

Assessment of structural components of Iranian heritage building: Persepolis

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Abstract

Analysis of Iranian architecture shows that, in spite of abundance, variety, and complexity of structures, architectural principles, concepts and patterns have been used in different situations in different times. A study of these patterns shows that despite the fact that these were created in different eras of Iranian architecture, they have evolved and been refined through time and possess an identity that is independent of time. The importance of structural design in Iranian traditional architecture can be observed through an emphasis on stability of a structure. In order to harmonize structural and architectural design, an architectural plan should be created within the vicinity of structural feasibility and aligned with its own principles and concepts, and, in a nutshell, both disciplines should sympathize with each other.

Convergence structure, architecture and decoration are defined based on systematic harmony and partial unity, and therefore, Iranian traditional architecture is rooted in both complying with technical principles and applying geometrics and mathematical concepts. In other words, symmetry, equilibrium, and harmony in Iranian architecture are based on thorough mathematical calculations, which are turned into geometry. Creating and applying new construction methods had been commonplace in Iran since millenniums before Christendom and has continued after Islam, and has been the backbone to the development of public buildings, such as mosques, bazaars, schools, etc.

Based on the testimony of researchers, the courage of architecture has gone beyond its limit in the construction of Persepolis for the first time in the history of civilization. Using slim columns in this structure, along with special structural and architectural arrangements for column headers to compensate for long spans between columns, are among the main features of this structure. In addition to that, Iranian architects have beautifully blended decoration and structure, and by using bull-shaped column headers in whose bowl beams get placed, prohibiting displacement of beams, and concurrently harmonizing between form, architectural decoration, and structural functions.

By investigating and analyzing the columns of Persepolis, comparing their sizes and the accuracy in calculation of their sizes using Pi, and comparing the density of the stones that were used in the construction of the stone columns with sizes of similar concrete columns and the required reinforcement, the quality and durability of a similar concrete structure is compared with the stone-made Persepolis.

Keywords: Iranian architecture, technology of construction, harmony of Architecture and Structure, ancient high-tech structure, Persepolis.



1 Introduction

Iran's profound and ancient engineering background during its ancient era is evident, considering what is left from the Achaemenid Persia empire time. The astonishing Persepolis complex (the great construction) in which space and structure have combined to create a unique piece is significant in several aspects; firstly, the idea behind the stability of the structure is the fact that a mixture of stone wood and adobe is used while considering the features of each material, moreover, the precise size of the structural components is the result of the builders' technical knowledge of the material features for carrying load and critical structural points, the use of weight for stabilization of the structure, creating balance through connections based on the material's nature, etc. According to this, Iranian architects were aware of the compressive stress of adobe and stone, and used these materials in the vertical elements, such as walls and columns, and wood, due to its useful tensile, compressive and bending stresses has been used in making horizontal load carrying elements like posts.

The use of the right material, as well as applying new construction methods, have turned Persepolis into a structure which has maintained its magnificence through the centuries. Today, the new materials which have improved since the industrial revolution owing to the advancement in technology create new space features. For instance, by using compressive and tensile strength over reinforced concrete, the size of columns and their spans have changed and they create spectacular space. However, architecture is not achieved only by the construction materials and various functions. Architecture is the changing spirit of each historical period that influences the social life, religion, science and art of that period. The new architecture was not created when there were metal and concrete buildings, but these innovations appeared when a new spirit required their appearance. Calculating the size of the columns in Persepolis by using materials such as reinforced concrete is indicative of this point at which the creative mind of the Iranian architects, who have used the materials in the best possible way, have brought lots of innovative achievements to improve the structural systems.

2 Architecture

Persepolis is a collection of magnificent palaces that are built near Parse, which has been called Persepolis by the Greeks. The main plan of Persepolis goes back to the first Darius in 518 B.C. To build this, first they had to prepare a long platform with a width of 135000 m² and a height of 8 to 18 meters from the ground. To do that, a vast area of a rocky foot of the mountain was made flat to the desired height and filled the hollow parts by arranging huge stones, which were brought to the site from mines nearby. From the beginning, large gutters were designed to run-off surface water. To join the stone pieces used, no mortar was applied, but surprisingly the precision of the surface carving is so high that you can hardly see a gap between the attached pieces. To join the stones, some



holes were designed in the pieces and metal pins with lead-covered surface were used.

