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Structural Analysis Comparing The Minarets of The Selimiye Mosque with Ince Minaret Madrasa

By

H. A. Erdogan* M. E. Basar* R. Sezer** N. Kara**

Abstract:

The Anatolian Seljuk's Minarets exhibit similar characteristics with the Classical Ottoman Minarets and are more slender and completely all parts built in comparison with the minarets of the period before Anatolia. The footing element of minarets not seen at the Turkish Minarets before Anatolia has been first seen at the minarets of the Anatolian Seljuks. The footing element is a transition part providing and softening the structural transition between the wider cubic pedestal and the more slender polygonic or cylindrical body, also integrates the two structural parts statically and visually, and additionally assists the minaret to stand against the earthquakes. All parts of minaret were reached to the peak level in Ottoman Period.

In this study, the seismic performances of two minarets (Selimiye Mosque Minaret in Edirne belonging to Ottoman Period with Masjid Minaret of Ince Minaret Madrasa in Konya belonging to the Anatolian Seljuks period) will be compared. The seismic performances of these minarets was first modeled in three dimensions by using the SAP2000 computer program and then investigated by the Pushover Analysis in accordance with the TEC-2007 (Turkish Earthquake Code, 2007). The development of masonry minaret custom will be discussed with obtained findings. Moreover, these findings will be created a data for restoration of masonry minarets.

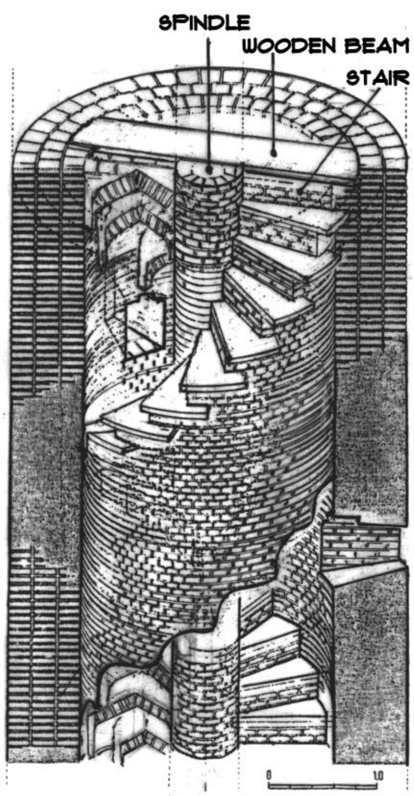
Keywords:

Masonry minaret, finite element analysis, historical masonry building

* Faculty of Engineering and Architecture, Department of Architecture, Selcuk University, Konya, Turkey.
Phone: +90 332 2231964 Faks: 0 332 241 06 35 e-mail:archmim@hotmail.com
** Faculty of Engineering and Architecture, Department of Civil Engineering, Selcuk University, Konya, Turkey.

1. Introduction:

Minarets are one of the most important indispensable elements in the Islamic city skyline. According to pre-Anatolia Turkish minarets and minarets of other Islamic countries, the Turkish minarets which adorn the city skyline of Anatolia are different in terms of height and frailty. The Anatolian Seljuk minarets carry the whole parts of the minaret (pulpit, footing as a transition element, balcony, cone etc.) within their shaft unlike the previous minarets. During this period, minarets were built of brick-stacking technique (***figure-1***). The most famous of them is the minaret of Konya Ince Minaret Masjid which is built with two balconies (Başar, 1997) (***figure-2***).



