



SARADNJA ARHITEKATA I KONSTRUKTIVNIH INŽENJERA U PROJEKTOVANJU SLOŽENIH ARMIRANO BETONSKIH KROVNIH KONSTRUKCIJA

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Abstract:

Istorijat odnosa arhitekata i konstruktivnih inženjera prolazio je kroz niz faza od polovine 19. veka kada je armirani beton počeo da se tehnološki usavršava. Taj odnos je imao svoje uspone i padove, ali je postao posebno važan kada su počeli da se oblikuju veliki natkriveni prostori. I arhitekti i konstruktivni inženjeri teže da armirano betonske krovove učine što atraktivnijim, ali je zato njihovo projektovanje sve kompleksnije. Ta kompleksnost se neposredno odražava na odnos arhitekta i konstruktivnog inženjera, na međusobno razumevanje ideje i mogućnosti da se ona materijalizuje. U radu se detaljnije analizira nekoliko značajnih primera, na osnovu kojih se može izvući zaključak o stanju ovog odnosa u 21. veku i ukazuje na potrebu harmonizacije odnosa arhitekta i konstruktora.

Keywords: arhitekta, konstruktivni inženjer, saradnja, AB krovne konstrukcije

COOPERATION BETWEEN ARCHITECTS AND STRUCTURAL ENGINEERS IN THE DESIGN OF COMPLEX REINFORCED CONCRETE ROOF STRUCTURES

Abstract:

The history of the relationship between architects and structural engineers went through a series of phases from the mid-19th century, when reinforced concrete began to be technologically advanced. This relationship had its ups and downs, but it became especially important when large covered spaces were formed. Both architects and structural engineers tend to make the reinforced concrete roofs more attractive, but their design is therefore becoming more and more complex. This complexity directly reflects on the relation between the architect and the engineer, on the mutual understanding of the idea and the possibility of materializing it. This paper will deal in more detail with this problem by analysing several important examples, based on which a conclusion can be drawn on the state of this relationship in the 21st century and points out the need to harmonize the relationship between the architect and the structural engineer.

Keywords: the architect, the structural engineer, collaboration, RC roof structures

1. INTRODUCTION

Throughout the history, people have been creating different structures with the ability of builders. This term, builders, means both, technical knowledge of construction engineers and architects formal and aesthetic sensibility. Most of the large, stone or brick made, highly aesthetic buildings were invented by such a person. When in the mid-19 century came to a stark division between structural engineers and architects, it was time when it was also open discussion on how to cooperate and who is more important for creating and life of the structure. New materials, especially reinforced concrete, and their application gave a particular advantage to structural engineers at that moment, but soon after that, a period of searching for a modality of successful cooperation emerged. Since the architect is the person who solves the functional requirements through the project and visually shapes them, he, as a rule, expects the structural engineer to design the appropriate structures. This second phase, Felix Candela, a famous Spanish-Mexican designer of bold and unusual concrete shells, witty depicts: "The second design phase....consists of a tremendous battle between the structural engineer and the architect...The result of the struggle is always the same: science prevails and the final design has generally lost the eventual charm and finesse of detail dreamed by the architect".[1] After this description we could imagine how stressful and yet inspiring the cooperation between architect and engineer can be, and that projects become possible only through a cooperation of those two professions, despite the complex relationship. [2] There are lot of examples which show that the relationship between architects and structural engineers is not always expressed in mutual appreciations. That this is rather a common opinion it can be concluded by reading Pfammater statement when he comes to touch upon another difference between professions: "For an engineer most design effort involves analysis. For architects design is the process of synthesis". [3] If those start points are harnessed, the integration of those two opposing approaches is the aim of collaboration and the source of its value. Architects are considered the creative ones who always want to create masterpieces and push the boundaries of the physical feasible. In contrast to this, structural engineers are sometime seen as a person who behaves in a way that spoils others' pleasure, especially by not joining in an activity, as "killjoys" or "spoilsports", who reduce the complex designs, because the design removes structural elements or is much too expansive. But apart from these impressions, the two professionals complement each other perfectly and they can rely on one another. Extraordinary structures of structural engineering have been created only thanks to their cooperation. [4]. A number of references is used in this text, which testifies that this is always a very important topic.