In order to protect the building against the enemy's possible attack, in the south and west platform, flat walls with a height of 7 meters were built. To build these walls, first the foundation of the adobe wall, which consisted of three parallel walls with a width of 19 meters altogether, were made and then they were covered with mud and sand to make a flat surface. Next, a wall with a height of 7 meters was made of adobe of sizes 33x13x13 centimetres on the foundation.

2.1 Apadana Palace

Apadana means columned hall. This palace was designed in appropriate space to entertain guests and representatives of other countries, as well as holding national celebrations like Nowrouz and Mehregan. Great attention has been paid to the construction of this formal palace. The palace consists of a main hall and three terraces, Eastern and Northern stairways and columns, which have been delicately carved and display a unique precision (which is rarely seen). From the exterior, each dimension is 250 feet and each central room's dimension is 195 feet. The three widths of each of the terraces are about 65 feet with 36 narrow tall columns that tapered towards the end and held the building. Each column was 7 feet wide and 60 feet high. Each column had 36 or 48 carvings. On the top of the columns some capitals were designed, such as lions and imaginary animals with an eagle's nose that were said to be unpopular at the time and were left incomplete. Three-meter high capitals, which were like two cows sitting back to back, were coloured by a wide variety of colours. Inside Apadana Palace there was a clump of columns among which adobe walls were hardly seen. Apadana is a large public hall with a capacity of 10000 people.

2.2 One Hundred Columns Palace

This palace is located in the east of Apadana yard, which is called the 100-columns palace or the bed hall. This 4690 m² palace was the biggest indoor hall in the ancient world, which had 100 columns, ten columns in ten rows and two gates on each side.

2.3 Mirror Palace

This palace was specifically for winter and was built on the mountain rocks higher than Persepolis, and compared to Apadana had a more beautiful outlook. Mirror Palace opens to the sunrise in the east wing, is considered the main and central hall and has 12 columns, six in two rows and a gutter to lead the water away, just like Apadana.

Also there are some more parts which are called The Gate of Nations, Hadish Palace, The Treasury, Sewerage, etc.



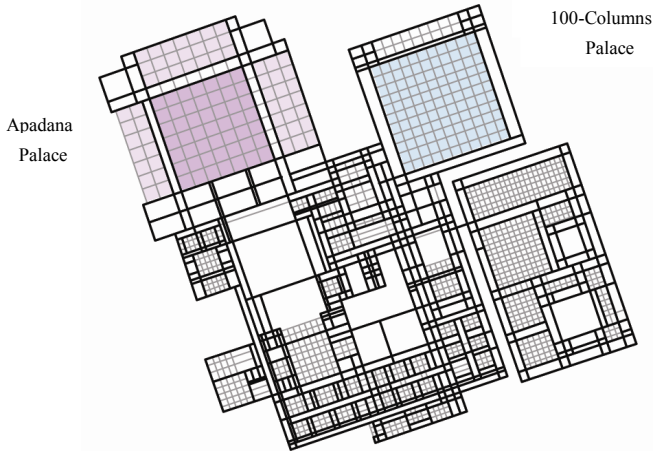


Figure 1: A pure geometry, which is based on simple geometric shapes that head the plans. Direct lines connect the columns and develop the major axes of the building.

It is noticeable to say that every building in Persepolis, except Apadana Palace, which is introverted, has a specific look inside the building. The common point in such buildings is systems that prevent warming inside weather, stone skeletons, wooden ceilings and adobe walls, which are good thermal breaks to prevent cold weather entering in cold seasons. This architecture is a mixture of Iranian, Babylon, Assyrian, Egyptian and other types of Greek and Urartu styles, which are mixed with Iranian innovations and led to an independent style. Persia, with setting up these huge buildings, tried to show the magnificence of their powerful empire to the world.

3 Structure

Setting up a structure is not a simple task, but it means solving the stability problem regarding available materials and their functional limits and their space characteristics. Iranian architects paid specific attention to structure and did not regard that separately from beauty. They were trying to innovate new methods of construction to provide stability of buildings.

