AN INNOVATIVE METHODOLOGY AND STRUCTURAL ANALYSIS FOR RELOCATION OF HISTORICAL MASONRY MONUMENTS: A CASE STUDY IN HASANKEYF

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ABSTRACT

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Historical monuments are the most invaluable reflections of our architectural heritage and cultural identity, both of which have significant roles to create a strong link between the past and the present. They should be conserved in their own settings with their original characteristics or with as minimum changes as possible. However, natural or man-made hazards cause a serious risk for the survival of historical monuments. While some of them require to be strengthened only, some should be relocated to a new site since there are no means to save them without transporting.

In this study, an innovative methodology is developed in a general sense for transporting historical masonry monuments without destructing their unity. In the proposed methodology, which is applicable especially to the slender historical structures, it is aimed to transport the structure by tilting it up to a horizontal ground level without dismantling into pieces. Due to the fact that masonry is a very brittle material, externally located prestressed cables are used to strengthen the structure against tension forces, which occur at the time of tilting.

Hasankeyf, which is the cradle of various civilizations, is an impressive medieval city located in Mesopotamia region in Turkey. Unfortunately, this unique heritage will be flooded by the reservoir of Ilisu Dam unless the project is cancelled. Therefore, a masonry minaret located in Hasankeyf is selected as a case for this study. Because of the non-homogeneous characteristics of the structural material, Finite Element Method, as a powerful analytical modeling tool, is used in order to evaluate the validity and effectiveness of the proposed methodology. Finally, it is certified that this methodology is successfully applicable for the relocation of historical masonry monuments.

Keywords: Historical Monuments, Masonry, Transportation and Relocation of Historical Structures, Strengthening, Prestressing, Finite Element Analysis, Hasankeyf

ÖZ

TARIHI YIGMA ANITLARIN BASKA BIR YERE TASINMASI ÜZERINE BIR YÖNTEM VE BU YÖNTEMIN YAPISAL ANALIZI: HASANKEYF'DE ÖRNEK BIR UYGULAMA

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Geçmisle günümüz arasinda güçlü bir bag olusturmak için çok önemli bir role sahip olan tarihi anitlar mimari mirasimiz ve kültürel kimligimizin en degerli temsilcileridir. Bu anitlar orijinal özelliklerine sadik kalinarak ya da mümkün oldugu kadar az degisiklik yapilarak kendi yerlerinde korunmalidir. Fakat, dogal tehlikeler ya da insanlarin neden oldugu zararlar tarihi anitlarin yasamlarini sürdürebilmeleri açisindan ciddi bir risk olusturmaktadir. Bu nedenle bazi anitlar sadece güçlendirilerek korunabilirken bazilarinin bulundugu yerden baska bir yere tasinmasi kurtarilmalari için tek çözümdür.

Bu çalismada, tarihi yigma yapilarin bütünlügünün bozulmadan tasinabilmesi için genel hatlariyla yeni bir metot gelistirilmistir. Özellikle diger iki boyutuna göre yüksekligi fazla olan (ince uzun) tarihi yapilara uygulanmak üzere önerilen bu metotta, yapinin parçalara ayrilmadan belli bir yatay seviyeye kadar egilerek tasinmasi amaçlanmistir. Yigma tas ve tugla yapi malzemesi çok kirilgan bir yapiya sahip oldugu için, egme sirasinda ortaya çikacak çekme kuvvetlerine karsi güçlenmesi amaciyla distan sarilan öngerme kablolari kullanilmistir.

Birçok uygarliga besiklik etmis bir yer olan Hasankeyf, Ortaçag döneminden bugünlere kadar ayakta kalmis, Türkiye'de, Mezopotamya bölgesinde bulunan etkileyici bir sehirdir. Ne yazik ki, bu nadir miras, proje iptal edilmedigi takdirde, Ilisu Baraji'nin sulari altinda kalacaktir. Bu nedenle, Hasankeyf'de bulunan yigma bir minare bu çalisma için örnek seçilmistir. Yapi malzemesi homojen bir malzeme dagilimi göstermedigi için, önerilen metodun geçerliligini ve etkinligini degerlendirmek amaciyla güçlü bir analitik modelleme araci olan Sonlu Elemanlar Analizi yöntemi kullanilmistir. Sonuç olarak, bu metodun tarihi yigma yapilarin tasinmasi ve yeniden yerlestirilmesi için basarili bir sekilde uygulanabilir oldugu dogrulanmistir.

Anahtar Kelimeler: Tarihi Anitlar, Yigma Yapi Sistemleri, Tarihi Yapilarin Tasinmasi ve Yer Degistirmesi, Güçlendirme, Öngerme, Sonlu Elemanlar Analizi, Hasankeyf

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"It is the only with one's heart that one can see clearly.
What is essential is invisible to the eye"

Antoine de Saint-Exupéry

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To the ***Rose***

in the Glass Cover

with a Hope of its Bloom

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CHAPTER 1

INTRODUCTION

1.1. Importance and Ethic of Conservation

Historical sites and their contents are one of the most essential parts of the cultural heritage that reflect history of mankind. Historical monuments are like gates opening into the past. They are the witnesses of our old traditions and the symbols of the cultural identity. Without them, it is not possible to understand, interpret and retrace the period of civilization.

Ancient structures represent the details related with the use of technology in design, material characteristics, workmanship, architectural features and spiritual value of their periods. Due to the fact that historical monuments reflect cultural, aesthetic, social, archeological, economical, architectural, constructional, political or religious features of their time, realizing and interpreting them will open the way of creating a significant link between our past and present and also help us to plan our future in a good manner.

Actually, there exist only two basic ways to bring the past into today's world; literature and ancient monuments. Since ancient monuments could be remarked as the living history, on which human beings past is reflected, it will not be wrong to say that they are the proof's showing the spirit and charm of the heritage. Therefore, conservation and restoration of ancient monuments have a big importance in order not to lose our past, to transfer it to the present and so to reveal the cultural evolution.

Conservation and restoration of historical monuments require a careful-systematic study in order to achieve high quality results. In addition to a deep knowledge about the ethic of conservation, one should have good technical skills and sufficient information related with the structure and material on which he/she works. This means that the conservation study should be performed by specialized people who take the necessary education.

As well, conservation requires a multidisciplinary work including history, architecture and engineering as the basic sciences. In order to attain a real success, a continuously well-communicated team should be created and a control mechanism should be formed to manage the works and to balance the relationship between different disciplines.

The most essential aspect of conservation is based on making minimum change in the original structure. It is very important to conserve the original conception in order to lighten the past correctly and to carry it to the future with its own characteristics. Moreover, a monument should not be separated from the setting in which it occurs since it bears the witness of that history. Historical monuments and their sites are the constituents of an integrity. They become to live together in the course of time and so their creations would be more meaningful with their own surroundings.

Archeological sites and their context should be taken into account carefully in order to prevent the destruction or deterioration of the heritage at the preliminary survey state of the public works or engineering projects. These projects can create significant damage to historical and natural heritage unless properly implemented. According to the conservation charters, importance of historical and archeological sites should be assessed and necessary measures should be taken in order to conserve them, preferably, in-situ places. The new conservation concept which is primarily based on integrated conservation, actually states that implementation of such projects should be done by regarding the concept of "conservation with well and proper documentation". Integrated conservation of cultural heritage of sites and monuments are the most important aspects to safeguard the heritage for future generations. In this respect, cultural heritage should be survived with minimum negative impact. Moreover, such major projects should not be undertaken without assessing their direct and indirect territorial impacts which include spatial and environmental assessment and possibilities should be investigated to change the proposed routes where potentially significant archeological remains are likely to be damaged [1,2].

In this manner, moving all or part of a monument cannot be allowed except when it is the only safeguarding way to conserve the monument or when it is justified by national or international interests of paramount importance; as indicated in International Charter for the Conservation and Restoration of Monuments and Sites, Venezia-1964. In order to hand the heritage down to future generations with all its beauty, authenticity and diversity, an integrated conservation should be anticipated as far as possible.

1.2. Protection of Heritage in Turkey; Impressive City of Hasankeyf

Turkey has numerous historical monuments due to her geographical location and rich cultural heritage. She has been homeland for many civilizations along the centuries. Therefore, Turkey has one of the most significant places of the human life for the accumulation of various cultures through history. Unfortunately, historical monuments in our country are generally not given the importance they deserve. Although they all present unique symbols of our heritage, natural or man-made hazards cause much harm, some of which are not returnable. Preservation and conservation of historical monuments are the major points for the continuity of history. Therefore, it is crucial to develop suitable salvage projects, and so to protect the heritage by bringing it to light without neglecting any of the unique cultural values.

Due to its combining character of various civilizations (Byzantine, Artukid, Eyyubid, Ottoman, etc.) and number of periods faced in the history, Hasankeyf is one of the most important natural and archeological medieval sites, not only for the Turkish national heritage but also for the world's historical background. Its history, in fact, has been traced back to 7th century BC. Since it is settled between the Tigris River and Raman Mountains (28 km. far away from the city of Batman in Turkey), Hasankeyf constitutes a sole landscape feature and rich cultural heritage. The vicinity of Hasankeyf is a natural creation of hundreds of caves/caverns in the deep canyons, so it is also defined as the main city of "Mesopotamia cavern inhabitant".

Especially, the main significance of Hasankeyf comes from its imposing location. It was located at the junction of two important routes, the *Silk Way* and the *King's Way*, and near an important waterway; the Tigris River. This also caused a rapid development of the city in the periods of 11th and 12th centuries.

However, sadly, the Hasankeyf settlement will be under the risk of being flooded by the reservoir of Ilisu Dam, which is planned to be constructed on the Tigris River approximately in eight years. In fact, there are still some speculations related with this project; it is not clarified yet whether it is altered/cancelled or not.

If new project alternatives are not considered, particularly, the architectural heritage of the lower city of this unique heritage, including significant monuments such as Koç and Sultan Süleyman Mosques, will be submerged under the water of Ilisu Dam. Moreover, the historical bridge on the Tigris River and Zeynel Bey Tomb will be under the reservoir level of this dam. This means that lots of invaluable historical monuments will be lost. Hence, it is required to save this heritage as far as possible.

The lower city has mainly lost its site integrity and a well-assessment has not been performed for the whole of this invaluable medieval city. However, the most magnificent monuments that survive up to these days are generally located in the lower city of Hasankeyf. Because of the fact that Ilisu Dam reservoir will cover the integrated natural and archeological heritage in Hasankeyf, a comprehensive documentation of the site and monuments should be done before the construction of the dam [2].

Unfortunately, it is not possible to preserve the whole historical settlement; however, relocating the monuments located in the site can save at least some single architectural works. Although separating the monuments from their own sites harms the completeness and so the spirit of the region, it seems to be the only alternative for saving these precious monuments. But, transporting them to another place should be done after the completion of excavations and careful research for documentation.

1.3. General Methodology for Structural Conservation or Restoration of Historical Masonry Monuments

In order to make a correct decision for conservation and restoration of historical structures, it is necessary to follow a precise methodology whose main steps are survey, diagnosis, safety evaluation, selection of techniques and control. Diagnosis, which is related with the past, is the first phase of any study. It is the judgment on the cause and nature of the factors (damage, decay, etc.) that have affected the structure. Safety evaluation, on the other hand, is related with the present and the future after completing the strengthening works. It evaluates the capacity of the structures to resist the potential risk due to mechanical actions (earthquake, overloading, eroding, wind, etc.). After making a careful diagnosis and evaluation of the safety of the structure in its present state, the best type of solution can be chosen properly. Material type and properties, behavior of the structure, load variation and propagation, architectural feature and historical value of the monument should be considered deeply for achieving the most effective and successful study. Science, history and culture play significant roles in understanding the structural behavior and evaluating the importance and consequences of the developed solutions in conservation of historical monuments. Modern techniques, if used properly, particularly offer exciting solutions for preservation of our heritage [3].

Masonry is the most widely used and important construction material among the historical monuments. Because of the fact that it is composed of two different materials; i.e., the masonry units and the mortar, it exhibits a heterogeneous structural character. The block nature of masonry and binding material governs the deformation and failure mechanism of the structure. It is usually too hard to predict the behavior of the ancient masonry structures. Therefore, structural analysis performed by conventional methods is not sufficient in studying the historical masonry structures accurately.

In this manner, with the help of analytical studies for analyzing the ultimate behavior of these structures, it is possible to develop more effective structural strengthening methods. Finite Element Analysis Method is one of the most appropriate and powerful modern computer based tools for the analysis of historical structures. By means of this approach, structures can be described comprehensively with better physical models than those traditionally used. Moreover, the mechanism of the behavior of the structure subjected to vertical and/or lateral loads can be observed well.

1.4. Purpose and Objectives

Historical monuments are invaluable structures which carry messages from the past. As it was emphasized before, it is very important to preserve and so transfer them undamaged to the next generations. Unfortunately, they have been continuously exposed to natural or man-made hazards and this results in a respectable loss considering their priceless significance and inreturnable value.

Masonry minarets are one of the most common structural forms which are present in our architectural heritage. They can be considered as the basic part of the mosques. Several different studies have been performed up to these days in order to conserve the masonry monuments as good as possible. The main objective of this study is to take a new step in the conservation of such ancient structures by transporting them to another site in the case of necessity (construction of dams, roads, railways; earthquakes, landslides, floods; political reasons...). Although separating the ancient monuments from their own surroundings should not be permitted, relocation could be the most effective way if there are no means to save them.

This study presents a model for transporting a historical masonry minaret "without dismantling into pieces" through a horizontal position. For this reason, a methodology is first developed to tilt the masonry minaret safely up to a horizontal level. And then, the system is analytically modeled with computer aided simulation methods. Because of the constitutive characteristics of the structural material and also its high physical and geometrical behavior especially when subjected to lateral forces, the masonry minaret is analyzed with Finite Element Method (FEM).

The primary purpose of this study is to develop an innovative methodology for the transportation and then relocation of slender historical masonry monuments. The vertical structural form of minarets, spires, towers and bell towers is the most significant aspect causing high risk of failure and collapse. High stress acting at their base and their great susceptibility to the dynamic actions (earthquake, wind, vibration, settlement, etc.) provoke the vulnerability of such kind of slender structures especially against tension cracking [4]. Furthermore, masonry is a brittle material, which is weak in tension but quite strong in compression and moderately resistant against shear forces. In order to compensate the tensile forces occurred during tilting and also to stabilize the minaret safely, radial and vertical prestressed cables are externally placed on the model which wraps the minaret like a cable net. Post-tensioning offers innovative solutions for the strengthening of masonry against tensile failure, which would probably prevent the collapse of the structure.

In this study, firstly, characteristics of masonry, aspects of structural analysis, and vulnerability of historical masonry structures and strengthening measures, especially by using prestressing, are discussed in the second, third and fourth chapters, respectively. Then, in the fifth chapter, an innovative methodology for the transportation and relocation of a masonry minaret is explained in details. Finally, in the sixth chapter, structural analyses of the methodology, which is applied to a selected minaret in Hasankeyf, are performed by using Finite Element Method. Stress variations, deformed shapes of the minaret, tabular and graphical analyses results obtained from the analytical modeling of the structure under different conditions are presented at the end of sixth chapter and analysis results are discussed in order to see the validation or vulnerability of the proposed model.

CHAPTER 2

STRENGTH AND MATERIAL CHARACTERISTICS OF MASONRY

2.1. Material Properties and Types of Masonry

Masonry is the oldest construction material which has been used more than eight millennia from the early civilizations. The majority of the existing historical structures around the world are especially made of masonry.

Simply, masonry is the composition of units joined by mortar. There are many types of units, among which stone and brick are the most widely used materials in old masonry structures. Stone generally exists in a natural form; rubble or field stone or in an artificially handmade specified shape, but brick masonry includes a variety from unfired, dried mud (adobe) to fired clay brick.

Masonry, whether it is stone or brick, is the most durable form of the construction material. Moreover, it is usually reasonably easy to handle and it is one of the most versatile structural form which has been used for arches, vaults, domes, walls and pillars from the very beginning of history. However, these masonry structures cannot be considered or evaluated as a continuum due to the fact that they are formed from two very different materials; masonry units and binding mortar [5, 6, 7].

Masonry is a very complex material that it is very difficult to determine the strength and deformation characteristics of its structural elements. Since masonry is a non-elastic, anisotropic and non-homogeneous material, it is not always possible to get the actual behavior of historical masonry structures and also their strength properties. By taking small samples from different locations of the masonry structures and testing their individual elements in the laboratory may be a method to analyze these structures. However, this method does not clearly represent the overall behavior of the existing structure [8, 9, 10].

In order to understand the structural system in a complete manner, both the mechanism of the behavior of the structure subjected to vertical and/or lateral loads, and mechanical properties of the construction materials should be understood very well [11].

The structural performance of masonry structures mainly depends on the physical and chemical properties of the material. Durability, workability, ease of quarrying, strength, hardness, porosity, color, grain, texture, absorption, solubility and expansion-contraction due to temperature changes are some of these material properties. Durability is the ability of material to withstand environmental conditions; i.e., rain, wind, dust, freeze, fire, air pollution, spray. It mainly determines the life time of the structure. The type of the texture also affects the mechanical response of masonry. The way of arrangement of internal blocks deeply influences the structural behavior [12, 13, 14].

Masonry possesses very low tensile strength and shear resistance. The compression-resistant approach in the structural form of the historical structures (pillars, arches, walls, domes...) is primarily based on this fact. The basic principle is to reduce the tensile forces to a minimum value and to preserve the overall bearing capacity in the limits of the entire structural safety [15].

The compressive strength is the major parameter influencing the structural capacity of masonry. The type of connection, binding pattern, unit and material, and the characteristics of mortar are the most significant factors identifying the compressive strength of the masonry. In general, the size of masonry unit and its bonding characteristics with mortar joints define the mechanical properties of masonry. The homogeneity ratio of the masonry also depends on these aspects [12, 16].

2.1.1. Stone Masonry

Stone is the oldest construction material known to man. From the earliest ages, it has been regarded as the most preferred material in the construction of majority of significant structures, especially the historic ones. This is, in fact, due to its unique qualities; i.e. aesthetics, permanence, workability and accessibility, among others [14].

Prior to the turn of the twentieth century, stone continued to be the predominant structural material, but then it has started to be used as a veneer (in the form of surfacing material) rather than as a basic construction material. The main reason for such a change arose from the increasing height of the buildings which requires more careful design, considering the mass of the materials. Particularly, stone type construction is held low in the earthquake regions. However, many historical structures of stone masonry have endured for centuries if they were constructed with good design and good-quality conditions [14, 17].

Structural strength, durability, attractive appearance, ease of quarrying are the main desirable features of regularly cut and shaped stone (good dimension stone). Moreover, availability; i.e. ease of transport from quarry to site and environmental consequences of quarrying are the other factors that influence the choice of stone to be used [18].

Understanding the geological origin, structure and composition of building stones has a great importance in choosing stone or analyzing it. Stone can be divided into three broad categories depending on its geological origin; igneous, sedimentary and metamorphic rocks [14].

Igneous rocks are formed by cooling and consolidation of molten, or hot, liquid materials (magma and lava) that were brought to earth's surface by volcanic action. They are classified according to texture and composition. Existing evaporative materials and rate of cooling define the texture of this rock type. If it forms at or near the earth's surface (faster cooling), the rock would be fine-grained extrusive rock; but if it hardens beneath the surface, coarse-grained intrusive rock is formed. Igneous rocks are generally crystalline and relatively hard. Composition of magma, temperature and pressure at which they form are also the aspects affecting the properties of them. Granite, quartz, felsite, obsidian, andesite and basalt are the most common igneous rocks [14, 19].

Sedimentary rocks can be considered as a weathering product. They form from weathered igneous, metamorphic and other sedimentary rocks, at or near the earth's surface. These rocks are generally classified according to their formation way and the composition materials. Temperature differences, abrasion and chemical reactions result in disintegration, either on land or under water. After deposition of weathered sediments by wind, water and ice, they are buried and hardened into rock with time. Many sedimentary rocks are deposited in stratification of layers that the youngest bed is at the top. Sedimentary rocks have extensive range of composition and character. The most common ones are sandstone, siltstone, shale, conglomerate, limestone and rock gypsum [19].

Metamorphic rocks are formed from igneous and sedimentary rocks by the action of extreme pressure, heat, moisture, chemical fluids or various combinations of these forces. The differences in texture and mineral composition ensure the classification of these rocks. Marble, quartzite, schist and slate are the most common metamorphic rocks [14, 19].

In history of construction, stones have been used either as found or they have been reshaped. Natural form of stones may be rounded, angular or flat. Although it is possible to use all forms, angular and flat ones produce more stable structures. Rounded stones are generally used for filling spaces between other stones. Shaping of stones may be done by just breaking or chipping or it could be done by a great precision or accuracy. While natural and minor shaped stones are called rubble, reasonably accurate rectangular forms are called ashlars [17].

Dry block masonry is another kind of masonry which is generally attained using almost perfectly squared stone, without mortar. Stone is precisely shaped to obtain uniform contact that it has a good resistance. Walls and arches of Roman's were mostly constructed by dry masonry [15].

Stone is a heterogeneous substance characterized by wide ranges of mineral composition, texture and structure. Consequently, its chemical and physical properties are extremely variable. Because of the reason that structural durability depends on these properties, it is essential to test the stone masonry for the derivation of material strengths. Indeed, preservation and conservation of historical masonry structures are extremely dependent on the material characteristics of the structural elements.

Furthermore, characteristics of stone unit, mortar, nature of stone work and bonding texture are the major features determining the properties of stone masonry such as strength and durability. Structural stone is very strong in respect of compressive strength but weak in tensile one. Actually, compressive strength of stone is approximately ten times of its tensile strength and its shear strength is ten percent of its compressive strength. The exact values change depending on the formation of the material [12, 20].

2.1.2. Brick Masonry

Brick is the oldest artificial construction material. There are even records for construction of brick buildings about 9,000 years ago in Palestine, where stone was scarce. The earliest bricks were composed of sun-dried mud (adobe), but later burned brick and glazing brick were used respectively as the major construction materials of several historical structures. For instance, the early Romans reconstructed the Pantheon (123 A.D.) by using burned brick [14, 21].

Clay, a very complex material, is the basic ingredient of brick. Clay consists of silica and alumina with varying amounts of metallic oxides and other oxides. It generally exists in three principal forms: surface clays, fireclays and shales. Surface clays are formed from sedimentary rocks or they are exposed to older deposits. Fireclays, which have the ability to resist high temperatures, are found at deeper level and have a relatively uniform character. Lastly, shales are obtained by exposing to high pressure until they harden at a certain level. For historical structures, sun-dried or burned brick were mostly used ones for clay bricks [14].

Because of the reason that bricks have a wide range of composition, its strength depends on several factors; dimension and quality of the brick, the kind and thickness of the mortar and the laying process. Moreover, mechanical characteristics of the brick are influenced from its composition, drying process, baking temperature, history and the associated decay phenomena if any. Actually, a good quality baked brick has a compressive strength between 10 MPa to 30 MPa. The tensile strength is about % 8 and shear strength is about % 30 of its compressive strength. The modulus of elasticity increases with its strength and it varies between 5,000 MPa to 10,000 MPa [15].

Brick is stronger than the stone. The main difference of it from the natural stone comes from its ductility. While natural stone is elastic and brittle, the composition of elastic clay brick and plastic lime mortar produces the ductile masonry. Therefore, brick withstands against the climatic conditions, or any concentrations of stresses caused by unequal settlements, natural hazards or technological aggression much more than natural stone [21].

For structural purposes, brick is preferred to construct mostly walls, vaults, arches and piers. Especially, it is possible to construct large span structures (vaults, pyramids, arches...), if mud mortar is used. Because, covering the sun-dried mud against rain with a protective coating ensures more resistance against compressive loading [21, 22].

2.1.3. Mortar

Mortar is a mixture of cementitious material, aggregates and water. The binder (cementing) material, especially the new ones, usually consists of cement and plasticizer or cement and lime. Plasticizer and lime help to increase the workability of the mixture. On the other hand, more specific mortar was used for historical masonry structures [5, 12].

Mortar is used for many purposes, but the fundamental one is to bond or join the masonry units together to form an integral structure. In order to resist the applied compressive loads, mortar should hold the units together as a composite material. The strength of masonry mainly depends on the mortar used. If the stone has more strength than the mortar, the strength of the built-up masonry is affected a little from the crushing strength of the stone [23, 24].

For ensuring a good quality of masonry, the binding mortar should be equally distributed for brick laying and load carrying after it is hardened. It has such workability that the masonry can fill all the joints easily. Before laying each brick, the mortar–brick system should have a reasonable rigidity to prevent excessive racking movements. In addition, the strength of the bond directly depends on the water interaction between the mortar and the unit. The mortar absorbs the water for setting and hardening while the unit sucks the water out. Since less suction results in low bond strength and more suction cause dehydration of mortar (so not to strengthen), water content should be well balanced [23, 25].

The quality and type of mortar has an important role on compressive, shear and flexural tensile strengths of masonry. Basically, there are two types of bond strength: tensile bond strength and shear bond strength. While the tensile strength resists to the perpendicular forces to a mortar-unit joint, shear bond strength resists to the parallel forces [26].

2.2. Mechanical Properties of Masonry

Masonry is a two-phase material, consisting of masonry unit and mortar, and so properties of masonry depend on the properties of its constituents and binding material. Because of this complexity, knowledge of the mechanical properties of masonry is quite limited. In fact, the main difficulty in assessing the structural behavior of historical masonry structures comes from the insufficient knowledge about their mechanical features [20, 27, 28].

Being composed of two dissimilar materials, masonry presents a heterogeneous structure and a discontinuous system. As stated before, it is usually too difficult to determine the strength and stiffness characteristics of masonry structures. Even, using the mechanical properties of the constituent materials as input parameters for the laboratory tests does not give the actual results. Consequently, new methods such as Finite Element Analysis Method are required for analyzing the ultimate behavior of these structures [7, 8, 11].

The compressive strength of masonry can be defined as the load per unit of net cross-sectional area of masonry. It is related with the coursing joint and also depends on the type of connection, strength, deformation and material characteristics of the masonry units and the mortar. Compressive strength of the masonry units is generally quite high, whereas the strength of mortar is too low. Thus, compressive strength of the masonry prism, which forms after laying these materials, lies between the strength of the units and the mortar. The strength of the prism is less than the strength of the unit. Increasing mortar strength increases the prism strength while increasing mortar thickness decreases it [12, 20, 29].

Masonry has a very limited tensile strength, decreasing with time due to fracturation and deterioration of mortar. Even, some evaluation methods of masonry structures are mostly based on the hypothesis of total lack of tensile strength of masonry. According to this theory, masonry structures can be considered by the ideal no-tension material; resistant to compression, but unable to withstand tension [30].

As emphasized before, the tensile strength of masonry depends on the bond between mortar and masonry units and the binding pattern. When the water retentivity of the mortar is balanced with the suction from the masonry unit, a good bond will be obtained and an increase in bond strength exhibits an increase in the tensile strength. Also, the moisture content of the masonry unit at the time of laying is important for the tensile strength of the unit [23, 26].

Regarding the practical importance of the modulus of rupture, flexural tensile strength (resistance to bending or flexure) is much more important than the direct tensile strength. Several test results explore that density and thickness of mortar, and texture and moisture content of units are effective on the flexural tensile strength [12, 26].

The shear strength of masonry is relatively higher than its tensile strength. However, it is not of primary importance owing to the fact that masonry structures are rarely exposed to shear failure. Shear resistance of masonry depends also on the bond between mortar and masonry units. Shear stress mostly results from the movements existing parallel to the joint (joint shear) or the tension occurring in the unit oblique to the joint (diagonal shear) [6, 12].

In order to understand the behavior of the historical masonry structures, strength and stiffness properties of masonry should be well understood. The value of maximum stress that can be resisted and the stress developed under a given deformation are the measurements for these features. Type of loading also causes a variety in them. Since there isn't a constant increase rate in deformation, stress and stiffness of structural materials vary with the rate of deformation. Stress-strain curves are used to represent these variations and modulus of elasticity of a material can also be obtained from these curves (Figure 2.1). Modulus of elasticity of masonry indicates the nonlinear relationship between the stress and the strain. The behavior of the material can be interpreted by studying on this relationship and the characteristics of the curves [12].

2.3. Failure Criteria for Masonry

Unlike some other construction materials, masonry is a non-homogeneous complex material which has different component properties. Therefore, masonry structures may have several causes and so types of failure. During the analysis of failure mechanism of masonry, the most important factors can be counted as the geometry of the structure, strength characteristics of the material and load propagation through the structure [12]. The factor resulting in the lowest bound is considered as the critical failure. Thus, according to the failure type, the most proper theory is chosen in order to overcome the vulnerability of the structure.

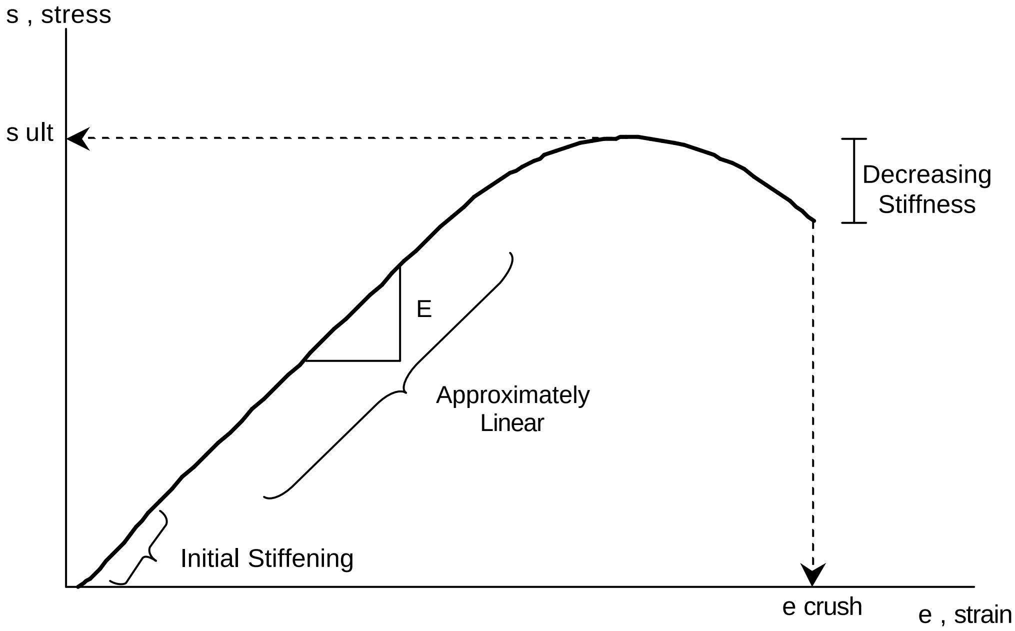


Figure 2.1. Stress-strain curve illustrating modulus of elasticity of masonry

Moreover, mortar joints cause distinct directional properties in masonry and acts as planes of weakness. Failure may occur only in the joints or as a combined mechanism including both the mortar and the masonry unit. This mainly depends on the stress state acting on the joints. So, critical failure mechanism of masonry should be evaluated by taking into account all of the preceding factors [27].

State of stress is directly related with the stress-strain relation of masonry. From previous experiments, it has been understood that masonry shows a non-linear and anisotropic behavior under biaxial and uniaxial compression. On the other contrary, the masonry walls behave in an isotropic manner under biaxial tension-compression or uniaxial tension [27].

The weak bed planes generally affect the precise fracture pattern but masonry mostly cracks perpendicular to tension and parallel to compression (Figure 2.2).

In biaxial compression, masonry cracks in the plane of compression. On the other hand, in biaxial tension-compression, it cracks parallel to the compression, perpendicular to the tension (Figure 2.3) [31].

The complex interaction between the masonry unit and the mortar joints also causes failure in masonry due to different stress-strain characteristics. Under uniaxial compression, the mortar in the joints has larger transverse strains than the masonry units. When the differential deformation is prevented by the bond between materials, horizontal stresses occurred in the mortar and in the masonry units by a uniaxial external load. As a result, a multi-axial state of stress exists in the masonry which is displayed in Figure 2.4. Stresses in the units increase along path (1) in Figure 2.4 until when this path and failure envelope of the unit intersects each other. This leads to vertical cracking and each of these cracks cause a reduction in the horizontal to vertical stress ratio which changes the stresses along paths (1),(2) (3), etc. When the stress path reaches point A in Figure 2.4 (the intersection point of the strength envelopes of units and mortar), failure of the masonry happens [32].

The orientation of head and bed joints of masonry has a very important role in determination of elastic and strength properties and so its failure criteria. The head joint is the vertical mortar joint between the ends of masonry units, whereas the horizontal layer of material on which a masonry unit is laid is the bed joint. Tensile behavior of masonry includes tension both normal and parallel to the bed joints. In the first one, failure generally occurs because of the failure of the relatively low tensile bond strength between the bed joint and the masonry unit or failure of the unit if the tensile stress is larger than the unit's tensile strength due to high quality mortar. On the other hand, in the latter one, failure involves the tensile strength of the head joint, the shear strength of the bed joints and also the tensile strength of the masonry unit [33].

