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Architect – Structural Engineer Collaboration In Sustainable Structural System Design

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ABSTRACT

This paper explores ways of collaboration between architects and structural engineers in the design of sustainable structural systems. Areas of collaboration are explored in terms of seismic design of new structures and rehabilitation of existing structures. Multidisciplinary design teams and an integrated design approach are critical to the process of sustainable building construction. The required group-work skills should be acquired by architects and engineers during their professional education. As a result, this paper also investigates ways in which the structural design education of architects and structural engineers can be redesigned to make their future professional collaboration more harmonious.

Key Words: *Sustainability, Sustainable Structures, Architectural Education, Finite Element Analysis, Seismic Design, Rehabilitation of Structures.*

1. INTRODUCTION

In 1987, Brundtland Commission, formally known as the United Nations World Commission on Environment and Development, published their report entitled "Our Common Future", in which sustainable development was defined as: [1]

"...the development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Human activities as a race inevitably consume energy and raw material. Most of this energy and material is provided from finite, in other words, non-renewable resources. These resources are made available by the eco-system provided by our planet. In addition, our activities produce waste in various forms, which in turn is released back into the environment, disrupting the functioning of the eco-system and decreasing its ability to provide more resources. The delicate eco-system of our planet cannot continue to function forever under the self destructive influence of humanity. Sustainability requires a harmonious combination of social, environmental and economic factors. Combining these factors together at a level that can have a positive impact on global environment can only be possible by a worldwide political commitment. [2]

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As a general reputation in the public, the detrimental environmental impact of human activities is most commonly associated with "*Global Warming*". This phenomenon itself is correlated with the amount of carbon emissions into the environment. In contrast with popular belief, it is estimated that 40-50% of this carbon emissions is caused by the buildings while only 25% is caused by transportation and another 25% by industrial activities. Among the vast amount of energy depleted by the buildings only 5% is consumed by the construction processes while more than 45% is consumed by management, repair and maintenance activities. This situation reveals that building industry is going to play a pivotal role in the continuing efforts to decrease the total energy consumption or at least shift some of this consumption from non-renewable resources to renewable ones. [3]

2. "*The Design Team*" INSTEAD OF "*The Designer*" FOR A SUSTAINABLE STRUCTURE

There was a time when the "master builder" was responsible for every aspect of creating a new building. The writings of the Roman architect Vitruvius and the studies on the Ottoman Imperial architect Sinan clearly demonstrate that the builder of those times had to assume the roles of architect, structural engineer, mechanical engineer as well as the city planner and the contractor. However, those were times when scientific knowledge and available technology were limited and could be within the grasp of a single person. Over the centuries, the developments in science and technology exponentially multiplied the amount of knowledge necessary for the design and construction of a building. As Spyros Raftopoulos states: [4]

"… The developments in the building industry, especially in our recent times, demanded a specialization of the various disciplines. These were also enhanced by the complexity of the market demands. This complexity was very high especially in the engineering field, with all the additional prerequisites of the seismic calculations, the new technological developments and the introduction of computers. This development naturally increased the exclusion of architects from the engineering part of their job, a fact which was evident even before that. Similarly the complexity and the increasing demand of designed buildings, gradually excluded engineers from the architectural field, especially in relation to larger projects."

This specialization of disciplines brought along some advantages and disadvantages. The main disadvantage was the alienation of disciplines. In time, some architects and engineers developed a misconception that their responsibilities mutually excluded each other's concerns and sensibilities. For architects, structure was a technical issue that had to be solved by engineers who had no idea about architectural design. Engineers, on the other hand, have begun to see architects as mere artists whose, demands were in contradiction with the principles of effective and economic structural design. This alienation of professions and the consequent mutual disdain of architects and engineers may perhaps be best characterized by Le Corbusier: [5]

"Engineers are healthy and virile, active and moral, happy and useful. Architects are disenchanted or unemployed, whafflers, or morose. The reason is that soon they will not have anything left to do. We don't have any more money just to maintain historical memories. We need so cleanse ourselves."

