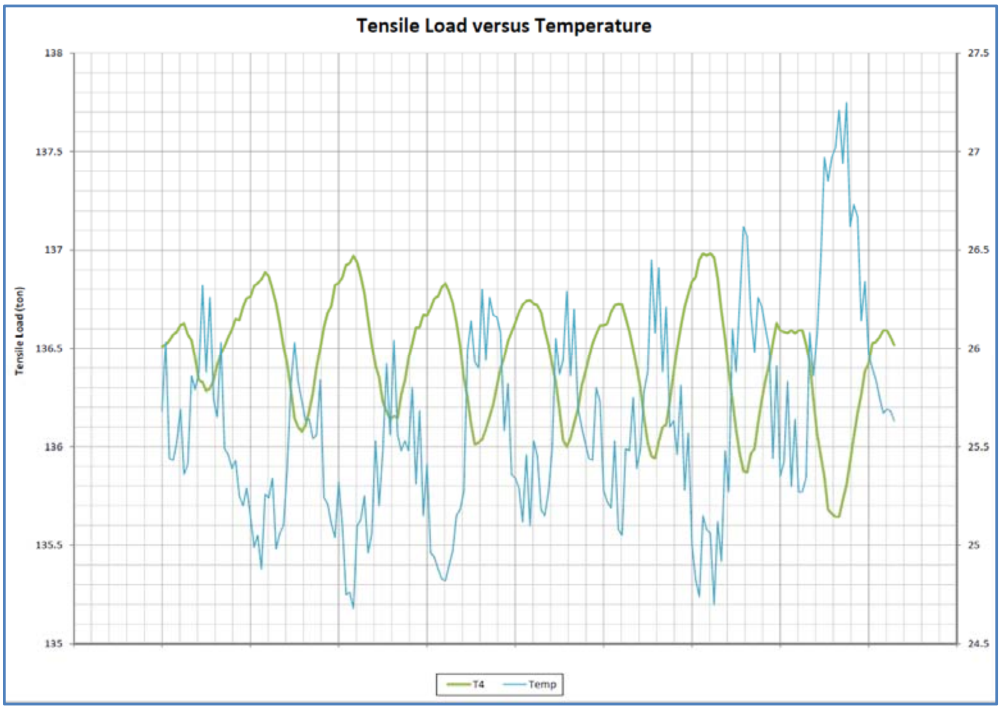

Figure 12: Tensile loads variation on tension rods versus temperature

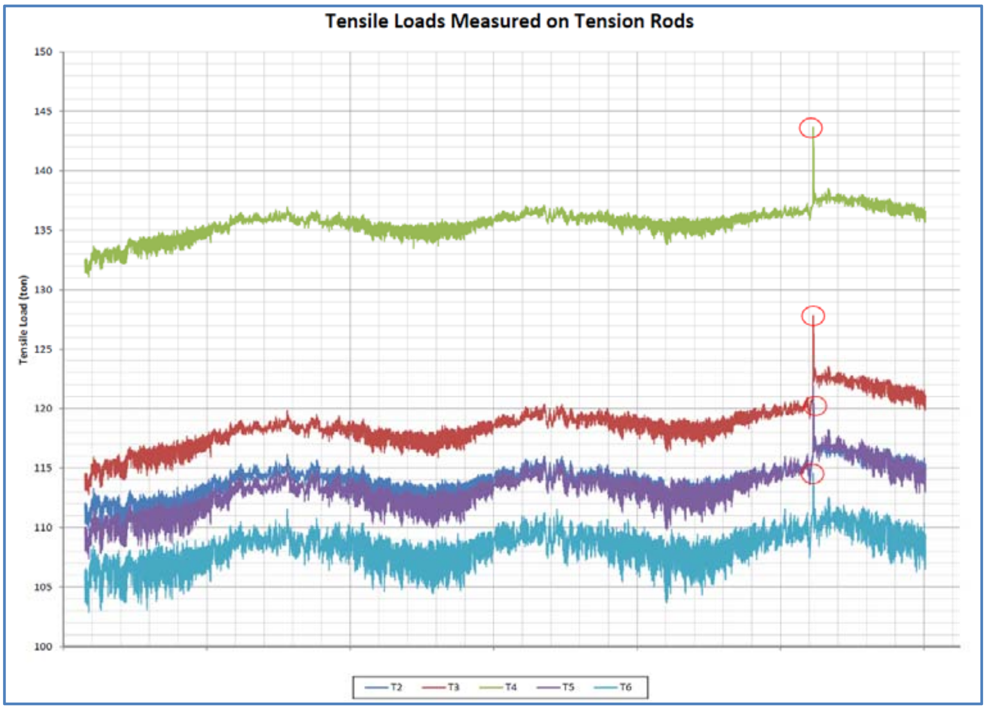

Figure 13: Tensile loads variation on tension rods for the three-year period

5. Conclusion

Izmir Adnan Menderes Airport Domestic Terminal Building Barrel Vault Roof Project was successfully completed by addressing numerous engineering challenges, from the initial design phase to the final installation process. The single layer roof passing a critical span length of 72 m with special connection detail primarily distinguish current structure from conventional steel roofing structures. A general view of the airport terminal building after the completion of the project is provided in Figure 14 below.

Figure 14: General outside and inside views from the completed project

The project's notable features include the detailed analysis of propping and de-propping sequences, alongside the implementation of structural health monitoring. These aspects represent modern and innovative applications in civil engineering structures. In summary, the following have been achieved with the applied monitoring system:

a. Tensile loads acting on tension rods are monitored with SHMS during de-propping stages which provide detailed information about general structural behavior of the steelwork.
b. De-propping works were conducted with direct control where improper implementation might have resulted in several failures such as progressive buckling of temporary supports, failure in concrete slab due to excessive concentrated load, irreversible deflections, etc.
c. The SHMS data has also been collected after completion of the installation works through online communication channels. Tensile load variation is observed under long term intervals which provide very useful information about the structural performance of the building in long term.
d. Correlation between temperature and tensile loads acting on rods have also been investigated. Although its impact on tensile load seems is relatively minor under climatic environments with low temperature variation, significant changes might be observed under high temperature variations.
e. Possible permanent deformations on structure can also be detected with the SHMS if the structure is subject to severe outside forces such as heavy snowfalls, earthquake, etc.

With this study, we aimed at briefly introducing all these modern applications to the civil engineering society. In our view, the engineering methods applied in this particular project provide novel insights and ideas for future (and challenging) steel structure projects.