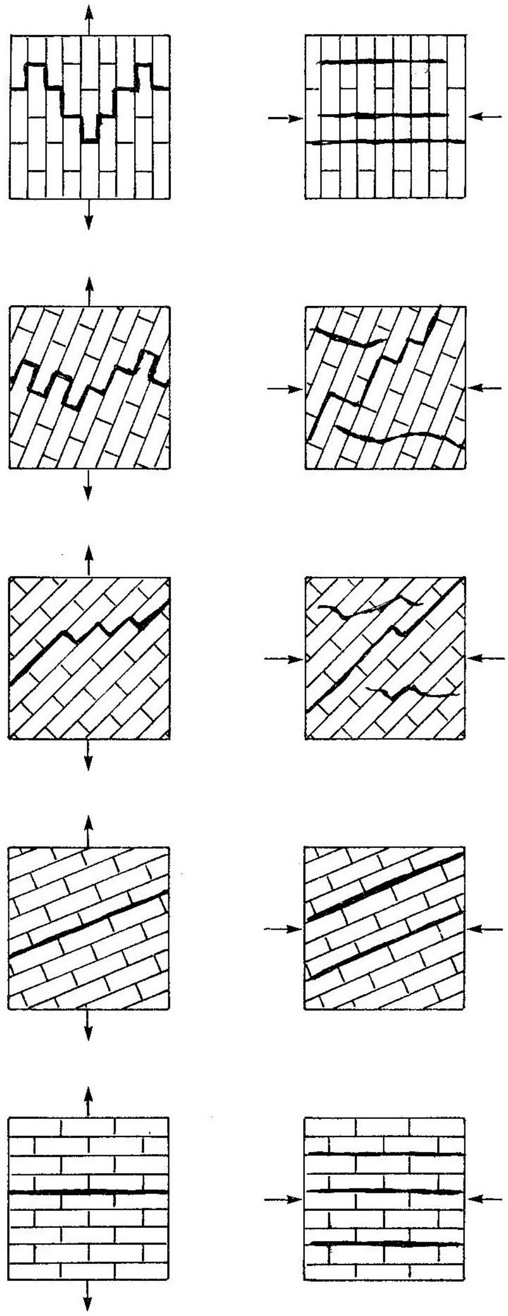


Figure 2.2. Fracture patterns in uniaxial tension and uniaxial compression for masonry, stressed at various angles to the bedding plane (0°, 22.5°, 45°, 67.5° and 90°)

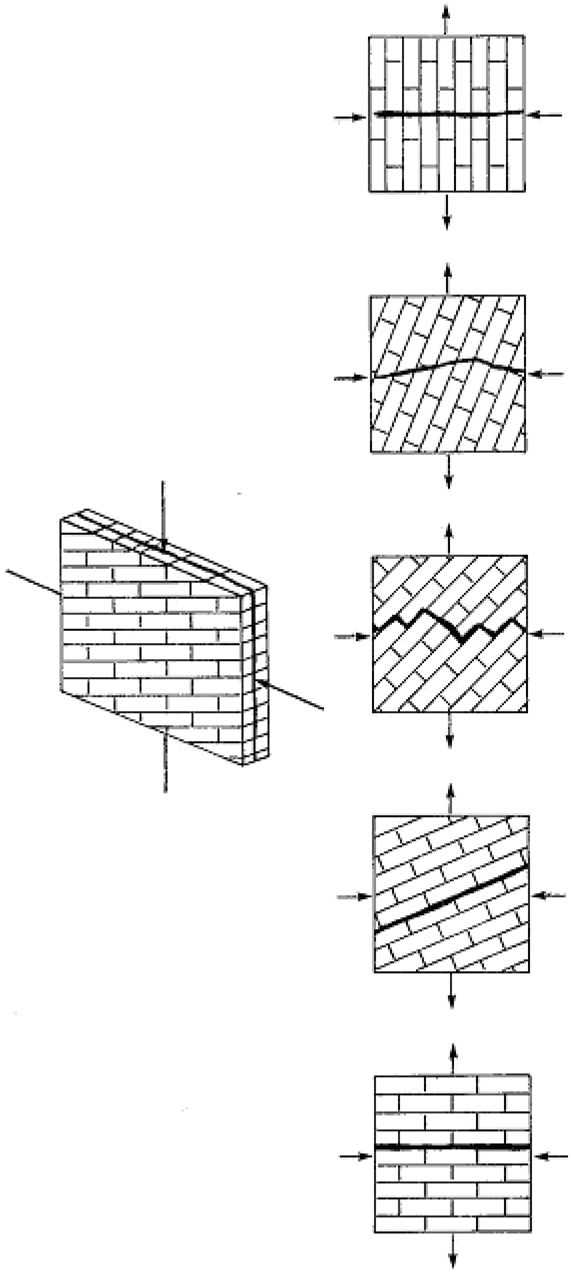


Figure 2.3. Fracture patterns in biaxial stress states for masonry

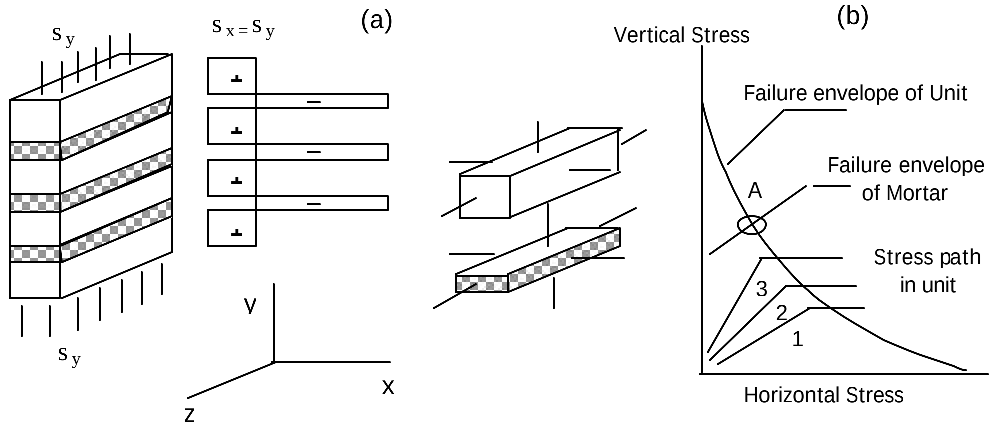


Figure 2.4. Interaction of masonry units and mortar joints

a) Prism under uniaxial compression and stresses in unit and mortar

b) Failure criterion for masonry

In a general sense, failure of masonry elements and material can be categorized basically in three groups:

- Failure under compression forces
- Failure under shear forces
- Failure under tension forces

As it was emphasized before, the main reason for the compression failure of masonry results from the different strain characteristics of the mortar and masonry units. In other words, when the contact between the masonry units exceeds the uniaxial strength of the masonry, compression failure occurs in the masonry (Figure 2.5). Furthermore, Poisson's ratio, modulus of elasticity, bond between masonry unit and mortar, coefficient of friction between mortar and masonry unit, shear resistance and tensile strength of masonry are the other important factors related with the axial compression failure [34].

The shear stress in masonry exists in two forms, sliding (joint shear) and diagonal shear which depend on the assemblage of units and mortar of masonry. The joint shear results from the resistance of mortar between the adjacent stone or brick units to the relative movement of these units in a parallel direction to the mortar joint (Figure 2.6). On the other hand, diagonal shear is caused by the tensile stress of masonry existing in a masonry structural element at some angle to the direction of shear. In order to prevent the diagonal shear failure, it is required to have a sufficiently good bond between the mortar and the masonry units forming the masonry structural element. If it is not provided, a stepwise failure along a diagonal in the plane of the masonry element occurs as presented in Figure 2.7 [12].

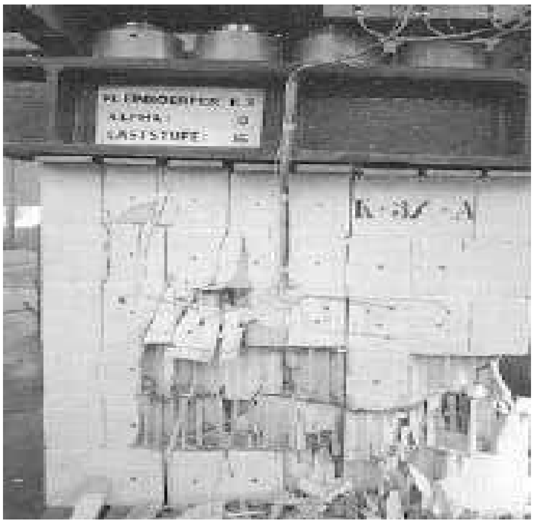


Figure 2.5. Compression failure of masonry units

Lastly, due to its brittle material characteristics, masonry has a great tendency for a sudden failure in tension (Figure 2.8 and Figure 2.9). Tension failure caused by flexure starts mostly from the joined points. With this failure, masonry element losses its balance resulting in an increase in the tensile stresses of it which causes a partial or total collapse. Moreover, expansion and contraction of masonry because of moisture or temperature changes may give rise to an increase in tensile stresses [35].

Figure 2.6. Sliding failure along joints

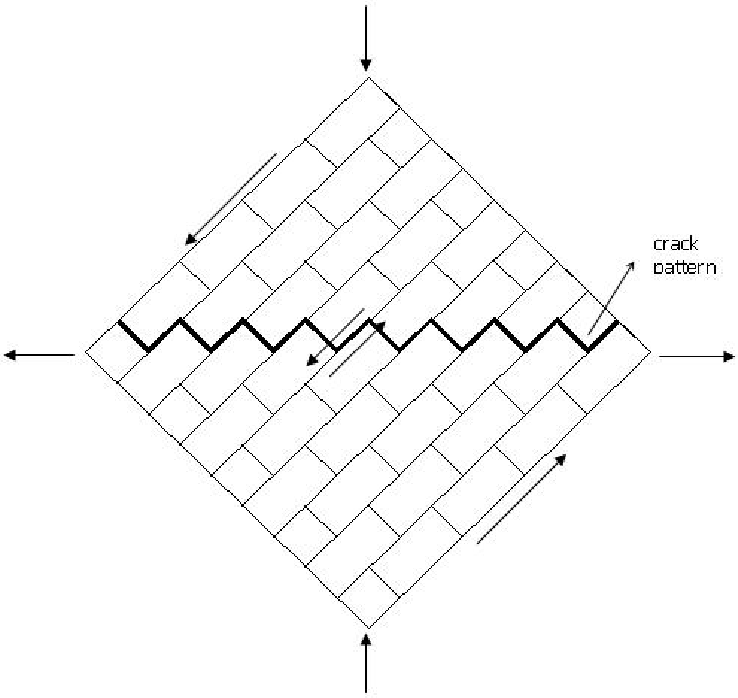


Figure 2.7. Stepwise failure along diagonal

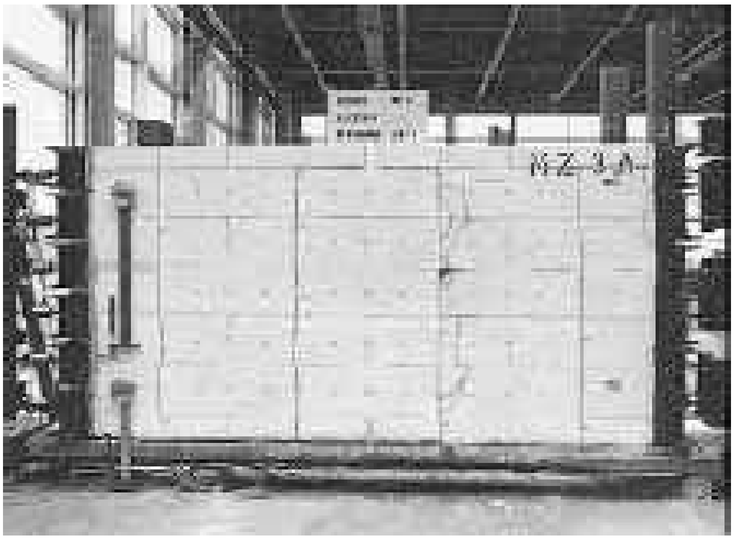


Figure 2.8. Tension failure of masonry units

Figure 2.9. Tension failure along joints

CHAPTER 3

STRUCTURAL ANALYSIS OF HISTORICAL MONUMENTS

3.1. Method of Structural Analysis

Conservation and restoration of historical monuments have a significant role for ensuring the continuity of our history. However, it is actually not easy to achieve this completely. Indeed, a detailed evaluation of historical, cultural, architectural and structural aspects is required in order to make correct decisions.

Conservation of historical built heritage starts with understanding the structural behavior of monuments and so their construction material. This is then followed by two important aspects of conservation; the safety assessment of structures and analytical studies for the development of structural strengthening methods. For a sensitive-correct approach and accordingly a successful protection work, a synthesis system should be created, combining all the data taken from every single step of the study [36].

The structural system of historical monuments usually has a very complex form. Therefore, it is not easy to understand and analyze the structural behavior of monuments. Moreover, complexity of the masonry material makes it impossible to evaluate the ultimate behavior of historical masonry structures. Even the laboratory tests, in which the mechanical properties of the constituent materials are used as input parameters, do not give the actual results. After considering their complex geometries and distinct material characteristics, it is required to use an effective method in the analysis of historical masonry structures [35].

In the analysis of structures, strength, stiffness and stability characteristics are considered as the three main criteria. The structure should be strong enough to carry the imposed loads, including its self weight. Large deflections and differential displacements should not occur in the structure, either locally or overall. In this respect, it is also important to know the load history of the structure also. Lack of information about the loading history, strength and stiffness characteristics of the structural materials reduce the accuracy and validity of the results obtained from the structural analysis. In addition, an exact structural analysis should take into account the crack patterns, the crushing phenomena and the actual deformations [12, 37].

A reliable structural analysis requires a good knowledge of mathematical model. Without interpreting the present mechanical condition of a structure, it is not possible to obtain a perfect structural analysis. A proper description of the physical and geometrical properties of the material and structural elements in the model is also essentially required for a comprehensive study [12].

In the Middle Ages, the structural design and analysis methods were only based on the practical and empirical knowledge of forces coming from known structural failures. The calculation of internal forces and displacements were too difficult especially for the complex structural forms. However, starting from 19th century, new methods of structural analysis have been developed. Nowadays, much more refined studies which are based on conventional analysis methods are used [12].

The complex heterogeneous material characteristics of masonry, however, limit the validity of conventional methods. Because of the developing techniques in construction, even experimental results become to be an insufficient reference for developing a correct model. Thus, numerical analysis methods of computer based system, have gained increasing importance and started to be the most preferable ones for both engineers and architects in order to perform an inclusively successful study on historical masonry structures. In addition, understanding the failure, designing the strengthening system, creating 3D representation of the structure and static & dynamic analysis of the material require numerical analysis methods. Especially, seismic behavior of masonry structures represents a very difficult task if handled with traditional methods. Analytical modeling of masonry monuments could also reveal that the load is shared by different structural components and load path followed, which cannot be predicted by conventional analysis methods due to non–linear behavior and intrinsic geometrical complexity of the material (made of blocks interconnected by mortar joints) [7, 38, 39, 40, 41].

3.2. Structural Analysis According to the Behavior of Masonry Structures

The structural analysis is basically carried out according to the behavior of the material. The behavior of the structural elements could be mainly based on two different terms: elasticity and plasticity. These terms actually relate the stress-strain properties of the material. Elasticity represents the capability of the material to return to its original shape after the load is removed. On the other hand, the material does not completely return to its original shape upon the removal of loading in the plastic behavior. Moreover, in plastic behavior, the deformation is uncontrolled and the speed of deformation depends on the stress. Therefore, for an elastic behavior, the deformation state is the same whether the material is being loaded or unloaded at a given load. Whereas, non–recoverable deformation generally takes place in a plastic behavior [42, 43].

3.2.1. Linear Elastic Behavior of Masonry Structures

Linear elasticity is the most common material model in the structural analysis of masonry structures. In the elastic analysis of masonry structures, it is assumed that masonry units and mortar behave as a single material, having unique mechanical properties [42].

The preliminary assumptions of the linear elasticity model are:

1) As stress is increased/decreased the resulting strain increases/decreases in a linear proportion.
2) Strain, which is perpendicular to an applied strain, is linearly proportional to the applied strain (Poisson's ratio effect).
3) The material is homogeneous and continuous.

The linear stress–strain assumption is valid for a wide range of structural materials. Without tensile cracking and under short term loading, it is also acceptable for the masonry material. In fact, the "object of the study" is the determining factor for the selection of material model [42].

3.2.2. Non-Linear Behavior of Masonry Structures

Structural analysis is generally performed in the elastic field, often following with Finite Element Methods which can be extended to non–linear behavior for more sensitive cases. In the non–linear analysis, the material behaves elastically up to its yield point (at which deformation becomes non-recoverable). But beyond the plastic limit, it continues to withstand its yield stress without taking further stress (Figure 3.1). The deformation development and the crack patterns are usually indicated by this analysis [15, 42].

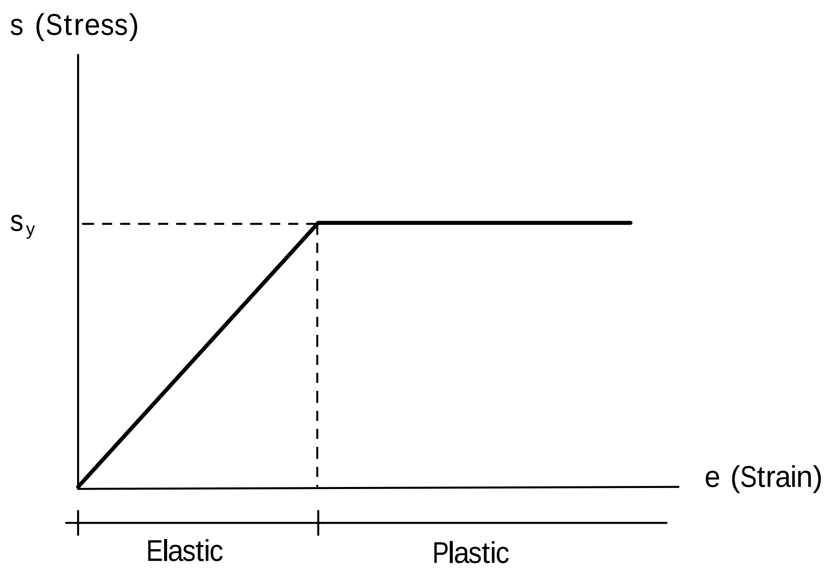


Figure 3.1. Elasto-plastic stress-strain diagram

3.2.3. Limit Behavior of Masonry Structures

Structural analysis, which is based on limit behavior of masonry structures, identifies the collapse mechanisms, ultimate stress distributions (at least on critical sections) and load capacities. It is an effective tool for understanding the main aspects of the overall behavior and for evaluating the structural system of the historical masonry constructions [15].

Limit analysis, which was first assured by Heyman (1977), assumes a rigid no-tension constitutive model for masonry. This method implies that the masonry body behaves as an assemblage of rigid elements kept together by compression forces (by plastic zones where all the deformations are concentrated and where the stresses reach the border of the strength domain) (Figure 3.2) and crack at regions characterized by tensile stresses [43].

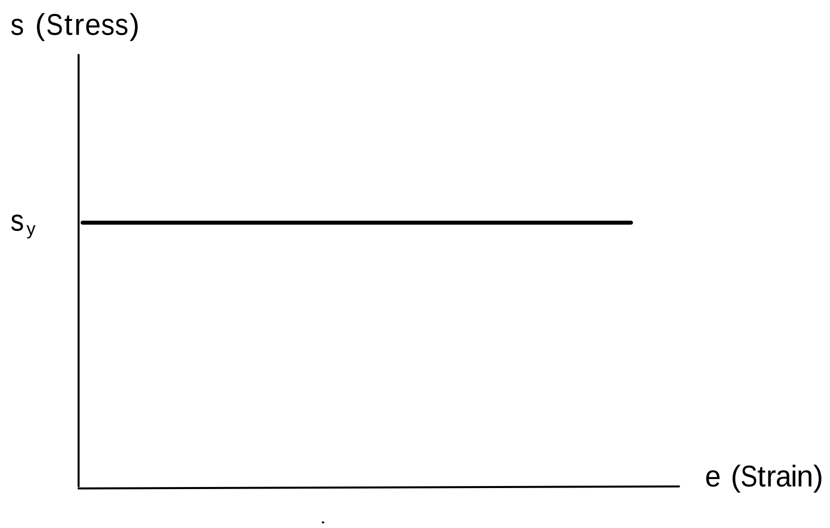


Figure 3.2. Plastic stress-strain diagram

In this approach, if the line of thrust passes outside the entire cross-section, plastic hinges are developed and finally, a mechanism forms meaning the failure of structure. Plastic behavior of masonry structures is defined by this limit state [44].

The mechanism approach has some basic assumptions [45]:

- The masonry has no tensile strength.
- The masonry has infinite compressive strength.
- The blocks initially fit together perfectly.
- Strains in the masonry are small, so cause negligible changes in the global geometry of structure (generally for arch).
- Sliding failure of adjacent masonry units cannot occur.

This assumption is certainly verified for the masonry made of rigid blocks with no mortar. However, it is also applicable to the ancient masonry made of tuff (tufa) blocks or bricks with mortar joints and to the case of opus caementicium since mortar is weakened by time and the structure loses its initial tensile capacity. Moreover, if the tensile capacity of the structure is considered to be suddenly deteriorated because of the events causing cracking, such as dynamic actions, this hypothesis holds true for materials characterized by a finite tensile capacity [43].

3.3. Analytical Modeling of Historical Masonry Structures

Due to its simplicity, structural masonry has been a very popular construction material among historical structures. However, for new applications of structural masonry, where the traditional empirical rules are inadequate, rational design rules are required. Especially, most of the assessment and strengthening strategies for old masonry structures increasingly based on computational modeling techniques owing to the discontinuing nature of the structure [46].

3.3.1. General Principles of Analytical Modeling

Structural Analysis starts with the construction of the analytical model of a structural component or the entire structure. This is actually done by discretizing the structure. According to the requirements of the problem, the structure or its components are divided into elements. The accuracy of the system depends on the number of elements used in the model. Defining the structure by appropriate number, size and type of materials bearing in mind the geometrical features, the movement ability of the joint restraints and the connection points of elements and the loading conditions applied to the structure is called analytical or mathematical modeling of a structural analysis [35].

The purpose of analytical modeling is the correctly determination of the actual behavior of a structural component or the whole structure under a variety of loading or several physical effects. Since the actual behavior of the structure is usually too complex, it is required to make some simplifications during modeling. In order to obtain a refined model, the behavior of the material should also be represented correctly [12]. In this respect, historical masonry structures needs a special attention to model and analysis of these structures is mostly performed by Finite Element Method which will be explained in the following sections.

Analytical modeling has some main principles [35]:

- The most effective analytical model is the simplest one which satisfies the requirements of the problem. Complexity does not ensure any advantages unless it is necessary.
- In the design of element dimensions, all of the structural effects necessary for the analysis should be considered carefully.
- It is not enough to investigate the detailed behavior of a part or element of a structure with a model made by extracting that part from the large model representing the complete structure. For a detailed behavior analysis, a special model supporting the needs of the problem (correctly taking into account the boundary condition and connection ways) should be performed.

3.3.2. Structural Analysis with Finite Element Method

The Finite Element Method (FEM) is a numerical method for analyzing structures and continua. Conventional analyses methods are mostly insufficient to solve the complicated problems while Finite Element Method can produce several simultaneous algebraic equations generated and solved with a computer based analysis [47].

Finite Element Method models the structure by dividing it into small elements, called finite elements. A finite element model is the assemblage of these elements. Since each finite element has a simple geometry, it is easier to analyze them rather than analyzing the whole structure. In other words, the Finite Element Method converts a problem with an infinite number of degrees of freedom to a problem having a finite number of degrees of freedom in order to simplify the solution [47, 48].

In Finite Element Method, finite elements are interconnected at joints, called nodes (nodal points) and external loading is distributed equally to these nodes. Relation between the response of the nodes and the elements indicates the behavior of the element. The main objective of the Finite Element Method is to approximately calculate the stresses and deflections in a structure. Furthermore, discretizing a structure into a mixture of different types of finite elements is possible in a finite element model [12, 48].

Since almost any shape can be constructed using triangles, first finite element formulation was based on triangular element approach; introduced by Cough in 1960. Then, a mesh–based system, taking the finite difference approach as basis, was developed and this method was called as “dynamic relaxation” by Otter in 1965. While the first one concentrated on the stiffness method with direct solution of equations, the second one is based on the formulation of equations of motion leading to a static solution. Nowadays, an integrated system, taking the advantage of both approaches, is used as a general Finite Element Method [49].

The algorithm of *Finite Element System*, which is displayed with a detailed sequence in Figure 3.3., can be basically divided into three steps [28, 49]:

1) *Pre – Processor*; prepares the finite element model by generating the complete input file, storing the material data, generating the nodes and

elements, defining the elastic limit of the analysis under the given load condition, defining the number of increments and an initial incremental step of the loading and defining the failure domains for each material.

2) *Main – Processor*; solves the finite element problem for a given incremental step, performs the displacement and stress analysis.
3) *Post – Processor*; processes the results of finite element problem, checks the state of stress at the center of each element referencing to the failure domain, plots the characteristics of model and gives a graphical representation.

In order to model the structure accurately, and to reveal the actual physical nature of the problem, it is very important that elements should not only reflect the shape of the structure but also ensure the true flow stress from the loaded zones to the reaction zones. Therefore, elements should be mapped perfectly onto the structure and the position or joining ways of all nodes should be defined correctly in order to well describe this mapping within the system [49].

The first step in the finite element technique may also be considered as modeling of the real structure into a simplified and idealized system from which a solution is available. This also ensures the system to be clarified better which is crucial to increase the accuracy and the efficiency of the analysis. Besides, it is possible to understand and interpret the results more correctly because of the fact that the system could be visualized easier even by a person who is not familiar with the logic of the structural formation.

Figure 3.4 illustrates the analytical modeling of a real structure into a simple system. The analysis is performed on the idealized model shown in Figure 3.4-b. This model consists of a number of elements obtained by means of fictitious cuts through the original structure, as indicated by lines. Adjoining elements may be thought of as being connected at nodes, but they are separated elsewhere by the imaginary cuts [50].

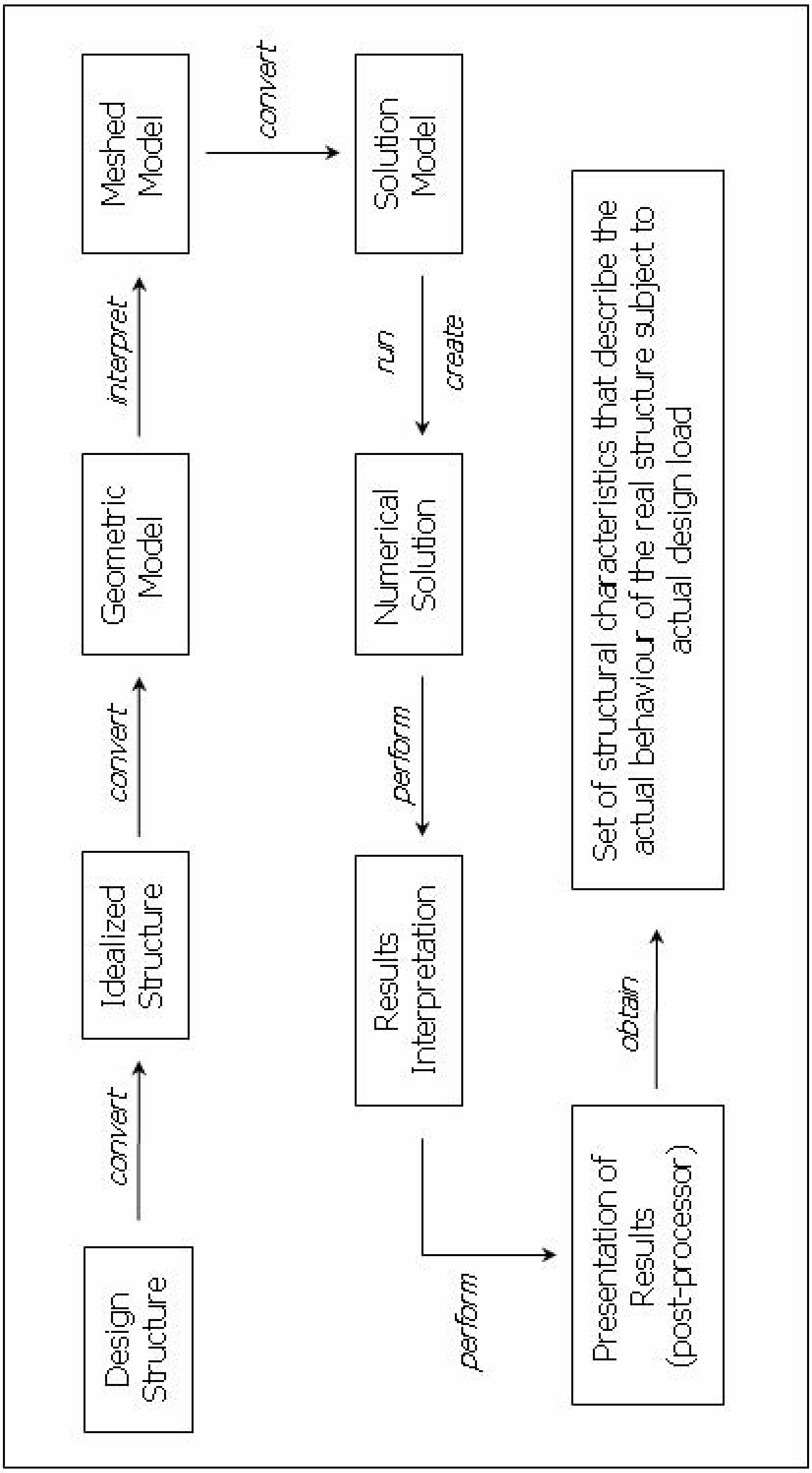
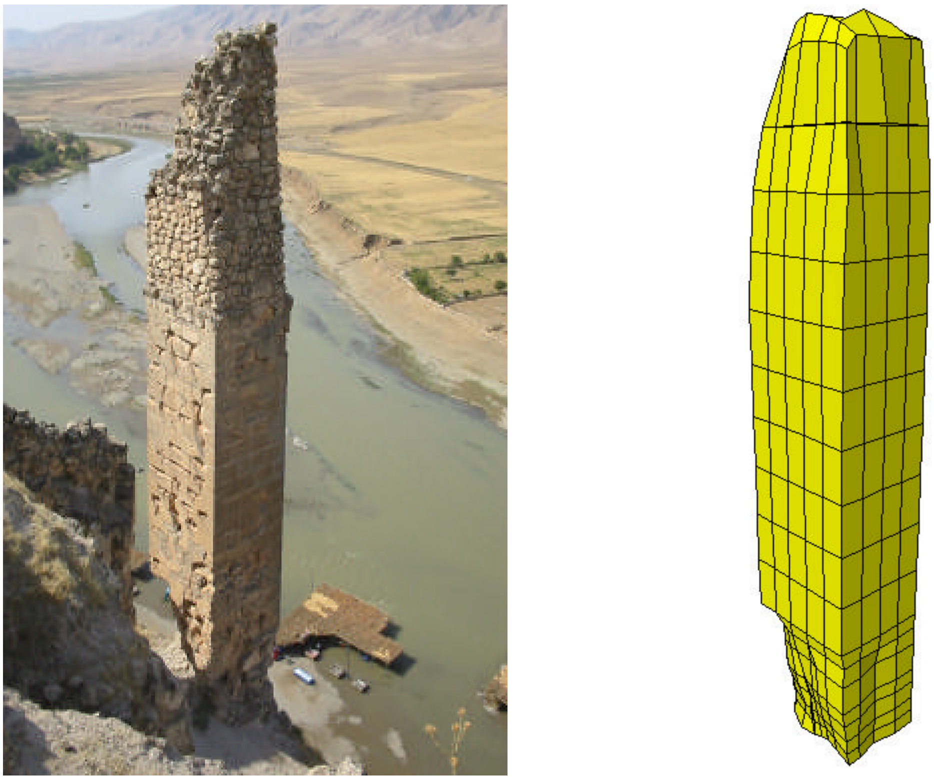


Figure 3.3. Sequence of Finite Element System



a) Real model b) Idealized model

(a masonry monument located in Hasankeyf)

Figure 3.4. Modeling of a structure into a simplified system

As mentioned previously, Finite Element Method is a very powerful tool for the analysis of historical structures due to their complex structural geometry and behavior. The analysis with this method requires the solution of the following two main problems of the historical masonry structures regarding the study area and so used method:

1) Investigation of single structural element and its behavior (element analysis)
2) Investigation of the overall behavior of the entire structure (system analysis)

The element analysis involves [50]:

- The selection of functions that uniquely describe the displacements within the elements in terms of the nodal point displacements.
- The derivation of corresponding stresses.
- The derivation of fictitious nodal point forces that equilibrate the distributed boundary stresses.

The element analysis yields a relationship between nodal point forces and nodal point displacements. This relationship is expressed in terms of stiffness or a flexibility matrix for the element. Alternatively, the system analysis may be formulated in such a way that it is completely unaffected by the type of element used in the analysis. Consequently, it is possible to write a program for the system analysis that can work on any type of element for which the stiffness matrix is available. Moreover, such a program should also be capable of handling structures which include combinations of different element types [50].

Research developments on the Finite Element Method are being increased in each day. Especially, finite element analysis of historical masonry structures become much more sophisticated with the development of numerical techniques. By this way, different perspectives exist in the evaluation of structural behavior of these structures which help to reach more refined analyses.

For the appropriate constitutive description of anisotropic behavior of masonry material, there exist two fundamental approaches: the “micro-model”, or “two–material approach” and the “macro-model”, or “equivalent–material approach” (Figure 3.5) [46].

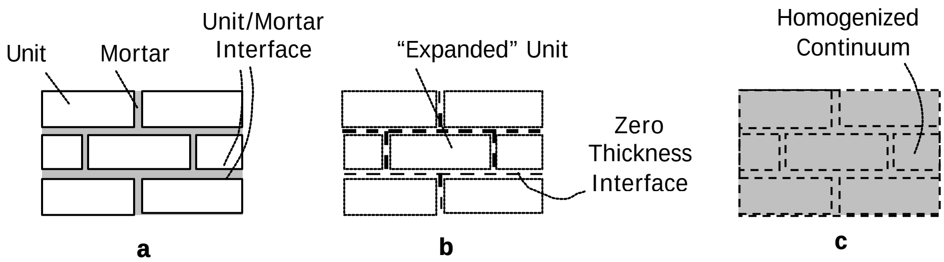


Figure 3.5. Modeling of Masonry

a) Detailed micro-modeling

b) Simplified micro-modeling

c) Macro-modeling

In the micro-modeling, the masonry material is taken as a discontinuous assembly of blocks connected to each other by joints. So, the blocks and the mortar joints are modeled separately. This model is mostly preferred when a single structural element analysis is needed to be performed. Conversely, the macro–modeling approach analyzes the masonry material without separating units and joints and by formulating a fictitious homogeneous and continuous material equivalent to the actual discrete one. Thus, the single element has a constitutive model which should be capable of reproducing an average behavior. By means of this assumption, the global behavior of an entire structure can be investigated by decreasing the extremely large number of elements to be generated. Because of the reason that increasing number of elements may result in prevention of detecting the actual distribution of blocks and joints, the size and complexity of the structure is decreased by this assumption [33, 35, 41].