In Persepolis, the method of stabilizing the structure is a combination of using available materials, such as stone, wood and adobe, regarding their behavioural characteristics and their role in structural systems regarding dimensions, technical knowledge of critical structural points, such as capitals, proper use of dead load (weight) to achieve stability and balance of structure due to resistance against applied loads. Therefore, they used northern Iranian local architecture, which uses a timber skeleton and central Iranian's architecture to cover the building, and more use of local materials simultaneously. The awareness and experience of builders from compressive strength of adobe and

stone resulted in the use of these materials in vertical elements, such as walls and columns and were used in the construction of load carrying beams from wood, which has better tensile and bending strength.

Precision and delicacy in construction of the conic columns of Persepolis is so high that researchers believe that they had been aware of π ratio and the calculation of height and method of construction of columns and the pressure that they bear and load distributing in columns sections is a result of this discovery [13]. The comparison of vertical and horizontal dimensions shows some specific relations between the columns' height and their sectional sizes. The result of dimensioning different parts shows that they had measuring tools with precision of up to a few millimetres. Also, there are some signs that might have been used to show the axes of columns and walls. As said, apart from using specific measuring units in the plan, columns and walls are designed as a specific module, in addition to numerical proportions and metric relations governing the complex's elements.

3.1 Design process; structure and relation with other elements

To better understanding the structural role in Persepolis, we take into account the structure in relation with material, function, form and the geography of the site as the most important influencing factors.

3.1.1 Structure and materials

Structural form is highly influenced from the material specifications, the physical characteristics of the materials, the type of internal forces that they bear and, as a determining result, the type of structural element [8]. Thus choosing the material usually happens before choosing structural systems. This choosing is relative to how these materials should be set up more than everything and is evaluated on bias of different properties, such as lightness, heaviness, hardness and elasticity.

The abundance of specific materials in one region has great effects in usage of those materials and as a result plenty of usage of specific structural systems in that region. In Persepolis, they used stones, wood, clay and bricks in the buildings. As described, the methods of setting up structures in northern Iran and the awareness of architects of compressive, tensile and bending strength of wood resulted in usage of these materials in beams and some columns. From existing grave-stones, which are about the construction procedure of the building, we conclude that they used Lebanese Cedar wood to satisfy the required strength of the wood. This wood has a specific weight of 0.46 [11] and before that, they had used wood to cover spans of 2.5 to 3.5 meters in length, but in Persepolis, the ambition of architecture overcome that era and led to spans of more than 6.5 meters in the 100 columns hall and also 9 meters in the Apadana hall. Weakness of wood in bearing loads (which are vertical to fibre directions) lead to low shear capacity, especially in cases where there are bending loads on wooden elements (such as load bearing beams); also the weakness of wood in bearing concentrated stresses, which happens in mechanical connections, increases the need to design detailed connections.



Stones that have been used in platforms and Persepolis columns are white, grey and black limestone, which had been extracted from nearby mines. These stones, which are from calcium (CaCO_3), are from the most important calcite stones. They are crystallized and with a plasticity degree equal to 3 (soft stones). These stones have the high capacity of polishing. Based on experiments, the density of the stones is 2.57 gr/Cm^3 [12]. In other words, each stone weighs about 6.2 ton. Every capital of Apadana Palace is about 12.5 m^3 or 32 ton (volume and weight of engraved capitals are equal to half of this) and the weight of columns reaches 16 ton.

In the construction of doors and windows they used engraved stones, although the form of lintels has been extracted from Egyptian architecture, against Egyptian architecture they had not consisted of usual shapes. They had engraved the stones artistically and used that as a decorative element [9].

The outer layer of walls consisted of stone and the inner parts are made from glazed bricks. In the construction of walls and the covering of ceilings, they used adobe. Adobe consists of clay as an element that provides adhesiveness after drying and some other combinational elements (depending on which mine was used), which has a role in reducing the thickness of the ceiling, such as sand, gravel, etc. Clay bricks, more than covering spans, work as an insulator. The main problem in construction is shrinkage of clay after drying (equal to 10 percent of initial length); clay does not have enough strength against deformation and movement of buildings, thus sometimes they used brick, which is more expensive than adobe, having more strength [2]. They found a kiln near Persepolis, which is said to be used to kiln bricks as there was no suitable clay near Persepolis. They carried suitable clay from Isfahan.