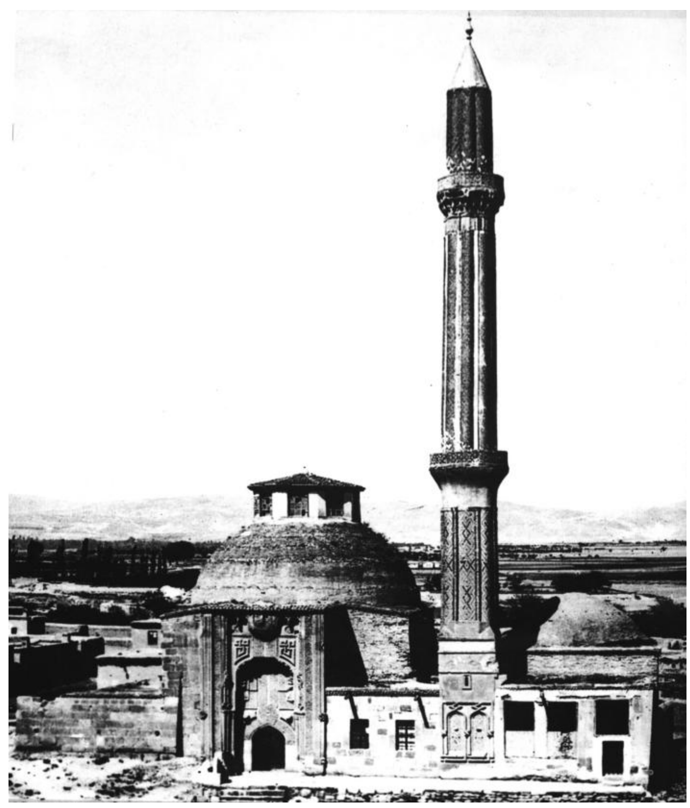


figure (1): *The section of brick minaret*

figure (2): *İnce Minaret Madrasa*

Pre-emirates Anatolian Seljuk minarets vary from predecessor Karahanli and Ghaznavid minarets as well as the Principality and Ottoman minarets in terms of technical point and materials.
Emirate Period and Ottoman minarets were usually built in stone-stacking technique. Mimar Sinan's mastery of works, Edirne Selimiye Mosque, is one of the most important Classical Ottoman mosques with its different characteristics, as two minarets built adjacent to the narthex and three balconys and three armed stairs reaching to those three balconys (***figure-3***).

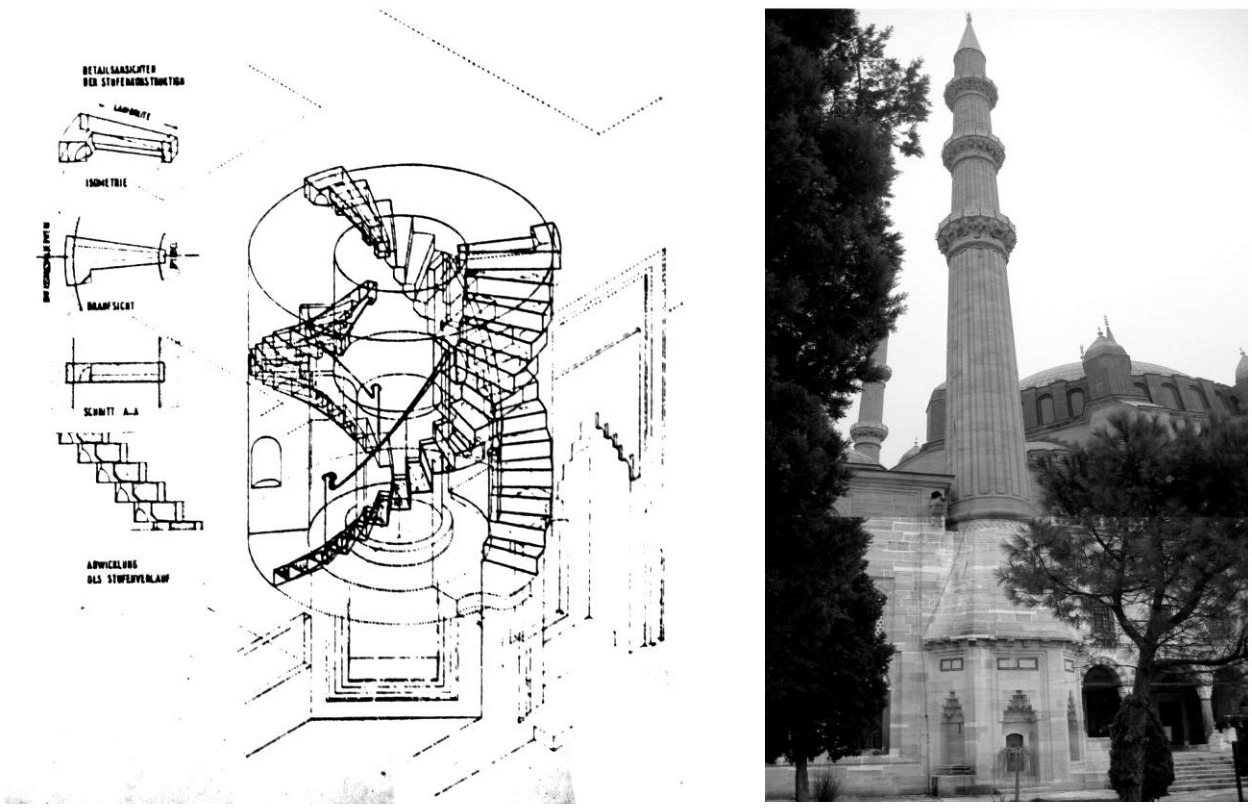


figure (3): *The section and view of Selimiye Minaret (Kulac, 1979)*

It is seen that there are precautions taken for earthquakes at the time both Ottoman and Seljuk minarets mature. According to TDY-2007, the prayer room of Ince Minaret Madrasa, the Anatolian Seljuk minaret, and the minarets of Selimiye Mosque, Classical Ottoman mosque, was investigated and modeled via SAP2000 software. In the evaluation of these minarets in terms of earthquake, the organization of stairs and steps systems, material status, stylistic editing has been taken into consideration.