The selection of the method mainly depends on the problem requirements. Masonry is considered as an assemblage of brick/stone and mortar. For the comprehensive analysis of the whole structure, a homogeneous model is usually assumed and the influence of mortar joints acting as planes of weakness is ignored. This approach is suitable for predicting deformations at low stress levels. But, at high stress levels, masonry should be regarded as a two–phase material consisting of elastic bricks set in an inelastic mortar array of which non–linear material behavior and local failure indicates adequate results [12].

The power of Finite Element Method comes from its versatility. It is possible to analyze structures having arbitrary shapes, loads or support conditions. In addition, mesh generation can provide a mix for the elements having different types, shapes and physical properties. The physical resemblance between the actual structure and its finite element model is an important factor for using this method. However, without a good engineering judgment, a reliable computer program and correct & sufficient data, a good model cannot be obtained [47].

3.3.3. Understanding and Interpretation of Finite Element Analysis Results

The analysis results obtained from Finite Element Method is important both for understanding the overall structural behavior and contribution of its components. This method breaks down the structural system into several discrete elements. In order to create a comprehensive model, computer algorithm combines the spatial information of these discrete elements and the mechanical properties of their material that an extensive structural evaluation can be done [51].

Computer analysis is based on a mathematical model which is constructed to characterize the structure or its specific parts. Nodes, elements, applied external forces and specified nodal restraints are the principal components of the system. Therefore, a good knowledge of mathematical model is the beginning point for an accurate and valuable interpretation. Putting the results into a well-arranged order will also help to efficiently evaluate and discuss the results of the analysis. Owing to the fact that an intermediate size finite element model usually includes hundreds of data items, using graphical outputs can essentially ease interpreting the analysis results. Indeed, technical education is not strictly required to evaluate these graphical outputs of finite element analysis results. As a result, in addition to structural engineers, for architects, archeologists, restoraters, city planners and architectural historians, it will be beneficial to use these kinds of graphical or tabular results in the studies of structural assessment and analysis of historical masonry structures [9,12, 51].

The best and easy way to understand and interpret the behavior of a structure in an analysis is to concentrate on the deformation in the structure under the applied loads. The deformed shape of the structure will be very helpful to put forward the relationship between the previously known behavior and the validity of the obtained internal forces and deformations [12].

3.4. Importance of Load Estimation for the Structural Analysis of Historical Monuments

The art of performing an effective and correct structural analysis of historical monuments depends on applying the principles of engineering to the structure in a good way by which an effective, safe and accurate model could be obtained. This, in fact, requires a clear understanding of material properties of the structure and also forces imposed on it at the beginning of the structural analysis. Although, estimating the material properties are more difficult than estimating the loads, load propagation has more importance for this study due to the fact that a homogeneous material characteristic assuming a single element behavior are considered during the performed analyses.

The main purpose of all structural elements in the carrying system of a structure is to transfer the dominating loads to the soil. The safety of the structure is determined by considering whether the structure has the requirements for safely carrying the loads imposed on it. The loads effecting on a structure influence the shape and dimensions of the structural elements. Then, the structural elements influence the structural carrying system and this system influence the form of the overall structure. Consequently, it is essential to know the expected loads and load combinations during the design process [12, 35].

3.4.1. Structural Loads

Structural loads can be classified in several ways. Depending on the case, too special and variable loads are needed to be considered in the analysis of different projects. For the structural design of an ordinary building type of structures, loads are basically classified into two groups. These are:

1) according to their source
    a. natural loads
    b. service loads
2) according to their way of application
    a. horizontal loads
    b. vertical loads

Considering the source of the loads, the most essential one among the natural loads are the self-weight of the structure. It involves permanent components of the structure (self-weight of domes, arches, minarets, etc.), architectural components (window fixtures, glazing, etc.), all nonstructural partitions and covering elements, etc. Since it is more difficult to define the actual dimensions of structural elements of historical masonry structures, they should be studied carefully for the load estimation. Actually, this results from larger cross-sections of the architectural and nonstructural finishing elements. Earthquake loading is also seriously effective on these structures. Due to the fact that the main structural load carrying system of historical structures is mainly formed of heavy masonry construction, their structural safety is predominantly governed by earthquakes and support settlement. During the analysis, these two conditions create the most critical loading combinations. Some other natural loads can be counted as wind load, snow load, soil pressure, etc. [12].

Service loads are mostly defined as the live loads and depend on the usage purpose of the structure. Live loads are the loads generally created by humans, furniture and the temporary structural components.

The loads in the second group (according to way of application), horizontal and vertical loads, are closely related with the structural behavior. In a general sense, self-weight, moving loads, snow load are defined in vertical loading. On the other hand, earthquake load, wind load and soil pressure are defined as horizontal loading. It is very important to determine the magnitude of loads, period of loading and their critical combinations in the evaluation of ultimate safety of historical structures [35].

Although a variety of loads are considered in the analysis of historical structures, the most common ones expected on a historical structure are [12]:

- dead loads due to gravity
- earthquake loads
- snow loads and ice pressure
- differential settlements of supports
- soil pressure and ground movement
- creep
- thermal loads particularly in case of fires
- accidental or armed impact loads
- surcharge on walls

3.4.2. Loading Conditions in Historical Masonry Structures

Loads, which are used for the analysis of contemporary buildings, are not valid for the analysis of historical structures. Load intensities, given in the modern structural design codes, are guides which can only provide the minimum values. Thus, load estimations or criteria for load combinations for historical structures are based on historic documents, observations, past experiences and so engineering judgment [12].

Throughout the analysis, the loads imposed on a structure are indicated in terms of forces, bending moments and deformations. In order to interpret the resistance of the masonry elements and to make the safety evaluation of the structure, the analysis results should be attentively assessed and a comparison should be made between the effects of load actions and the strength of the material [26].

In the analysis of historical masonry structures, it is very important to estimate the gravity loads in order to evaluate the safety factor of the structures accurately. Since gravity loading is directly related with the structural behavior, any possible errors could be detected by investigating the results taken from the structural analysis of the monuments under gravity forces. In addition, masonry structures are resistant to the gravity forces due to high compressive strength of masonry. On the other hand, lateral forces mostly results in failure or collapse of the historical masonry structures since seismic actions cause great tension forces in the structure. Especially, earthquake forces are not easily determined without knowing all related information about the structure and the environment on which it stands. Therefore, the exact safety evaluation of these structures, considering the seismic forces, is primarily not possible. However, newly refined analytical methods have an important role in the structural analysis of historical masonry structures [12].

CHAPTER 4

STRENGTHENING OF HISTORICAL MASONRY STRUCTURES

4.1. Structural Vulnerability of Masonry Structures

Masonry structures, which are subjected to external loads due to natural or manmade hazards, are prone to considerably extensive damage followed by failure and collapse. Structural weakness, overloading, vibrations, settlements and in-plane or out-of-plane deformations are the main reasons for the failure of unreinforced masonry structures. Especially, high wind pressures and earthquakes result in more serious deformation on historical masonry structures [52].

Actually, masonry is the oldest man-made building material, invented almost ten-thousand years ago. For centuries, it was widely used due to its simplicity, strength and durability. However, with the industrial revolution, new construction materials; concrete, iron and steel, are started to be preferred for the structural systems. Nowadays, masonry has been generally used for nonstructural applications, such as veneered constructions and non-load bearing partitions [32].

As it was emphasized in the previous chapters, the main disadvantage of masonry material is its too low tensile strength. Therefore, it has been primarily used so far in construction of vertical members, subjected particularly to gravity loads and at most small lateral loads which can be resisted by the members self weight.

Indeed, there exist a big risk of failure and collapse for larger lateral loads. In order to overcome this vulnerability, masonry is needed to be strengthened. As a result, historical masonry structures should be studied carefully in order to find the most effective conservation technique.

It is very important to decide on the appropriate strengthening solution for a historical masonry structure. Thus, the structure should be evaluated from different views regarding the bearing capacity and stability, safety level and its evolution on short, medium and long-term, environmental conditions, so that the loading history and other related properties of the structure.

4.2. Structural Damage and Appropriate Strengthening Measures for Historical Masonry Structures

Damage can be produced by increasing mechanical actions (forces, deformations, accelerations, etc.), change in the structural behavior (removal of a wall or an arch, addition of a floor, etc.), or reduction of the strength (decay of the material characteristics, etc.)

Mechanical actions are generally divided into two categories:

- static actions
- dynamic actions

Static actions are also divided into two subcategories:

1) *Direct Actions:* These are basically the loads that are directly applied to the structure, such as dead loads (self-weight), permanent loads and live loads.
2) *Indirect actions:* These are related to the deformation or strain of the structure, such as soil settlement, thermal vibrations, viscosity or shrinkage of materials.

Dynamic actions mainly result from an acceleration applied to the structure, such as earthquakes, wind, vibrating machinery, explosions, etc. The intensity of the forces depends on the intensity of the acceleration, natural frequencies and capacity of the structure to dissipate the energy.

Seismic action, which is the most significant dynamic action, induces accelerations and movement in the structure. It is actually the major cause of damage and collapse of historical structures because of small tensile resistance or strength of masonry material as mentioned in the previous chapters. The assessment of seismic vulnerability of old masonry structures needs an appropriate strengthening to overcome the destruction of these structures when subjected to strong ground motion.

In Figure 4.1 [7], structural response of some simple masonry blocky structures; a single column, a set of two columns with a lintel and roman arch, are displayed when they are subjected to a vertical load and seismic action. During earthquakes, the structure becomes more and more disconnected and cracks which reduces the overall stiffness of the structure. In fact, seismic actions are often the most hazardous actions affecting the structures not only due to the intensity of the produced forces but usually due to improper design of structures; i.e., without taking account of horizontal forces [53].

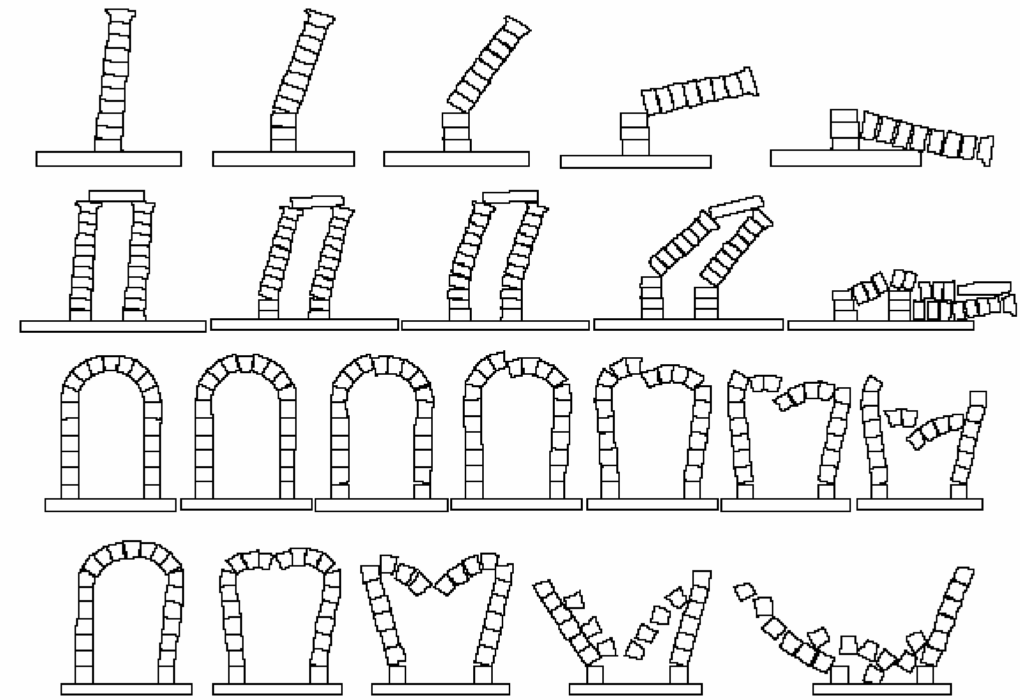


Figure 4.1. Seismic behavior and collapse patterns for different structural elements

There are many remedial measures which can be taken by considering these two routes. In our case, surrounding the masonry structure by using prestressed cables will be an effective solution in order to eliminate the radial and vertical tensile stresses produced in the structure during tilting process. Prestressing also strengthen the structure against failure and collapse against this artificial high seismic actions.

A conservation study using prestressed cables was done by Forni in 1997 for the S. Giorgio bell tower in San Martino del Rio. Figure 4.2 displays the collapse sequence of this tower under a seismic action. During the analysis, forces slightly higher than the observed ones had been applied to the structure. But the early stage's damage shown in the figure is also quite similar with the "in loco" observed damage [7]. The simulation of the bell tower response to the same seismic action using two different reinforcement schemes is displayed in Figure 4.3. On this figure, (a), (b) and (c) illustrates the following responses of the tower:

(a) response of the unreinforced tower
(b) response of the reinforced tower with vertical cables
(c) response of the reinforced tower with vertical and horizontal cables

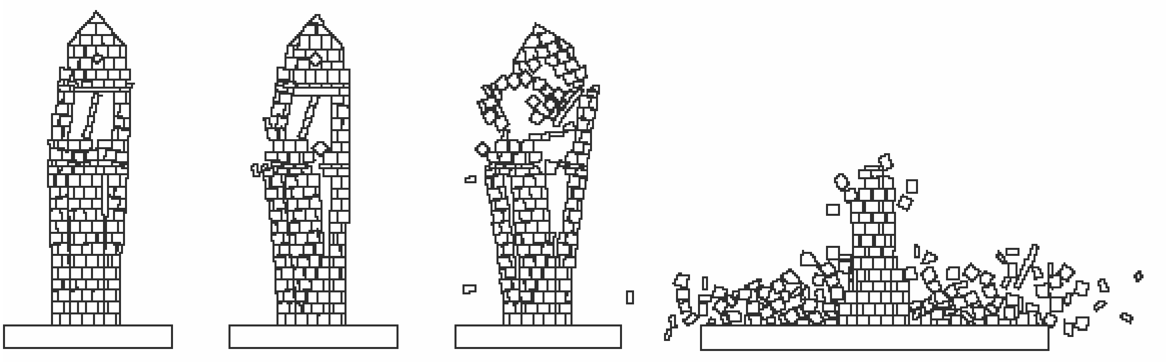
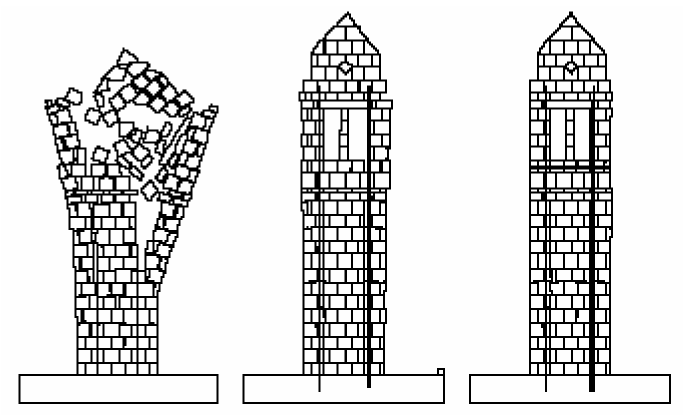


Figure 4.2. Collapse sequence for the S. Giorgio in Trignano bell tower



(a) (b) (c)

Figure 4.3. Bell tower seismic response with alternative reinforcing schemes

Furthermore, it is very important to consider various loading conditions either occurred during construction or over a lifetime of use for any structure. This is also valid for the prestressed structures. However, design of these structures is much more complex than any routine ones. As a result, it should be done with a detailed study in order to see the problem from all possible points of view. For instance, the design should incorporate many different events over the life of the structure; but for unique applications there should be some reasonable tolerance for errors in assumptions [17].

4.3. Prestressing Masonry

Masonry structures may require strengthening for several reasons. Increase in the deformations of the structure or redistribution of stress within a structural element may cause creep in that structure. If loads are redistributed, then the masonry would be carrying more loads over time. Failure of structure will be inevitable if this redistribution combines with a decrease in strength from external environmental factors [54].

In history, there are many examples of strengthen masonry by using different methods. These are mainly due to the necessity to minimize the life-threatening effects of natural hazards, material degradation, and human misuse and so to preserve valuable constructions from these destructive effects. One of the earliest strengthening methods was to place a heated flat iron or steel bar across the damaged area and then bolt it to solid material on either side. The damaged masonry would be compressed due to contraction on cooling, which results in placing the bar in tension but leaving residual strength to resist any load increase. Over the years, technology has gradually developed and new materials have been discovered [54].

Because of the low tensile strength of the masonry material, prestressing is regarded as one of the most powerful techniques used for strengthening of ancient masonry structures. In order to overcome the intrinsic vulnerability of masonry, an additional force should be implemented to the structure. In this respect, prestressed masonry gains an accelerated importance.

Prestressing a structure deliberately induces some internal stress into the structure prior to its sustaining of service loads. The main purpose is to compensate some anticipated service load stress in advance which is some high level of tension stress for masonry (or concrete). Therefore, the “pre“ stress is usually compressive or reversal bending stress. Prestressing is mostly achieved by stretching high-strength steel strands (bunched wires) inside the masonry element. The stretching force is transferred to the masonry and the desired compression in the structure is produced [17].

Masonry is very strong in compression and prestressing also simply adds compression to the masonry. Prestressed masonry can compensate any of external-horizontal forces (wind, earthquake, etc.) by using masonry’s strength under compression that would normally cause cracking or failure from tension.

Prestressing is an effective way for strengthening masonry walls, towers, spires and minarets; i.e., for structures which could resist the vertical forces but not capable for the horizontal ones (except very small ones). Especially, horizontal prestressing is a preferable method because it does not cause a significant change in the original structure. It may be performed by anchoring tendons at the external surfaces of the masonry. On the other hand, vertical prestressing is more difficult to perform due to the requirement of bottom anchorage on either side of the structures. But it can be considered for such structures since it provides a more consistent stress distribution [55]. Actually, choosing the suitable method depends on the problem itself.

The main problem for strengthening masonry structures by prestressing is the increase in the bearing capacity and the capacity to dissipate energy due to the change of force distribution. One other problem is the loss of prestress force during the life of the structure. As time passes, the force that is initially placed in the prestressing tendon will decrease for a variety of reasons. This results in a net compressive stress on the wall that is less than the originally assumed one in the design [56]. So, prestressing masonry requires a careful investigation and continuous study for the success of the system.

Prestressing uses two common procedures: pre-tensioning and post-tensioning. In pre-tensioning, the tendons are first installed and tensioned and then the masonry is poured around tendons. After curing of the masonry, tendons are released and bond to the masonry and so the stress is transferred to the masonry. However, most applications are done by post-tensioning although it is more difficult. In post-tensioning, firstly the masonry is constructed along with the tendons. After partially curing of masonry, tendons are tightened, thereby putting the masonry in compression [57].

Post-tensioning masonry is an emerging and preferable technique for strengthening especially historical masonry structures. Post-tensioning, offers basically the possibility of actively introducing any desired level of axial load in the structure to enhance strength, performance and durability of the masonry structures. The prestressing steel helps to avoid any brittle tensile failure [32].

According to the load tests on post-tensioned masonry walls, Mojsilovic and Marti [58] concluded that post-tensioning,

- enhances cracking loads
- improves the cracking behavior
- results in an increased flexural resistance of masonry walls

4.4. Post-Strengthening of Masonry with Fiber Reinforced Polymer

As it was mentioned in Section 4.3, strengthening masonry using post-tensioning is one of the most attractive techniques for the conservation of historical masonry structures. External post-tensioning with steel tendons has been applied successfully to improve the structural integrity and resistance to lateral loads of walls and for structures having similar structural systems [59].

Strengthening techniques for ancient constructions have been traditionally applied in a conservative sense. This is primarily the main necessity involved by architectural reasons, where saving the existing heritage is the basic purpose. In the nonstructural restoration works, using traditional technologies, regarding both materials and techniques, is related with the classical concept of restoration. However, for structural restoration when the upgrading of either structural or functional features is explicitly required, more advanced technologies, relying on the use of modern materials and techniques, are preferred in order to benefit from the newly developed solutions and perform an effective restoration study [60].

As it was stated in the previous sections, masonry is a composite material whose mechanical behavior is influenced by different variables, such as material properties of brick and mortar, geometry of bricks, joint dimensions, joint arrangement, etc. Thus, more refined models are tried to be developed in order to take into account the nonlinear effects of the masonry material. Composite materials are also being used for strengthening the historical masonry structures [61].

In this manner, fiber reinforced polymer (FRP) materials offer feasible solutions in the restoration of ancient structures, fundamentally to solve or lessen the effects of overloading. Actually, FRP composites have focused on concrete structures. But, there are many examples showing the high potential use of FRP for the strengthening of unreinforced masonry structures subjected to stresses by wind or earthquake loads. Lower installation costs, improved corrosion resistance, flexibility of use, minimum disturbance to occupants and minimized loss of usable space can be counted as the advantages of FRP. Moreover, considering from the structural point of view, FRP creates little addition of weight by which dynamic properties of the existing structure remain unchanged [59, 62]. Although FRP material is expensive than many traditional materials, it satisfies the requirements of the problem with high efficiency from both moral point of view of restoration concept and the structural necessities (like minimum repair, great respect to the originality of the construction and reversibility) [61].

Investigations on strengthening masonry walls with fiber-reinforced polymers were first realized by Schwegler (1994). In his study, the load bearing walls of a six-story building were strengthened with carbon FRP laminates. Then, Laursen (1995) used carbon overlays to mitigate seismic strength and ductility deficiencies of masonry wall as a retrofit and repair technique. On that study, out in-plane and out-of-plane tests on one-story walls were carried out and the shear and flexural strength of repaired, retrofitted and original masonry walls were analyzed. Afterwards, Ehsani (1995-1996), Saadatmanesh (1997) and Velazquez-Dimas (2000) studied on strengthening of masonry walls in seismic endangered zones. In these studies, different types of carbon and glass fiber sheets were combined with different forms of matrices and the position of the sheets on the walls was varied. The strength of externally bonded laminates under out-of-plane and in-plane bending and in-plane shear (all combined with axial load) was studied in 1998 by Triantafillou. Moreover, different tests of post-tensioned masonry columns with FRP by using different types of brick-mortar composition were studied by Bieker, Seim and Stürz [63]. All of these studies show that strengthening masonry structures with FRP, increases the ultimate load and ductility essentially.

4.4.1. Fiber Reinforced Polymer Materials

Fiber reinforced polymers have attractive properties for post-tensioning applications. Wrapping of structures with FRP restores and increases the strength of damaged masonry structures. While this technique is not directly appropriate to conserve historical masonry structures, developing reconstruction methods have permitted to effectively strengthen those structures [54].

FRP composites may provide technically and economically viable solutions for strengthening of masonry. Especially, in strengthening of historical structures, FRP materials have a unique value due to their significant advantages. FRP improves the structural behavior when used for reinforcement, renovation, restoration or retrofitting masonry structures against seismic forces. It responds well to the application of cyclic loads. In addition to its high mechanical strength, its resistance to chemical agents and impermeability to water are the favorable factors for its high potential usage. Furthermore, corrosion problems and little reversibility of steel increase the importance of FRP. Since adhesive materials which transmit stresses can be removed, FRP is completely reversible. This feature of FRP has an extra significance for historical structures regarding their historical and architectural value since using the FRP is non-invasive [64].

FRP composites have excellent tensile strength in the direction of the fibers and negligible strength in the transverse direction to the fibers. The fibers having load-bearing role give high tensile strength and rigidity to the composite along longitudinal direction. For strengthening of masonry, three types of fibres which are carbon (CFRP), glass (GFRP) and aramid (AFRP) fibers are mainly used in FRP composites. Different material characteristics of fibers are shown in Table 4.1. All composites are of light weight and high strength compared to metal materials. According to the fiber characteristics, composites also show different features. For instance, while GFRP's are usually sensitive to alkaline solutions, AFRP's are prone to creep. On the other hand, CFRP tendons have a propensity to rupture under shear or lateral loading, so the anchorages used for steel tendons cannot be used on CFRP tendons. Moreover, especially the materials of GFRP and CFRP need to be protected from ultraviolet light which causes embrittlement of most of the polymer matrices currently in use. Thus, the FRP's should be completely hidden inside a masonry assemblage, or coated with paint [54, 59]. Table 4.2 shows a comparison between various types of composites and also metal materials. This table is valid for one-directional fabrics; in the case of multi-axial fabric, results are improved by 30 % [64].

Table 4.1. Material characteristics of various types of fibers and metals

Fibre/Material	? Density	E (GPa) Elastic Modulus	s (MPa) Tensile Strength	? % Ultimate Elongation
Carbon Fibre	1.7 – 1.9	200 – 600	2000 – 3000	~ 1
Fibre Glass	2.5	70 – 85	3000 – 4500	4 – 5
Aramide Fibre	1.45	60 – 130	2700 - 3000	2 – 3
Steel	7.8	200 – 210	500 - 2000	2 – 10
Aluminium	2.8	75	500	10
Titanium	4.5	110	1200	14

Table 4.2. Comparison of composite and metal materials

Reinforced Plastic/Materials	? Density	E (GPa) Elastic Modulus	s (MPa) Tensile Strength
Carbon Fibre Composites	1.5	195	1125
Fibre Glass Materials	2.0	34	1300
Aramide Fibre Composites	1.4	77	1750
Steel	7.8	200 – 210	500 - 2000
Aluminium	2.8	75	500
Titanium	4.5	110	1200

Because of their good durability performance vinyl ester or epoxy resin constituents have been mostly used for the impregnation of fibers. The ratio of the resin may differ according to the fiber type and also application area of the study. Depending on the case, FRP composites can be prefabricated and procured in a factory or fabricated and cured in-situ [59].

Studies on reinforcing masonry show that using FRP composed of aramidic fibres and epoxy resins (in an average ratio of 50 % fibre to 59 % epoxy resin) performed the best results. In addition to its low modulus of elasticity and high strength, AFRP has an excellent resistance to alkaline agents. Furthermore, it has great flexibility in size variations due to adverse atmospheric conditions and is extremely resistant to high temperatures. Another advantage of AFRP is its usability for wrapping the entire exterior surface of masonry by placing sheets at various levels around the sides of the structure. Because, they are very easy to shape and mould on difficult contours [64].

The peripheral binding technique is improved using AFRP and also this peripheral binding can be connected to vertical strips to form a chain net depending on the structure's state of preservation. It is also possible to use aramide fibre reinforced bars with a reduced tensile and shear elastic module and thus with a reduced stress concentrations compared with steel. Furthermore, it is better to use aramide fibre reinforced pins or dowels instead of steel ones in order to avoid the risk of sliding of stone block masonry structures. For vertical connections between the block, AFRP reduces the risk of cracking of the blocks and also allows little relative movements increasing the energy dissipation due to reduced shear stiffness of aramide. If it is required to counteract against tensile stresses, simple sheets on one side of the masonry panel can be used or sheets can be applied on both of the panel side faces in case of dangerous bending moments [64].

4.4.2. Strengthening Techniques with FRP

In order to strengthen masonry structures, FRP materials can be applied in the form of externally bonded laminates, Near Surface Mounted (NSM) bars and post-tensioning.

FRP laminates are generally formed manually by wet lay-up over the surface of the masonry member which would be strengthened. Firstly, masonry surface is prepared by sandblasting and puttying for the first coat of resin (saturant) by the dry-fiber ply. Then, the fiber ply is impregnated by a second coat of saturant. This enables the newly formed laminate to become an integral part of the strengthened member after hardening. Hand laying-up the laminates may also be done by directly applying a pre-impregnated fiber ply to the masonry surface. Additionally, prefabricated (pre-cured) FRP can be used by adhering the laminate to the substrate similarly to a steel plate [59].

Externally bonded FRP laminates have been successfully used for flexural and/or shear strengthening of masonry members. However, there may exist some modes of failure in this system. Tests on unreinforced masonry (URM) walls show these modes basically in three phases [59]:

1) debonding of the FRP laminate from the masonry which is directly related with the surface characteristics such as roughness, soundness and porosity
2) flexural failure (rupture of the FRP laminate in tension or crushing of the masonry in compression)
3) shear failure

In this context, instead of FRP laminates using another technology, application of NSM FRP bars into a groove cut on the masonry surface, can be a preferable method in order to increase flexural and shear capacity of masonry members. In fact, placing NSM bars does not require any surface preparation or long installation time compared to FRP laminates. Moreover, it is more feasible to anchor a NSM FRP bar into masonry members adjacent to the one being strengthened. For instance, if FRP bars are desired to strengthen a masonry infill, it will be easy to anchor them to columns and beams. In this technology, firstly, the groove is partially filled with epoxy or cement-based paste and then the bar is placed into the groove by pressing it lightly to force the paste flow around the bar. For the final step, the groove is filled with more paste and the surface is leveled [59, 65]. After considering the anchoring and aesthetic requirements, this technique may be more convenient in certain cases.

Structural repointing is another NSM FRP technique which consists of placing FRP bars horizontally in mortar bed joints. In order to resist out-of-plane forces NSM FRP bars are used mostly for the flexural strengthening of unreinforced masonry walls. On the other hand, structural repointing technique is used for strengthening masonry wall against in-plane forces which means shear strengthening. Repointing is a traditional retrofitting technique in the masonry industry. It is denominated as structural repointing due to the fact that it allows for restoring the integrity and/or upgrading the shear and/or flexural capacity of the masonry walls in addition to its traditional role; i.e., replacing missing mortar in the joints [62, 65].

Post-tensioning technique by using FRP bars, which was mentioned in the previous sections, is also an effective way of strengthening masonry. They can be used in order to avoid out-of-plane bending similar with steel tendons. These bars also minimize the impact on the aesthetics without causing any durability problem. External post-tensioning with FRP instead of steel is a valuable method to improve the structural resistance and to withstand the lateral loads. Especially, for strengthening historical masonry structures, use of FRP will compensate many problems existing in steel [59].

CHAPTER 5

RELOCATION OF A MASONRY MONUMENT:

A CASE STUDY IN HASANKEYF

5.1. History of Hasankeyf

Hasankeyf, which is located in the south-eastern region of Turkey near Batman city, is a unique civilization that leans against the cost of Tigris and faced with splendid Raman Mountainous (Figure 5.1). In addition to its man-made forms and beauties, hundreds of incredibly beautiful natural caves/caverns exist in the deep canyons and in the vicinity of the city. Here, which is globally known as North Mesopotamia, has hosted many civilizations through the history. Therefore, all marvelous structures of the history from the Archaic Ages to the Middle Ages could be seen in Hasankeyf. In the early stages of human settlements in Mesopotamia, Hasankeyf has become the pupil of the civilizations of the Orient and Western. Except the Archaic Ages, it has brought together the civilizations and so cultures of Byzantine, Mervanid, Artukid, Eyyubid and Ottoman.

So, it is not wrong to state that, Hasankeyf, with its many secrets waiting to be revealed, is the most valuable, exciting, unique historical site of the Medieval Period. Because of the fact that it reflects the values of many ways of lives during periods, Hasankeyf could be considered as an exciting open air museum.

Figure 5.1. A view of Tigris River and Raman Mountains

It is not known when and by whom Hasankeyf was first established. However, the geopolitical location of the city and thousand of caves around the area strengthen the probability of being an old residential center. City residents are known to have used these caves as shelters for thousand of years. Even today, there are approximately 5000 caves in the limestone bedrock (Figure 5.2 and Figure 5.3), which makes an idea that the settlement has existed as far as from the prehistoric ages. For this reason, Hasankeyf is called as “the capital of cave residents” by many researchers and travelers making investigations on Medieval Period.

Figure 5.2. Natural caves/caverns in the vicinity of Hasankeyf

Related with the origin of Hasankeyf name, there are lots of written sources which give different information. However, it is generally believed that the origin of the name "Hasankeyf" comes from the Aramic word, *Kipani*, meaning rock. Also, it is known that this name had been changed in the Roman Period as *Kefa* and *Cepha* and *Siphos* in Greek. Based on this information, the history of Hasankeyf has been traced back as far as to the late Assyrian Period around the 7th century BC. Hasankeyf was the farthest base in Eastern Anatolia during the sovereignty wars between the Persian Empire (the Parthans and Sasanis), the super powers in the Ancient East and the Romans, the super powers of the west and later the Byzantines. In the early Medieval period (4th -6th centuries AD), one of the oldest Christian Communities of the eastern world and an independent church were established in Hasankeyf.

Starting from the 8^{th} century, Hasankeyf is the first settlement of Anatolia being affected by Islam as a result of Arab raids. The area was called Diyar-u-Bekr after the conquest of region by the Early Islamic Sovereignties during the Emevi and Abbasi periods. Since the area had already been Muslim during the 1071 AD Seljuk conquest, there was no need to change any cultural transformation. This helped to conserve the area in terms of its culture and art. When the conquest of the region by Arabs during the first century of Islam, the site was named as *Kayfa* with the same root. And by time, it took the name of *Hasin-Kayf* or *Hisn-Kayfa*, meaning rock fortress. Finally, at the end of the 11^{th} century, it was pronounced as ***Hasankeyf*** when the region was conquered by the Artukids, a kingdom within the great Seljucide Empire. In addition, Hasankeyf and Diyarbakir are alternatively became the capital of the Artukid Sultanate during that period.

Figure 5.3. A deep canyon in Hasankeyf

The golden period of Hasankeyf was between the years of 1100-1236. The Sultan of the Artukids, Karaaslan, had the famous bridge built around 1140. The bridge was really a marvel of engineering and art and was the biggest of its kind at that time. Moreover, Hasankeyf was located along the historic Silk Road by which it became the most important point of entry into Anatolia from the east. So, it had a critical role for being an important transit center during this era.

The area was captured by the Eyyubid in 1236 and it was the princedom of them until 15th century. Afterwards, Hasankeyf became a major conflict between Akkoyunlu, Ottoman, Safavid Powers and the local Eyyubi principality. Several Europeans, especially the Italians, had also played various roles in these disputes. The region fell under the rule of Ottomans in the 16th century and Hasankeyf was incorporated in Turkey.

Since historical records do not mention about the great bridge over the Tigris after the 17th century, it has been thought that this bridge was probably destroyed in the late 16th or early 17th century. In addition to this loss, the change in world's commercial traffic caused Hasankeyf to lose its importance. In fact, the city was never completely disappeared. Until the first quarter of 20th century it appears to have survived with the character of a small city with a regular market and regional economic activity. But then, it is mentioned in very few sources.