2. CONCRETE AS MATERIAL OF GREAT BUILDING POSSIBILITIES

The first two decades of the 20th century witnessed the wide use and expansion of reinforced concrete as building material all around the world. Nevertheless, there was a small number of architects who realized the sculptural possibilities of reinforced concrete and used it in this way. One of the first to notice this reinforced concrete power was Antonio Gaudi, one of the most celebrated architect of Catalan modernism. One of the most important buildings of Antonio Gaudi is the temple "Sagrada Familia" in Barcelona, still under construction. The first period while Gaudi was author of the building, acting as the architect and as structural engineer lasts from 1883 to 1936. During that period the notion of using concrete was spreading very fast, and Gaudi was familiar with its use. The

Gaudi's attitude about the concrete has been discussed by various authors. The first Portland cement factory in Catalonia was property of his dear friend and supporter Eusebio Güell. That is why Gaudi was well informed and even used it in some of his buildings, but very modest and not for main structures. The design of small building such as the school for the children of the workers employed at the site of Sagrada Familia shows how deeply he understand the geometry of nature's organic forms and managed to find an architectural language to express similar forms in his work.

When Gaudi in 1918 moved his atelier to the construction site of Sagrada Familia he continued to design the rest of the building and that was the moment when he decided to use reinforced concrete discovering good properties of this material for shaping his extravagant pinnacles of the towers of "Nacimiento" (Nativity) façade. These elements are located 110m high and has a structural function as it was confirmed in 1997 after the analyses undertaken to determine the first use of reinforced concrete of this building [5] Gaudi possessed a special ability to model and analyses volumes as well as huge imagination to develop geometric models, especially ruled surfaces like hyperbolic paraboloids, hyperboloids, helicoids and conoids.



*Figure 1. School at Sagrada Família in Barcelona, designed by Gaudí.
Photograph from 1909. (unknown author)*

As the knowledge of the concrete properties became more and more thorough and wider in the vision-focused of modern movement in the 1900s, reinforced concrete started to become a material of choice by well-known architects who used it for many notable buildings. Considering the unusual, stratified forms of its buildings, including their roofs, Antoni Gaudi can be considered as the precursor of a whole series of creators who used reinforced concrete to create unusual and sculptural like roof structures. Not only the concrete industry provide the ability to create a fire-proof structures, but air-entraining agents and other chemical additives, developed in the 1930s increased resistance to freezing and improved workability. These attributes solved a number of technical issues, but the plastic, flexible properties of poured-in-place concrete open the door for new forms of free flowing and expressive of nature. Increasing curiosity and boldness in research of the reinforced concrete building limits allowed construction of thin shell structures and thinner concrete slabs. Some construction companies became known for how efficiently and how well they could "get concrete up in the air." [6]. This possibility of using concrete for incredible roof exhibitions opened a new period of cooperation between architects and

structural engineers. Architectural trends until the 1940s, however, advocated rectilinear and rather rigid forms, mainly with flat, simple roofs.

3. COOPERATION BETWEEN ARCHITECTS AND STRUCTURAL ENGINEERS IN THE DESIGN OF COMPLEX REINFORCED CONCRETE ROOF STRUCTURES

Buildings in which complex roof structures could be applied were, as a rule, of specific functions. Various warehouses, hangars, especially sports and religious buildings, airports, fairs, public houses were among the first to use complex roof structures. The simplest form for which architects began to apply reinforced concrete were the dome. Although domes made entirely from reinforced concrete were not built before 1900, the architectural historians mentioned the church of Saint-Jean-de-Montmartre, which began to be built in 1894 after the design of Anatole de Baudot. It was completed only in 1904 due to distrust in the system developed by the engineer Paul Cattoncin. It is a small brick shell dome with reinforced concrete ribs. In the late 19th and early 20th centuries, the Guastavino family, from United States, developed the masonry dome using layers of tiles in fast-setting Portland cement which allowed mild steel bars to be used to counteract tension forces. This model was applied to the dome over the crossing of the Cathedral of Saint John the Divine in New York, built in 1909. It was a part-spherical dome, 30 m in diameter from the top of its merging pendentives and with average thickness 1/25th of its span and still rods embedded within pendentives. After Mainstone this dome “looked forward to modern shell construction in reinforced concrete”. [7]