On the other hand, the greatest advantage of specialization was that, as a result of advanced technology, materials and knowledge, it was now possible to design and construct stronger, complicated, efficient and more economic structural systems. Another advantage was the introduction of team collaboration. Besides the obvious economy of time, the design of the building was now realized with the participation of a larger scope of specialists who can support each other's efforts by contributing with their knowledge; and serving as an error-check mechanism, reducing the possibility of man-made mistakes, which would otherwise be the responsibility of one person. [6]

Growing concerns over the sustainability of buildings makes team work an absolute necessity during not only the construction but also through the entire life cycle of a structure. The design team in question here does not consist of just an architect and engineers from relevant branches of engineering anymore. The social, economic and environmental aspects of sustainability require group work on a much larger scale. (Table 1) The network of collaboration includes "*partners*" from pre-construction phase as well as construction and post-construction phases. [3]

Table 1. Design Team in "Sustainable" Construction.

PROPERTY OWNER	
LIFE CYCLE PARTNERS:	CONSTRUCTION PARTNERS:
USER	ARCHITECT-ENGINEER
ADMINISTRATOR	CONSTRUCTION MANAGER
MUNICIPAL AUTHORITY	CONTRACTOR
INVESTOR	ADVISORS
	MANUFACTURERS

This "design team" is first and foremost necessary to overcome one of the most common misconceptions against sustainable architecture. It is often argued that the initial construction costs for sustainable buildings are so high that such an enterprise is not economically viable. It is true that certain sustainable building systems require a higher investment when compared to traditional constructions. However, with the professional contribution of the design team members, the life-cycle analysis of the building can be realized optimizing capital investments for design, construction, usage, maintenance, repair and demolition. The results are often in the favor of sustainable buildings. [7] Within this design team, there are various areas where architects and structural engineers who are responsible for most of the fundamental decisions can collaborate in close cooperation. In this paper, possibilities of cooperation for the architects as the "primary designers" and structural engineers as "the ones who make the buildings stand-up" are explored in areas which are relevant for the building industry in Turkey.

3. COLLABORATION BETWEEN THE ARCHITECT AND STRUCTURAL ENGINEER TEAM IN PROFESSIONAL EDUCATION

As mentioned in the previous section, one of the fundamental requirements of sustainable design is to work and collaborate within a team. The tradition of working as a team can be given to architects and structural engineers at the initial stages of their carriers, meaning during their professional education. However, there are certain obstacles ahead of such an endeavor. These obstacles are related with the professional alienation of architects and structural engineers.

The separation of architecture and structural engineering as different professions had profound effects on the way architects and engineers trained themselves in the ways of the art of building. Some architects have solely focused on theoretical studies and engineers have exclusively sharpened their skills in overcoming structural challenges. This phenomenon is also described by Tom F. Peters in the book 'Bridging the Gap: Rethinking the Relationship of Architect and Engineer' as follows: [8]

"… While engineering hopes to be moving toward a more comprehensive approach to design and building, and the very nature of the word 'design' in engineering seems to be shifting to mean more 'configuration' than 'dimensioning', architecture is in danger of diversifying into literary and purely graphic pursuits, on occasion so strongly that some architects become mere aesthetic consultants or even abandon building altogether."

The confusion about the mutual standpoints of structural engineering and architecture is also reflected on the way the architectural profession is taught in the world. Is architecture a branch of fine arts? Is it a discipline of positive sciences or social sciences? Is it closer to structural engineering or city planning? Is it all of these; none of these or is it a combination of everything stated above? Briefly, there is a problem of disciplinary classification when it comes to architecture. Consequently, there is confusion about under which institution; the schools of architecture should be established. Today, throughout the world, the schools of architecture are located under faculties of fine arts, faculties of engineering, departments of building science, departments of city planning as well as in the form of independent faculties. [6]

The curriculums of the architecture schools are generally organized around a central course which is mostly in the form of a design studio. The studio is supported by technical courses as well as lectures concerning theory, as well as the history of architecture. This design studio is considered as the environment where the knowledge acquired in the lectures is transferred to the process of architectural design. As far as structure courses are concerned, basic concepts of structural mechanics and structural design are taught in the form of lectures. The general character of such an architectural education may be summarized by the words of Raftopoulos: [4]

"… One can recall the normal methodology architectural students are introduced in their profession, in the first stages of their studies, by demanding projects that enhance their creativity and imagination without applying any structural restrictions. The gradual introduction of structural parameters reaches a level of a realistic representation of the design project until the end of the studies, nevertheless without ever attempting to materialize it following structural calculations… the system is trying to educate architects to comprehend the requirements of the engineering aspects of the building and encourage the idea of collaboration within a multidisciplinary group, with defined responsibilities and obligations."