The information related to the history of Hasankeyf is collected from a number of several sources, for giving a comprehensive perspective about the city, including different books and web sites [66, 67, 68, 69, 70].

5.2. Historical Monuments in Hasankeyf

The historical monuments of Hasankeyf mostly belong to Artukid, Eyyubi, Akkoyunlu and Ottoman periods. The majority of them involve a combination of Syrian Early Islamic Style, Iranian Seljuk Style and Byzantine, representing Roman cultural influences, resulting in an uncomplicated and rigid style. In this manner, the real architectural beginnings of the "Turkish Synthesis" can be observed here [69].

The fortress of the city (Figure 5.4), which was built in the 12th century by Artukids, is placed on a massive rock hill, 100 meters high from the south of the Tigris. At the top of this hill, the Grand Mosque (Figure 5.5) was built in the 14th century. The ancient Silk Road Bridge on the Tigris, known to be 100 meters long, was first built in the 7th century and rebuilt in the 12th century. Unfortunately, only three of its pillars could survive to our times (Figure 5.6).

Figure 5.4. The fortress of Hasankeyf city

Figure 5.5. The Grand Mosque in the *Upper Town*

Figure 5.6. The three pillars of the historical bridge

Tomb of Zeynel dated from Akkoyunlu period whereas Sultan Suleyman Mosque, El-Rizk Mosque, Maiden's Mosque and Little Palace are the most important structures belonging to the Eyyubid period. Since Eyyubid were responsible for the most extensive development of Hasankeyf during the Islamic Period (100-1300), these archeological remains are considered as the unique features to understand the history of southeastern Anatolia.

Actually, all of the historical monuments of Hasankeyf, have not been determined yet. The first and most trustworthy examination was conducted and recorded by Albert Gabriel (Voyaces Archeoloqiue Dans La Turquie Orientale, PARIS, 1940). Figure 5.7 presents the map of Hasankeyf City made by Albert Gabriel in 1940 and the legend of this map are also shown in the following table (Table 5.1.) [71].

The historical monuments around the city of Hasankeyf can be defined mainly by three regions [72]:

1. *The Upper Town (*called as *"Castle"* by the locals*)* ; set on a high terrain surrounded by deep canyons formed by the flood waters over the course of thousand of years on the south side of Tigris.
2. *The Lower Town* ; set on the plain lining of southern banks of the Tigris (on which the public of this small town live).
3. *The district on the skirts of Raman Mountainous* ; on the northern banks of the Tigris.

The *upper town* lies on top of a cliff from an elevation of 550 m. up to 590 m. From the low terrace at 480 m. to the upper town, features like a pebble road, man-made caves, monumental gates and a tower are found. The remains of the dungeon are above 530 m. and sits on a second cliff rising between the upper town and the lower town. On the left bank, all the monuments are below the level of 490 m. The base of the monuments in the *lower town* sits between 483 and 500 m. and the man-made caves are mainly above 510 m [71].

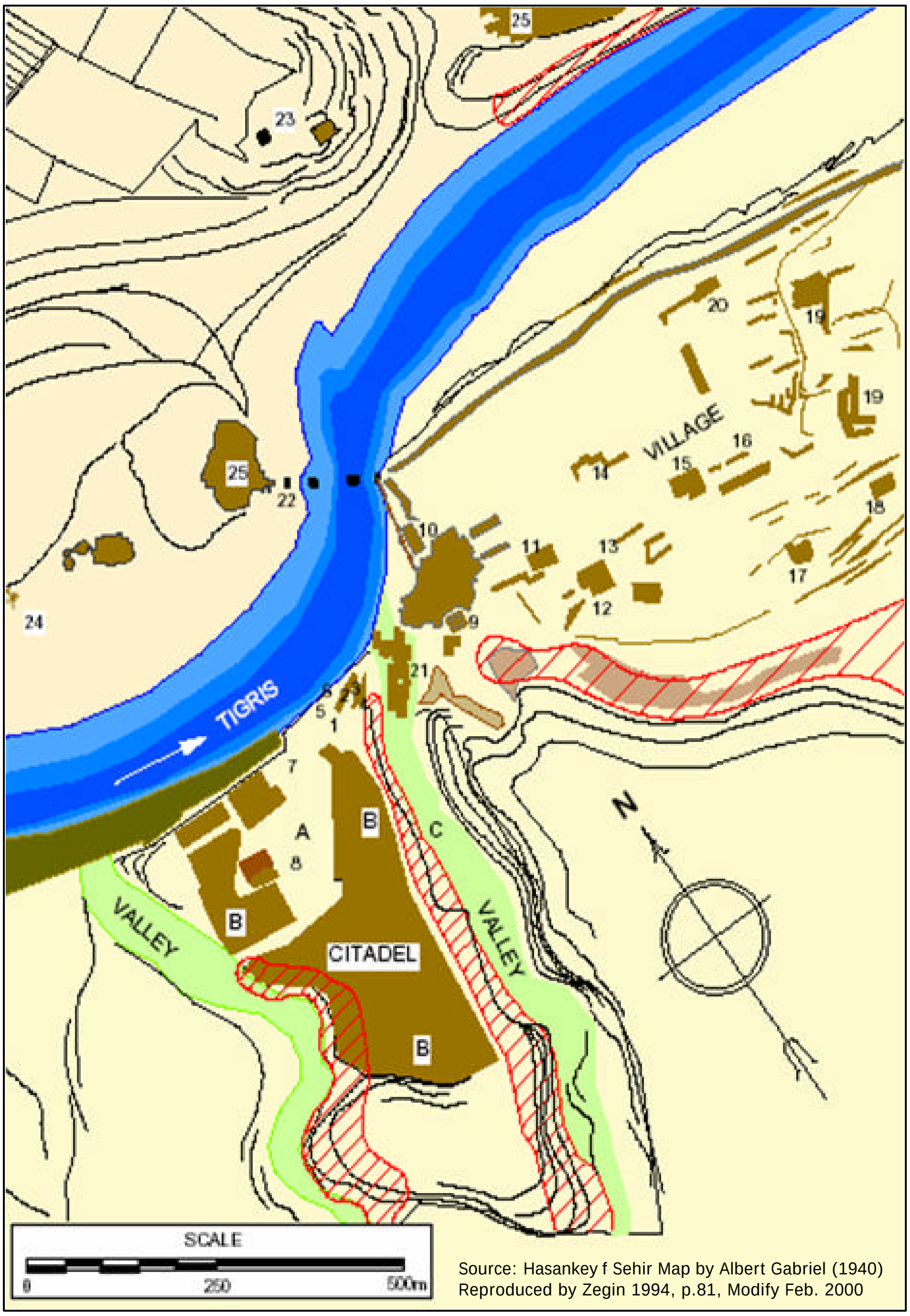


Figure 5.7. Hasankeyf City Map by Albert Gabriel

Table 5.1. Legend of the Hasankeyf City Map made by Albert Gabriel

LEGEND		
Citadel	**City**	**Left Bank on the Tigris**
A) Hippodrome B) Parts of Settlement C) Narrow Valley	9. Watch Tower/Donjon 10. Mosque El-Rizk 11. Mosque Sultan Süleyman 12. Mosque Harabesi / KOG	23. Imam Abdullah Mausoleum 24. Zeynel Bey Tomb 25. Modern Settlement
1. Footpath 2,3,4. Gates 5. Staircase inside cliff 6. Small Palace 7. Big Palace 8. Grand (Ulu) Mosque	13. Medrese (?) 14. Kervasaray (?) 15. Turkish Bath (?) 16. Mosque Remains 17. Small Mosque 18. Mosque Kizlar (Mausoleum) 19. House Ruins 20. Old Wall Remnants (?) 21. Bazar and Modern Settlement 22. Bridge (Ruins)	
Man-made Caves (some still inhabited) (some used for livestock)		

Table 5.2 displays the most prominent monuments which are listed in the Cultural Inventory List of the Ministry of Culture, stating also their century, location according to the river and ground elevation. Some other features which are not listed in Ministry of Culture List are also shown in Table 5.3. (The ground elevations for both tables are those indicated on the 1:1000 and 1:25000 maps while heights are only rough estimates.) [71].

Table 5.2. The most prominent monuments which are listed in the Cultural Inventory List of Ministry of Culture

Name	Type	Century	River Bank	Ground Elevation (m)	Height (m)
Bridge	Bridge and road	12th	Left and Right	460	45
El-Rizk Mosque	Mosque with minaret	13th	Right	480	40
Building	?	?	Right		
Sultan Süleyman Mosque	Mosque with minaret	14th	Right	500	40
Koc Mosque	Mosque	15th	Right	502	7
Religious School	School	15th	Right	502	?
Kizlar Mosque (now Eyyubi Mosque)	Mosque	13th	Right	499	3
Cemetery	Graveyard	?	Right	490	1
Zeynel Abidin Türbesi	Mausoleum	13th	Left	470	8
Türbe	Mausoleum	?	?		?
Imam Abdullah Türbesi	Mausoleum	14th	Left	480	20
Building	Baths?	16th	Left	465	8
Cemetery	Graveyard	14th	Left	490	1
Shops (caves)		12th	Right	490	3
Castle Gate No. 1	First entrance	12th	Right	490	?
Castle Gate No. 2	Fort entrance	12th	Right	510	7
Castle Gate No. 3	Fort entrance	12th	Right	550	6
Little Palace		13th	Right	540	15
Man-made caves	Houses	12th	Right	510	3
Big Palace	King residence	12th	Right	550	5
Türbe	Mausoleum	13th	Right	500	?
Büyük Mosque	Mosque with minaret	12th	Rigth	550	5

Table 5.3. Features which are not listed on Ministry of Culture

Name	Type	Century	River Bank	Ground Elevation (m)	Height (m)
Stairs carved in/on cliffs		12th	Right	460	70
Vineyards	Gardens	?	Right	470	0
Mescid-i Ali Mosgue	Mosque	15th	Right	?	?
Water canals		12th	Right	?	?
Basilica		10th	Right	?	?

5.3. Inundation Danger in Heritage of Hasankeyf

Since Turkey has a critical geographical location and rich historical background, it plays a very significant role in the world's cultural heritage. Being one of the most impressive medieval sites in Turkey, Hasankeyf also has a special value which should be preserved and conserved. As stated previously, this unique medieval city has been the meeting point of several civilizations for centuries and carries a combination of these different cultures.

While evaluating the importance of its heritage, the significant location of Hasankeyf should be considered deeply. The unique architectural heritage of the whole city is more than the sum of its parts [67]. Since the architectural and natural forms at Hasankeyf live one within another and integrate with time, the site should be preserved as a whole.

However, Hasankeyf is faced with a danger of being inundated by Ilisu Dam which is planned to be constructed on the River Tigris approximately in 8 years. The dam is 77 km. far away from the city of Hasankeyf and its reservoir will extend over a length of 136 km along the Tigris valley. The maximum reservoir level is estimated as 525 m. This means that except the upper part of the city, almost all of the remaining region will be submerged under the reservoir of Ilisu.

The upper part, on the other hand, will face with a serious stability problem since the rock masses existing on that part will be exposed to water. The expected change in the behavior of rock masses due to saturation or submergence will accelerate the failure of the caverns in the area [73]. Unless the project shall be cancelled or altered, it will actually destroy this unique site.

Unfortunately, it is not possible to save the entire region if the Ilisu Dam is constructed. Especially, the natural texture of the area which is deeply integrated with the architectural creations cannot be liven up. As a result, transferring at least some of the monuments to another site seems to be the only alternative in order to prevent losing the whole cultural heritage.

5.4. Major Techniques in the Conservation of Historical Monuments by Transportation

Historical structures have an incredibly essential role to conserve the link between the past and the present. They can also be referred as the living history which reflects the social, cultural, architectural, economical, political or religious features of their time. Our cultural heritage constitutes a synthesis of these ancient structures. However, there are lots of hazards which threaten these invaluable items of history. Natural disasters, such as flooding, landslides and earthquakes, foundation settlements, time effects, fires, air pollution, vibration of heavy traffic, urban sprawl, public works and human vandalism are some of the critical ones from which cultural heritage suffers. Since they have been mostly neglected, historical monuments of Turkey are especially in a very poor situation. When the significant historical background of Turkey is considered, this negligence is really a big loss in the name of humankind's past.

Conservation of historical monuments lightens the way of correctly evaluating the past, interpreting the present and constructing the future. Therefore, it is very important to conserve historical monuments in their own place. The theory of conservation states that the structure should be kept as entirely as possible. A monument is inseparable from the setting in which it occurs. However, public works, such as road and dam constructions, geological condition or natural hazards can make it impossible to conserve the historical monuments in their in-situ places. When all other solutions are disappointing, historical monuments should be transported to another site.

The type of transportation of a monument is determined according to the dimensions, material and construction technique of the structure. Furthermore, availability of financial sources, technical tools and skilled specialists affects the preferences. Luckily, modern technology serves several alternative methods. The easiest and the least costing one is to dismantle all elements of the monument and then reassemble them in the new site. After a careful photographic documentation and survey, dismantling is done by giving a number to each stone block. Detailed numbering system demonstrates the relationship between the stones and this prevents any disorder during the relocation. Although this is the easiest and mostly used technique to transport the monuments, it has a very significant handicap. During the process, historical monument could lose some of its original details. Some blocks may break down or crumble. Binding elements may require to be changed or replaced. The workmanship is eventually different from the original one. This technique is suitable for transportation of cut stone constructions. It is not easy to dismantle the rubble stone monuments and not possible to re-erect them [74, 75].

Another technique which is the most favorable and regarded as the ideal one in recently is to transport the monument as a whole without cutting it into parts. Although it has a high operational cost, the value of historical monuments is priceless. Thus, possibilities should be forced to transport the monuments without breaking them into pieces. In this method, the monument is generally cut off from its foundation and mounted on a wheeled trolley. It has been widely used in both Europe and Egypt in transporting the cathedrals and palaces. Harakhty Temple in Egypt and Most Cathedral in Czechoslovakia are two important examples for the conservation of monuments with this method.

The most known conservation study of transporting type is the salvage of the Abu-Simbel Temples in southern Egypt. Due to construction of Sadd El Ali Dam on Nile, two Abu-Simbel Temples had to be transported from their original sites. In order to keep the water away from the temples, a cofferdam is constructed in front of the temple until the dismantling had been fully completed. After the temples were broken into large sections according to the characteristics of the structures and totally dismantled, each block was transported to the new site. During transportation, blocks were always kept in the same relative vertical position; i.e., never tilted during transportation [76]. In Turkey, the mosques of *Eski Pertek*, which were faced with the danger of being flooded by the reservoir of Keban Dam, were relocated with a similar method.

Transporting monuments is a difficult task. It requires a multidisciplinary study; a sufficient financial support, a good knowledge of engineering, a deep architectural view, an aesthetic anxiety, a well interpretation of the conservation theory and lastly a power of organizing. Unfortunately, in whatever technique the relocation is performed, it is never possible to preserve the original atmosphere completely. But if there is no way to save the whole heritage or preserve the monuments in their own site, relocation of the monument to another site is the only way to save at least a value from our history. In order not to lose the architectural, cultural and historical background of the monument, a well-detailed documentation and survey should be performed carefully and systematically before transporting it. Moreover, beforehand studies should be done which provide a similar landscape for the monuments to acquire maximum possible dignity and integrity. The most precious decisive factor in selecting a new site is naturally its old setting.

5.5. An Innovative Methodology for Relocation of a Masonry Minaret in Hasankeyf without Dismantling into Pieces

In this study, it is aimed to propose an original method to transport a historical monument without disturbing the completeness of the structure. This is important to ensure the continuity of the real value of the monument as correct as possible. The method, which is formed in this study, is applicable to the structural forms of having quite short width relative to their height (slender structures), such as minaret, tower, spire, etc. The study in this thesis was carried out in a general sense. A masonry minaret (Sultan Süleyman Mosque's minaret) in the lower part of the Hasankeyf city, which would be submerged under the water of Ilisu Dam, was taken as a case regarding its historical importance and structural suitability and environmental availability. The methodology was first developed logically and then the structural validity of this method was evaluated analytically by a well developed computer aided structural analysis program. It should be emphasized that achieving the most proper salvage project directly depends on a comprehensive understanding related with the existing situation of the monument. Structural characteristics, load propagation and material behavior of the historical monument should be well examined.

Although the Sultan Süleyman Mosque is completely ruined; some of its parts, luckily, survive today (Figure 5.8). Its masonry minaret, which is approximately 37 meters high, is one of these rare remaining parts (Figure 5.9). The minaret was built in the time of Sultan Süleyman in 809/1407 AD. It is one of the oldest and impressive samples of the minarets with a very significant and delicate workmanship. The cylindrical body is placed on a square base. This body is decorated with mouldings and divided into four stories with bands. The minaret exists up to the balcony which was bearing a honeycomb that fell down. The face stones had been arranged side by side with regular cut stones, and the inner part of the minaret had been constructed by rubble stones.

Figure 5.8. The Sultan Süleyman Mosque

Figure 5.9. The Sultan Süleyman Mosque's minaret

Actually, plans and sections of existing situation of the minaret were not drawn. But the geometrical dimensions of Sultan Süleyman Mosque's minaret are close to the geometrical dimensions of El Rizk Mosque's minaret, which is obtained from historical data. The only important difference between these two minarets is their number of staircases. While the minaret of Sultan Süleyman Mosque has one staircase, the El Rizk Mosque's minaret is double-staircased. So, geometrical dimensions of Sultan Süleyman Mosque's minaret are approximated to be used in this study.

In fact, using approximated values is not so significant since the aim of this study is to develop a proper method not only for the chosen minaret but also for all similar kinds of historical structures. This means that Sultan Süleyman Mosque's minaret was taken into consideration as a representative monument in order to show the validity of the proposed method among these forms of historical structures.

As it was explained in the previous section, relocation of a monument could be performed by several methods. However, the method of "transporting a slender ***masonry*** monument as a whole in a horizontal position" is completely a new one. With this method, it is possible to conserve the unity of the monuments which would safeguard the cultural and architectural value of them. The inscriptions and decorations on the monument would not face with any danger of disturbance. The original workmanship and binding patterns of the stones would not be deformed. Moreover, depending on the case, this method may be more economical than the others.

The main idea of the method is to tilt the masonry minaret safely to a horizontal position and then transport it to its new relocation site. Thus, a proper-understanding of the forces which are dominant on the structure is required. Furthermore, weakness of the masonry material against tension and bending and so related failure mechanism should be investigated carefully.

As it was stated previously, tensile strength of masonry materials is much more less than their compressive strength, even it can be neglected. As a result, load carrying capacities of masonry structures are quite different with regard to various loading directions. Actually, masonry structures are generally able to carry vertical loads in a safe and stable manner, however; they do not have the ability to carry horizontal loads. Undesirable tensile stresses may arise in the structure even under low horizontal loading conditions.

In order to achieve an efficient and successful method, a systematic study should be followed. In the proposed method, the first thing to be done is to strengthen the minaret against horizontal forces. Because of the reason that the minaret is tilted until it comes to a horizontal position, an artificial seismic action is developed on the structure. Due to this action, tensile stresses are produced in the masonry as a result of material's brittle nature and resulting tensile cracks or fissures might cause failure or even collapse of the structure. So, suitable precautions should be taken to prevent the hazardous effects of the tension forces.

Prestressing is one of the most effective ways to compensate the tensile stresses occurred due to tilting. In this case, external prestressing cables (radial & vertical) are used to strengthen the structure without making a significant change in the original structure. Because, confinement of masonry with prestressed cables give an additional strength to the structure which is considerably helpful to prevent the tension failure of the structure.

The locations of the radial cables on the structure should be covered with a protective coat to transfer the tensile stresses occurred before placing the cables on the minaret (Figure 5.10). This can be done by fiber reinforced laminate to take the advantage of its technical and economical characteristics. As it was stated in the previous chapter, FRP offers viable solutions in strengthening of ancient masonry structures.

Vertical prestressed cables are then located on two sides of the minaret by which the minaret is confined in a cable cage system, as seen in figure 5.10. These vertical cables are anchored to a system (consisting steel I-beams) constructed to the top and bottom of the tilted part of the minaret which will be explained later.

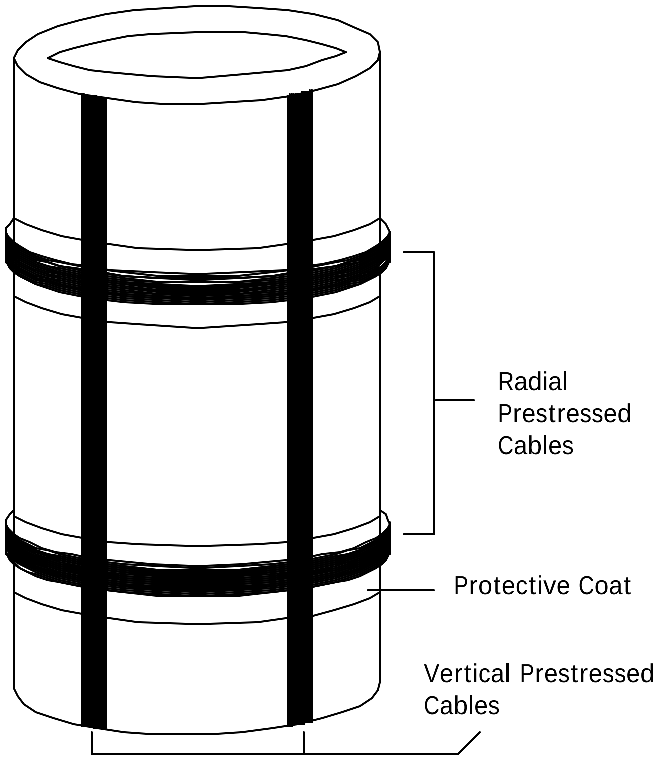


Figure 5.10. The minaret confined in a prestressed cable cage system

Indeed, wrapping the minaret with prestressed cables can be regarded as the most proper strengthening technique for this study. Because, tilting the minaret and transporting it to another site take only a certain time. After, the minaret is relocated, tensile stresses vanish and prestressed cables become useless. Consequently, there would be no problem related with the loss of prestressing forces with time and the monument would be saved without losing its integrity.

In order to tilt the minaret, a pushing force is applied to the structure. This is done by a pulley system located on the side towards which the minaret is tilted. This system is anchored firmly to the ground and connected to the top point of the minaret by steel cables (Figure 5.11). During tilting, the pulley would be used to start the first motion for the structure.

Before starting to tilt the minaret, it is required to stabilize it in a box-like system: three steel cranes and an overturning mechanism are located around the minaret as presented in Figure 5.11. Steel cranes actually stands as rocket launches to hold the minaret, while the overturning mechanism plays the role of setting the point of rotation. Since it is not possible to ensure the safety of the minaret in tilting without supporting it against the tilting direction, this mechanism is strictly necessary.

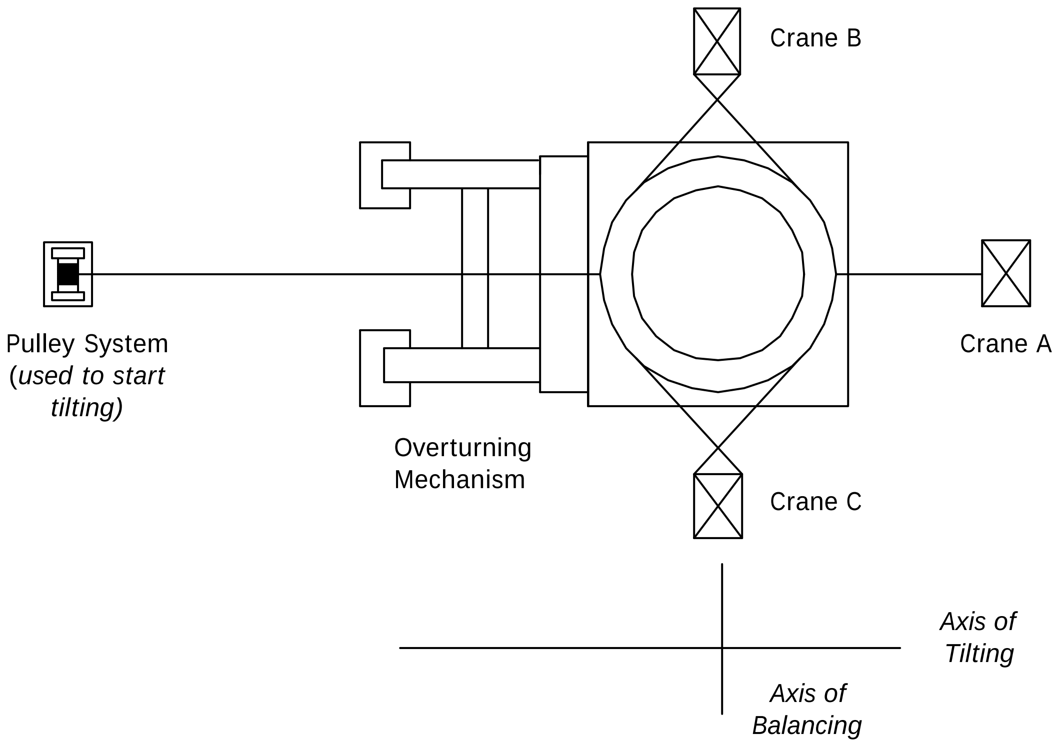


Figure 5.11. Top view of the box-like stabilizing system

There is a pulley system on top of each steel crane which is used to properly balance the minaret during tilting. The pulley's cables of the cranes which look face to face on two sides of the minaret; i.e., pulleys of the cranes B & C, are diagonally anchored to the top of the minaret from two different points as presented in Figure 5.11 in order to prevent the lateral sliding of the structure.

On the other hand, the tilting cables of the pulley of the third crane, crane A, which is located on the tilting side of the structure, are anchored to the selected prestressed cables on the minaret with tilting cables (Figure 5.12). Selection of the location of these cables should be considered carefully in order to tilt the structure safely in the desired way and to the desired location. In addition, it is important to emphasize that, increasing the number of cables and selecting the appropriate anchoring points for these cables would be helpful for decreasing the stresses occurred in the structure during tilting. The reducing effect of "increased number of tilting cables" in stress values is discussed in the next chapter in details according to the finite element analyses results.

Moreover, crane A is anchored to the cables on the minaret with horizontal rods at each prestressing point as shown in Figure 5.12, in order to guarantee the safety of the structure after separating it into two parts which will be explained later. Tilting of the minaret is performed by slowly releasing the tilting cables on the crane A and the balancing ones on the cranes B & C by using the pulley systems after giving the first push-over to the minaret.

The point where the minaret and the top point of the overturning mechanism coincide is referred as the point of rotation (point of moment). By this way, the tilting force is supported by an opposite force (Figure 5.13) resulting from the overturning mechanism. The minaret starts to lean under the control of the steel cranes over this point. Since too much pressure would be observed at the point of rotation, a protective coat may be needed to be wrapped around the minaret along the tilting axis.

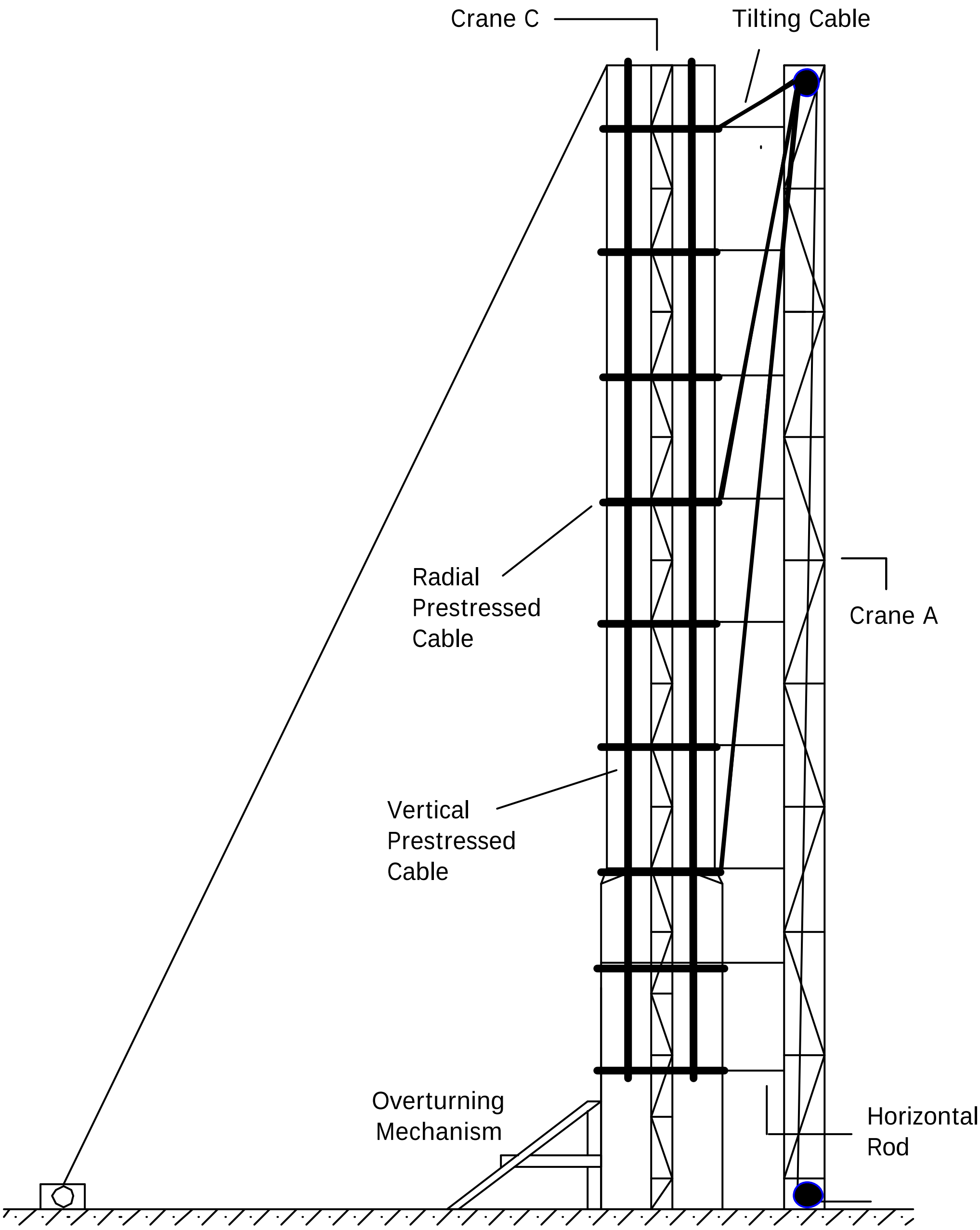


Figure 5.12. Side view of the minaret with the stabilizing system

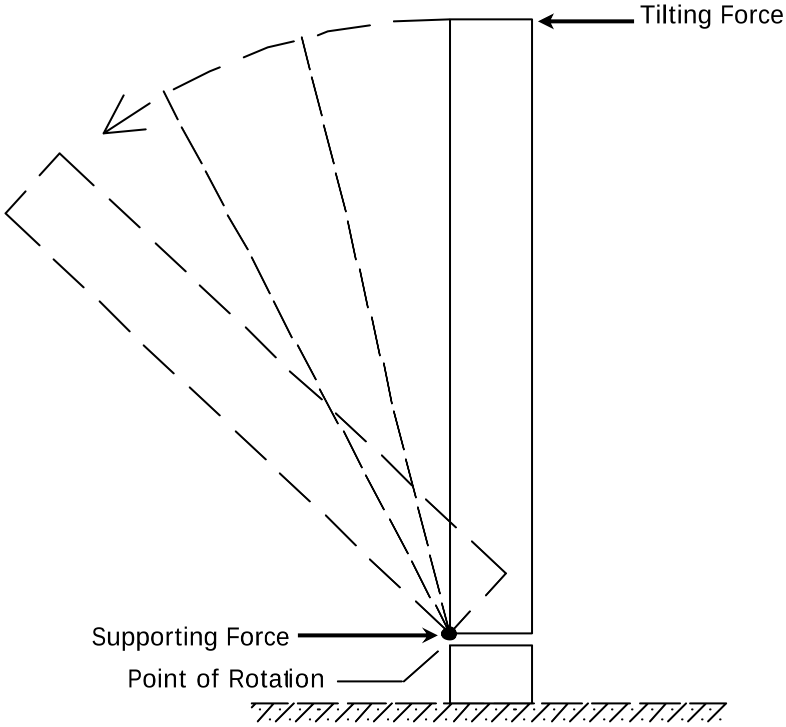


Figure 5.13. Tilting and supporting forces occurred during tilting

At this point, the important question is: from where should the minaret be tilted? Essentially, the answer is hidden in the aim of conservation. The minaret should be saved as complete as possible. It is, in fact, not possible to tilt the minaret without separating it from its foundation. Because it crushes improperly starting from the point of rotation and this crushing most probably continues in an irregular way through the structure until it is totally separated from its foundation. In addition, line of cutting has a significant importance for the operational easiness; i.e., efficient and easy workability.

The minaret should be cut possibly close to its foundation regarding both the structural safety and the conservation ethic. So, the special handworks on the minaret (Figure 5.14) can also be saved from destruction. As it was emphasized before, the main aim of this study is to conserve a historical monument as a whole (as far as achievable) with all of its architectural or cultural features reflecting its historical value. Since, innovative methods should be primarily based on to ensure minimum deformation or change on the structure.

Figure 5.14. Special handworks on the Sultan Süleyman Mosque's minaret

In this study, cutting the minaret means to divide the minaret approximately "3 meters" above from its foundation due to the existence of a gate at that portion. Figure 5.15 shows the *line of cutting* from which the minaret is separated into two parts in order to tilt it safely. Thus, the upper part of the minaret is completely separated from the lower part. For the separation process, the first thing to be done is to dismantle the regular masonry stones of the minaret just below the cutting line one by one.

Dismantling process should be done with a precise systematic study which was explained in the previous section. There exist rubble stones inside the smooth cut stones on the surface of the minaret (Figure 5.16). After all of the cut stones are dismantled, two holes are drilled into the rough stones through the minaret. Finally, steel I-beams are placed into each hole (Figure 5.17) in order to construct a *supporting system* for the upper part of the minaret.