Figure 2. The Dome of Saint John-the-Divine Cathedral, Guastavino tiles

Methodist Central Hall, today better known as Central Hall Westminster in London was designed in 1904 by architect Edwin Alfred Rickards. The domed ceiling of the Great Hall is reputed to be the second largest of its type in the world. The vast scale of the self-supporting ferro-concrete structure reflects the original intention that Central Hall was intended to be "an open-air meeting place with a roof on". The hall was eventually finished in 1911. [8] Synagogue with a spacious dome of reinforced concrete was built in Augsburg in the period 1914-1917 according to the project of architects Landauer and Lompel. And here, as in the case of the Westminster Hall, an interesting combination of extremely conservative and anachronistic façades and a dome of new material whose qualities are

constantly improving show the strong struggle that architects lead with tradition and the acceptance of innovations. [9]

On the basis of the winner's project of then well-known architect Friedrich von Tierch, the construction of a Festhalle in Frankfurt took place in 1907. The multifunctional hall, which was completed in 1909, was then the largest in Europe. It had the biggest self-supporting dome made in steel and glass. Festhalle in Frankfurt has largely influenced the formation of the Centennial Hall in Wroclaw (Breslau), considered by most historians of architecture as a key building and important example of large-scale dome-shaped structures in reinforced concrete. It was built from 1911-1913 to commemorate the rising-up of Prussian and German people against Napoleon's occupation. The architect Max Berg create cupola in reinforced concrete, with inner diameter of 69m and 42m high, so this was the largest building of its kind at the time of construction. Above cupola there was built lantern which itself is 23m high and was made of steel and glass. In this case, the idea of the structure form was the concept of the architect Max Berg and the main contractors were only mentioned, even Dyckerhoff&Widmann Ag (DYWIDAG), with their engineers Günter Trauer, Willi Gehler, was leading company for concrete structures in Germany.



Figure 3. Interior of the Centennial Hall in Wroclaw with RC cupola

The following example, the grandiose Leipzig Market Hall is a reverse case in which municipal architect Hubert Ritter, although designing the building, leaves the initiative to structural engineer Franz Dischinger who designs polygonal shell domes. Shell domes were made using the Zeiss – DYWIDAG patented method. This process involved the construction of a framework of rigid and self-supporting steel bars that divided the desired shape into a number of polygonal shapes, which were wrapped in wire mesh. Workers then spray a thin layer of gunite, a type of concrete, onto this system, with formwork “used as a backing to prevent spray-through”. Once the concrete had dried, the formwork was

removed and used for the next section of the shell that was to be sprayed with concrete. The domes of the Leipzig Market Hall only had a thickness of 9 cm [10]



Figure 4. Great Leipzig Market Hall with two RC domes

From the early 1910's until the late 1930's, many structural engineers in Europe try to develop shell structures because they spanned very large spans, used less material, and cost less than other options. This period was dominated by admiration for the shells in reinforced concrete. The easiest way to see their material and cost efficiency is through their ability to greater span distances without the need of intermediate columns, which would require more material. Developments in concrete prestressing and reinforcement, and also the development of stronger steel rebar, were primarily responsible for the newfound ability to design and build these shells [11]. Thin shells were additionally seen as a sound design choice because when shaped correctly, they experienced little to no bending moment, and any compression that was found within the shell was uniformly distributed [12].

But, for this structural shapes the engineer's knowledge was needed and architects have to rely on structural engineers if they wanted to develop fascinated structures. In that case, what was the best solution? The architect and structural engineer in on person!