3.1.2 Structure and function

Architecture is not an aesthetic shape but it is a dynamic fact that can be proved only by human activity. In fact, function is the effect of architectural space on human kind. The main aim of the structure is to set up a stable skeleton that could satisfy the functional needs of building and space ambitions. In fact the structure is in close relation with the building's function. In other words, the needs always stimulate engineers to innovate and use new structural systems. As mentioned before, Persepolis Palace was a palace for religious functions and ceremonies, The Persian empire wanted to show their power to the world by its greatness. Thus they needed a vast and high hall, which can welcome more than 10,000 people to show their deep willingness to greatness. Structural systems that had been used up to that time could provide spans of up to 3.5 meters. Therefore, an architect should have had some innovations to build his new forms, to overcome their functional needs and because of lack of knowledge and technology to create materials, he tried to improve the existing material specification and some innovations in structural systems and he created a masterpiece which is called Persepolis.

3.1.3 Structure and form

Form is a pursuit of multidimensional living, what an architect does more than everything is an answer to humans' nature. In fact, every constructed space could

not be realized if it did not have any idea to have any adaptation with human living. Form is not the purpose, but only a reason to describe function. We can conclude the relation between form and structure in relation with the structural system and form of the building as a final result [1].

On the basis of this relation, we can predict different structural systems for various forms of building. In this condition, we should not get it wrong by looking at outer decorative parts of the building. In Persepolis, the architecture form is full of beauty, a pure geometry which is based on simple geometric shapes that head the plans, views and perspectives. Direct lines connect the columns and develop major axes of the building; we also have their lines in the third dimension, and in surrounding walls. Iranian architecture relies on purity and simplicity of buildings and omitting on every exaggerated decoration leads to a combination of structure and form that we cannot separate from each other, which is clearly seen in the capitals of Apadana Palace and the 100-Columns Palace. Thus the pure structure heads the overall building. Architecture designs the connections details artistically such that there is no need to hide the structure in thick walls. Architecture and structure combined together make great halls, which are based on stone trees and which should be admired by every visitor.

3.1.4 Structure and natural geography

The structural system is in close relation with natural factors, especially weather. In Iran, with diverse natural specifications and different weather, each part has its own special architecture. As described, in the north of Iran with humid and rainy weather wooden material is used, in the central mountainous part of Iran stone and clay materials are used and in some parts a combination of two materials have been used. In Persepolis, as they regarded load carrying in large spans and insulation of building against cold weather in winter and hot weather in summer, both construction methods were applied. The compressive tensile and bending stress of wood made it suitable to use for load carrying in large spans and certain capitals, and some specifications of clay material, such as being an insulator, made it appropriate for covering roofs and the central pore of walls, which are covered outside by stones and inside by glazed bricks [9].

4 Stability system of beam covering

In this system, applied force (which is usually weight) is transferred with elements such as columns. This force adds to the weight of vertical elements (columns) and transfers to supporting parts. As a point of view in this system, there is not enough rigidity in the connection between beams and columns, the deformation of the beam does not transfer to the column completely. Although they used this system in Persepolis, we can see an amazing innovation to improve quality and mechanical specifications of materials and to increase the efficiency of the structural system. As described, until the construction of Persepolis, using wood to cover spans of up to 3.5 meter was usual. Iranian architects used different methods to increase the length of spans such as:



- Using beams in both perpendicular dimensions. Persepolis's architects used this method to prevent exerting extreme loads in beams of unique directions. Thus they used a special connection at each end of every beam to have a uniform distribution of load.
- Designing the capitals of columns. As they used ropes to assemble two beams together in local Iranian architecture and then used wood on them as small pillow [6], this kind of connection has been modified to connections in Persepolis. It seems that the idea of the capital of Persepolis came from Iranian local architecture. The capitals of the top parts of the Persepolis columns are important from some aspects:

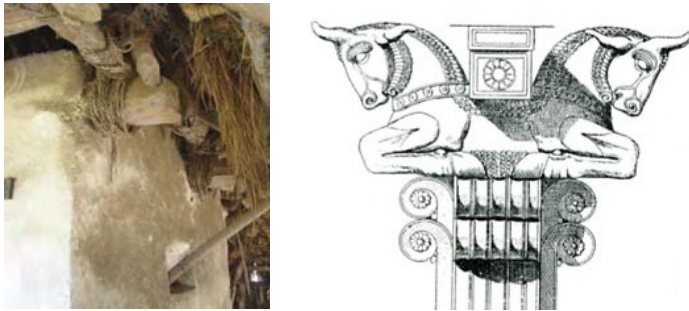


Figure 2: The capital of Persepolis came from Iranian local architecture.

- By using capitals with 3.5 meter width, they reduced the distance between the load exertion points. For example, in cases that we have 4.30 meter distance between two columns, we can reduce it to 3.20 meter with capitals of animal shape.
- Beams are placed in the depth of the central part of every capital to prevent buoyancy.
- The low shear strength of wood capitals increase the area of connecting between beams and columns and prevents the concentration of loads in one point and makes a better distribution for applying uniform loads.
- There are some rooms in Persepolis that have two columns inside and are connected to wooden beams together with hemp to connect them to columns, thereby increasing their capacity to carry loads.
- Connections of stones in different parts of a building, such as columns, are designed precisely.
- Thus they made some holes in stones that they used metal hangs in and covered them with lead and increased their capacity to carry loads. The thickness and dimensions of walls are determined under the influence of applied loads and type of arrangement of pieces.
- Finally they created a uniform and strong combination. In the construction of door and window lintels they used sculptured stones which are a combination of structural and decorative rules.

5 Persepolis: a high-tech building in an ancient time

Architecture is not the achievement of construction materials and various functions and social conditions. It is the changing spirit of its time. New achievement of architecture is not a result of new materials made by technological progress, but is the result of the human need for new spaces; then, a new spirit makes their existence necessary. All of modern architectural progress is a kind of growth in which many historical limitations and restrictions have been replaced by discovery, awareness and a tendency towards developments. General principles of modern architecture are based on purity of building, using basic geometrical shapes in designing buildings and eliminating redundant decorations [4]. Viollet-le-Duc (1814-1879), a French architect who was an important theorist in modern architecture, regards the structure of gothic building dynamics and believed that the relation between structure and function is an underlying principle in renaissance architecture and should be a guide as an important principle for modern artists [5].

In high-tech architecture, a good follower of modern architecture is a result of the final decades of the 20th century. High-tech methods were based on the basic principles of modern architecture, especially in showing the construction procedure, displaying structure inside and outside the structure, displaying structure as a decoration while creating innovative forms and designing good details, releasing the building from unnecessary decorations and detaching mechanical parts from other parts. In fact, the main purpose of high-tech architecture is clarity of the building and displaying structure the same as gothic architecture. However, researchers know Persian architecture with its high columns to be a beginning for a different description of architecture, which later reached the sky searching tendency of humans to evolution. Is not Persepolis with its amazing features really the pioneer of the other buildings of its time in using mechanical features of materials and setting up a new system to structurally create vast and high spaces? Is not high-tech's major achievement in reasonable relation and active interaction of materials, structure and architecture? Maybe in the time of creating Persepolis, they were not ready enough to create modern materials with better specifications than masonry materials, but the architects overcame this limitation and designed halls with a capacity of thousands of people and a suggested sense of magnificence and greatness of building. An improvement of materials specification regarding exact mechanical specifications and their features after loading and combining with different construction methods to conclude best principles were used to achieve maximum spans and column height. The high-tech ideas that are in Persepolis, more than every other part, is in minimal thinking that governs the building and omits every unnecessary decoration and displays structure in the most magnificent, simple and powerful way, which is the main element of that architecture. Persepolis is really a modern and high-tech palace in its time.