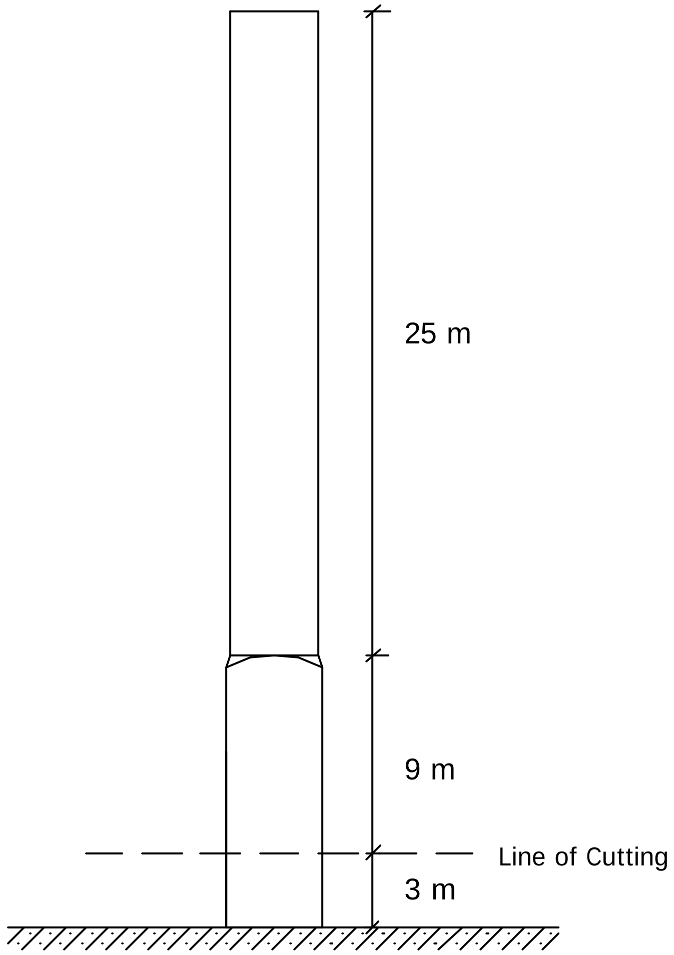


Figure 5.15. The line of cutting

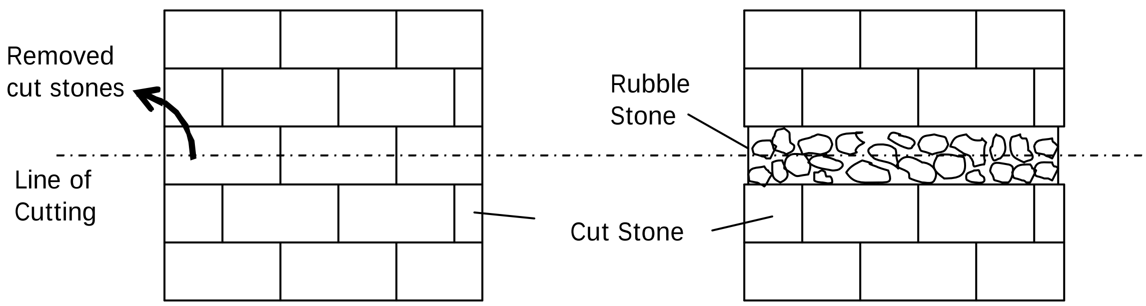
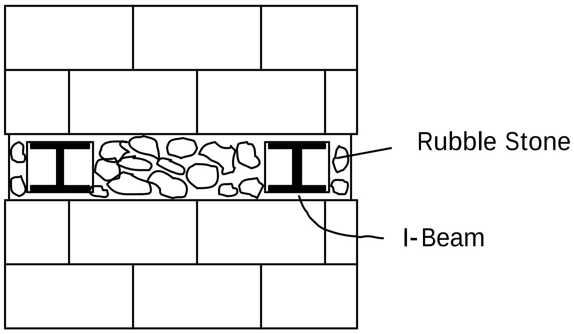


Figure 5.16. Removing the cut-stones on the surface of the minaret



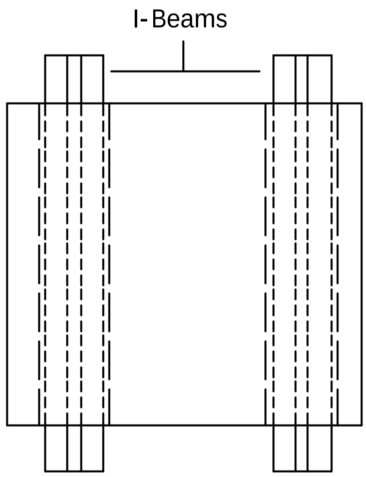


Figure 5.17. I-beams placed into the drilled holes on the minaret

In fact, the supporting system of the upper part should start to be constructed before the “cutting process”. Supporting system consists of two main parts: one is the *supportive I-beams* and the other is the *end-to-end I-beams*. The supportive I-beams are located on both side of the minaret parallel to the direction of tilting (Figure 5.18). Whereas, the end-to-end I beams are placed inside the drilled holes parallel to the direction of balancing which was explained before. In other words, the minaret is surrounded with

- a steel crane (crane A) and an the overturning mechanism located face to face to each other; *in the axis of tilting*

- two –face to face- supportive I-beams and two steel cranes (crane B & C) just behind them; *in the axis of balancing*

The end-to-end I-beams, placed inside the holes of the minaret, are anchored carefully to the supportive I-beams in order to fix the parts of the supporting system firmly and to ensure a stable connection of the system. The supportive I-beams are also well anchored from both of their ends to the ground as shown in Figure 5.19.

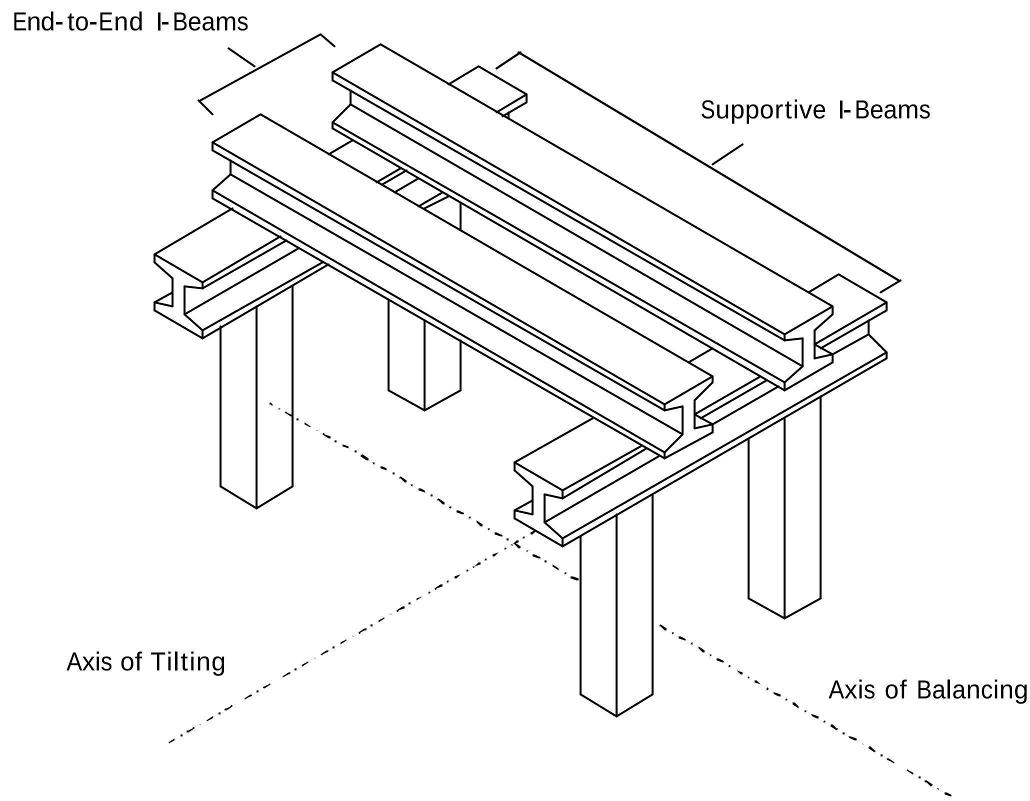


Figure 5.18. The supporting system for the upper part of the minaret

Since the shape of the “I” gives the advantage of having light weight and high strength compared to the other types of beams, I-beams are selected for this process. Moreover, it is essential to state that I-beams should be placed in such a way of resisting around the strong axis as demonstrated in Figure 5.18. In other words, the load on the beams should be carried by the axis which is more resistant to the coming forces.

When the supporting system is assembled, all of the rough masonry stones around the holes are dismantled completely in order to empty the space, which has been filled with masonry beneath the cutting line, just around the end-to-end I-beams. Thus, the connection can be broken and two clearly separated parts are formed (Figure 5.20). The relocation process is then utilized for the upper part of the minaret.

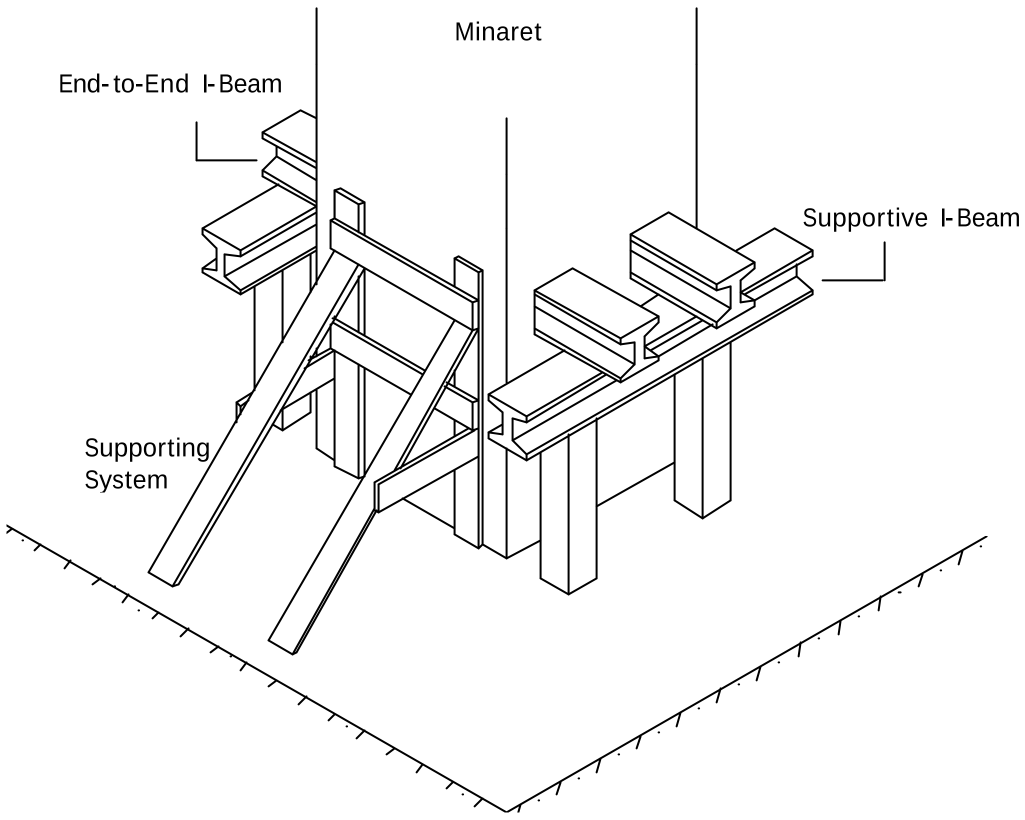


Figure 5.19. The minaret surrounded with the supporting system and the overturning mechanism

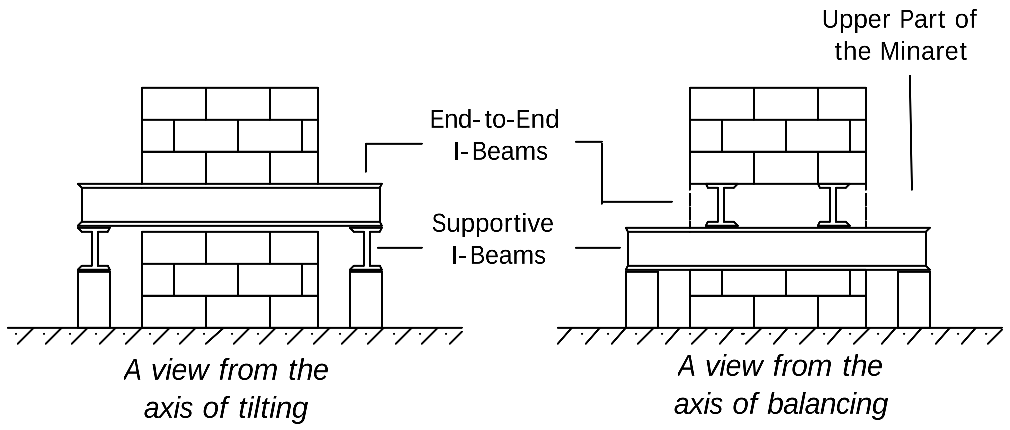


Figure 5.20. The two clearly separated parts of the minaret

As a last step before tilting the minaret, a system is constructed for the location of vertical prestressed cables. Each of these cables is anchored from their ends on the steel I-beams placed on top and bottom of the upper part of the minaret. For the bottom end anchorage, I-beams, which are placed before into the drilled holes as a part of supporting system, are used.

However, two new I-beams are located on top of the minaret for the other anchorage end. These upper steel I-beams should also be in a parallel direction with the lower ones in order to make a stable connection. Before placing the upper steel I-beams, a timber plate is located onto the minaret and I-beams are then anchored on to that plate (Figure 5.21). By this way, the pressure coming on the minaret due to the self weight of the steel beams could be distributed regularly and friction forces could be prevented eventually. Applying a distributed force instead of a direct one is also important to prevent the regional compression.

After dividing the minaret exactly into two parts, tilting of the upper part begins. The minaret is pushed slowly by the crane A by means of released tilting cables. At this moment, a truck behind with a hydraulic jack (car lifter) waits on the opposite side of the minaret (just near the supportive mechanism).

While the minaret is being tilted, the hydraulic jack is started to be risen. When the tilted minaret and hydraulic jack comes to the same level, the minaret is carefully placed into a specially prepared space in the hydraulic jack. Afterwards, they are lowered until hydraulic jack seats to its position behind the truck (Figure 5.22).

Lastly, the minaret is taken to its new relocation site. During the transportation to its new site, the minaret could be wrapped like a net by a beforehand prepared coating (as laminate) in order to prevent any destruction. This coating could be placed on the hydraulic jack and the minaret could be wrapped after it sits on it or the minaret could be covered before the tilting process. Moreover, the minaret should be fixed firmly to its place in the vehicle during transportation in order not to deform it from the truck movements.

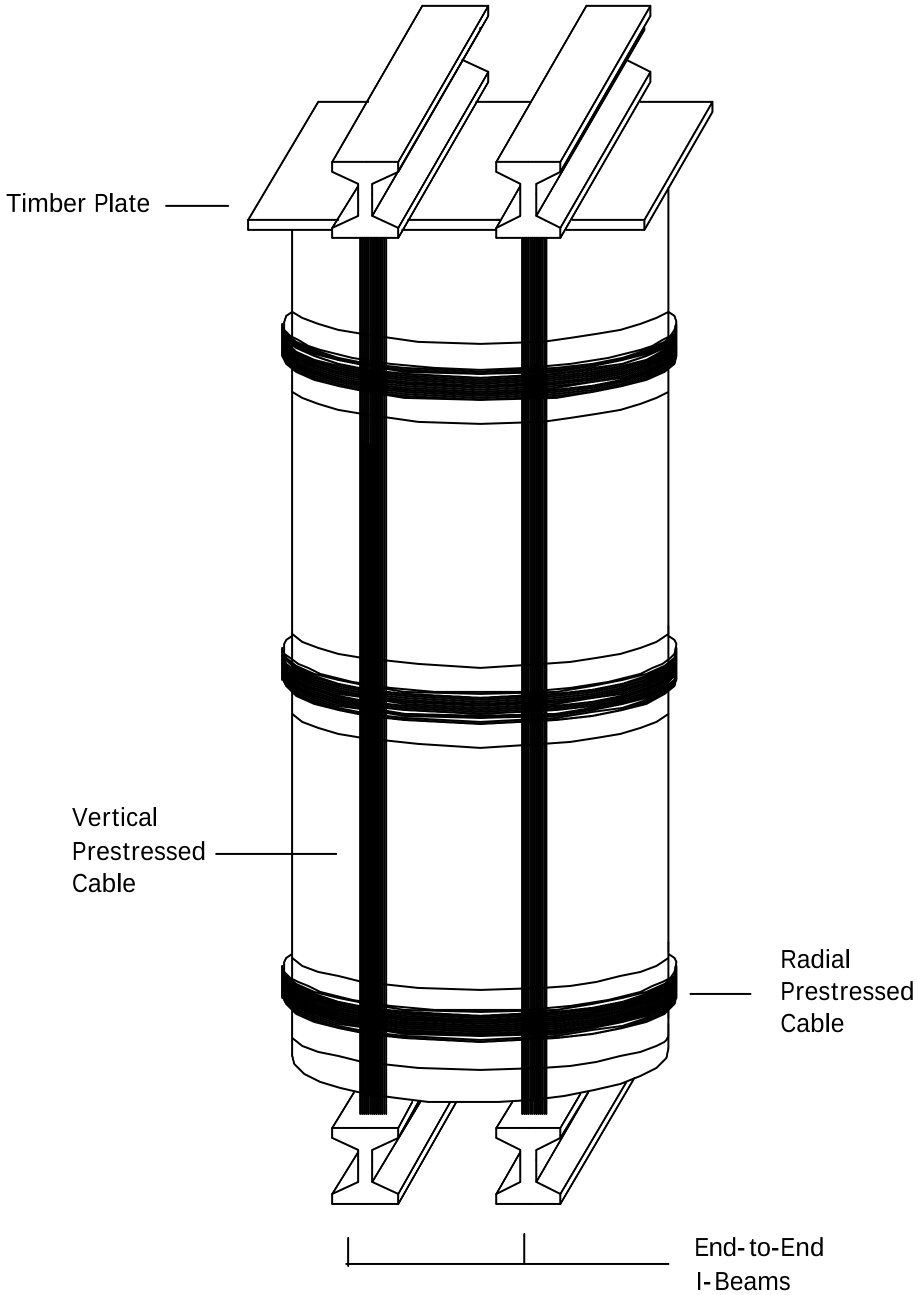


Figure 5.21. The cable cage system of the minaret with a protective timber plate for the upper steel I-beams

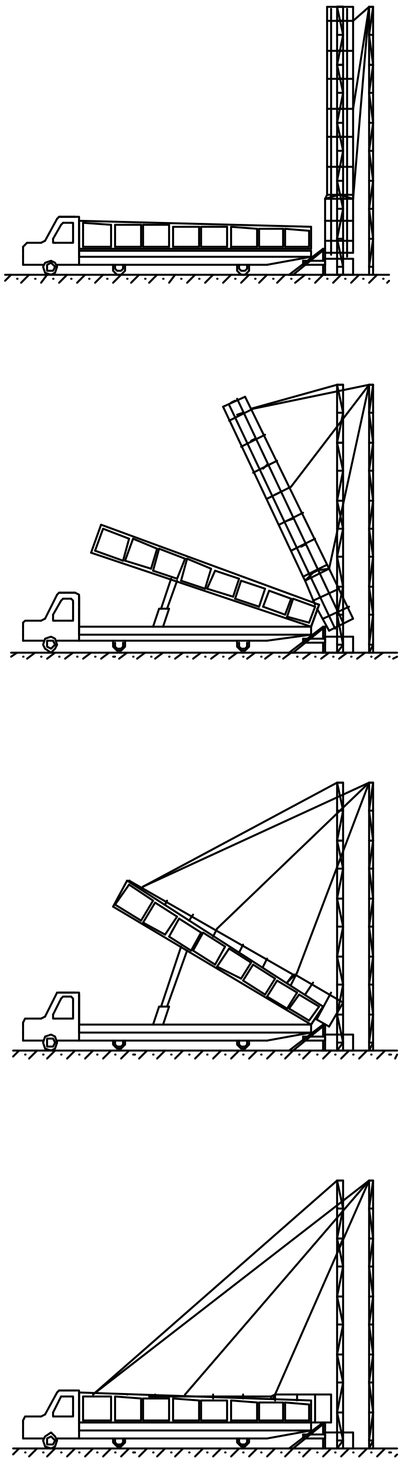


Figure 5.22. Tilting sequence of the minaret

Re-erection of the minaret is the last step of the relocation process. It is done with the same method of tilting. Before relocation of the upper part of the minaret, the lower part should be restored on its new site with a careful study according to the conservation charters. The new site should have similar landscape and context with the original one as far as possible. Furthermore, if the cutting line is taken as near as possible to the foundation, the monument can be thought to be saved almost entirely.

During the assemblage of the lower part, in order to ensure the connection between the lower and the upper parts, stainless steel bars are placed into the masonry and strengthened by means of epoxy resin (Figure 5.23). The base of the upper part is also drilled in order to place the steel bars before re-erecting it. These bars ensure the connection between the lower and the upper parts of the minaret as explained below.

Around the lower part of the minaret, the same system used for tilting is constructed (Figure 5.23). The truck is first brought near to this part. The necessary cables are anchored to the upper part of the minaret and then hydraulic jack starts to be risen over the point of rotation of overturning mechanism. The stretched cables of pulleys on the cranes balance the minaret safely. When the minaret completely places on the supporting system, the stainless steel bars of the transported (upper) and assembled (lower) parts of the minaret are reinforced and attached to each other as illustrated in Figure 5.23. After removing the steel I-beams safely, empty space between two parts of the minaret is filled with the pre-numbered dismantled stones. Finally, the prestressed cables on the minaret and the system around it are removed.

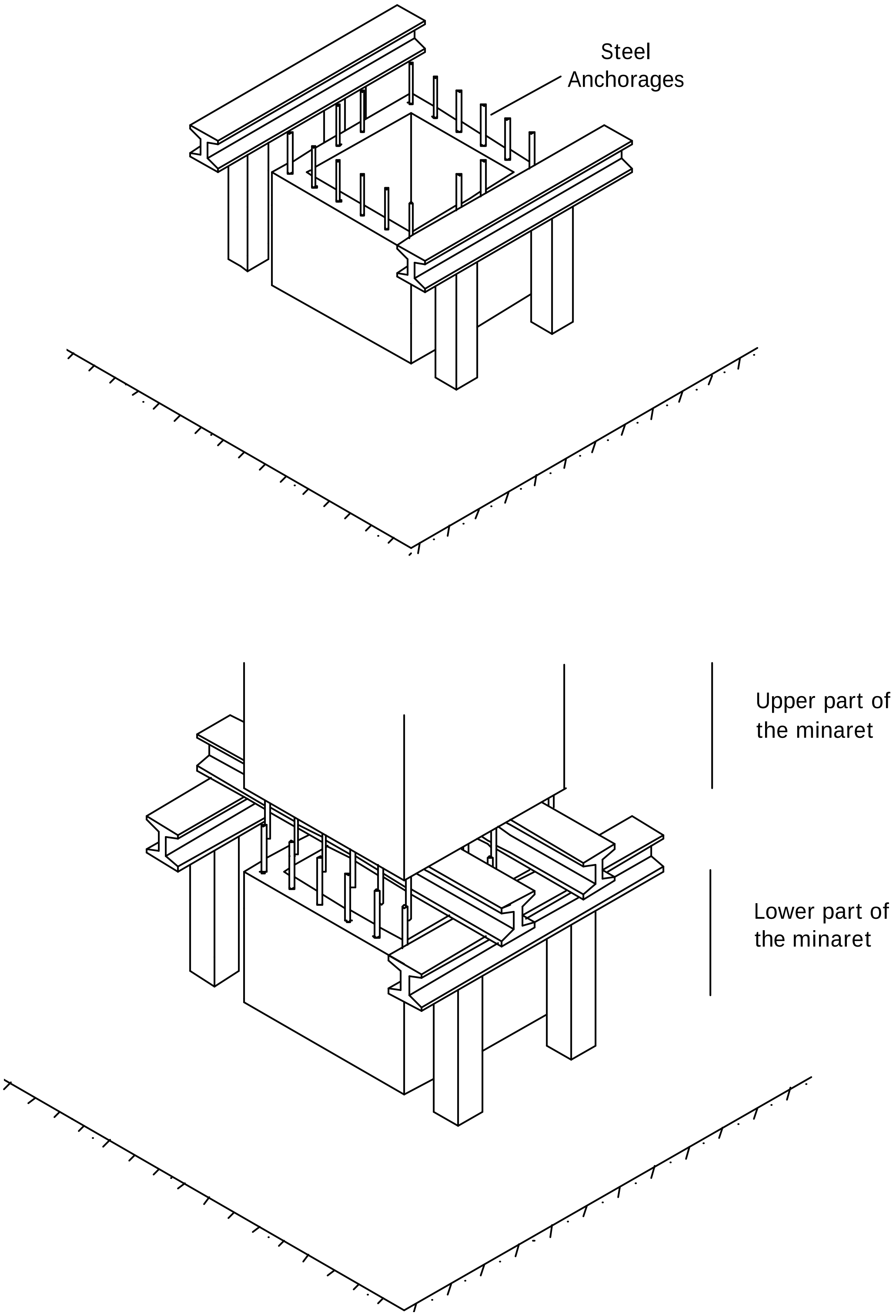


Figure 5.23. Sequence of the re-attachment of the lower and upper parts of the minaret at the new location site

CHAPTER 6

FINITE ELEMENT ANALYSIS OF THE PROPOSED METHOD TO TRANSPORT A MASONRY MINARET

6.1. Geometric and Material Characteristics of the Structure

In this study, the minaret of Sultan Süleyman Mosque in Hasankeyf is taken as a case to exemplify the proposed method which is explained in details in Section 5.5 for the transportation of slender masonry structures from their own sites.

The geometrical model of the minaret is established according to the data collected from the literature. Dimensions of the structure are taken similar to the actual ones and the values related with the material characteristics of the structure are based on the generally common properties of the masonry. The minaret is 37 m. in height with a 3.7 ? 3.7 m. square cross-sectioned at the base which continues up to 9 m. However, in the finite element model, it is taken as 34 m. due to the cutting process of the proposed methodology as explained in Section 5.5. The 25 m. long cylindrical body, which has a radius of 3.5 m., is placed on this square-base. The thickness of the wall along the minaret is considered as 0.75 m.

The self weight (?) of the masonry minaret including the staircases is taken as 30 kN/m^3, whereas the modulus of elasticity (E) is 20000 MPa and the Poisson's ratio (μ) is 0.2. The tension force in the radial and vertical prestressed cables around the minaret is taken as 1000 kN. The elastic modulus of steel elements is considered as E=210000 MPa in the finite element model.

6.2. Description of the Finite Element Model of the Minaret

In order to illustrate the transportation method in a numerical simulation, Finite Element Analysis Method is used. The masonry minaret is modeled by using 3-D solid elements which, actually, represents the complex geometries of the structures more correctly than frames or shells. In the model, the weakness plane between the masonry and the mortar is ignored and the analysis is performed by assuming linearly elastic structural behavior. The structure is evaluated according to the macro-modeling approach (Figure 3.5); i.e., without separating the units and the mortar and by formulating a homogeneous form. So, the structure is studied as a whole. In addition, non-linear material properties of the masonry are neglected during the analyses.

The aim of this study is to observe the stress changes within the body during tilting the minaret for the relocation process. Especially, this ensures a better understanding of the confinement effect provided by the prestressed cables. A number of structural analyses of the minaret are performed in order to test whether the proposed methodology works or not; the structure is analyzed under different tilting levels for both prestressed and not prestressed conditions.

In the finite element analysis, the minaret is modeled by 2112 joints and 1536 solid elements. Figure 6.1 shows the mesh model of this resulting numerical model. For the analyses investigating the confinement effect of prestressing, 32 prestressed cables are externally placed around the minaret laterally (with 1.5 m. intervals along the first 9 m. from the foundation and with 1 m. intervals along the upper cylindrical part of 25 m. height).

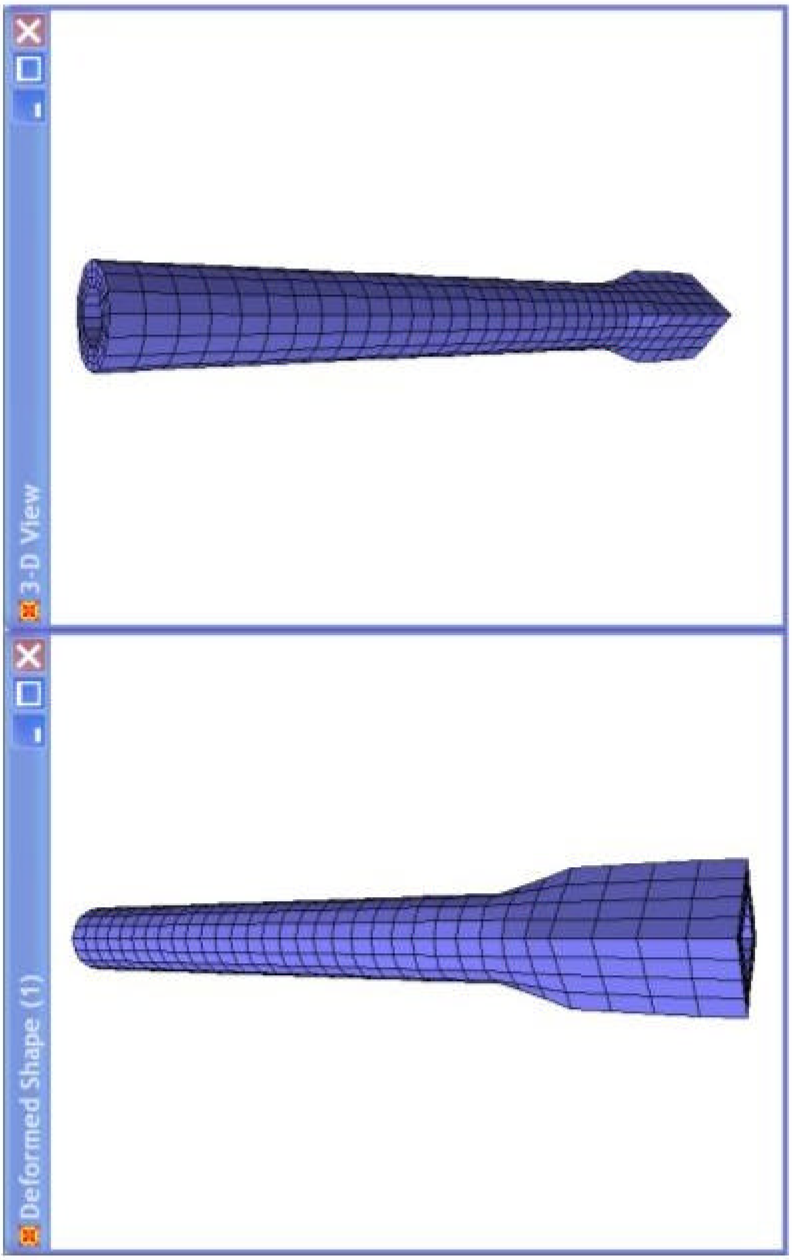


Figure 6.1. The Finite Element Model of the minaret

Moreover, 4 vertical external prestressed cables are placed on the sides of the minaret from which the minaret is not tilted (two cables on one side and two others are placed on the opposite side of the minaret). These face to face vertical cables on two sides are connected to each other with cables turning over the top of the minaret. As illustrated in Figure 6.2, these cables, which are modeled by using 660 frame elements, put the minaret in a cable cage system.

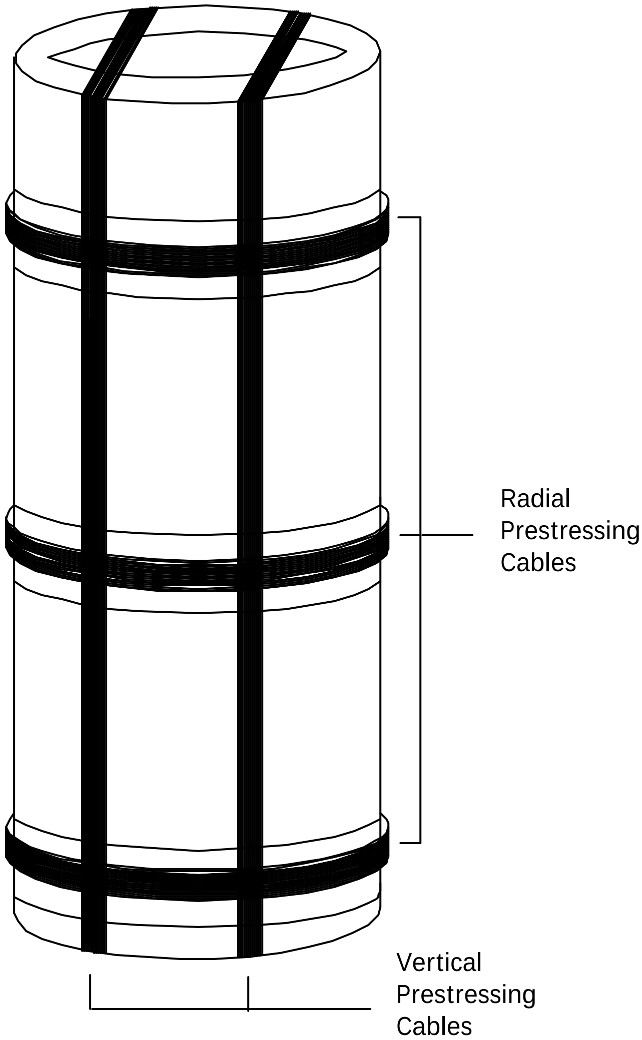


Figure 6.2. The cable cage system of the minaret model

6.3. Analyses Performed with Finite Element Method

In order to illustrate the model of transporting the minaret by tilting, four major analyses are performed by SAP 2000 Computer Program [77, 78, 79, 80, 81]. These numerical analyses are compared with each other to evaluate the efficiency of prestressing. Moreover, the positive contributions of increasing the number of tilting cables which make the connection between the minaret and the steel crane during tilting are studied. As it was explained before, these cables are anchored from the top of the crane to the selected prestressed cables on the minaret (Figure 5.12).