Known both as architect and an engineer Pier Luigi Nervi (1891 – 1979) explored the limitation of reinforced concrete by creating a variety of imaginative and inventive structural projects. Through his research process he proved that reinforced concrete is the material that will dominate in architecture movements of the coming years. His passionate dedication to the creation of incredible spatial forms, his ambition and ability to recognize opportunity in the midst of challenge made him a person with huge impact on several disciplines and cultures. Continuing the research into the bridging of large interior spaces with reinforced concrete constructions, Nervi carried out two aircraft hangars in Orvieto, between 1935 and 1939. The space was closed with barrel vaults with a reinforced mesh of ribs. Unfortunately, these hangars no longer exist, but Nervi always presented them as paradigmatic examples of a means of intuitive design, capable of challenging conventions, and as one of the first demonstrations of the potentials of reinforced concrete in the design of large-span roofs.

Another challenging project was football stadium in Florence built in 1931. The Stadio Artemio Franchi (originally Giovanni Berta, also called Comunale) is well known football stadium in Florence. The stadium is built entirely of reinforced concrete with a 70-meter tower that bears the stadium's flagstaff. Around the base of the tower, spiral ramps lead from the ground floor to the upper edge of the grandstand.



Figure 5. One of the aircraft hangars in Orvieto, photo before II World War

Another sporty building that Nervi gave his original seal was Palazzo dello Sport built for competitions at Summer Olympic Games in Rome in 1960. The building corpus was designed by architect Marcello Piacentini in 1957, but its reinforced concrete dome was engineered by Pier Luigi Nervi. Aside the Palazzo it was constructed a smaller building known as Palazzetto dello Sport and its dome was also engineered by Nervi. Today, the complex is renamed in Lottomatica and also modernisation was done in 2003.



Figure 6. Palazzo dello Sport, Rome, by P.L.Nervi

The latest sports structure in which Pier Luigi Nervi took part is the Norfolk Scope in Norfolk, United States, built in 1971. This multi-function complex consists of arena, theatre, exhibition hall, and parking garage. The design of whole complex was done by local atelier Williams and Tazewell, but Nervi was invited to design arena's monolithic reinforced concrete thin-shell dome measuring 134m in diameter and a height of 33.5m. For this, world's largest reinforced thin-shell concrete dome, Nervi was inspired by his own dome of Palazzetto dello Sport in Rome. Norfolk Scope won the Virginia Society of the American Institute of Architects Test of Time award in 2003. Many compliments have been made about this dome, and most often it is said that it is a happy marriage of art and engineering.



Figure 7. Norfolk Scope stadium, RC dome by P.L.Nervi

At the end of his career, Nervi was also involved in designing religious buildings. He was invited to design the saddle roof over the body of the Cathedral of Saint Mary of the Assumption, the principal church of the Roman Catholic Archdiocese of San Francisco in United States. The elementary plan was designed by local architects John Michael Lee, Paul. A. Ryan and Angus McSweeney in collaboration with Pier Luigi Nervi and Pietro Belluschi (at that time the Dean of the School of Architecture at MIT). The saddle roof is composed of eight segments of, one of the favorite Nervi's roof types. [13]



Figure 8. Cathedral of Saint Mary of the Assumption in San Francisco, RC roof structure by P.L.Nervi

Hyperbolic paraboloids were the favourite constructive type not only for Nervi, but also for numerous other creative authors in the 20th century, inclined to sculptural design of architectural structures. Japanese architect Kenzo Tange (1913-2005), with assistance of construction engineer Yoshikatsu Tsuboi, German architect Wilhelm Schlobbs, and Swiss architect Max Lechner, developed the catholic Saint Mary Cathedral in Tokyo in 1964. The layout of the church is in the form of a cross topped with eight hyperbolic paraboloids. Using this shape of roof some of building are similar to each other or referred to some predecessors. In this case, the church of Kenzo Tange was build some few years before the Cathedral of Saint Mary in San Francisco.



Figure 9. Saint Mary Cathedral in Tokyo, by Kenzo Tange

In the late years of his career, Piera Luigi Nervi was honoured by personal invitation of Pope Paul VI to build the new General Audience Hall within Vatican City. The project was started in 1963-64 to be completed in 1971. Almost always in the shadow of his ingenious father, this project was signed by Nervi and also by his son, Antonio, an architect. The Hall, approximately 80m wide by 100 m long, with a maximum height of 18m has the vault realized using the same system adopted on many occasions, composed of prefabricated elements used as permanent formwork for the site casting of the ribs. The building glow in white concrete with grains of white marble, between renaissance and baroque surrounding.