2. Analysis of Historic Masonry Structures :

Date stacking structures are able to reach to present with improving the structural forms and structural characteristics by means of transferring the experiences from generation to generation. Every culture and society developed its own systems and construction methods. Masonry culture and construction systems have been developed with cross-cultural interaction.

Historical structures are the masonry systems working with "pressure stresses" in general with respect to the technology in their ages. The tensile forces that would be created in the masonry systems are tried to compensate with wooden elements, hence the ways that let the wooden systems last longer in natural conditions are investigated. The tensile forces created in masonry structures are tried to compensate by using iron clamp and iron tension elements. Moreover the methods to protect the iron material from corrosion have been studied (Bayraktar, 2006). Very small amount of bending elements hewn out of block rocks or wooden bending elements are also used.

In Anatolia for the minarets categorized as masonry tower structures to compensate the tensile forces the wooden elements are used as in Seljuk minarets. In Ottoman minarets iron clamp and iron tension elements are used. In this study we presented the methodology of solving the problems related with two minarets which are built with 350 years after other and differ in terms of construction systems, materials by comparing the deformations in the case of an earthquake. It is also aimed to emphasize on the development in the transition period from Seljuks to Ottomans. Moreover, the solution methods to the problems of that period are also presented.

Recently there are several symposiums organized subjecting the structural systems of historical constructions. The international and national publications about that topic usually subject to the deformation created in the case of earthquake by modeling one or more structures in different systems via SAP2000. In another type of study, the authors modeled two different tower structures with same system from different countries and tried to compare them.

In our work different than the other studies on the topic, the deformation in the case of an earthquake is compared for two masonry tower structures (minarets) in two different countries following each other with same culture and the evolution was investigated. The comparison of earthquake related to deformation is based on structural elements consisting of foundation, pulpit, footing, shaft, balcony, upper body of shaft and spire structure of traditional Seljuk and Ottoman minarets (Lomlu, 1981; Uluengin et all, 2001; Başar, 1997; Sezen et all, 2008; Kulaç, 1979) (***figure-4***).

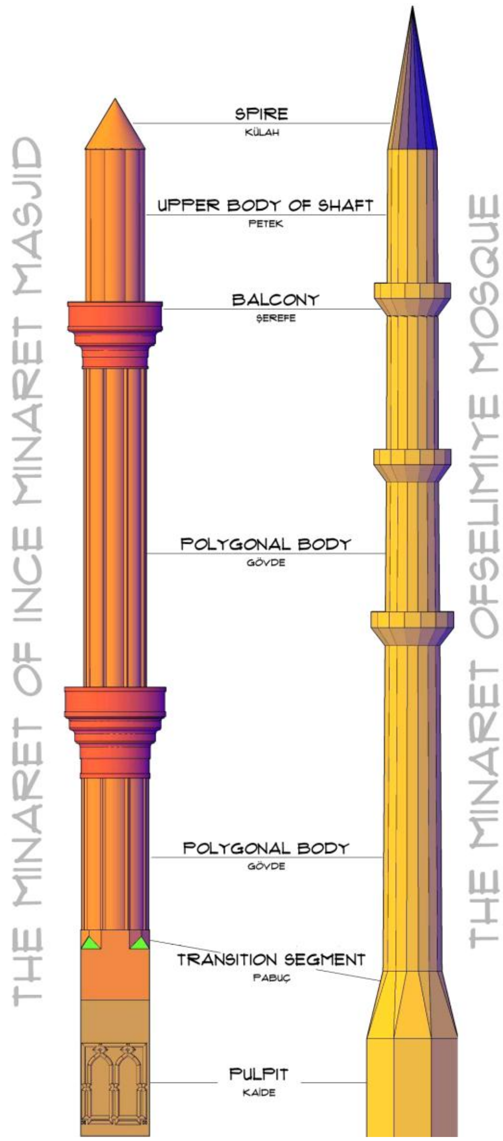


figure (4): *The parts of minarets of Selçuks and Ottoman*

Finite Element Analysis (FEA) is a numerical method that solves the complex physical problems faced by engineers with an acceptable accuracy. Finite element method is one of the most common and effective numerical methods that solves most of the problems in physics and engineering (Ünay, 2002). The method was first applied to the problem of stress analysis. Nowadays, it is widely used in strength, fluid, vibration and dynamic problems. The method is based on dividing the infinite drawings, material and the surface with an appropriate number of finite elements for facilitation.

In finite element method the structure is divided into several elements for which the behavior has been previously identified. Elements are combined at node points. In this way, a set of algebraic equations is obtained. In stress analysis these equations are the equilibrium equations at the nodes. Depending on the problem examined in this way hundreds or even thousands of equations are obtained. The solution of equations requires the usage of computers.