In the first part of the analyses, the finite element model of the minaret is created under the existing conditions, meaning that the structure stands without inclination (0° from the vertical), for five different load cases. These analyses are performed under the following loading conditions:

1. Gravity Loading
2. Lateral Loading
3. Gravity Loading with Prestressing Effect
4. Lateral Loading with Prestressing Effect
5. Prestressing only

As it is understood from the above sequence, the minaret is analyzed, firstly, under the effect of gravity forces. Then, lateral loading is applied onto the structure which induces a regular cantilever behavior on the structure. In order to comprehend the effect of prestressing on the minaret, the first two analyses are re-performed after adding the prestressed cables on the same finite element model. Finally, in the fifth condition, the minaret is subjected to only prestressed forces for understanding the working principle and effects of prestressing on a masonry structure.

Afterwards, this finite element model is analyzed for tilting condition of the structure. Tilting angles (inclination angle) of 30°, 60° and 90° from the vertical are used in the 2nd, 3rd and 4th parts of the analyses, respectively. That is to say the minaret is brought to the horizontal position at the end.

In the first part of the analyses (when the minaret is perpendicular to the ground level), the restraints of all the points at the base of the structure are assigned to be fixed. However, they are assigned to be hinged in the 2nd, 3rd and 4th part of the analyses due to cutting of the minaret 3 m. above from its foundation according to the tilting process as discussed in Section 5.5.

Each of these last three parts of the analyses is performed in three steps, also. This means, at each tilting angles (30°, 60° and 90° from the vertical) the structure is modeled firstly by using one cable, then 2 cables and lastly 3 cables. These tilting cables are anchored to the minaret at two points which are located on the prestressed cables. In FEM, these anchorage points are accepted as hinges to leave the rotation free. The elevations of the anchorage points of the tilting cables on the minaret are 1 m., 13 m., and 25 m. below from the top of the structure for the first, second and third steps, respectively (Figure 5.12).

All of these analyses are carried out under two loading conditions:

1) Gravity loading only
2) Gravity loading with prestressed cables

The dynamic effect, which could be occurred during the transportation of the minaret with a truck, is not taken into consideration in this study.

For a clear understanding, all of the performed analyses are shown in Table 6.1.

Table 6.1. A summary of all performed analyses in FEM

<table>
<tr><th rowspan="2"></th><th colspan="4">Name of Analysis</th></tr>
<tr><th>Part 1
(0° inclination)</th><th>Part 2
(30° inclination)</th><th>Part 3
(60° inclination)</th><th>Part 4
(90° inclination)</th></tr>
<tr><td rowspan="6">Loading Condition and Number of Tilting Cables</td><td>Gravity Loading</td><td rowspan="2"><u>One tilting cable</u>
1. Gravity
2. Gravity with prestressed cables</td><td rowspan="2"><u>One tilting cable</u>
1. Gravity
2. Gravity with prestressed cables</td><td rowspan="2"><u>One tilting cable</u>
1. Gravity
2. Gravity with prestressed cables</td></tr>
<tr><td rowspan="2">Lateral Loading</td></tr>
<tr><td rowspan="3"><u>Two tilting cables</u>
1. Gravity
2. Gravity with prestressed cables</td><td rowspan="3"><u>Two tilting cables</u>
1. Gravity
2. Gravity with prestressed cables</td><td rowspan="3"><u>Two tilting cables</u>
1. Gravity
2. Gravity with prestressed cables</td></tr>
<tr><td>Gravity Loading with Prestressed Cables</td></tr>
<tr><td rowspan="2">Lateral Loading with Prestressed Cables</td></tr>
<tr><td><u>Three tilting cables</u>
1. Gravity
2. Gravity with prestressed cables</td><td><u>Three tilting cables</u>
1. Gravity
2. Gravity with prestressed cables</td><td><u>Three tilting cables</u>
1. Gravity
2. Gravity with prestressed cables</td></tr>
</table>

6.4. Discussion of Analyses Results

In the analysis carried out under the gravity forces, the most known behavior of the structure is tested. Due to its self weight, the structure shows a stress distribution which resembles sausage pieces; i.e. the value of stress increases steadily towards the ground as shown in Figure 6.3 in the name of *loading (1)*. For the lateral loads, 40 percent of the mass of minaret (0.4G) is applied to the structure since 0.4G indicates a general earthquake load effect onto a structure and the effect of lateral loading through the global-X direction is investigated. Results of this analysis also indicate an expected normal behavior. Being under horizontal forces causes tension stress along the side to which pushing force is applied, and compression stress along the other side of the structure (Figure 6.3 in the name of *loading (2)*).

Figure 6.4 shows the stress distribution of the model in the existence of prestressed cables. As it is seen from the stress distributions, prestressing slightly takes care of the tensile stresses even under the vertical position of the minaret (no tilting condition). Furthermore, it is observed that the system is almost completely under compression when the prestressing forces are applied alone (Figure 6.5). As a result, with the help of these analyses, the correctness of the finite element model is realized which is important to make a true discussion for the analyses in which an inclination is induced on the minaret.

From the deformed shape of the minaret (Figure 6.5), it is seen that the structure is compressed under the prestressed cables. In this analysis, finite element model is formed by wrapping the prestressed cables directly to the surface of the minaret which would be eventually hazardous for the structure. For vertical prestressing, this problem could be prevented by anchoring the vertical cables to the I-beams that are placed on a timber plate at the top of the structure. Also, placing a coating under the cables could be protective for the surface against radial prestressed cables, as described in details in Section 5.5.

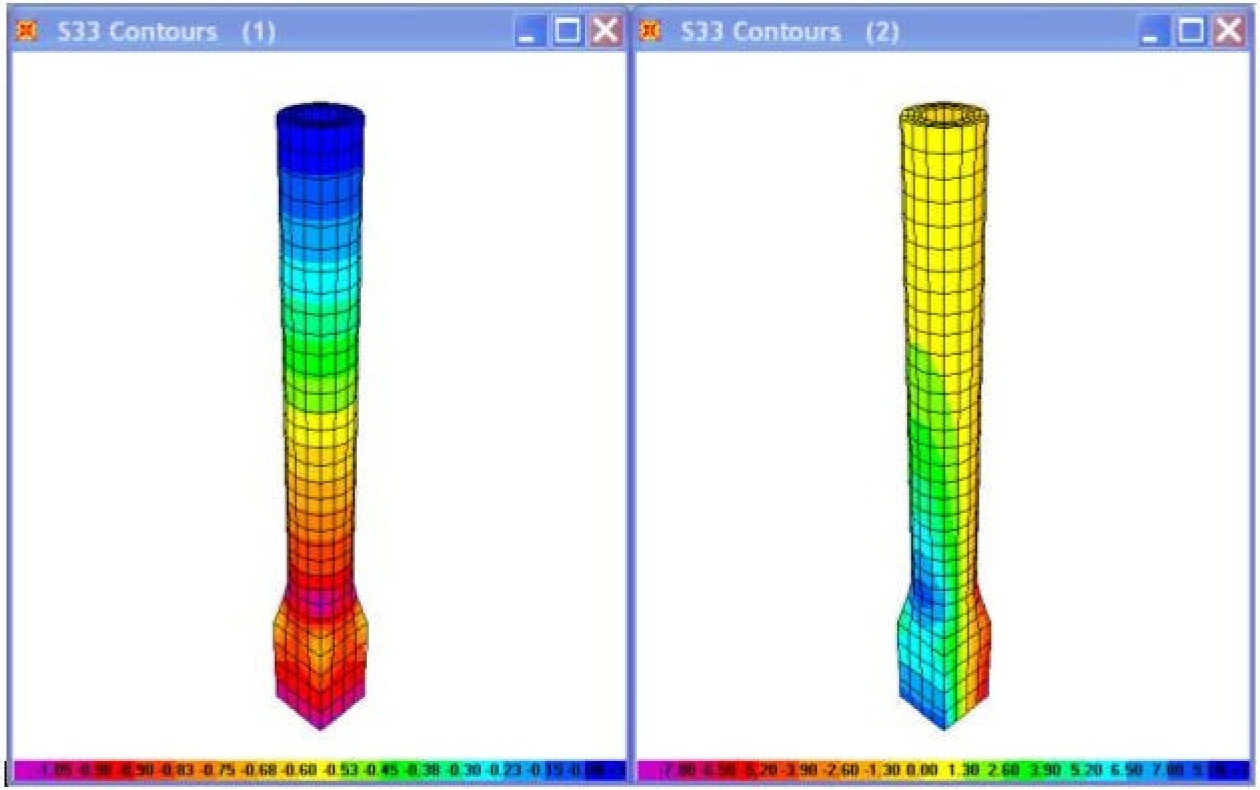


Figure 6.3. The stress, S-33, distribution in the minaret due to gravity forces (loading 1) and lateral forces (loading 2)

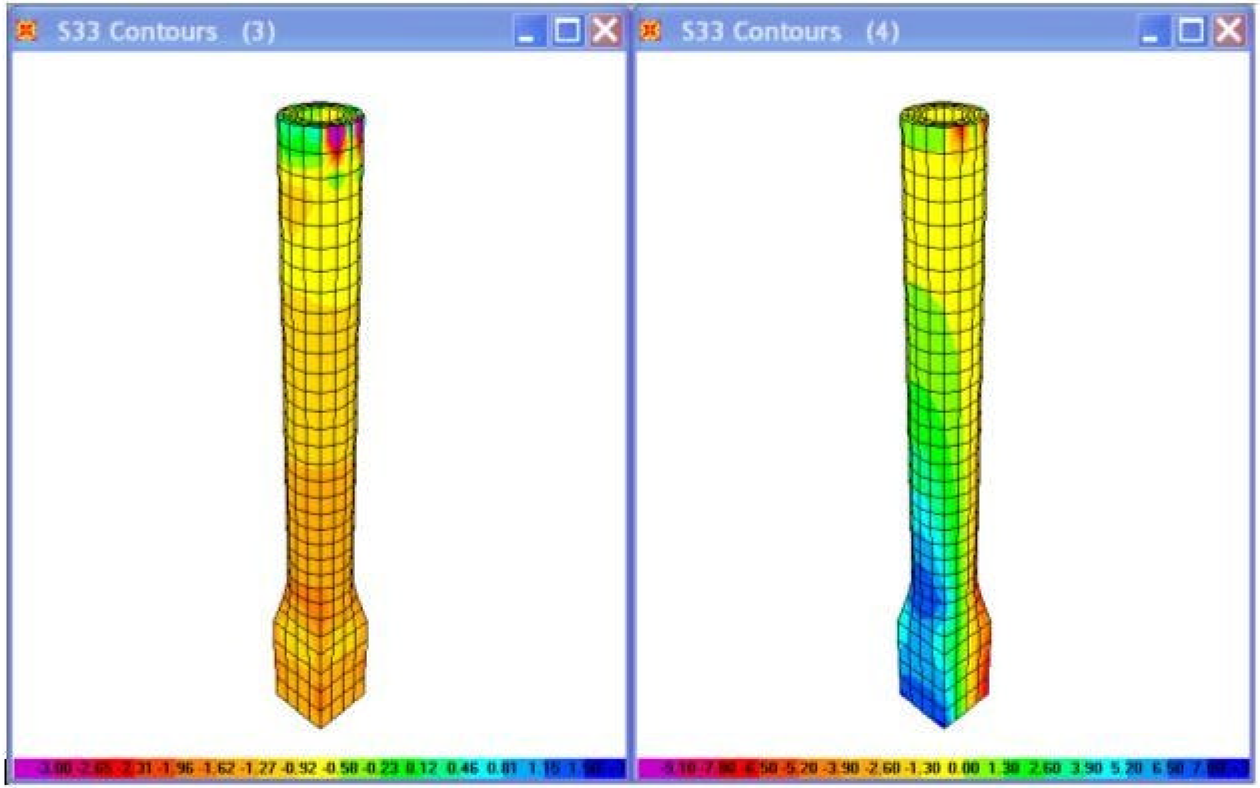


Figure 6.4. The stress, S-33, distribution in the minaret due to gravity forces (1) and lateral forces (2) with prestressed cables

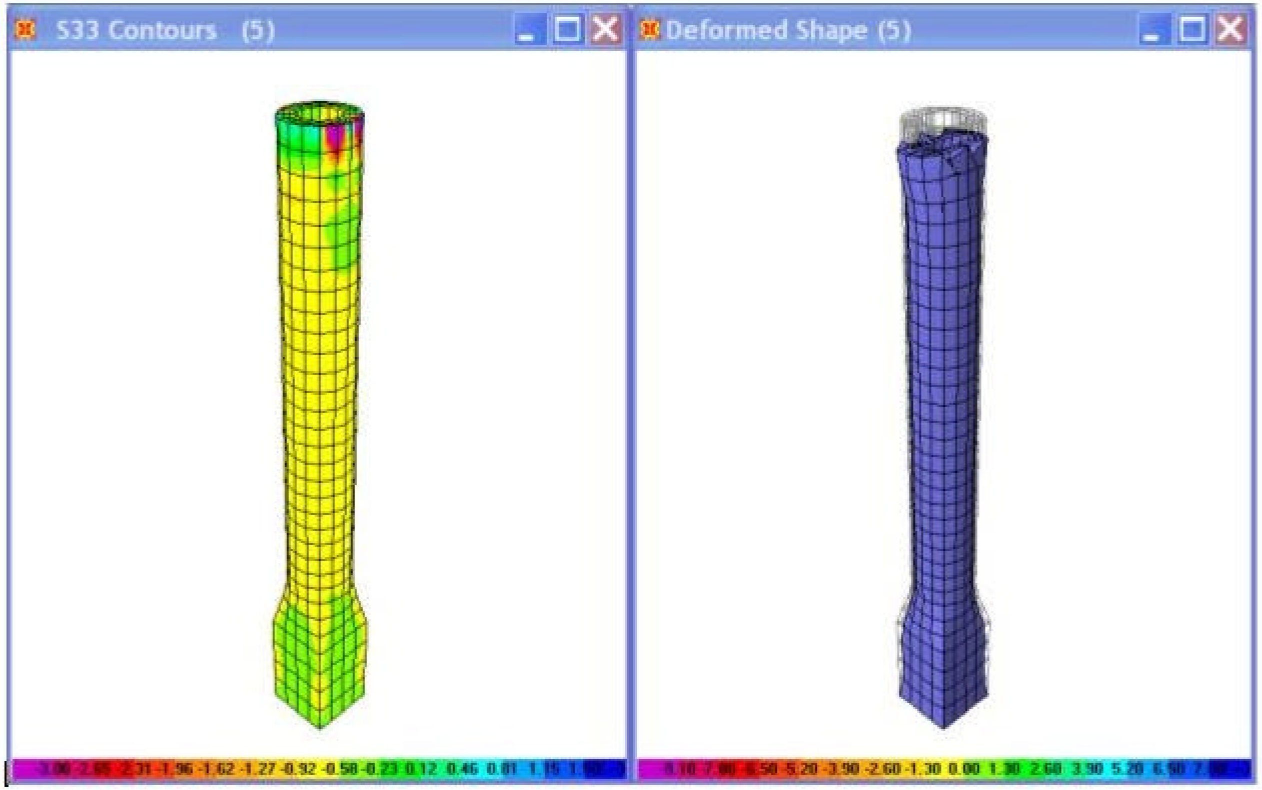


Figure 6.5. The stress, S-33, distribution and the deformed shape of the minaret under prestressing only

The variation of stresses along the minaret are examined step by step for each part of the analyses; i.e., for tilting the minaret with angles of 30°, 60° and 90° from the vertical. Stress distributions obtained from these analyses show that the observed tensile stresses in the model without prestressed cables are compensated in the model including the prestressed cables. Confinement of masonry with properly arranged external prestressed cables increases the strength and the strain capacity of the structure.

While radial prestressed cables take control of the stresses along the axis-11 (S-11), vertical ones take control of the stresses along the axis-33 (S-33). Figure 6.6 illustrates these axes in a solid element. Prestressing simply adds compression to the masonry as clearly observed from all of the analyses results. Accordingly, the vulnerability of the structure due to low tensile strength of the masonry would be handled and brittle tensile failure of the structure would be avoided by using the advantage of prestressing.

The high tensile stress values observed just at the point of location of prestressed cables would be also compensated by using coating systems under the cables which is helpful to distribute the direct forces coming onto the surface of the structure and also prevent the friction forces.

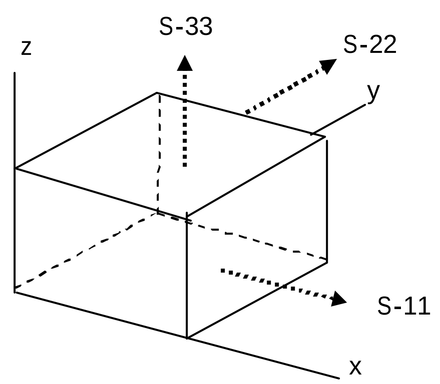


Figure 6.6. The local axes and stress directions in a solid element

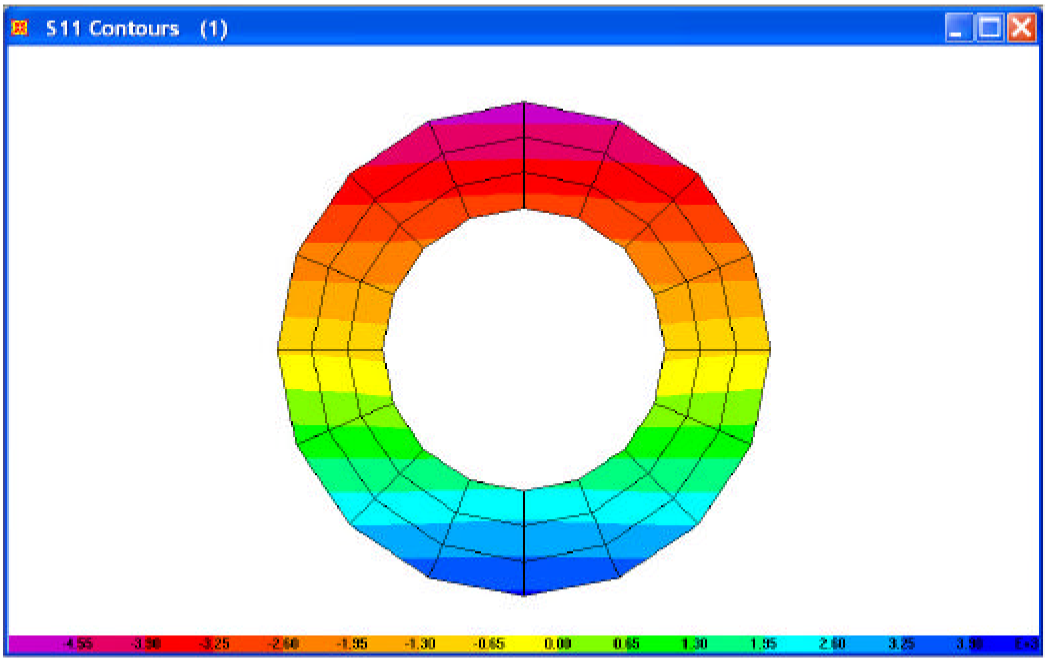
Furthermore, addition of each tilting cable to the structure reduces the span length which helps the structure to withstand to the loading more soundly. As it is observed from the deformed shapes and stress distributions obtained from the analyses' results, the structure passes to the safe side with the increasing number of tilting cables. Tension zone occurred in the structure decreases and accordingly compression zone, to which masonry can resist easily due to its high compressive strength, increases.

Although one tilting cable would never be used during this transportation process, it is seen that even under that situation, prestressed cables have a significant reducing effect on the tensile stresses. Hence, results of the analyses performed with three supports (three tilting cables) indicate that a combination of decreasing span length and taking the advantage of prestressing significantly reduces the tensile stresses and so prevent the tension failure. At the tilting angle of 60°, the changes in the stress values observed in a slice, which is selected from a point on the minaret, clearly verify this decrease in tension in Figures 6.7 and 6.8. In all of the Finite Element Analyses results, while positive sign indicates the tension zone, negative sign indicates the compression zone occurred along the minaret.

Undeformed and deformed shapes of the minaret model with different number of tilting cables for the selected three different tilting angles are illustrated from Figures 6.9 to 6.11. These figures are obtained under the first loading condition; i.e., without prestressing. Furthermore, results of the 3rd part of the analyses, which is the most critical and essential part for this study, are illustrated in a sensible order from Figures 6.12 to 6.17. These figures indicates the stress distributions of S-11 and S-33 with and without prestressed cables for three different numbers of tilting cables in order to ensure a well-developed understanding and interpretation related with the effect of prestressing.

Table 6.2, 6.4, 6.6, 6.8 and 6.10 shows the stress values for different directions; S-11, S-22, S-33, Smax and Smin, respectively. These tables indicate the stress differences between the analyses performed with and without prestressed cables and also the stress changes with the increasing number of tilting cables. All of the tables and related graphical figures show the stress values of the most critical solid elements located along the side to which the pushing force is applied to the minaret. When the numerical values in the tables are compared, it is again directly seen that the stress values pass to the compression side with the addition of prestressed cables and narrowing the span length decrease the tensile stresses even at 90°, up to which the minaret would actually never be tilted but only stored for a limited time in the hydraulic jack of the truck by which it is transported to its new relocation site as explained in Section 5.5. The location of prestressing points at where high tension stress values are observed are compensated with coating systems as discussed before. The legend of each stress table is illustrated in Tables 6.3, 6.5, 6.7, 6.9 and 6.11, respectively.

Finally, Figures 6.18, 6.19 and 6.20 demonstrate the graphical variation of **S-11** values. In each figure, variation of respective stress values along the critical side on the surface of the minaret are represented under the following conditions; with and without prestressing, with 1, 2 and 3 tilting cables and for 30°, 60° and 90° tilting angles. In the same manner, Figures 6.21, 6.22 and 6.23 evaluates them for **S-22**, Figures 6.24, 6.25 and 6.26 for **S-33**; Figures 6.27, 6.28 and 6.29 for **Smax** and lastly, Figures 6.30, 6.31 and 6.32 for **Smin** values.



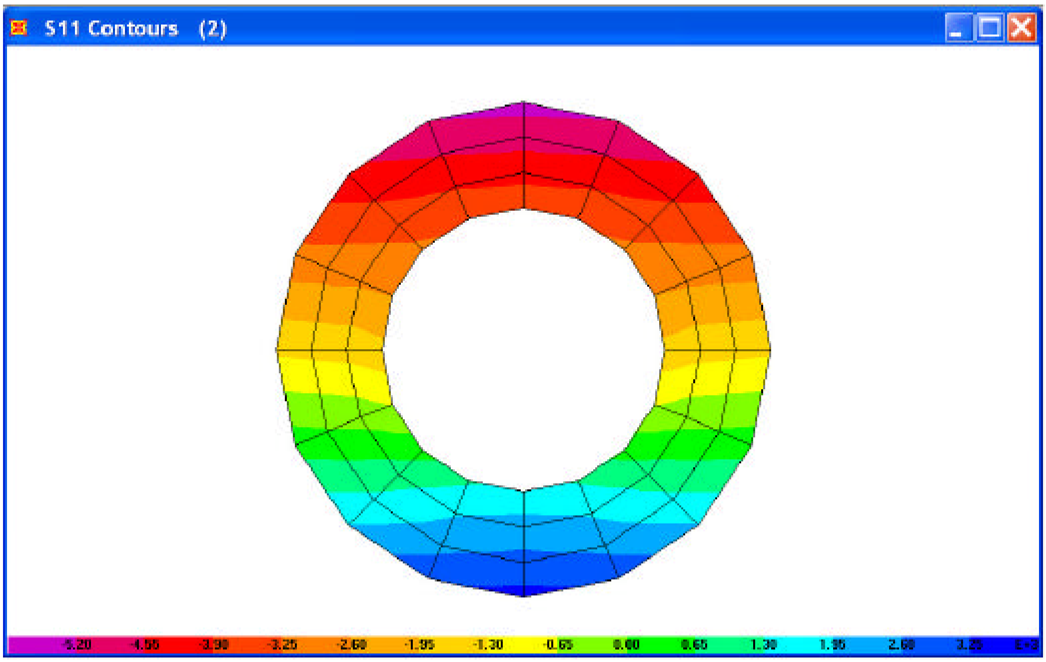


Figure 6.7. The stress changes, S-11, observed in the slices taken from a point on the minaret at 60° inclination angle

(1) without prestressed cables (2) with prestressed cables

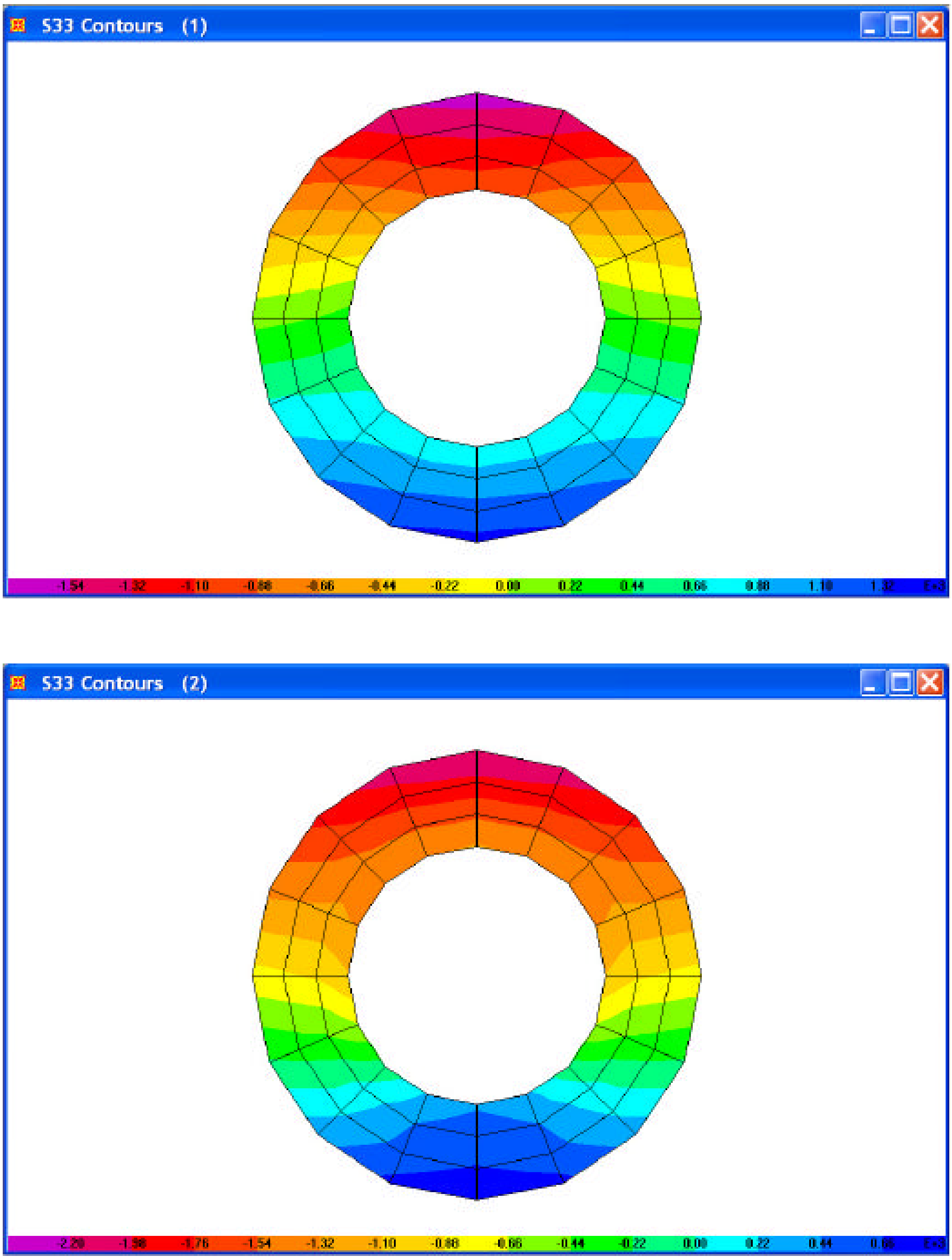


Figure 6.8. The stress changes, S-33, observed in the slices taken from a point on the minaret at 60° inclination angle

(1) without prestressed cables (2) with prestressed cables

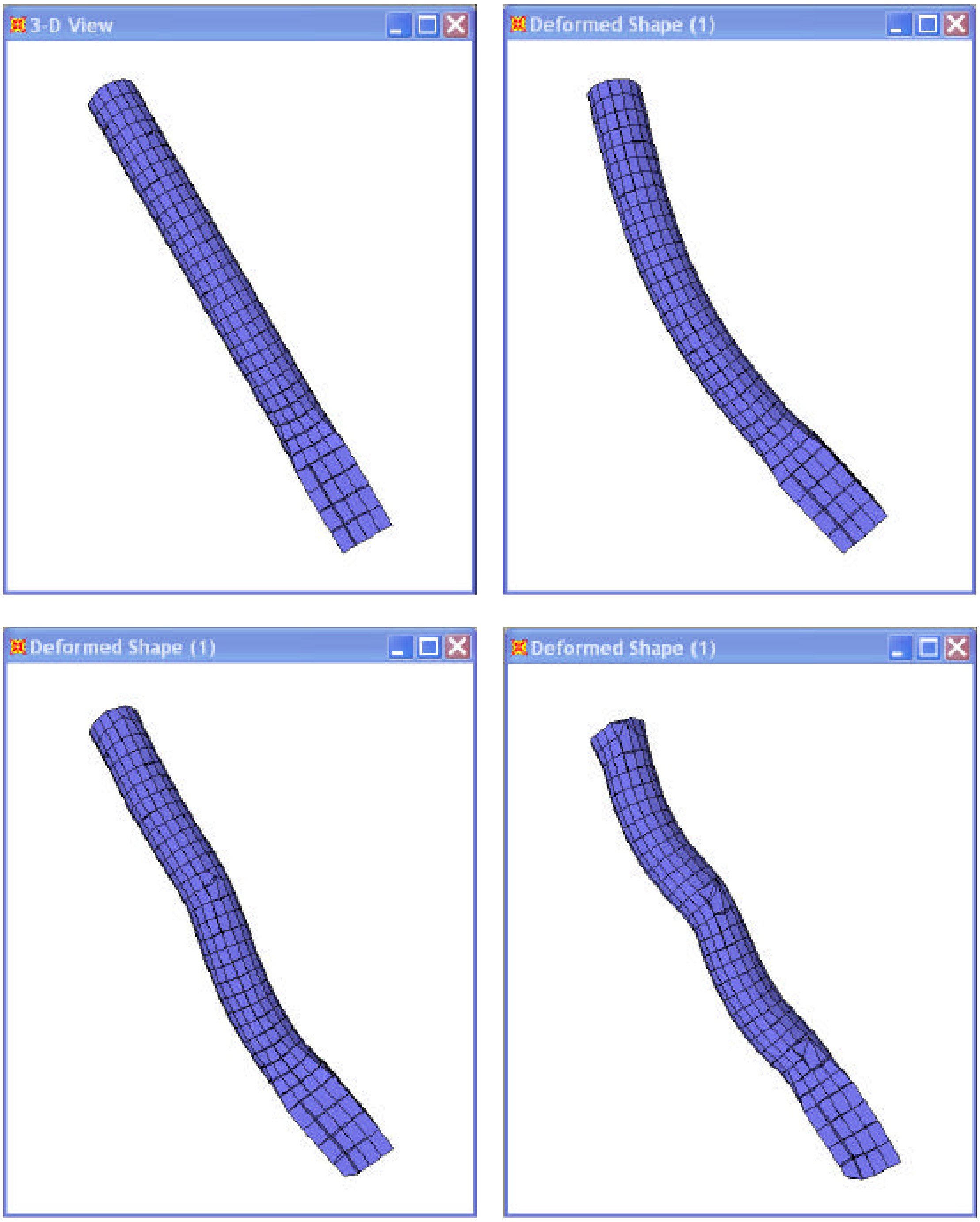


Figure 6.9. The undeformed shape and the deformed shapes of the minaret at 30° inclination angle with one, two and three tilting cables, respectively

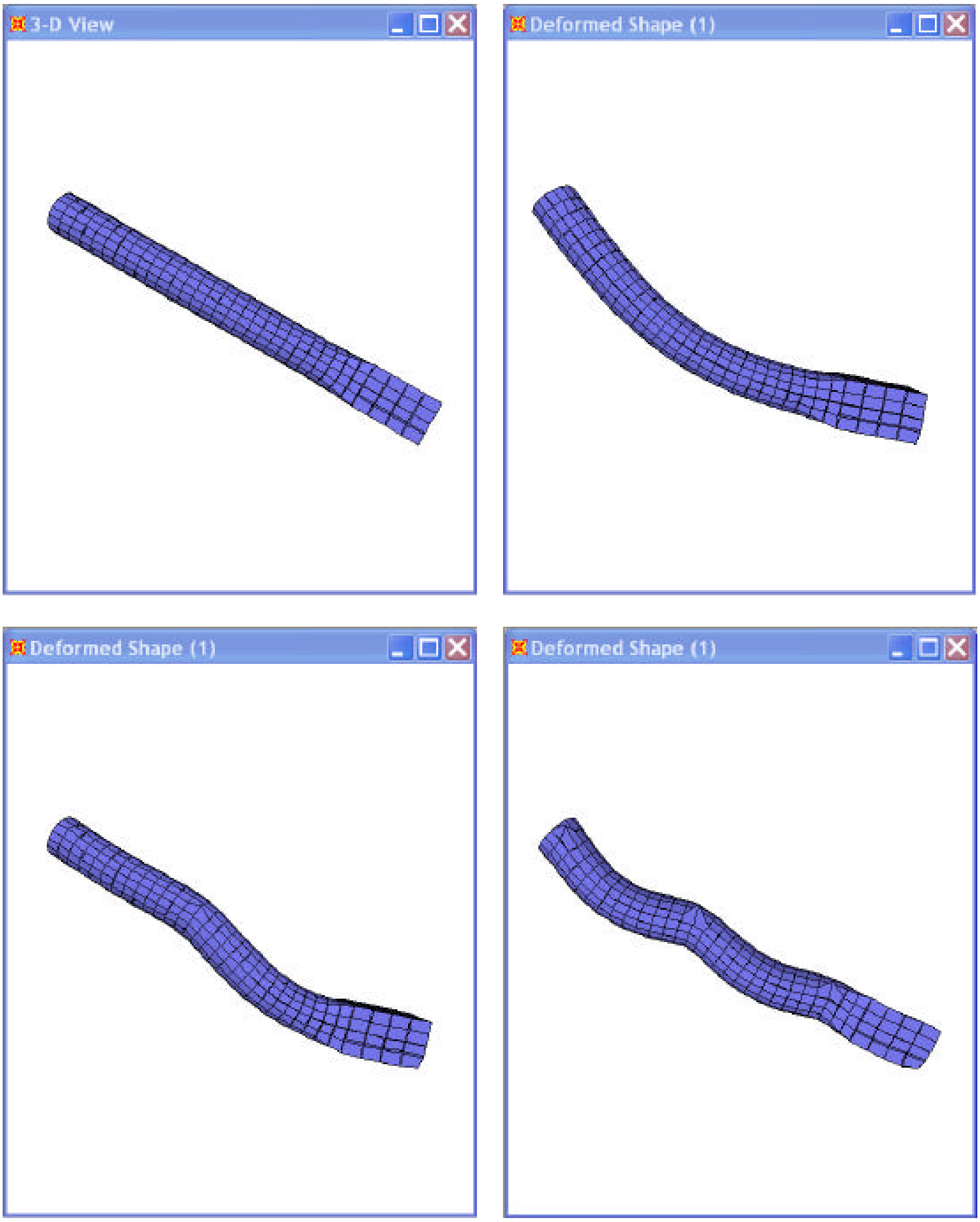


Figure 6.10. The undeformed shape and the deformed shapes of the minaret at 60° inclination angle with one, two and three tilting cables, respectively