While some schools prefer to keep the matter on a theoretical level, other schools with a more sustainable approach support the theoretical knowledge with relevant laboratory work. In such cases, the students are asked to build actual or computer models (Figure 1) of small-scale structures where they can observe the effects of the theoretical concepts they have learned, on simulated environments. [6]

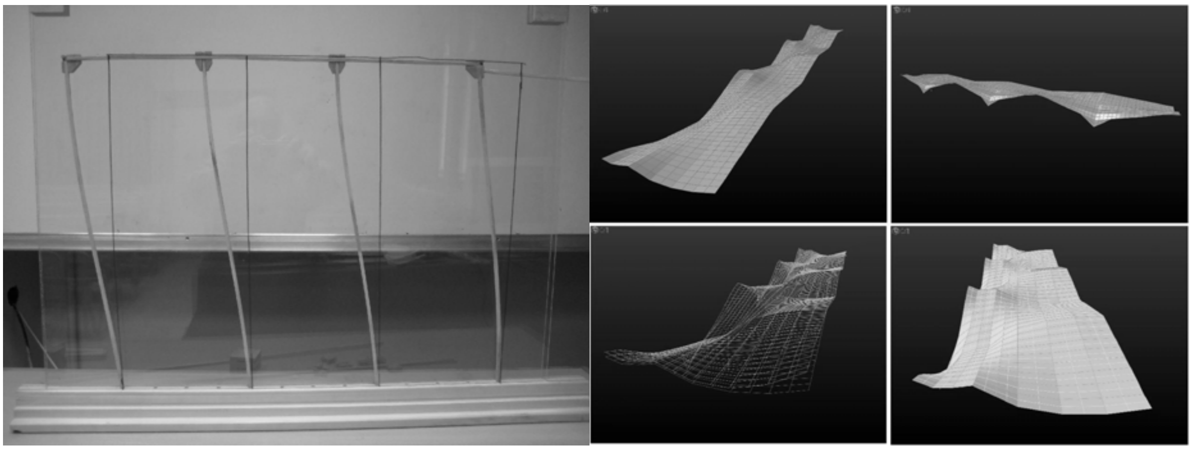

Figure 1. A Small-Scale Structural Model of a Continuous Portal Frame under Lateral Loads and Structural Computer Model of a Third Year Architectural Student.

A further step towards the teaching of team work practice can be achieved by the creation of multidisciplinary design studios, with tutors from different disciplines. In this system, the students are subdivided in smaller groups and each group has at least two or three architectural design tutors, one structural engineer and occasionally engineers from other relevant disciplines. (Figure 2) Even the architectural design tutors may vary by their specialization or by their background, by being designers, interior designers, or designers in architectural technology or finally, depending on the studio, city planners. In such an environment students of architecture will learn to work with professionals from various disciplines in order to create more sustainable buildings. [4]

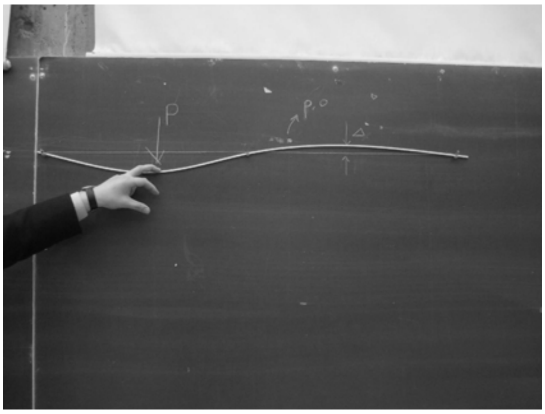

Figure 2. Teaching Architectural Students Basic Structural Behavior through Visual Methods.