The basic idea behind the finite element method is just interpolating the node values of the element for the desired property, for example the displacement. Therefore the unknowns in finite element method are the properties at the node points.

Finite element analysis and calculation has some advantages; those are:

1. Finite elements, because of the flexibility of size and shape, may represent a given object; even it may be more reliable for complex-shaped objects.
2. Multi-connected regions (i.e. one or more hollow bodies) or the corners of the region can be examined easily.
3. Different geometric and material properties do not introduce an additional difficulty. The distortion in geometry and structure of the material, unsteady (time-dependent) material properties can be easily taken into consideration.
4. The cause-effect related problems can be formulated in terms of generalized "forces" and "displacements". This feature of finite element method makes it possible to solve the problem and also simplifies the problem. Moreover this feature makes the problem clearer to understand.
5. Boundary conditions could be easily implemented.
6. The versatility and flexibility of the finite element method can be used to calculate the cause and effect relations in continuous media, area and other problems for complex geometries efficiently. It gives more accurate results than analytical and experimental methods.

3. Case Study: Comparison of The Seljuk and Ottoman Minarets :

There is only one static property in the minarets. This feature is that they are cantilever structures flushed to the ground. Like all cantilever structures, minarets also experience unstable and brittle behavior under horizontal loads. The elasticity of minarets is low. In other words, it is easy to broken down under deformations. These types of structures break suddenly without having plastic deformation with the loads a little bit larger than the safety limits. They can become unstable immediately from their steady-state equilibrium (Bayraktar, 2006).

In stone walled minarets, construction techniques as zero joint application increase the brittleness of the structure compared to mortar structures. There are problems occurring in minarets without joints since they are more rigid structurally. Those problems are arising in terms of the negative effects of time, environment and atmospheric conditions; not to be able to maintain and repair in a regular fashion and the damage of earthquakes (Bayraktar, 2006) (***figure-5***).

In historical minaret building techniques the shear forces are tried to compensate by increasing the cross-sectional area. Today it is better known that strengthening the masonry structures by shear forces is the most accurate method. The steps of the minarets are built as they are closing the 30-50% of the interior space. Mostly the steps are built as they are a single piece with shaft of the minaret. To achieve this, the outer walls are fully connected to those plaques.

The holes at the center of the stair plaques are superimposed and then melted lead is poured to these holes. Energy worked as damping factor in horizontal displacements. All these efforts are for building the minarets as soon as possible. Many minarets were destroyed in the earthquakes.

