STRUCTURAL WISDOM OF ARCHITECTURAL HERITAGE

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SUMMARY

Interpretation of structural functions and principles is gaining greater interest due to the prevention of architectural heritage. Analytical studies on the structural behaviour of historical structures present appropriate solutions in the assessment of structural performance. The Finite Element Method is the most suitable tool with its graphical outputs even for non-engineer colleagues.

1. INTRODUCTION

Magnificent structures have been built by our ancestors, as part of our historic heritage. Conservation and restoration of these historic structures is retaining increased importance while welcoming a new millennium. The architect and engineer take great pleasure observing the beauty, but is compelled to ask the puzzling question: Did our ancestors know what they were doing when constructing these structures? Or, did they simply use gross intuition, full of flows, which inevitably let to failures? In other words, did our ancestors have structural wisdom?

The answer to the above questions has excited many and historic structures have been intensively studied for load carrying efficiency. However, historic structures have very complex load carrying behaviour due to the massive and continuous interaction of domes, vaults, arches and pillars. The Finite Element Analysis Technique has opened up new possibilities for the analysis of such complex historic structures.

Three-dimensional structure can be modelled by using suitable finite elements to reflect the "close to reality" load transfer mechanism under different loading conditions: gravity loads, wind, earthquake and support conditions.

2. CHARACTERISTICS OF HISTORICAL MASONRY STRUCTURES

2.1 General Characteristics

Use of masonry in structures spans a period of about ten thousand years. First examples of masonry structures were mud-brick dwellings. Structurally, they were not very durable and were defined by simple forms, with timber tie beams span between the walls.

When the need for larger inner spaces arose, mostly for religious places, stone usually becomes the masonry unit used. The most successful examples of stone masonry structures of that period are Egyptian Pyramids. Even though they have no large spaces, they have a perfect structural form against environmental effects. This perfect structure is formed by putting such varying masses in natural angles related to the shapes of the individual blocks [1,2].

From the beginning of the Roman period to the end of the 18^{th} Century, because of the need for aesthetics and slender components and members, fired bricks were used as masonry units. The great contribution of the Byzantine and the Seldjuq to brick masonry was the development of the arch, the vault and the dome.

The dome was an essential structural component for large spanned masonry structures. The Pantheon of Rome is one of the first examples of this amazing structural form of masonry. In Anatolia, Hagia Sophia and all other Seldjuq and Ottoman masonry masterpieces reached the limits of brick and stone masonry art with their characteristic structural forms. In the Ottoman Empire, Sinan's Selimiye Mosque reached to a climax with a dome of 31 meters in diameter.

2.2 Structural Forms and Components

The structural form of buildings can simply be defined as the geometrical configuration of the space involved by the structure. However, within a similar external visible geometry, different structural actions could be responded by structure under the same kind of loads. Various capacities of different materials, internal detailing of cross-sections, the manner and sequence of construction and the dimensions of the structure can cause different structural actions in similar overall geometry of the structures. Therefore, the geometrical configuration is only one aspect of the structural form.

In determining structural actions of historical masonry structures, although external geometric configuration is the main factor of visualization of structural forms, some decorative non-structural extensions cause difficulties in determining the actual structural actions.

The main loads to be resisted by most historical masonry structures are their own dead weights and those imposed by wind and earthquake. The structural resistance depends primarily on two factors: the geometry of the structure and the characteristic strength and stiffness of the material used.

On the other hand, self-weight of structural and non-structural components varies with the size of the element. Larger size results in heavier elements that contradict the usual load-stiffness and load-strength ratios. Therefore, a unique and certain classification of historical structures in relation to structural actions is not easy.

There are several possibilities of classification schemes based on different features of historical masonry structures. As mentioned above, material type, strength and stiffness of cross-section and the construction techniques are major properties of structural form. Considering all these factors, structural form can be classified by elementary structural components and elements in a geometrical sense [3].

2.3 Behavior of Structural Elements

Major forms of masonry structures are arches, vaults, domes and walls. They reflect certain structural factors, through their characteristic thickness. Their thickness was directed by the coarseness of their constituent materials: stone, brick and mortar joints. Their inability to resist tensile stresses required widening of their cross-sections so that compression would reduce the effect of potential bending. Substantial thickness was often intuitively felt necessary to prevent buckling.

Arches are the structural elements that span a horizontal distance carrying its own weight and other loads totally or mainly by internal compression. The most important characteristic of the arch is that as a part of its primary action, it does always thrust outwards on its abutments as well as weighing down vertically on them. The thrust can be contained by an effective tie between supports. In the absence of such a tie, it is almost certain to spread to some extent unless its supports are being forced inwards by stronger opposing thrust.

The vault is a structural system that distributes loads by arch action through a single curved plane to continuous supports. The stresses within the vault are primarily compressive. It can be considered as a curved bearing wall enclosing a space. Lateral stability is developed within the plane of the vault, due to its continuous form.

The dome is the structural form, which distributes loads to supports through a doubly curved plane. It is a continuous geometric form, without corners or perpendicular changes in surface direction. It encloses the maximum volume with a minimum of surface area. The dome must be designed to resist compressive stresses along the meridian lines and to resolve circumferential tensile forces in the lower portion of hemispherical domes. The compressive forces within the dome are similar to those developed within an arch and must be resisted in similar manner. The dome will spread at its base if it is not restrained by either mass or ties. The thrust at the base of the dome is continuous and traditional methods of obtaining stability rely upon massive buttressing. The dome is an extremely stable structural form and resists lateral deformation through its geometry.