4. COLLABORATION BETWEEN THE ARCHITECT AND STRUCTURAL ENGINEER TEAM IN SEISMIC DESIGN

The few tasks an architect can accomplish without conceiving a structural system are the likes of garden arrangements or maybe an open-air automobile parking. Otherwise, all buildings require a space-cover or a system of floors, none of which can be created without a structural system. As the principal designer of a building, it is the responsibility of the architect to make the fundamental decisions about the structural design of their buildings. Structural engineers on the other hand are responsible for turning the “idea” of a structural system imagined by the architect into a “reality”. Since sustainability requires a harmonious and careful planning of a buildings entire existence from cradle to grave, it is crucial for architects and structural engineers to collaborate from the initial stages of a construction project. [6]

Architects and structural engineers have a significant role in the sustainable design process. Architect, as the chief designer heavily depends on the contribution of the structural engineer in the selection of the structural system. Joint decisions are also made when deciding on the building materials. As mentioned previously, specialized members of the design team make their contribution in taking the necessary precautions so that buildings can adapt to changes during their life cycle. Collaboration with other design professionals is critical to the architect-structural engineer team’s successful role on a project. Receiving professional input on various issues such as the lighting, heating, ventilation, and transportation enables the pair solve the relevant design problems with higher efficiency. [7]

Architects and structural engineers play a more critical role in regions of seismic hazard risk. Turkish Earthquake Code like many other seismic design regulations focuses on preventing the loss of lives and major structural failures rather than limiting the damage to a building’s nonstructural contents. Seismic performance levels expected from buildings by the Turkish Earthquake Code displays great similarities with the principles laid down in The Blue Book published by the Structural Engineers Association of California (SEAOC). According to this document: [7]

"Building performance targets after an earthquake are divided up into the categories of Operational, Immediate Occupancy, Life Safety and Collapse Prevention. For a building to achieve Operational Performance after an earthquake the building must have little or no damage to structural or nonstructural elements and business is uninterrupted. Immediate Occupancy performance allows for minor non-structural damage and repairable structural damage after an event, however, there is continued use of the building. Life Safety performance is defined as heavy non-structural and structural damage that must be repaired before the building can be used, and occupant casualties must be avoided. Collapse Prevention means that the building is heavily damaged and repair is not possible, however occupants are able to escape the building. Structures designed in accordance with the Blue Book should provide the following basic performance levels:

- *Have the ability to resist a minor earthquake without damage, Operational building performance.*
- *Have the ability to resist a moderate earthquake without structural damage and with only minor non-structural damage, Immediate Occupancy building performance.*
- *Have the ability to resist a major earthquake (MCE) without collapse but possibly with structural and non-structural damage, Collapse Prevention building performance."*

However, protecting the high-performance architectural and mechanical systems is essential for sustainable building design. In an earthquake country such as Turkey, it is likely for a building to experience a high-consequence natural hazard over its lifetime. Observations made in the aftermath of large earthquakes have demonstrated that buildings are damaged mostly as a result of excessive floor accelerations and uneven distribution of average storey drifts. These earthquake effects may not always be critical enough to cause damage on the structural system of a building nevertheless they can severely damage the nonstructural elements and contents of a building. Here, it should be remembered that repairing the nonstructural components and building contents comprise a large portion of the building's post-earthquake recovery cost. [7]

A study performed by Taghavi and Miranda in 2003 provides figures about the distribution of component costs in various types of buildings such as offices, hotels and hospitals. The findings of this study demonstrate that non-structural elements and components constitute a larger portion than structural elements in buildings. According to the figures obtained by Taghavi and Miranda, mechanical systems make up between 20-30% of the construction cost, while electrical systems constitute nearly 10%. In total, non-structural elements and various equipment of a building may comprise up to 44% of the cost while structural elements account for fewer than 20% of the total investment. [7]