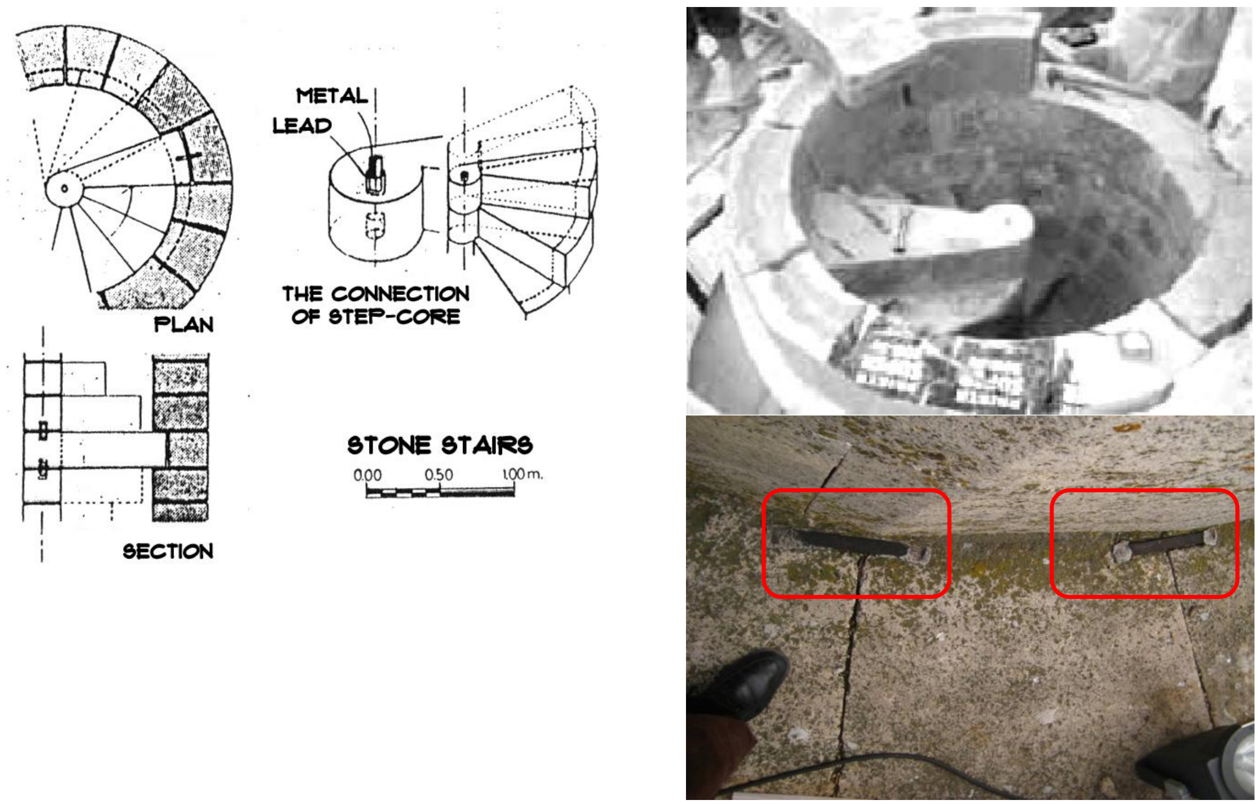


figure (4): *The detail contsruction of stone minaret (Kulac, 1979-Zorlu, 2007)*

The historical structures exposed to the corrosive effects of time and natural disasters are usually under the effect of enormous problems, hence under the risk of ruin and destruction. Some buildings, which are restored for safety, mostly do not withstand the problems due to incorrect restoration or inappropriate material usage during restoration.

The following results are obtained after the calculations performed via SAP2000:

- The displacements in both two structures are below the given limits of earthquake specifications under an earthquake or high wind case (***table-1***).

table (1): *Displacement of minarets* ($\Delta_{max}/H_{minaret}<0.02$ *– TDY-2007*)

	Eartquake & Dead Load	Wind & Dead Load
INCE MINARET	7.32 cm/4190 cm =0,0017	9.65 cm/4190 cm =0,0023
SELIMIYE MINARET	5.62 cm/7870 cm =0,0007	12.62 cm/7870 cm =0,0016