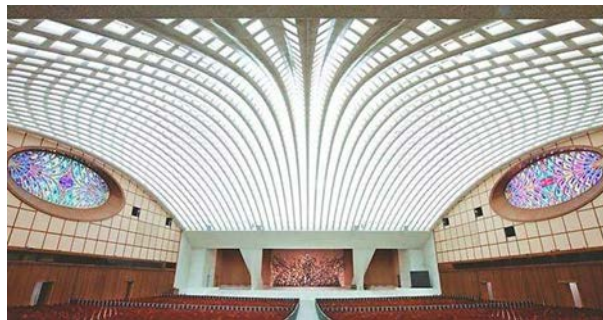


Figure 10. General Audience Hall, Vatican City, P.L.Nervi

If we return to the legacy of Antoni Gaudi, we have to mention several authors acting as architects and structural engineers in one. They all admired the architecture of Catalan modernist Antoni Gaudi and in one way or another continue to develop imaginative, brave and unusual building shapes. [14]

Eduardo Torroja y Miret (1899-1996) was Spanish structural engineer and pioneer in the design of concrete shell structures. At the beginning he worked with architect Manuel Sánchez Arcas, a Spanish modernist, sharing his interest in new architectural forms. They designed together an enclosed and semi-spherical shell for the 1932 Algeciras market hall. Market hall was covered with 9cm thick roof of 47.5m height, vaulted and supported on eight pillars. Many historians of architecture consider this roof as Torroja's engineering masterpiece.

Torroja also successfully collaborated with other architect in designing the Hipodromo de la Zarzuela in Madrid in 1930. The architects Carlos Amiches and Martin Dominquez

design the race course and Torroja added the extravagant distinctive hyperboloid roof over the stands.



Figure 11. Market Hall in Algeciras, Spain, E.Torroja



Figure 12. Hipodromo de la Zarzuela, Madrid, E.Torroja

Another world known Spanish and Mexican architect was Felix Candela Outerño (1910-1997). His major contribution to architecture was the development of thin shells made out of reinforced concrete, popularly called cascarones. Candela was real admirer of reinforced concrete in the shape of a dome or shell like shapes. He took any opportunity to design buildings which allow him to express this affinity. In his career he was always acting as architect and as structural engineer. That is why he has had a great influence on the work of many younger authors. His architecture is simple yet intriguing and complex roofs are designed to be clearly depicted in space, especially in the natural environment. L'Oceanogràfic in Valencia is the largest aquarium in Europe and planet's main marine ecosystems are represented here. The appropriate, but extravagant and avant-guard architecture of the complex is one of the latest works of the architect Felix Candela and the structural engineers Alberto Domingo and Carlos Lázaro, who made the structural design of the concrete coverings of the buildings, opened in 2002. [15]

Miguel Fisac Sema (1913-2006), architect and painter, belongs to the same group of Spanish authors who follow the open minded Gaudi. He started to be interested in experiments with new materials, especially with reinforced concrete. He found that reinforced concrete is material that is adequate to assume its analogies on "bone-beams". With this premises he designed the headquarters of the JORBA laboratories in Madrid in 1967. The popular name of the building La Pagoda refers to the visible structure of the

tower. The original structure of the building consisted of an office tower in which each floor was rotated 45° with respect to the previous one, a feature that made it appear as a pagoda. The transitions between the plants were resolved with a ruled surface in the form of a hyperboloid. This strange building was pulled down in 1999.