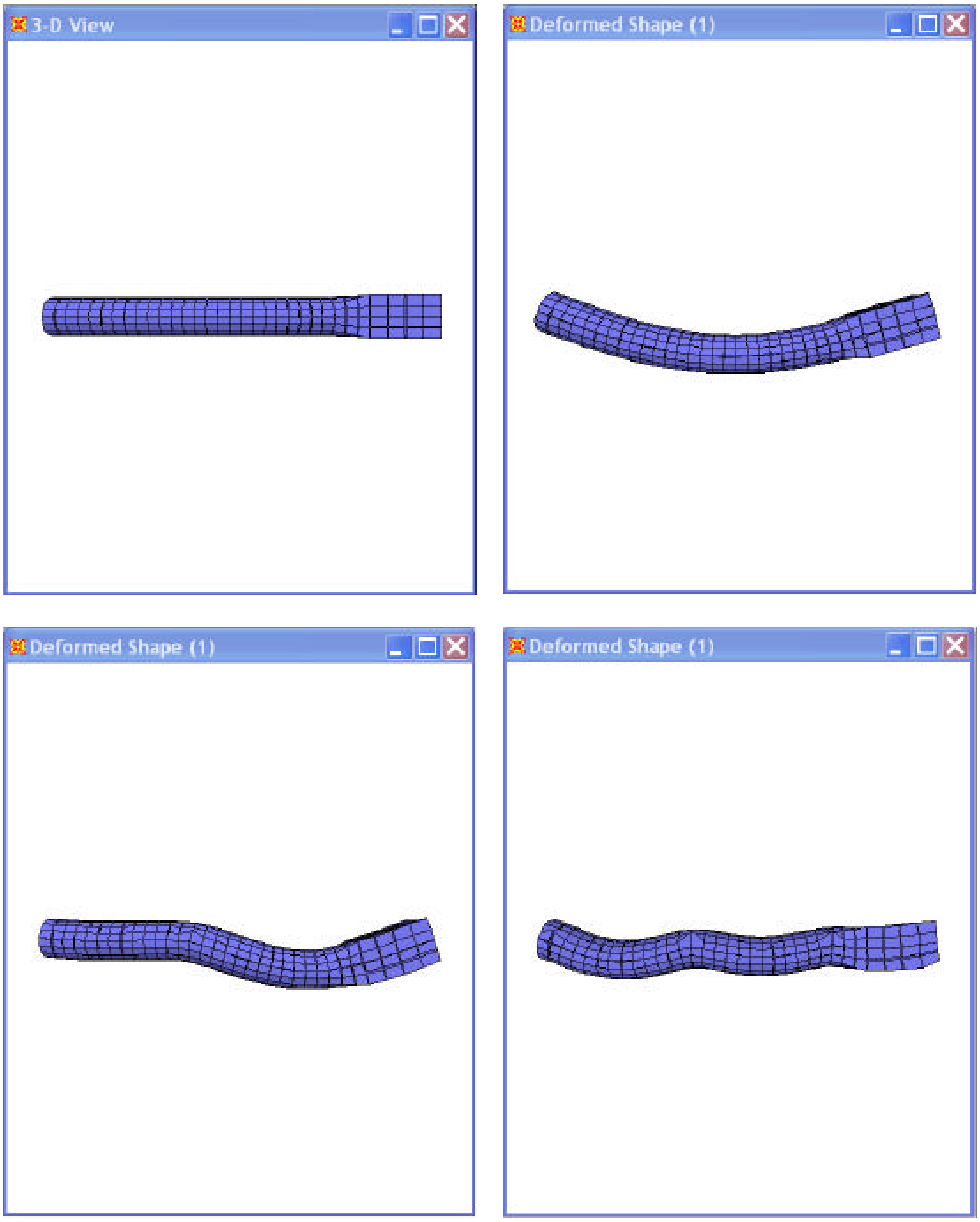


Figure 6.11. The undeformed shape and the deformed shapes of the minaret at 90° inclination angle with one, two and three tilting cables, respectively

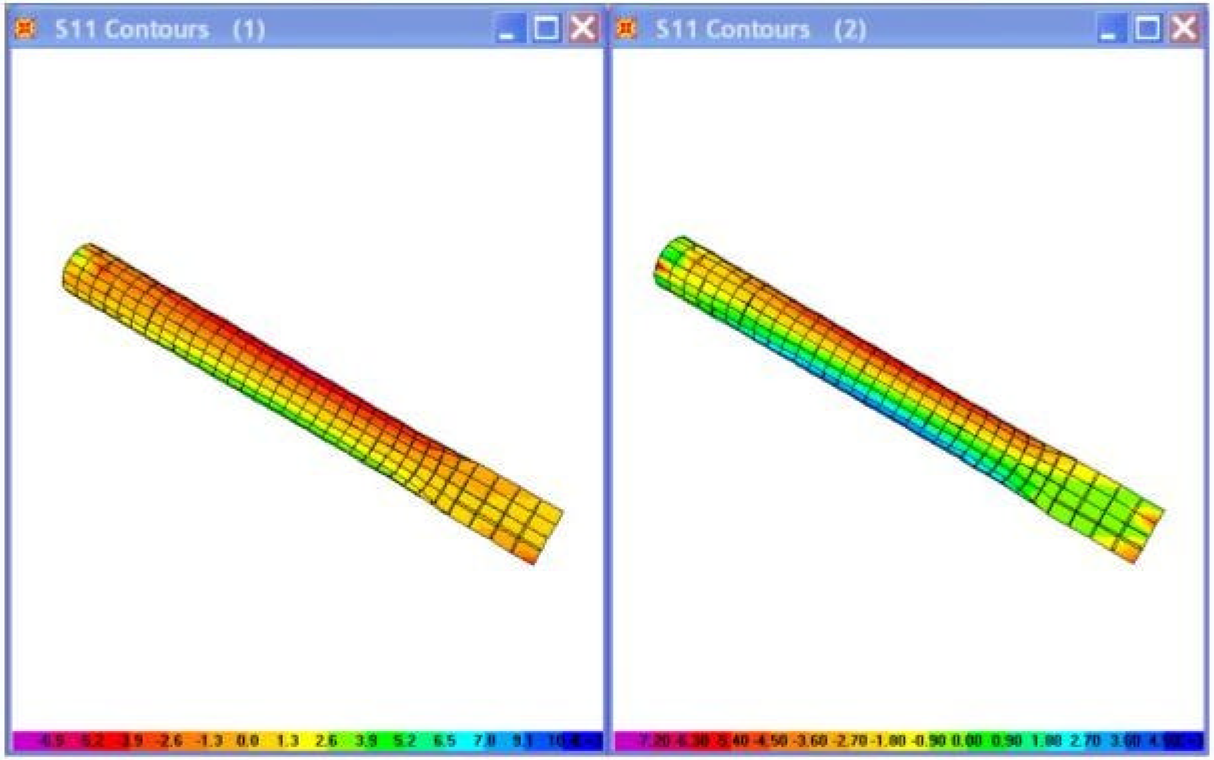


Figure 6.12. The stress, S-11, distribution in the minaret with one tilting cable at 60° inclination angle
(1) without prestressed cables (2) with prestressed cables

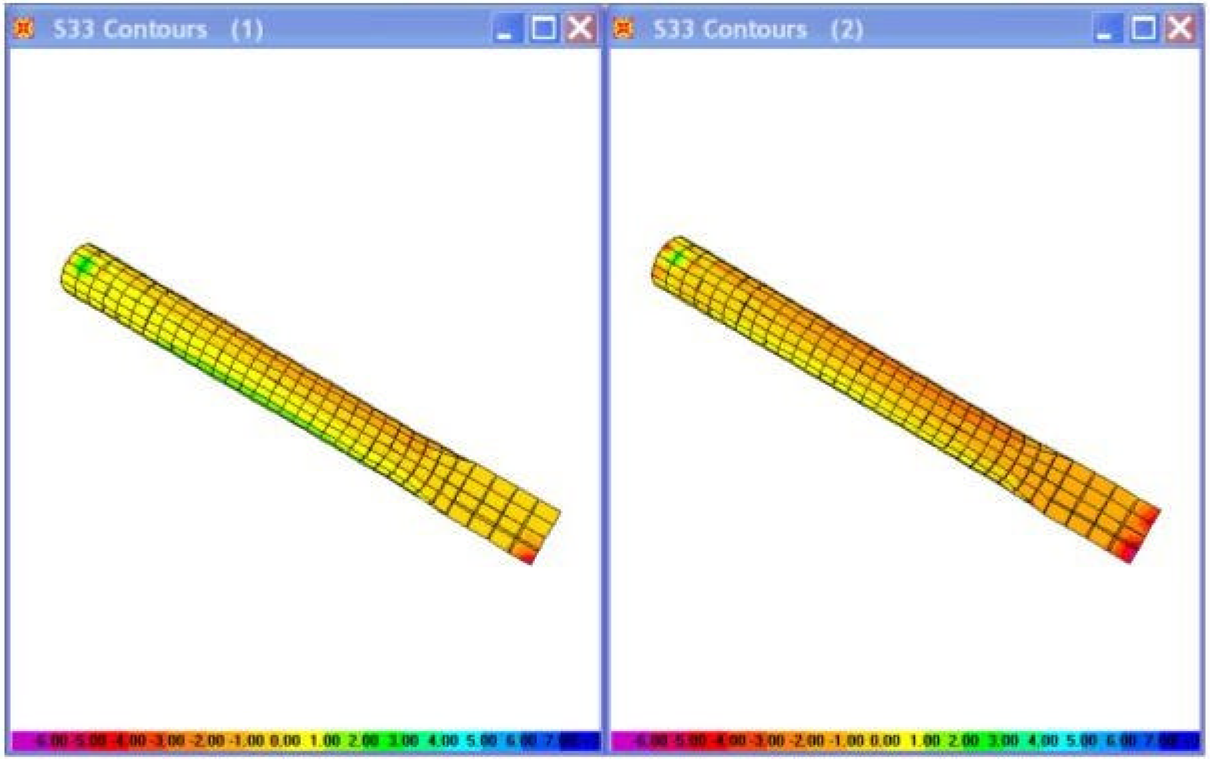


Figure 6.13. The stress, S-33, distribution in the minaret with one tilting cable at 60° inclination angle
(1) without prestressed cables (2) with prestressed cables

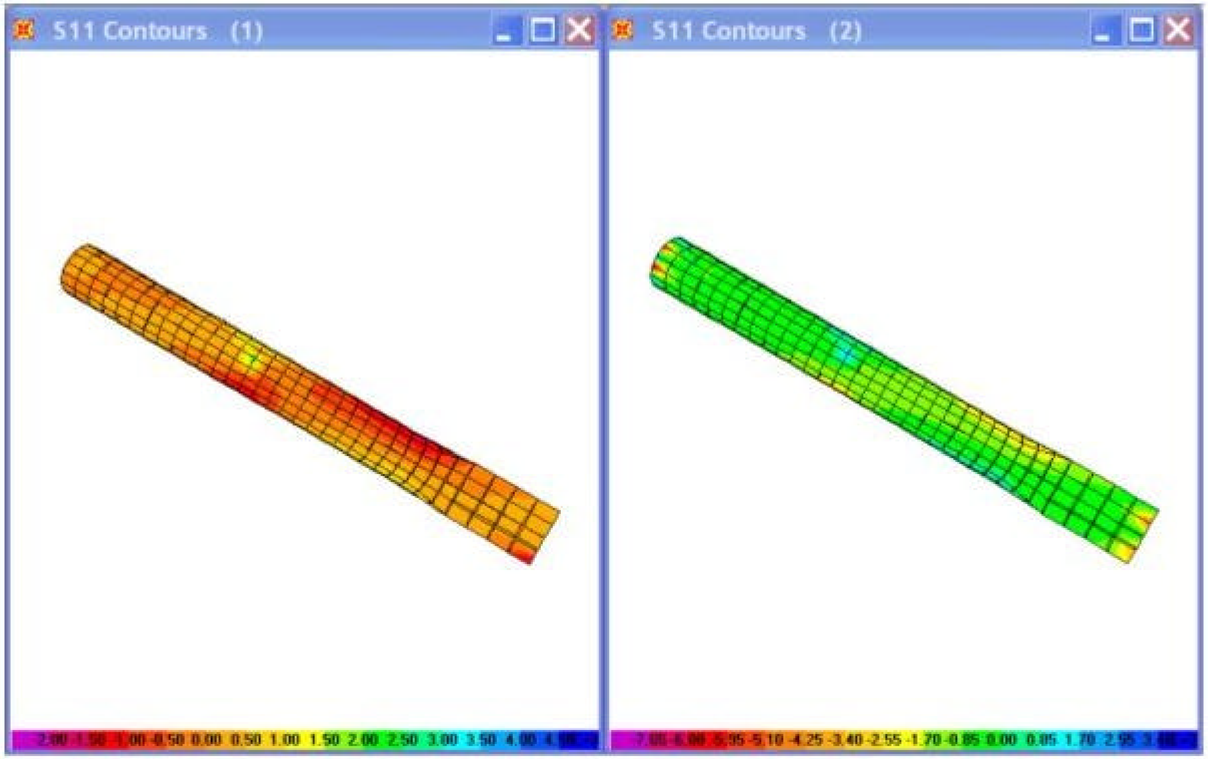


Figure 6.14. The stress, S-11, distribution in the minaret with two tilting cables at 60° inclination angle
(1) without prestressed cables (2) with prestressed cables

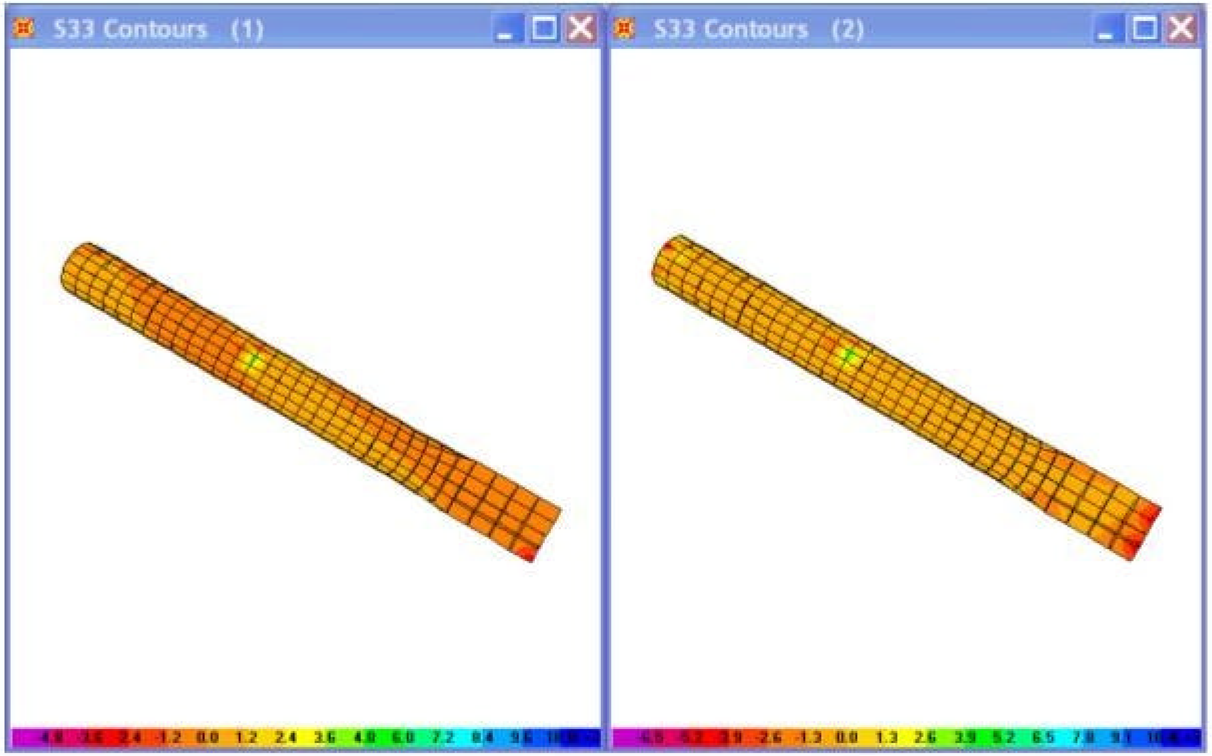


Figure 6.15. The stress, S-33, distribution in the minaret with two tilting cables at 60° inclination angle
(1) without prestressed cables (2) with prestressed cables

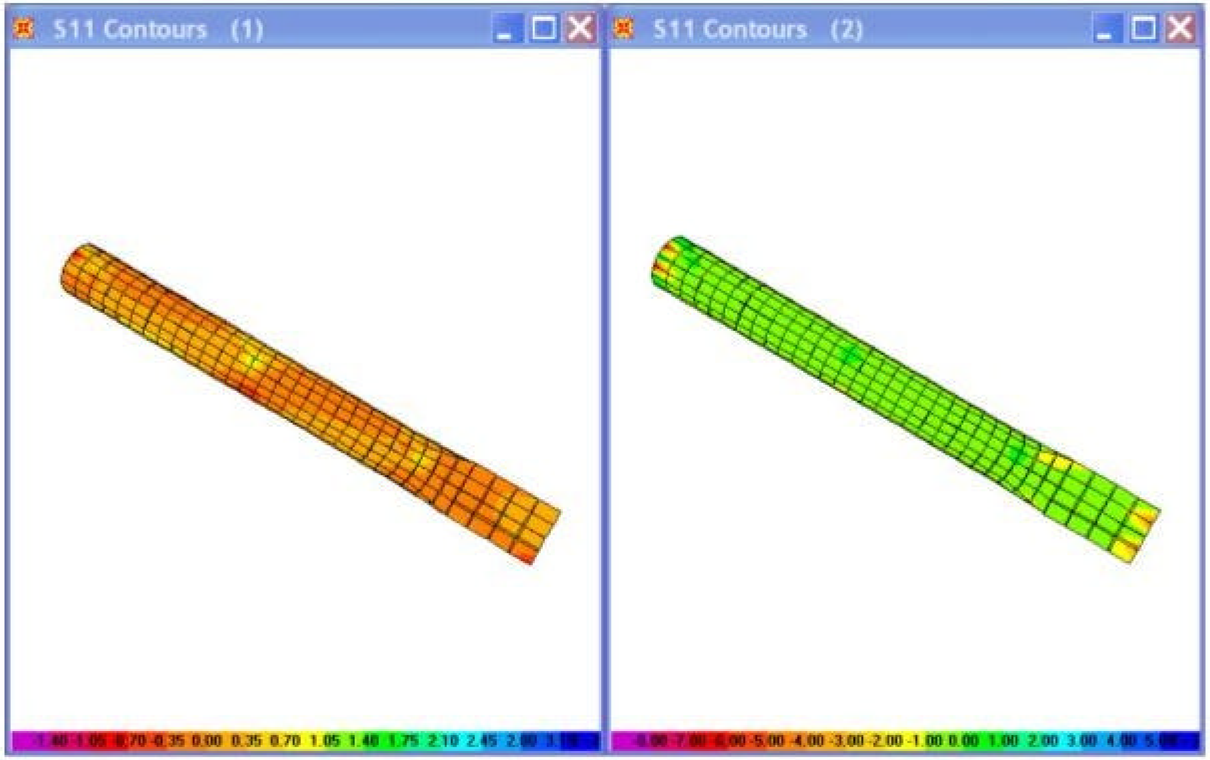


Figure 6.16. The stress, S-11, distribution in the minaret with three tilting cables at 60° inclination angle
(1) without prestressed cables (2) with prestressed cables

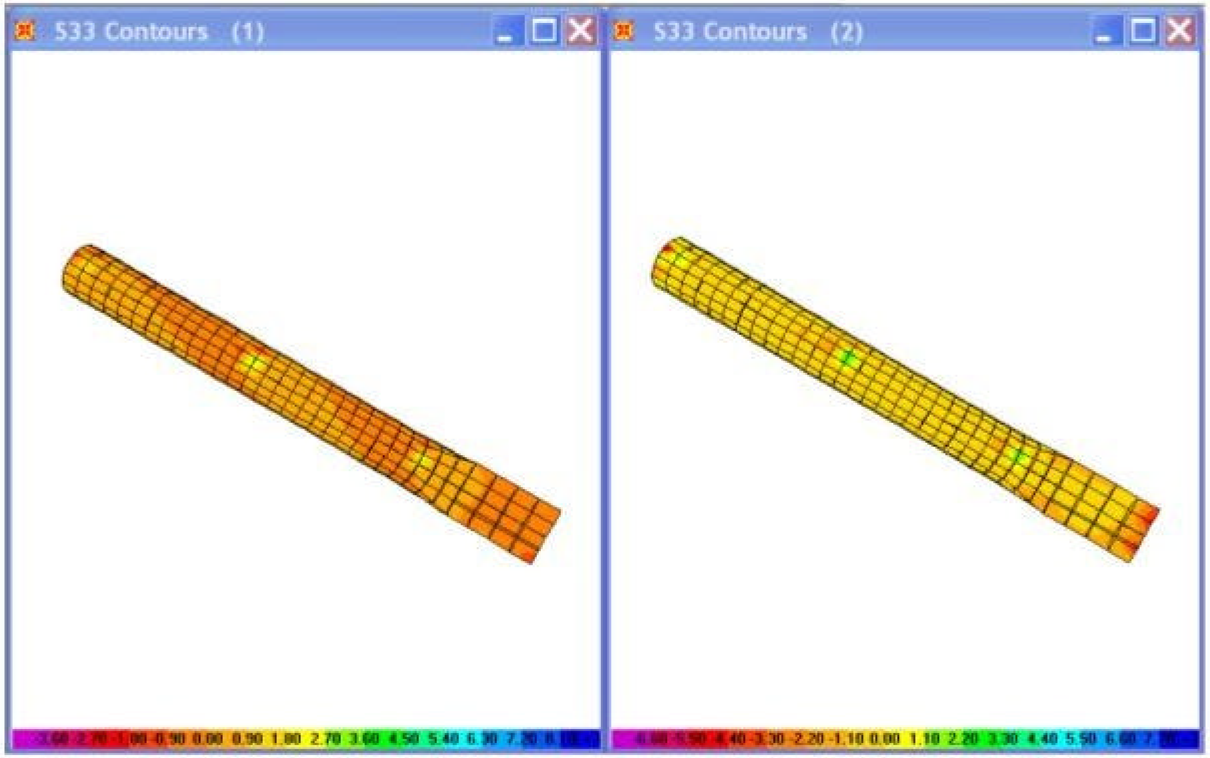


Figure 6.17. The stress, S-33, distribution in the minaret with three tilting cables at 60° inclination angle
(1) without prestressed cables (2) with prestressed cables

Table 6.2. The tabular form of the S-11 values under all performed conditions along the critical points of the minaret

				Elevation of solid elements from the ground level (m.)				
	Angle	Number of Cables	Prestressing	9	15	19	25	29
Stress S-11	30°	1	X	321.3	649	738.26	522.02	235.23
			✓	-228.74	128.33	209.19	-30.13	-363.92
		2	X	114.24	75.62	-233.71	44.96	42.73
			✓	-439.36	-461.58	-817.89	-523.36	-562.79
		3	X	-29.47	51.13	-152.56	84.67	58.54
			✓	-655.58	-481.59	-698.06	-460.96	-539.09
	60°	1	X	2884.63	4240.49	4567.57	3335	1830.34
			✓	2423.03	3785.44	4080.22	2787.37	1171.38
		2	X	1130.54	440.66	-1136.38	-122.75	210.77
			✓	660.2	-62.86	-1750.03	-719.69	-472.99
		3	X	-343.64	285.47	-437.63	398.41	438.66
			✓	-1024.53	-219.11	-954.62	-123.89	-213.02
	90°	1	X	5417.41	7224.54	7603.44	5575.63	3173.15
			✓	4999.28	6804.65	7137.55	5032.58	2494.14
		2	X	2156.61	721.13	-1753.26	-466.49	249.95
			✓	1728.15	237.36	-2372.56	-1075.32	-464.24
		3	X	-643.39	444.37	-486.33	589.47	729.63
			✓	-1358.29	-46.7	-985.1	82.73	61.43

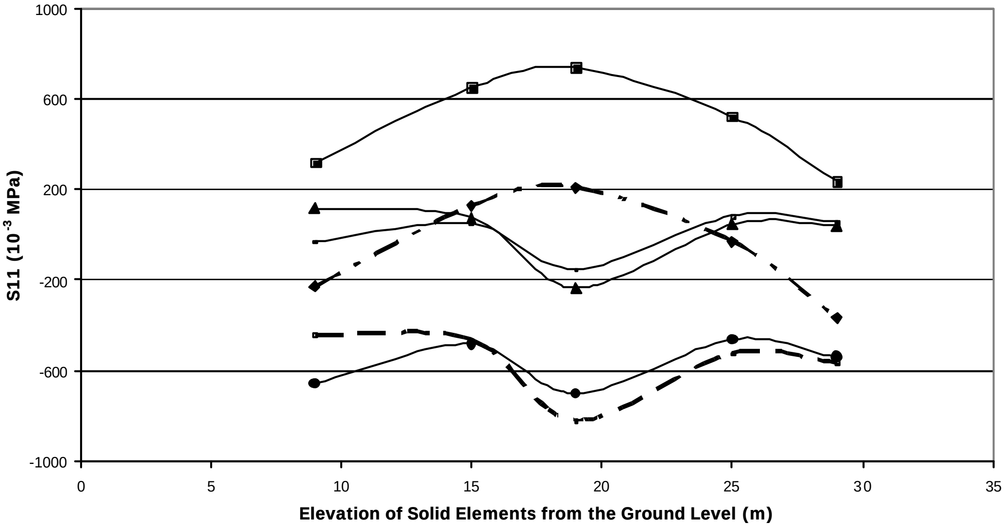


Figure 6.18. Graphical variation of S-11 along the minaret at 30° tilting angle

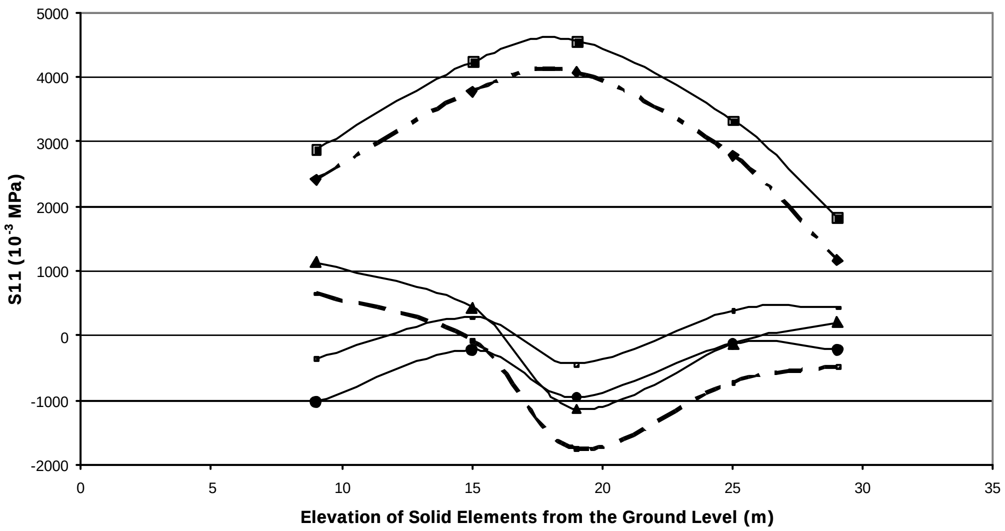


Figure 6.19. Graphical variation of S-11 along the minaret at 60° tilting angle

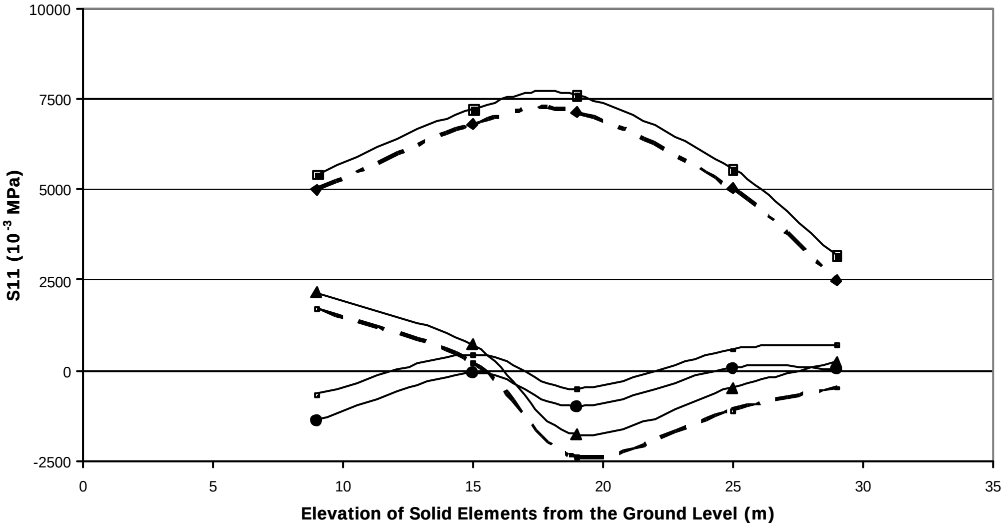


Figure 6.20. Graphical variation of S-11 along the minaret at 90° tilting angle

Table 6.3. Legend of Figures 6.18, 6.19 and 6.20

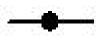
	S-11 Value with One Tilting Cable without Prestressed Cables
	S-11 Value with One Tilting Cable with Prestressed Cables
	S-11 Value with Two Tilting Cables without Prestressed Cables
	S-11 Value with Two Tilting Cables with Prestressed Cables
	S-11 Value with Three Tilting Cables without Prestressed Cables
	S-11 Value with Three Tilting Cables with Prestressed Cables

Table 6.4. The tabular form of the S-22 values under all performed conditions along the critical points of the minaret

	Angle	Number of Cables	Prestressing	Elevation of solid elements from the ground level (m.)				
				9	15	19	25	29
Stress S-22	30°	1	X	157.01	31.92	59.54	-7.14	-49.19
			✓	-1081.39	-1071.19	-1041.79	-1113.52	-1165.4
		2	X	70.95	6.8	130.87	54.08	-7.89
			✓	169.6	95.71	291.29	56.11	121.18
		3	X	-11.77	20.7	-94.06	48.1	-11.6
			✓	-1343.57	-1077.18	-1247.8	-1061.9	-1129.22
	60°	1	X	386.44	42.6	108.61	-26.6	-14.75
			✓	-851.13	-1060.18	-992.38	-1132.64	-1131.4
		2	X	156.59	-1.22	-183.34	67.33	35.68
			✓	-1083.14	-1103.4	-1343.45	-1042.53	-1078.04
		3	X	-45.92	34.63	-104.49	60.39	10.45
			✓	-1376.93	-1062.92	-1257.91	-1049.27	-1107.6
	90°	1	X	512.86	41.74	128.35	-39.08	24.49
			✓	-725.54	-1061.57	-973.19	-1145.65	-1092.78
		2	X	200.46	-8.97	-186.56	62.43	69.77
			✓	-1040.09	-1111.69	-1347.14	-1047.95	-1044.57
		3	X	-67.75	39.19	-86.9	56.4	29.9
			✓	-1399.6	-1058.9	-1240.8	-1053.79	-1088.78