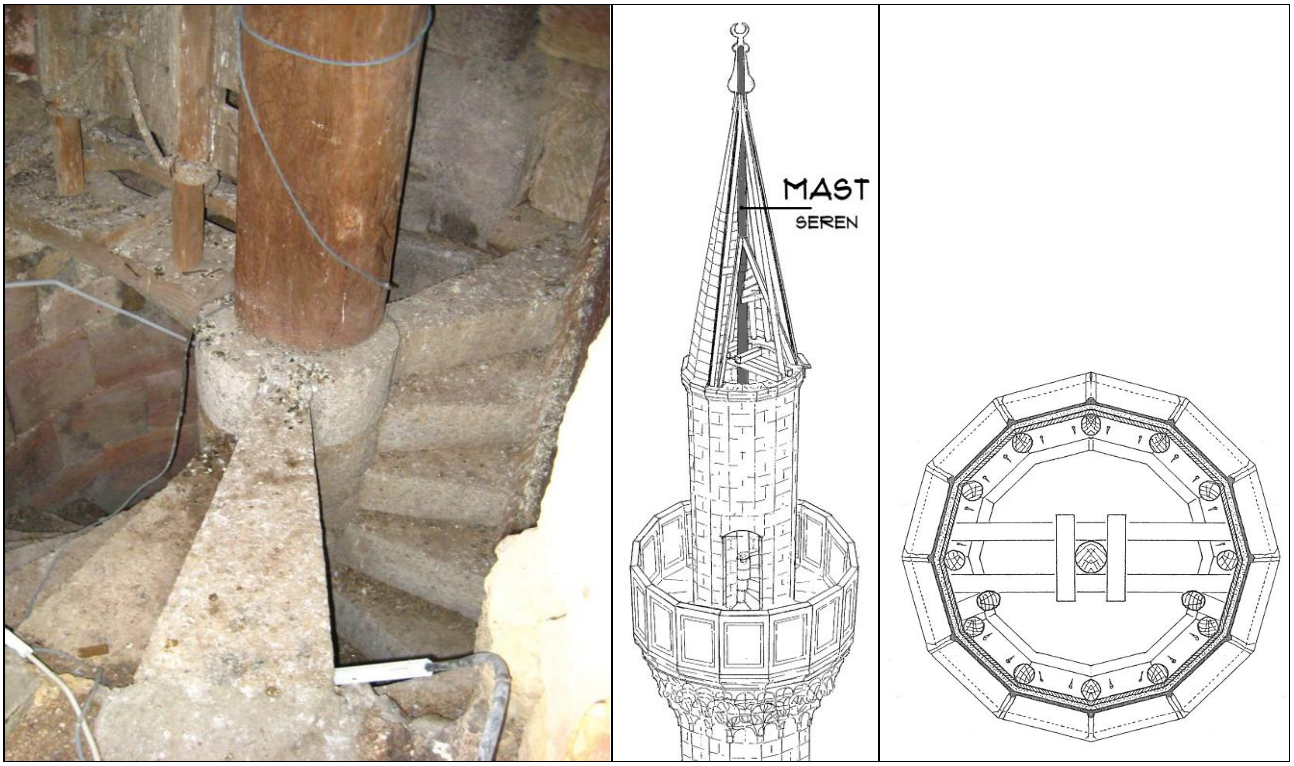


figure (5): *The Spireof minarets and mast (seren) (Uluengin et all, 2001)*

The critical point in minaret of Ince Minaret Madrasa is the transition segment from square to circular cross-section. This condition supports other studies in this subject (Dogangun et all, 2008; Higazy 2004). The 75 cm long transition region (footing) that is guessed to be used at the first time in history is found to be insufficient. On the other hand, this transition zone in The Selimiye Minaret is around 5 m. Therefore, collapses in this part were prevented in that stress accumulation in this area spread to the body (***figure-6***).

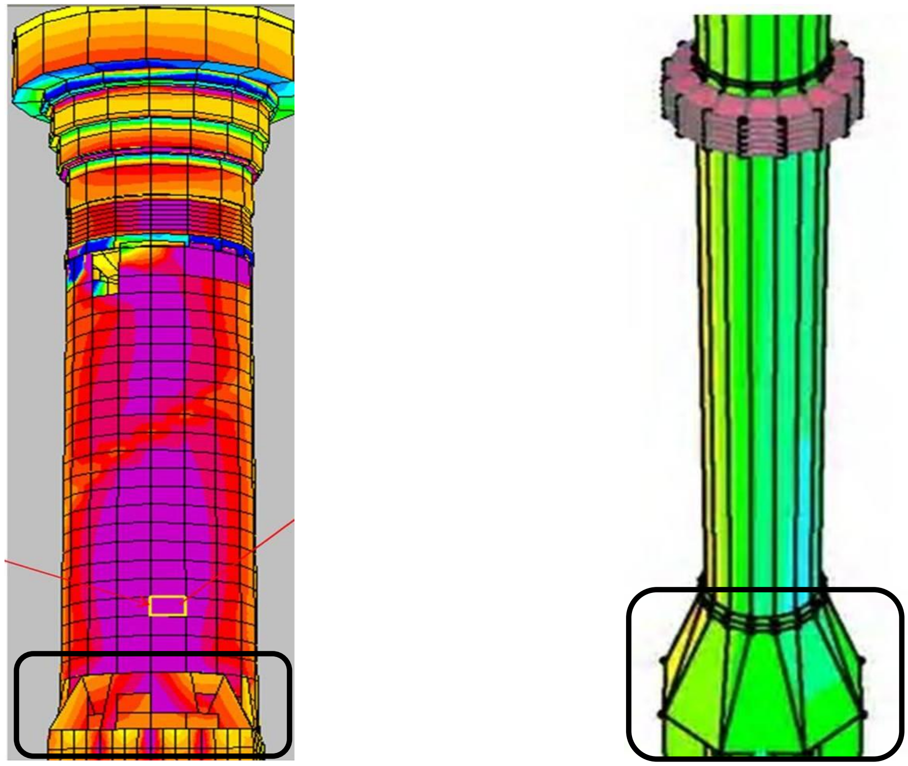


figure (6): *Transition segment (footing) of minarets*
(İnce Minaret, letf-top and Selimiye Minaret, right-top)

• Another most critical parts in both minarets are the sub-parts of the shaft after the balconies and the connection point of balconies and the shaft. These sections are the critical points where stress concentration occurs (***table-2***). In minaret of Edirne Selimiye Mosque it is sought to avoid stress concentration via increasing the cross-section of the transition region between balcony and shaft. To have a uniform load distribution under the balconies of both minarets, an angled transition with muqarnas was used.
As shown in ***table-2***, the difference of value of footing and first shaft bottom is lesser in Selimiye minaret.

table (2)*: The stress accumulation of minarets (n/mm^2)*

Part of Minaret	**Vertical Load**		**Ver. Load+Quake**		**Ver. Load+Wind**	
	İnce Minaret	**Selimiye Minaret**	**İnce Minaret**	**Selimiye Minaret**	**İnce Minaret**	**Selimiye Minaret**
Top of Trans. Seg.	0.1501	1.1614	0.3568	1.4679	0.3372	3.7630
1. Bottom of Shaft	0.8335	1.3455	1.8703	2.1117	1.5109	5.3658
2. Bottom of Shaft	0.4406	0.7451	1.0152	1.3764	0.4149	2.3703
3. Bottom of Shaft	0.0493	0.4646	0.2470	0.8754	04678	1.2823
4. Bottom of Shaft	yok	0.1373	yok	0.2860	yok	0.3423