3. FINITE ELEMENT ANALYSIS OF HISTORICAL STRUCTURES

Structural analysis of historical structures is mostly performed using Finite Element Analysis. The analysis begins by generating a finite element model of entire structure or structural element. This is called as the discretization of the structure. During the discretization, the structure is divided into elements that are critical in establishing the accuracy of the solution. The choice of the number, size and type of elements is a matter of judgment. All these modeling procedures, considering the geometry of the structure, joint restraints and the loading are called as a whole the analytical model of the structural analysis.

The purpose of analytical modeling is to try to represent the actual behavior of a structural component or entire structure in mathematical terms. The actual behavior of the structure is usually highly complex and many simplifications have to be made in order to model it. To achieve a refined model, material behavior has to be simulated properly, supports and connection of elements have to be modeled and the loading has to be defined [4,5].

The basis of the Finite Element Method is the representation of a structure as a finite number of lines and two-dimensional or three-dimensional subdivisions. These subdivisions are called finite elements. These elements are interconnected at joints that are called nodes. The external loading is transformed into equivalent forces applied to nodes and the behavior of the elements is prescribed by relating their response to that of the nodes.

4. APPLICATION OF THE FINITE ELEMENT ANALYSIS IN ASSESSMENT OF STRUCTURAL BEHAVIOUR

Almost in all engineering fields, Finite Element Analysis (FEA) plays an important role in researches and design. It provides precise solutions and accomplishes cheaper and quicker results as compared to large laboratory experiments. FEA has already become a regular tool in structural engineering in recent years. FAE can be used to examine the entire structure constructed of any material of known mechanical properties. It also explores overall performance of the total structure or individual elements. Within this framework, the strongest benefit of FEA appears in the analysis of historic structures. The graphical outputs of FEA contribute to the ability of interpretation of result and also provide great intuition even for non-technically educated colleagues. Therefore, architects, architectural historians, restoration specialists and archaeologists can also involve in analysis of structural problems of historical buildings.

Figure 1 illustrates investigation of structural problems, which occurred due to an earthquake, in one of the towers of Diyarbakir City Walls by FEA. Graphical outputs of FEA shows an explicit visualisation of the behaviour of a very complex structural form under a simulated earthquake.

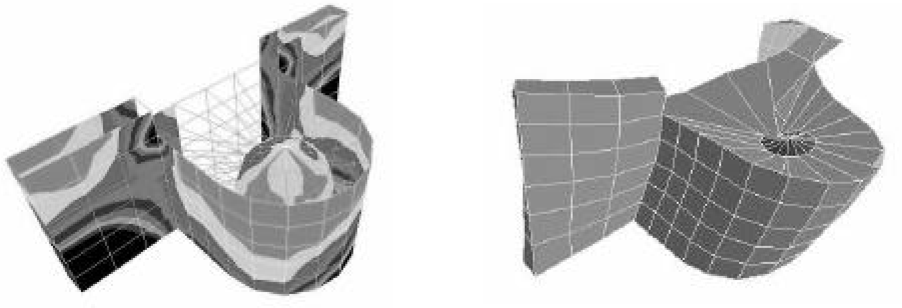

Figure 1: Finite element analysis of Diyarbakir City walls

Another example of FEA application is the investigation of the structural behaviour and damage assessment for Evdir Han Caravanserai in Antalya (Figure 2). Heavily damaged structure is modelled by using frame and general shell elements according to its original restituted form (Figure 3). A series of analysis is carried out for all possible external disturbances and load conditions. Results of analyses refer to remedies in the decision of rehabilitation and restoration. However, this rough model is not adequate for structural repair works; a more refined model is still needed (Figure 4).

Figure 2: Evdir Han Caravanserai, Antalya

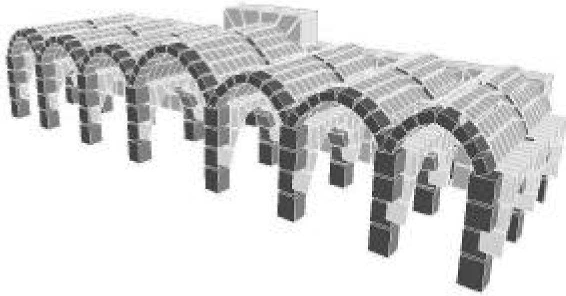

Figure 3: Finite element model of Evdir Han Caravanserai

Figure 4: Graphical output showing stress distribution

5. CONCLUSIONS

Structural functions and principles are one of the essential components of preservation of architectural heritage. Empirical approaches and structural intuition constitute a fundamental basis for the interpretation of load transmission mechanism of historical structures since the time of Masters who built them. However, today's advanced computer utilities provide new horizons for the definition structural functions of historical structure. Even though the illustrated results cannot be considered as fully realistic, deformed shape, graphical stresses and force distributions expose considerably true structural behaviour of the structure. Superior graphical input and output utilities enable the non-structural engineer to involve in the structural denotation of architectural heritage.

6. REFERENCES

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