From a sustainability point of view, the traditional seismic design approach which disregards the damage to a building's nonstructural elements and contents is no more acceptable. In a typical reinforced concrete residential building in Turkey, the structural system accounts for approximately 20% of the total cost. Designing the structural system in an earthquake resistant manner results in a 4 to 6% increase in the total cost of the structural system. This increase in structural system cost results in a minimal 1-2% increase in the overall cost of the building. The emphasis on a stronger hence more sustainable structural system must be made at the very beginning of a building's design phase. The fundamental decisions at the initial stage are generally made by the architects not the engineers. Therefore, it is the responsibility of the architects to design the various elements of their buildings to accommodate technical and spatial requirements of a sturdier structural system. [9]

The design of a sustainable structural system also requires attention on the amount of embodied energy invested into that design. The concept of embodied energy for a building can be defined as follows: [7]

"The embodied energy associated with a building consists of all the elements that were used to create the building. This starts from mining of the minerals to produce steel, to the harvesting of trees for lumber, to the quarrying of aggregates for concrete. Embodied energy includes the transport and processing of these materials in each step until they reach the construction site, and theoretically should include the energy expended during construction and within the construction waste materials."

As mentioned before structural components and elements account for less than 20% of the total investment, however the embodied energy of structural components constitutes nearly 25% of the total embodied energy of the building. This slightly higher percentage is the result of energy consuming manufacturing processes required for the production of concrete and steel. On top of this there are considerable transportation costs for both the raw materials and the finished products. [7]

The coordination of material procurement, building construction and determining the impact of these activities on the environment is possible through the collaborative work of the "design team" described in the previous section However, the optimization of the amount of embodied energy by the structural system of a building largely depends on the architect and the structural engineer. This is a pair of professionals whose collaboration is vital for sustainability in more than one way. [10]

5. COLLABORATION BETWEEN THE ARCHITECT AND THE STRUCTURAL ENGINEER IN THE REUSE AND PRESERVATION OF HISTORIC STRUCTURES

Turkey has a huge number of historic buildings both in the form of monuments and also in the form of vernacular architecture. The existence of this building stock can be advantageous in terms of achieving the task of sustainable development. The sustainability of historic buildings can be discussed from two points of view. First point of view argues the viability of these buildings in terms of cultural sustainability and the second point of view explores the technical advantages of reusing existing buildings from an energy and material conservation standpoint.

In terms of cultural sustainability, it is often argued that instead of three (social, economic, environment), there are four pillars of sustainable development, the fourth being cultural. *The Universal Declaration on Cultural Diversity* of UNESCO further elaborates the concept by stating that: [11]

"...cultural diversity is as necessary for humankind as biodiversity is for nature"; it becomes "one of the roots of development understood not simply in terms of economic growth, but also as a means to achieve a more satisfactory intellectual, emotional, moral and spiritual existence."

In this vision, cultural diversity is the fourth policy area of sustainable development. Cultural diversity requires us to preserve and protect the architectural legacy of past and present cultures. From an energy conservation standpoint historic buildings are naturally sustainable. Preservation and reuse of existing buildings makes use of the existing materials and infrastructure. Through the preservation of existing buildings, the historic character of older towns and cities is also protected helping the cause of cultural sustainability. In addition, historic buildings have many architectural and structural details in their design which respond to the requirements of the surrounding environment. The effective use of these features may provide considerable decreases in the required heating and air-conditioning costs. [12]

The example of old masonry monuments can be used to demonstrate how architects and structural engineers can collaborate in the reuse of historical buildings. From an architectural point of view, if the tendency is to restore and preserve old masonry buildings; it is almost inevitable to introduce architectural and structural modifications to the existing layout to accommodate the requirements of modern building techniques. However, the introduction of these elements can disturb the structural behavior of masonry buildings in an unpredictable and seismically unfavorable manner. Considering the complex form of many historical monuments, it is quite difficult for architects, who only have a basic knowledge of structural behavior, to predict the structural consequences of their modifications on their own. In these cases structural engineers' assistance and the use of numerical analysis methods is very helpful. [13]