Iranian architects paid special attention through construction methods and did not regard that separate from beauty. Therefore, making a beautiful structure omitted the need to cover the structure in wide walls and showed the beauty and



power that was in structural elements built with emphasis on stability and satisfying the sense of security. Therefore, the space's quality and structure of building are bonded together with omitting columns, not only the structure destroys, but also the spaces specification is disrupted, because the mutual relation of space's nature and construction system and materials is destroyed completely. This mixture of space and structure is combined in designing some parts, such as connections of beams to columns with decorations and precision and delicacy, which is used in designing, displays the details of a building as a sculpture in a building. In addition, in the construction of Persepolis, architects designed some dimensions to cover the palace experimentally, which were based on stability principles. Using bricks with fixed dimensions in walls, cutting and polishing stone pieces of columns in extract site and engraving some holes to put some steel pins to connect pieces together and installing these pieces on site, the balance of dimensions in plan and sections of Persepolis can be regarded as prefabrication of building. Therefore, many principles of high-tech, such as displaying the structure inside and outside of the building, avoiding unnecessary decorations, showing the construction process and load transfer from beam to column and finally to foundation, the exact design of structural details and showing the structure as beautiful, prefabrications and innovation in construction methods with available materials, all are used in the construction of Persepolis.

The architecture of Persepolis is based on space values, based on geometric shapes and free configuration, frequently without symmetry of plan and view, the appearance of architecture and decoration in structure and display of elements and structural details as general characteristic of space is stable and lasting because of the complete adaptation of construction methods on the function and homogeneity of structure.



Figure 3: To join the stones, some holes were designed in the pieces and metal pins with a lead-covered surface were used.

5.1 Comparison between columns and foundation of Apadana hall and 100 columns with similar reinforced columns

Regarding the spans, density of wood and clays that are used in Apadana Palace's roof covering and Persepolis, in modelling the structure we conclude that they had used the maximum capacity of material in construction of that era.

They needed a column of 1.25 m diameter for Apadana Palace instead of 1.55 m stone columns and foundation of 5x5x0.7 m and for the 100-columns palace they need it with 1.05 meter instead of 1.25 meter stone columns. If this masterpiece has to be built in the modern era, using new materials, we would not have a salient change in space specification as column dimensions are the same. Even though we should consider that in the case of not having surrounding load carrying walls and the ability to use glass with large dimensions, we could have better spaces and better connections of inside and outside of the building. Utilizing the maximum capacity of the chosen materials, the accurate calculation of dimensions and observing thickness to span ratios or columns diameters, has caused the stability of Persepolis up to now. Hence, in spite of the insistence of Iranian architecture to use local materials in construction, they used some woods for beams from Lebanon and some soils for adobe from Isfahan; this accuracy and obsession for choosing material shows its importance more clearly.

6 Conclusion

The main idea of the construction of Persepolis as a palace is the existence of halls with high columns; therefore, the architect needed some innovations to gain his ideas of space and function. Because of not having modern materials, they tried to improve the characteristics of existed materials and innovation in structural systems. Therefore, providing functional needs in Persepolis led to creating a magnificent structure that was bonded with architecture. According to researchers, in ideas based on the creation of a new method in the world's architecture that were inspired by the idea of columns that are looking and stretching towards sky and unique space specification of halls with column in this buildings, Persepolis is the pioneer of the other buildings in that era in using the best technologies available in that time. The Persepolis complex is a building that is ruled by the tendency towards progress and freedom of restrictions, using the best specification of materials and improving them (due to technical knowledge of their behaviour under loads), relying on principal geometric forms, displaying the structure, omitting decoration, prefabrication, innovation in construction methods and covering spans with precise design and details, stability of the space specification on structural system and therefore can be regarded as a high-tech building in its era. Comparing the construction facilities of existed materials at the time of the construction of Persepolis with modern materials, such as reinforced concrete, insisting on the structural innovations of Persepolis and the methods of using materials in that complex in situ and clarifying that if such a building with space ideas and reasonable discipline was built with modern materials, there would not be a salient change in space specification as column dimensions are the same. Thus we can assert that the durability of a structural masterpiece is not only the reason for progress in construction methods, but during history, the buildings that were made by using the least equipment of that specific era were solid and stable due to their innovative methods of construction and insistence on creating dramatic spaces.



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