• The First, second and third earthquake modes and weight of minarets are computed as shown in Table 1. Also compared with proportion of height- body, it is seen that Selimiye minaret is higher and slimmer. On the other hand compared with T_1 periods, it is seen that Selimiye minaret is more rigid (***table-3,4***).

table (3): *Eartquake mode of minarets and weight*

	İnce Minaret (248 Ton)	Selimiye Minaret (1100 Ton)
T_1 (1.mode)	1.814sn	1,628
T_2 (2.mode)	0.315sn	1,628
T_3(3.mode)	0.128sn	0,269

table (4): *The ratio of minarets*

	İnce Minaret (248 Ton)	Selimiye Minaret (1100 Ton)
$H_{minaret}/D_{body}$	41,90/2,50=16,76	78,70/3,70=21,27
$H_{minaret}/T_1 D_{body}$	41,90/(1,814*2,50)=9,24	78,70/(1,628*3,70)=13,07

4. Results and Discussions:

Before the year 2000, performing restitution for Ince minaret was decided and pre-investigative excavations were started. The depth of the excavations goes until 6.5 to 7 meters and it is seen that the foundation is still continuing downward. The 3 meter long part of the foundation of the minaret was made of face stone whilst the other lower part is made of mortared rubble stone. The foundation of Edirne Selimiye Mosque minaret is deeper than the foundation of Ince minaret and probably the foundation of Edirne Selimiye Mosque minaret is continuing until the stable pulpit. Based on our estimate the foundation depth is 1/3 of the height of the remaining part above ground or more.
The pulpit is constructed from hewn stones with the same dimensions as the foundation to carry the loads on it and not to let the base water to move up.
The footing as a transition element part, which is firstly appeared with Anatolian Seljuks, provides the transition from square pulpit to cylindrical or polygonal shaft. The footing distributes the existing stress concentration and therefore footing reduces the damage in case of wind and earthquake. On the other hand, this section is not in the desired size and form at that time.

The footing provides a visual transition, at the same time it avoids the material deformation due to freezing and thaw at upper margin between circular or polygonal shaft sitting on a square pulpit. In Edirne Selimiye Mosque minaret, the footing as transition segment is in its most mature form. In this state the damage that can be created by wind and earthquakes has been reduced to minimum.
It is observed that the first shaft stress concentration is maximum in Ince minaret. To reduce these stresses either the footing must be connected to the shaft with a smoother transition or balcony height must be increased a little (Başar et all, 2007). On the other hand in Edirne Selimiye Mosque this effect is reduced by the aforementioned two methods, increasing the shaft height and a smoother transition between footing as a transition segment and shaft (***figure-7, 8, 9***).
In Ince minaret the upper side of the steps in the shaft is covered with wooden planks. These planks are compensating the tensile stresses since they are connected to both core and the coating (outer wall) longitudinally. Therefore the core prevents the surface shear between the coating and the stairs and let them work together (Başar et all, 2007). On the other hand in Edirne Selimiye Mosque minaret to compensate the tensile stresses monolith stone steps are connected to the outer coating with clamps and connected to the up and down of the core with metals. The stone break is prevented by pouring lead to the connections of clamps and metals.
In the upper body of shaft region of the Ince Minaret it is seen that the tip of the cone has a displacement of 9,65 cm in the largest wind load case (Başar et all, 2007). Therefore the cones of these minarets, which are constructed as masonries, are double-walled and they are seen as cone from outside and as cupola from inside. The bending tensile stresses are not compensated by the small normal stresses in the cone. This displacement is 12,62 cm in Edirne Selimiye Mosque minaret. They are built by wooden and covered by lead. As a result, the tensile stresses are compensated (***figure-5***).
According to today's earthquake criteria both two minarets are performing well in an earthquake. Moreover, the survival of both minarets until now verifies that the minarets are resistant to earthquakes and wind.