Structural engineers often use the finite element method for the structural analysis of masonry structures. The basis of finite element method is the representation of a structure as a finite number of lines and two-dimensional or three dimensional subdivisions. The analysis begins by generating an analytical model of the entire structure or structural element. This is called the discretization of the structure. During the discretization, the structure is divided into various elements. The choice of the number, size and type of elements is a matter of judgement. This procedure, that takes into account the geometry of the structure, joint restraints and the loading conditions is called the analytical model of the structure. [14]

Results obtained through the finite element method and especially the use of graphic interface softwares such as SAP 2000 or ANSYS makes it easier for the architects who are primarily visual learners to grasp the structural consequences of their design work. (Figure 3) Such a graphic expression of mathematical analysis results, which are often too complicated for architects, also renders the communication process between the architects and structural engineers more harmonious. It should be noted that in an earthquake country, such as Turkey, any preservation work conducted on masonry buildings can not achieve the desired sustainability standarts without a thorough analysis of the structural and seismic impacts of these efforts on buildings. [15]

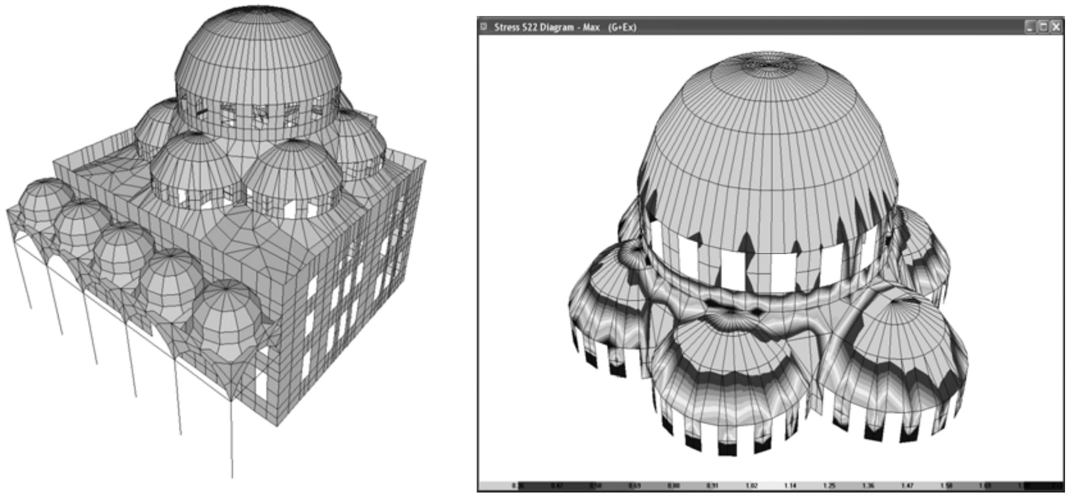

Figure 3. Graphic Expression of the Finite Element Analysis for the Dome of Kazasker İvaz Efendi Mosque.

6. CONCLUDING REMARKS

Designing and building sustainable structures is not an easy task. Various levels of collaboration and coordination is necessary between the design team members. Architects and structural engineers are only two of these professionals. Besides the required collaboration network, there are also challenges in achieving a balance in-between the three (or four with "culture") pillars of sustainable development. As Mita and Harris state: [10]

"There are measurable risks in terms of physical, social, economical and environmental issues. For example, if a structure is strictly designed to be used as an office building, it would be costly in economic and energy terms if we need to convert the building into, say, a condominium. Thus there is a risk of un-sustainability in social terms. Regarding earthquake hazards, if a structure is not well designed to survive against an extremely large earthquake, sustainability with respect to the safety will not be satisfied and the resulting destruction is costly in economic and social terms. In addition, the survivability of surrounding environments against such hazards should be also considered."

In this paper, three areas: education, seismic design and preservation of historic buildings in which architects and structural engineers must collaborate to achieve a more sustainable structure were presented. It is obvious that the arguments about these areas of collaboration are general in nature and careful and detailed studies must be conducted to establish a more comprehensive network of guiding principles. Nevertheless, it is the hope of the authors that this study will encourage architects and structural engineers to overcome certain obstacles in their mutual professional relationships for their collaboration contains a great potential in the creation of a sustainable environment.

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