Figure 13. Chapel Lomas de Cuernavaca, F.Candela



Figure 14. L'Oceanogràfic in Valencia, F.Candela

Oscar Ribeiro de Almeida Niemeyer Soares Filho (1907–2012), usually known simply as Oscar Niemeyer could be treated in the same way as previous authors fascinated with the possibilities of reinforced concrete. His exploration of the aesthetic possibilities of reinforced concrete was very influential in the late 20th and early 21st centuries. The critics who analyse his opus called him a “sculptor of monuments”. And, really, many of his buildings looks like gigantic sculptures. One of this “sculptural buildings” is the Church of Saint Francis of Assisi in Pampuhla region of Belo Horizonte. It is the first UNESCO listed modern architectural monument in Brazil and consists of four undulating concrete parabolas which exterior is covered with mosaics. The church was finished in 1943, but it was consecrated in 1959 because the Archbishop Cobral opposed both its architectural and artistic forms. If we put aside all huge structures in reinforced concrete

and with shell domes and hyperboloid-paraboloid roofs that Niemeyer had built during his long career, we can proof his genius analysing the small chapel of Nossa Senhora de Fatima built in the city of Brasilia in 1958. The whole roof structure relies on three inclined pillars only. [16]



Figure 15. Nossa Senhora de Fatima, Brasilia, O.Niemeyer

Religious architecture has welcomed many architects to demonstrate their ability to use shell domes and other curved roofs. Le Corbusier express his interpretation of the International Style by using monumental sculptural shapes and raw, unfinished moulded concrete while designing church architecture. The Chapelle Notre Dame du Haut, the small chapel in Ronchamp, France, has become one of his most iconic designs. Completed in 1954, the chapel was built for a Catholic church on a pre-existing pilgrimage site. The monumental curved concrete roof is a shell structure supported by columns hidden in the masonry walls. There is also the Church in Firmigny which carries special significance, as it was last major work of le Corbusier designed in 1963. It was left unfinished until 2006 keeping his essence alive. For the Church in Firmigny he used concrete hoping that this material would also give him control over volume and spaces in his overall goal of giving light a true meaning. [17]



Figure 16. Church in Firmigny, Le Corbusier

We can turn now to the cases with difficult relationship between architects and structural engineers during the necessary collaboration. The Sydney Opera House in Australia, became a mid-century icon of the artistic use of concrete formed into segments of spheres

to produce a dramatic structure that appeared light and airy, like sails on a ship. No project highlights the drama, conflicts, successes and failures of vision for the architect-engineer relationship more than Sydney Opera House. The history of Opera building starts when Danish architect, Jørn Utzon (1918-2008) won the competition with no more than a sketch on a scrap of the paper. Ove Arup, also Danish living in London, congratulate him and give the offer of his company to be involved in structural solutions. At that time, in 1957, Sir Ove Nyquist Arup (1895-1988) was well known structural engineer, leader of the company called Arup and Partners. One of his partners, Ronald Jenkins, was leading authority on the calculation of shell structures. Today, Ove Arup is considered to be among the best architectural structural engineers with deepest impact on the work of many architects and structural engineers in 21th century. The problems started because the construction began before the design had been fully researched. The only hope for resolving the incredibly complex geometries of the roof structure was through an intensive collaboration between architect and engineer, which is why Sydney's Opera is one of, if not, the greatest symbol of 20th century architect-engineer achievement and failure at the same time. The personal similarities and differences between Arup and Utzon were almost immediately visible. However, at first it seemed that Arup's dream of a deeply collaboration between architect and engineer could be realised. But, in 1966, utterly overwhelmed by how complex the project had become, Utzon resigned. In spite of this, the project still gripped Ove Arup. Personally, the whole situation about realisation of the project, left deep impact on Arup. It seems he lost his uninhibited enthusiasm for architect in general and he start to trust only to the architects of his own team. [18]



Figure 17. Opera House in Sidney, J. Utzon

Reinforced concrete was the material that in 1950-1970 impressed almost all architects and structural engineers willing to challenge its possibilities in realisation of most strange curved roof surfaces. American authors were also involved to contribute with their realizations that have also become the icons of modern architecture in the middle of the 20th century. One of the most influenced designers at that time was Eero Saarinen (1910-1961), Finnish architect that immigrated in the United States. His acceptance of reinforced concrete as a formative material was undoubtedly influenced by the fact that he first start studying sculpture in France and then he transferred to Yale University where he took diploma in architecture in 1934. With his own architects' office Eero Saarinen and Associates, he was involved in number of most important works in United States until his early death. The most cited are two airport terminals, the Terminal 5 of TWA Flight Centre and Washington Dulles International Airport, both opened in 1962, a year after Saarinen died in 1961. Saarinen and his team successfully collaborated with civil engineering firm Ammann and Witheney as in both projects the thin shell-shaped concrete roofs were designed over the main interior spaces. Both airports were always highly estimated for its