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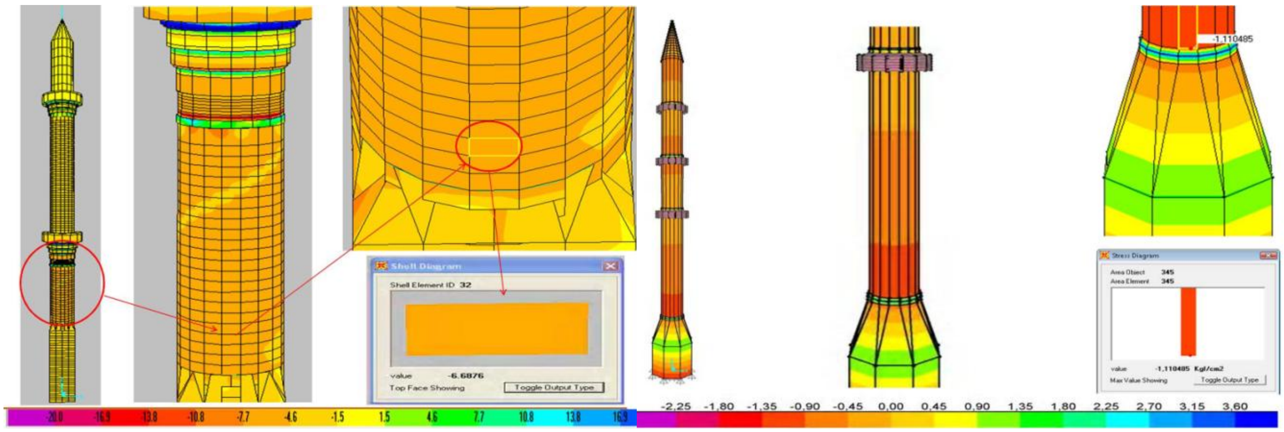

figure (7): *The stress of Dead Load (kg/cm²)*

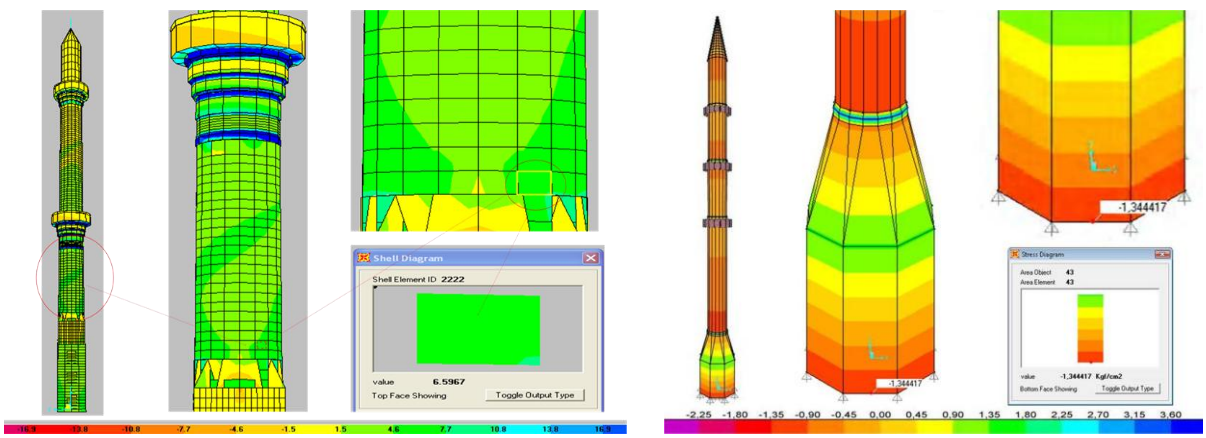

figure (8): *The stress of Eartquake+Dead Load (kg/cm²)*

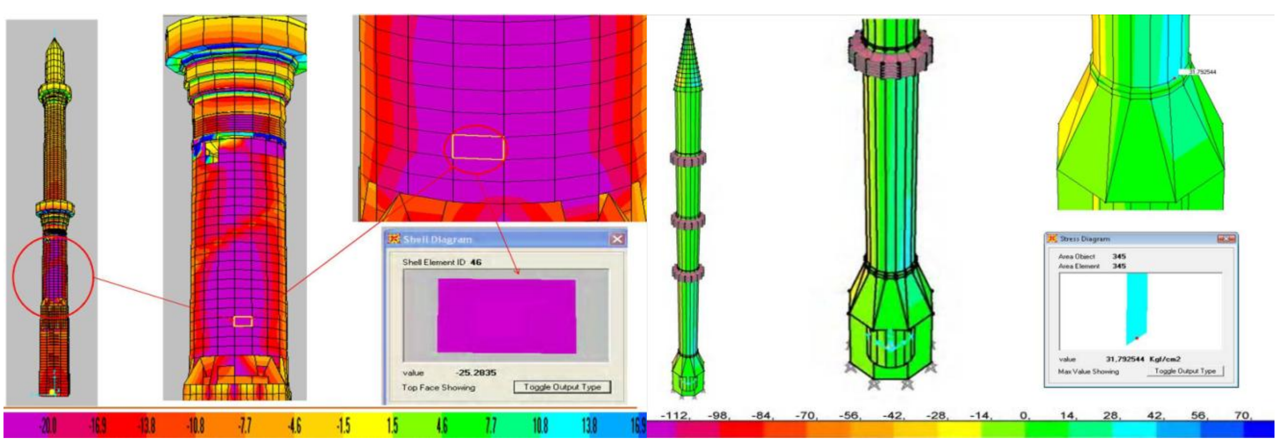

figure (9): *The stress of Wind+Dead Load (kg/cm²)*

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