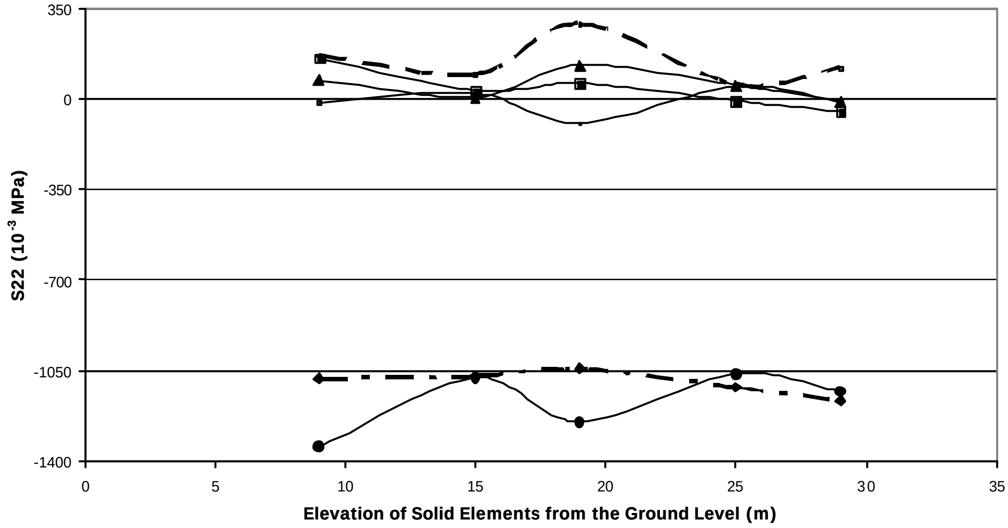


Figure 6.21. Graphical variation of S-22 along the minaret at 30° tilting angle

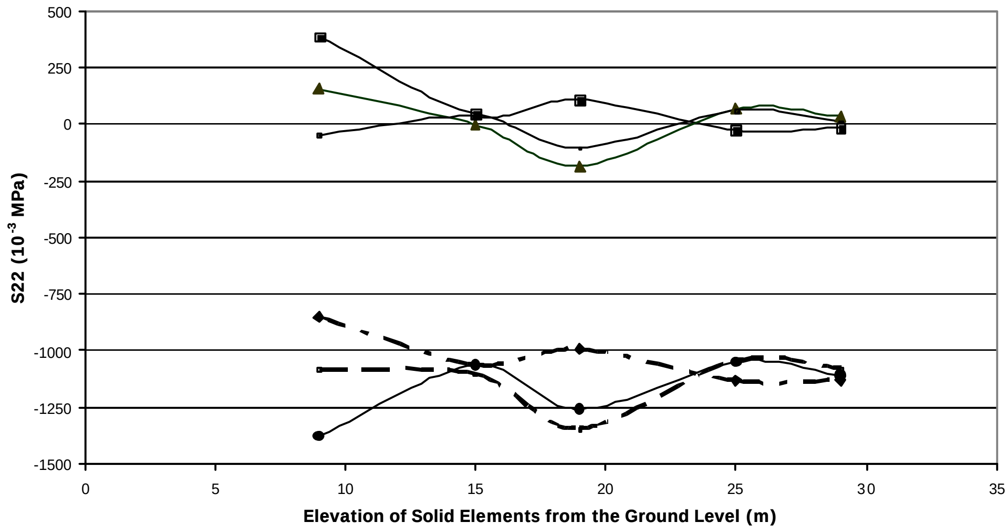


Figure 6.22. Graphical variation of S-22 along the minaret at 60° tilting angle

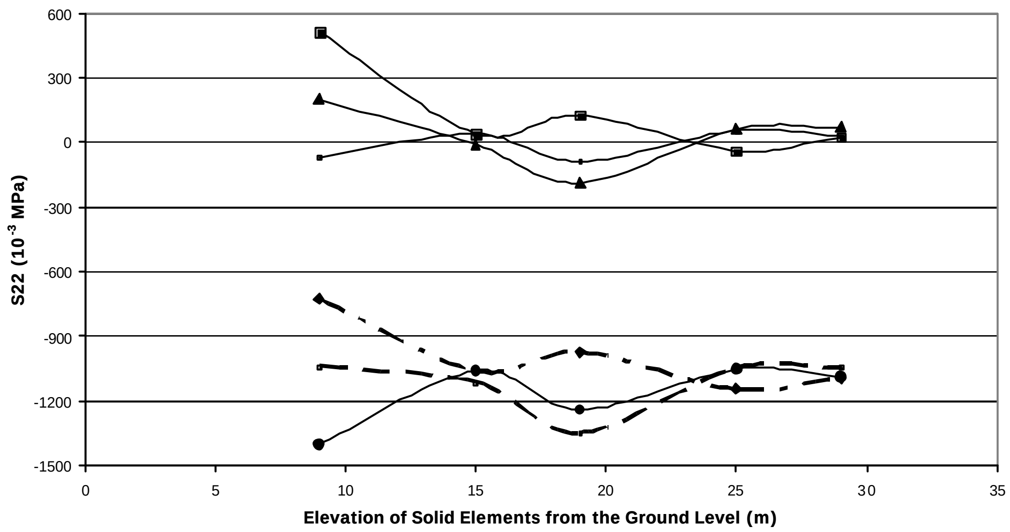


Figure 6.23. Graphical variation of S-22 along the minaret at 90° tilting angle

Table 6.5. Legend of Figures 6.21, 6.22 and 6.23

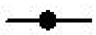
	S-22 Value with One Tilting Cable without Prestressed Cables
	S-22 Value with One Tilting Cable with Prestressed Cables
	S-22 Value with Two Tilting Cables without Prestressed Cables
	S-22 Value with Two Tilting Cables with Prestressed Cables
	S-22 Value with Three Tilting Cables without Prestressed Cables
	S-22 Value with Three Tilting Cables with Prestressed Cables

Table 6.6. The tabular form of the S-33 values under all performed conditions along the critical points of the minaret

	Angle	Number of Cables	Prestressing	Elevation of solid elements from the ground level (m.)				
				9	15	19	25	29
Stress S-33	30°	1	X	941.46	1887.42	2173.94	1719.86	969.1
			✓	477.43	1436.79	1687.62	1176.67	328.39
		2	X	403.06	310.89	-394.95	77.39	185.76
			✓	-67.89	-187.25	-990.8	-514.97	-482.16
		3	X	-192.92	177.07	-237.6	213.46	250.58
			✓	-888	-329.05	-747	-301.29	-381.59
	60°	1	X	941.46	1390.73	1501.62	1134.78	652.49
			✓	477.43	873.2	972.36	585.88	73.68
		2	X	403.06	170.9	-301.22	-53.58	72.27
			✓	-67.89	-362.55	-869.22	-618.77	-515.46
		3	X	-192.92	100.73	-99.51	125.8	154.55
			✓	-888	-435.17	-639.03	-413.69	-421.59
	90°	1	X	65.48	-7.85	-3.91	-76.27	-74.72
			✓	-530.5	-559.67	-553.82	-628.91	-632.88
		2	X	3.4	-48.42	-107.85	38.41	11.91
			✓	-592.8	-600.58	-669.22	-513.96	-544.73
		3	X	-5.79	-3.7	-53.74	20.01	-10.95
			✓	-612.21	-552.07	-610.53	-534.12	-569.91

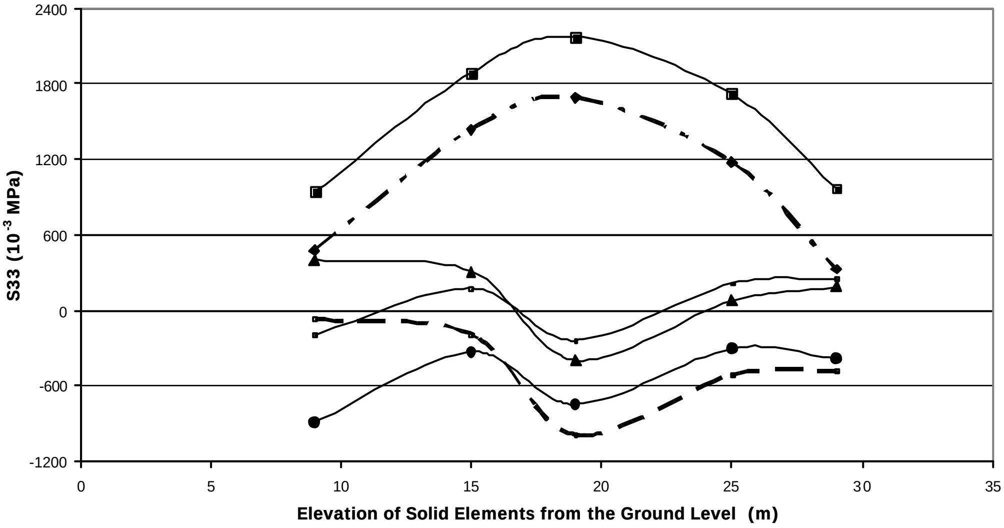


Figure 6.24. Graphical variation of S-33 along the minaret at 30° tilting angle

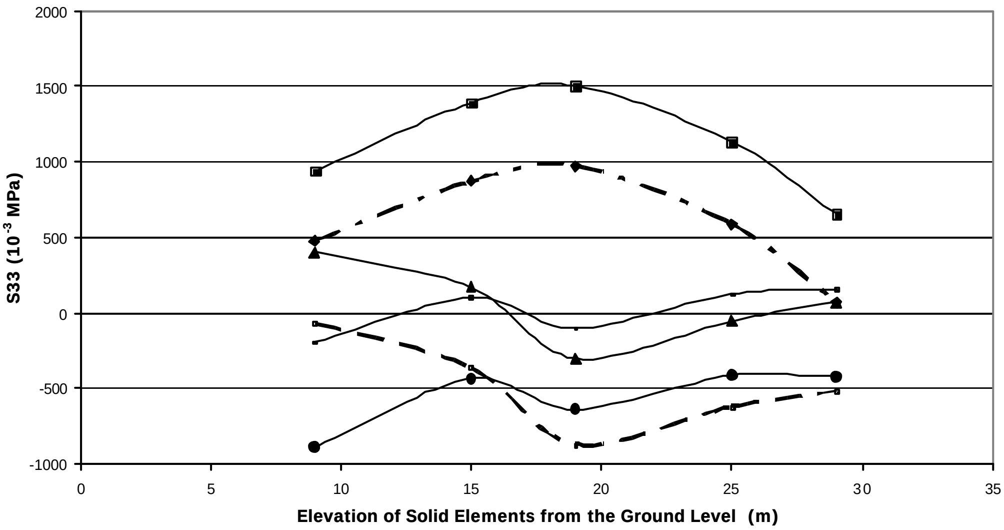


Figure 6.25. Graphical variation of S-33 along the minaret at 60° tilting angle

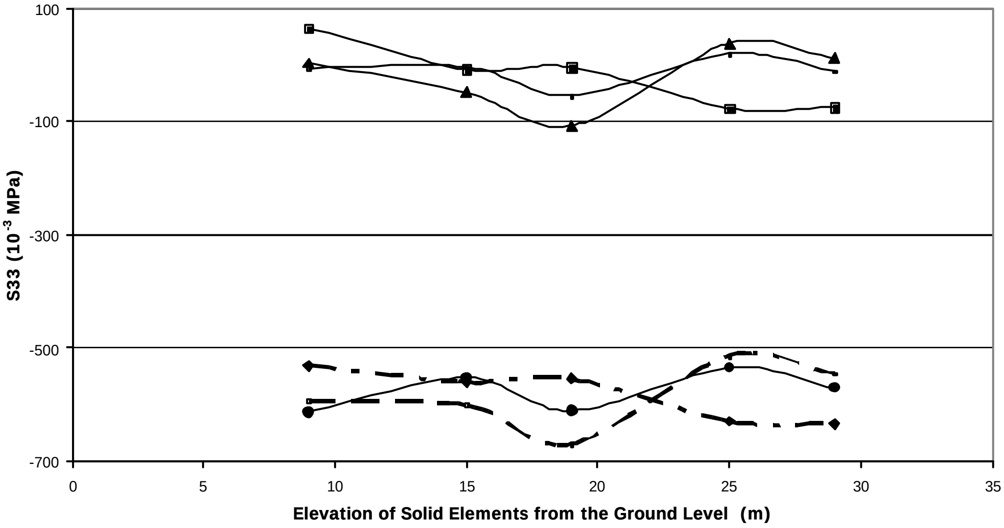


Figure 6.26. Graphical variation of S-33 along the minaret at 90° tilting angle

Table 6.7. Legend of Figures 6.24, 6.25 and 6.26

	S-33 Value with One Tilting Cable without Prestressed Cables
	S-33 Value with One Tilting Cable with Prestressed Cables
	S-33 Value with Two Tilting Cables without Prestressed Cables
	S-33 Value with Two Tilting Cables with Prestressed Cables
	S-33 Value with Three Tilting Cables without Prestressed Cables
	S-33 Value with Three Tilting Cables with Prestressed Cables

Table 6.8. The tabular form of the Smax values under all performed conditions along the critical points of the minaret

	Angle	Number of Cables	Prestressing	Elevation of solid elements from the ground level (m.)				
				9	15	19	25	29
Stress Smax	30°	1	X	1263.19	2530.03	2908.36	2270.28	1255.36
			✓	843.05	2110.09	2442.46	1727.03	577.23
		2	X	527.18	400.82	-36.92	113.73	238.56
			✓	98.13	-83.5	-571.15	-498.31	-472.86
		3	X	11.39	230.46	-24.57	288.88	322.65
			✓	-576.88	-260.68	-553.39	-218.23	-343.92
	60°	1	X	3861.74	5632.18	6069.43	4531.43	2560.65
			✓	3442.1	5212.32	5603.65	3988.34	1882.61
		2	X	1550.43	653.43	-76.9	74.24	281.59
			✓	1121.04	167.13	-614.17	-502.25	-432.19
		3	X	5.12	389.77	-38.54	508.35	607.67
			✓	-585.2	-101.68	-570.25	7.04E-01	-59.58
	90°	1	X	5427.36	7224.7	7603.63	5577.68	3180.73
			✓	5008.44	6804.78	7137.75	5034.56	2503.09
		2	X	2158.79	731.57	-95.61	68.88	250.8
			✓	1730.17	244.29	-632.59	-491.66	-464.1
		3	X	6.97E-01	444.65	-41.14	591.41	730.14
			✓	-589.26	-46.64	-573.03	83.51	63.21

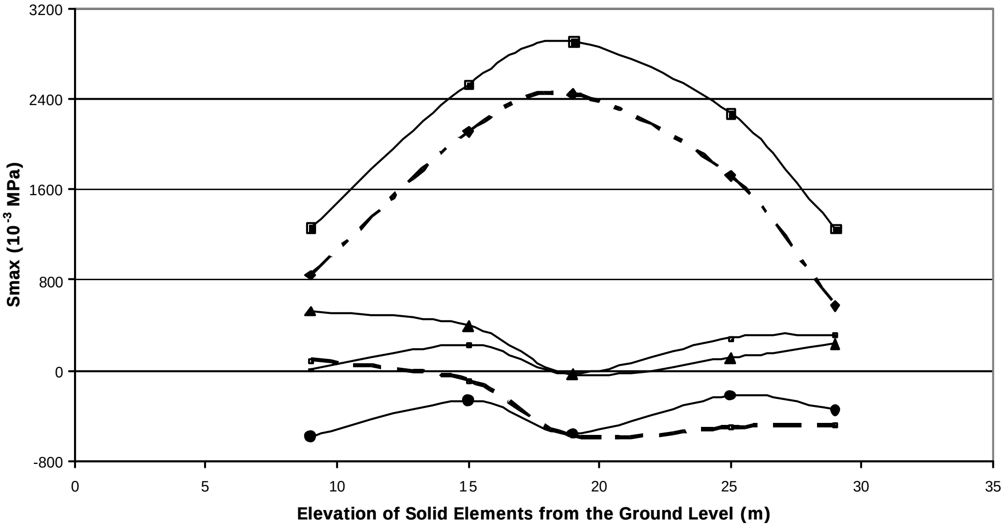


Figure 6.27. Graphical variation of Smax along the minaret at 30° tilting angle

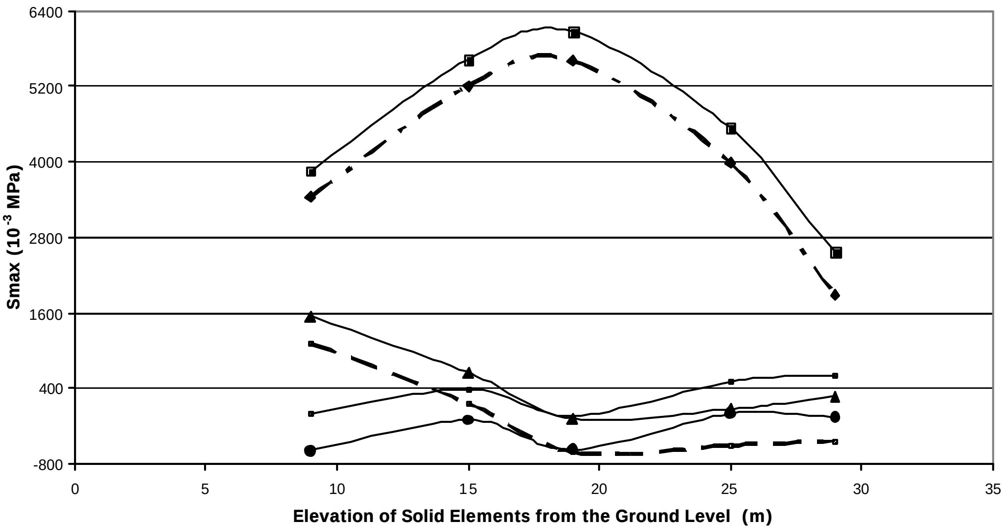


Figure 6.28. Graphical variation of Smax along the minaret at 60° tilting angle

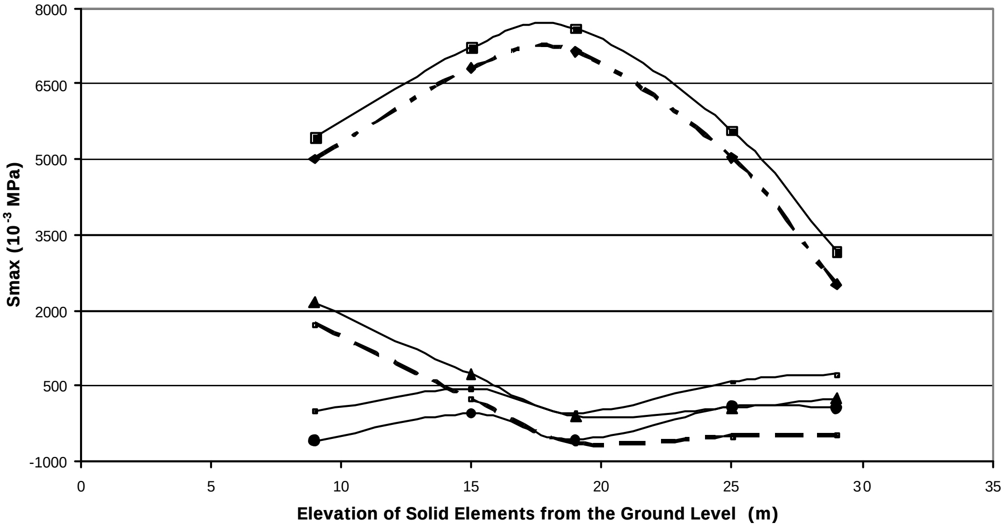


Figure 6.29. Graphical variation of Smax along the minaret at 90° tilting angle

Table 6.9. Legend of Figures 6.27, 6.28 and 6.29

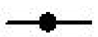
	Smax Value with One Tilting Cable without Prestressed Cables
	Smax Value with One Tilting Cable with Prestressed Cables
	Smax Value with Two Tilting Cables without Prestressed Cables
	Smax Value with Two Tilting Cables with Prestressed Cables
	Smax Value with Three Tilting Cables without Prestressed Cables
	Smax Value with Three Tilting Cables with Prestressed Cables

Table 6.10. The tabular form of the Smin values under all performed conditions along the critical points of the minaret

	Angle	Number of Cables	Prestressing	Elevation of solid elements from the ground level (m.)				
				9	15	19	25	29
Stress Smin	30°	1	X	4.45	5.69	2.76	-29.08	-57.04
			✓	-1111.45	-1092.43	-1062.84	-1134.97	-1191.45
		2	X	-10.13	-13.54	-597.09	11.18	-14.96
			✓	-1194.32	-1117.68	-1345.56	-1077.25	-1144.71
		3	X	-228.91	-2.5	-370.49	8.38	-18.69
			✓	-1366.9	-1098.78	-1278.8	-1082.7	-1153.36
	60°	1	X	37.85	-2.37	-2.2	-62.9	-79.45
			✓	-887.38	-1080.17	-1012.27	-1153.1	-1152.78
		2	X	-6.29	-38.55	-1367.73	-213.17	6.88E-01
			✓	-1107.3	-1125.63	-1997.13	-1068.18	-1098.69
		3	X	-504.56	-4.66	-505.18	15.25	-14.04
			✓	-1399.58	-1083.04	-1294.93	-1069.42	-1130.65
	90°	1	X	61.77	-9.75	-6.42	-79.8	-91.39
			✓	-768.04	-1081.64	-993.31	-1166.42	-1108.93
		2	X	-4.01E-01	-53.35	-1772.8	-473.21	8.26
			✓	-1064.65	-1135.49	-2399.21	-1121.18	-1061.69
		3	X	-645.76	-5.69	-504.59	17.91	-12.39
			✓	-1426.33	-1078.87	-1279.45	-1074.56	-1109.19

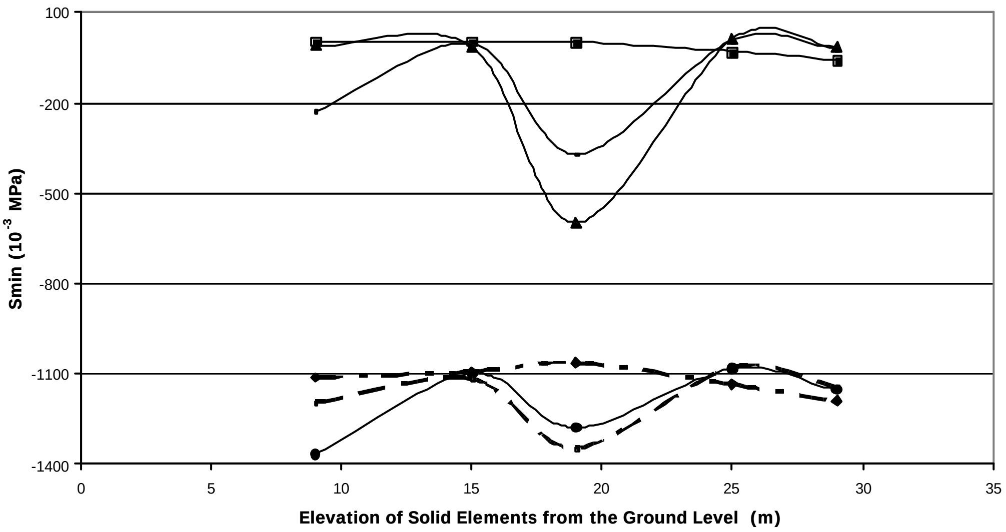


Figure 6.30. Graphical variation of Smin along the minaret at 30° tilting angle

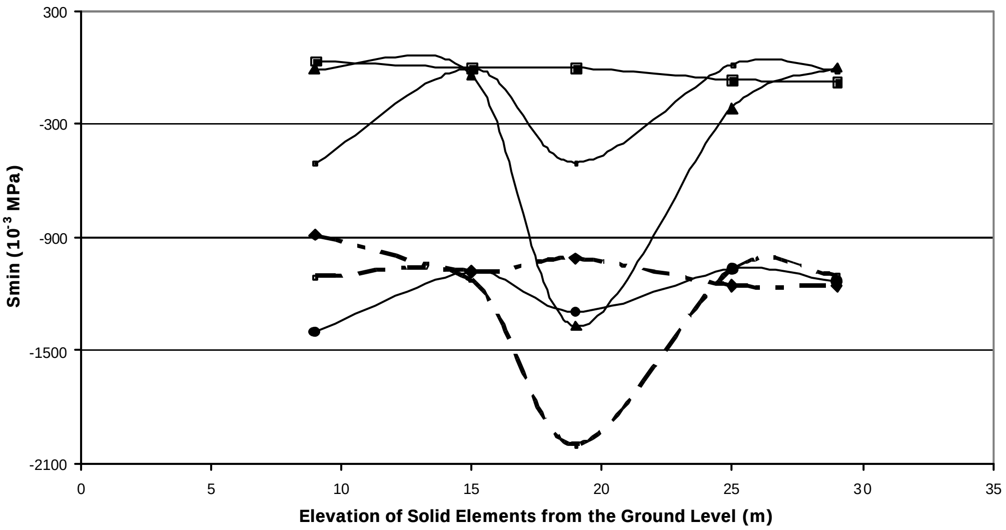


Figure 6.31. Graphical variation of Smin along the minaret at 60° tilting angle

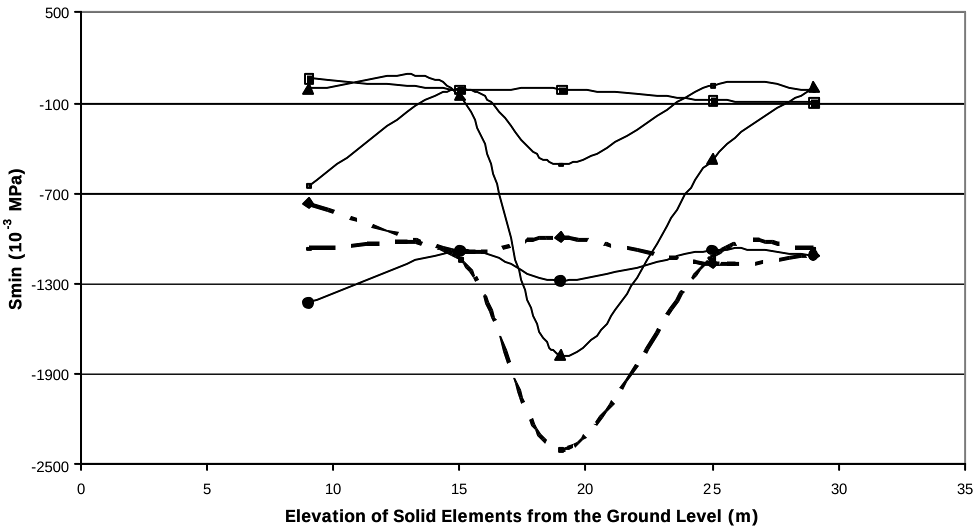


Figure 6.32. Graphical variation of Smin along the minaret at 90° tilting angle

Table 6.11. Legend of Figures 6.30, 6.31 and 6.32

	Smin Value with One Tilting Cable without Prestressed Cables
	Smin Value with One Tilting Cable with Prestressed Cables
	Smin Value with Two Tilting Cables without Prestressed Cables
	Smin Value with Two Tilting Cables with Prestressed Cables
	Smin Value with Three Tilting Cables without Prestressed Cables
	Smin Value with Three Tilting Cables with Prestressed Cables

CHAPTER 7

CONCLUDING REMARKS

7.1. In General

Historical monuments are one of the most important representatives of our cultural heritage. Their role of reflecting and representing the past has a priceless value. Living the present in the light of our past and so being aware of our historical and cultural identity are the major aspects for having more enlightened tomorrows. Therefore, conservation and restoration of historical structures are the key points for the continuity of our history during centuries.

The beauty and diversity of vast number of historical sites and structures make Turkey one of the most impressive countries in respect of the world's cultural heritage. Hasankeyf, which is one of Turkey's medieval sites, has witnessed the passage of many civilizations and so, is seriously important for the history. This exciting site as a whole has a significant role more than the sum of its parts. Actually, Hasankeyf presents the characteristics of an open-air museum city. Its unique natural and architectural creations have become an integrated form over time.

The construction of Ilisu Dam, about which there is still not a definite decision, threatens the city of Hasankeyf. If the project is not cancelled or changed, almost entire settlement will be inundated by the reservoir of Ilisu Dam. The impact of this dam will be long-term and irreversible. Damage in cultural heritage of Hasankeyf would be a significant loss for our history; hence, a solution should be urgently considered to save this unique city. Unfortunately, it seems that there are no ways to save the natural settlement of the region. However, some parts of the architectural heritage can be saved by transporting them to another site. Developing technology offers several methods for the relocation of historical monuments which are explained briefly in Section 5.4.

In this study, it is aimed to develop an innovative methodology to transport a historical masonry monument from its original location to another site. Conserving the originality of the monument is the main objective and the beginning point of this research. In this manner, after completing related investigations, an original methodology is proposed in a general sense and then the methodology is examined on a case, selected in the city of Hasankeyf. For this purpose, a number of structural analyses are carried out in order to comprehend the logic behind this study and to question the effectiveness of the proposed method.

7.2. Conclusions

The major conclusions drawn from this study are summarized as follows:

- Masonry is the oldest and most widely used construction material among historical structures.

- Masonry is a brittle material, which is quite strong in compression, weak in tension and moderately resistant against shear. Therefore, the compressive strength of masonry plays an important role in the plan and so construction process.

- Historical masonry structures that have been mainly designed to overcome compressive stresses instead of tensile stresses should be strengthened in order to prevent the tension failure and collapse of the structure.

- Since it is composed of two different material; masonry units and mortar, masonry has a heterogeneous material characteristic. This results in difficulty for the prediction of the strength and stiffness characteristics of historical masonry structures. In order to overcome this complexity, it is required to use analytical modeling techniques instead of conventional analysis methods for an effective analysis.

- The Finite Element Method is one of the most powerful and suitable numerical methods used for analyzing the historical masonry structures. The idea behind this method is based on the representation of the real structure in a mesh model using finite elements. Modeling the structure in mathematical terms would be helpful to understand and interpret the analyses results more easily and accurately. Furthermore, finite element analyses results are presented in a simpler manner by the help of graphical outputs. This also ensures to compare the results and make a valuable discussion.

- Historical masonry structures are generally suffer from man-made (dams, railways, new settlement, vandalism, etc.) and natural (earthquakes, floods, landslides, etc.) hazards. Especially, the ones causing lateral stresses onto the structure should be studied carefully. The structural vulnerability of old masonry against the tension forces necessitates to find the most effective strengthening technique in order to conserve the historical monuments for a long time.

- In order to make a correct decision on the strengthening technique for an historical masonry structure, a comprehensive evaluation (structural diagnosis and safety assessment) should be done. The investigation of the site and the existing structural condition, material characteristics, load propagation of the structure, etc. should be carefully carried out for such a study. Moreover, the criteria of choosing a particular and an effective solution should be compatible with the techniques and materials used in the original construction of the monument and respectful to its unique conception and historical value.

- Prestressing technique in masonry is considered as the most effective technique used for strengthening historical masonry structures because of the low tensile strength of the masonry material. Prestressing compensates the weakness of the masonry against tension since it increases the compressive strength of the masonry and so reduces the tension stresses occurred in the structure. In addition, the problem of losing the prestressing force as time passes would not cause any trouble for this study since tilting and re-erecting the minaret takes only a limited time.

- Externally placed prestressed cables (vertical and radial) which are used for strengthening of ancient masonry structures, have the advantage of being easily removed and replaced, and so they do not give any destruction to the originality of the structure. By means of aesthetic anxiety, application simplicity and efficient results, strengthening the historical monuments without altering them is particularly essential according to the conservation ethic.

- Instead of steel cables, using FRP (Fibre Reinforced Polymer) material for the confinement of masonry by prestressing is relatively easy and cheap. In addition, FRP wrapping or strips have the advantages of light weight, reversibility, flexibility of use, lower cost, minimum disturbance to the structure and quite high tensile strength. Especially AFRP is very useful in the peripheral binding strengthening technique. Due to these positive contributions, strengthening of historical masonry structures with FRP composites has many priorities considering the conservation application.

- The structural stability of ancient slender structures of a considerably less supporting area, such as towers, minarets, spires, industrial chimneys, is really a big problem. Since most of them are especially vulnerable to the lateral forces, they need to be strengthened with a suitable method urgently.

- Masonry minarets are the most constitutive parts and the very important symbols of our architectural and cultural heritage. Conservation of these massive structures requires a careful-systematic study. The appropriate method should be decided according to the situation and necessary analyses should be performed in order not to lose these invaluable monuments.

This study actually gives a guideline for the conservation of slender historical masonry structures by relocation in a broad sense. Since the primary aim is to conserve the structure without dismantling into pieces, an innovative methodology is first developed as explained in Section 5.5. The main objective of this study is to transport the monument after tilting it up to a horizontal level to the ground without deforming its form.

Tilting the monuments, in fact, is not a new technique; for instance, the obelisks at Luxor are transported in a similar way. However, the main difference of this study comes from the type of the material. While the obelisks are made of single stone blocks which do not have such a tendency of cracking when tilted, the binding pattern of masonry creates a big risk of failure.

In this study, linear elastic analyses of the masonry structure of the Sultan Süleyman Mosque's minaret in Hasankeyf is presented as a case study. The reason of assuming linearly elastic behavior is mainly based on the aim of this study. Due to the fact that an analysis of the overall structure is desired to be performed, a homogeneous material behavior (unique mechanical properties) is assumed. Linear analysis would be the most proper behavior assumption for giving an initial approach to gain an insight into the fundamental aspects of the structural behavior. Moreover, it is the most suitable analysis method which satisfies effectively the requirement of the problem in order to see the validity of the proposed prestressing system.

In order to see the efficiency, availability and soundness of the proposed transportation method, finite element analyses of the minaret model are performed. In the SAP 2000 computer model, 3-D solid elements are used to obtain more reliable and accurate results. The mathematical representation (finite element model) of the selected masonry minaret, related deformed shapes and different stress configurations at 30°, 60° and 90° tilting (inclination) angles are presented taking into account basically two systems:

- Different number of span lengths (obtained by increasing the number of tilting cables)

- The effect of prestressing (obtained after adding radial and vertical prestressing cables to the model)

Visual analyses results, graphical outputs and related tables show that decreasing the span length by increasing the number of tilting cables reduces the tension zone. Similarly, it is concluded that confinement of masonry with prestressed cables strengthen the masonry against tensile stresses and the proposed methodology is certified to be successful and applicable for the relocation of slender masonry structures.

7.3. Recommendations for Further Studies

As stated before, this study primarily defines the starting point for a newly proposed method for transportation of historical slender masonry structures by conserving the unity of the structure. Therefore, instead of investigating the actual behavior of the structure or going into detailed calculations, the applicability and efficiency of the method is studied in general.

For more sophisticated studies which could be done in the future, non-linear static or dynamic analyses regarding the non-linear material characteristics of masonry might be included in order to enhance the model. The proposed method could be also systematically carried out in a more specified way. Every single step would be carefully discussed in more details. In this way, by taking into account all related factors into consideration, almost completely exact results could be reached. Moreover, studying on a sample model in the laboratory conditions would be helpful to observe the validity and efficiency of the proposed methodology in a more real way.

Some historical structures are so weak that the factor of safety reflecting their stability is close to 1. For a detailed study, the structure should also be checked whether it is capable of carrying additional loads coming from the technique used for strengthening, such as prestressing force, in all stages.

The proposed strengthening method could be also evaluated from the economical point of view for an extensive study. Although, historical monuments have priceless value and they should be conserved in any case, making a study regarding the cost analysis would be more realistic and make the system more acceptable in these days.

Finally, more sensitive strengthening methods for conservation of historical masonry monuments could be developed by performing more comprehensive studies.

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