graceful beauty, but today they are completely changed. But, Kresge Auditorium at MIT is estimated to be one of the best known thin-shell structures in United States. Designed in 1955, it was listed in “One Hundred Years of Significant Building” already in 1956. The elegant reinforced concrete dome comprise one eighth of the surface of a sphere and its primarily supported by three pendentives and rising to a high of about 15m and sliced away by sheer glass curtain walls, so that the shell dome comes to the earth on only three points. Thin shelled concrete technology was innovative and the dome is very thin. This project was successfully realised with help of consulting engineers Amman and Whitney. [19]

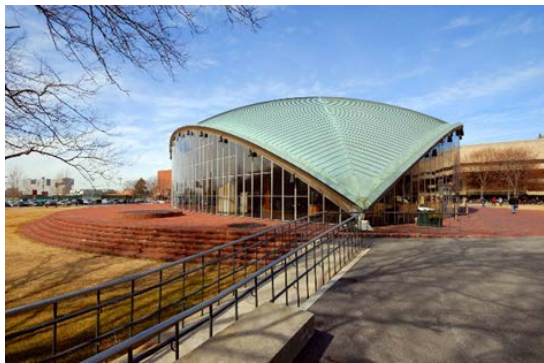


Figure 18. Kresge Auditorium at MIT, E.Saarinen

At the end of the 20th century, there was a change in the form of collaboration between architects and engineers. In some cases, the construction becomes so significant that the architect can not at all realize his idea without the dominant role of structural engineers. Yet, still today there are individuals who are able to independently realize their own ideas, At the end of the 20th century, there was a change in the form of collaboration between architects and engineers. In some cases, the construction becomes so significant that the architect can not at all realize his idea without the dominant role of structural engineers. Yet, still today there are individuals who are able to independently realize their own ideas, as is the case with Santiago Calatrava Valls (1951). This extraordinary talented Spanish architect, structural engineer, sculptor and painter in his work is guided with the principle of the early 20th century famous Swiss engineer Robert Maillart (1872-1940), that "with an adequate combination of force and mass, you can create emotion." [20] Although Calatrava is the author of numerous projects, a relatively small number of those are with roof concrete structures. Numerous new materials that enable even more unusual and curved forms than concrete can be used today, and Calatrava uses them frequently for his various realizations.



Figure 19. Palau de les Arts Reina Sofia, Valencia, S. Calatrava

Reinforce concrete as roof material was applied only in some of his projects, such as Bilbao Airport terminal. Another building with “concrete” shell roofing is Palau de les Arts Reina Sofia (Opera House) in Valencia. In form, the building is a series of apparently random volumes, which become unified through their enclosure within two symmetrical, cut-away shells of laminated steel clad with white concrete.

4. CONCLUDING REMARKS

Undoubtedly, in modern practice, there are still many examples of the application of large and curvilinear roof surfaces, but when analysing the applied building material, it is revealed that it is almost never pure reinforced concrete, but that it is used marginally, and that the dominant is steel and other new technologically advanced materials that are more flexible, easy to install, and can be cheaper. However, there remains one characteristic of reinforced concrete, which is still difficult to overcome, which is its service life. The historical distance is still insufficient to define the durability of new materials with security. Some materials, for which some of the world famous buildings have already been constructed, already show signs of decay and almost parallel to construction are being done repairs and reconstructions. Today, we are beneficiaries of all of the past exploration, technical achievements, and creative experimentation by creative and curious individuals, associations, design professionals and construction companies that have worked with concrete. Further refinements into materials research, engineering, and the science of concrete combined new designed methods and technology have allowed architect to demonstrate innovative and exiting new capabilities.

Yet, the concrete in any of its derivation lost the battle when large span roof shells and other extravagant roof curvatures are planned. A large number of new types of concrete are available and each has a specific use value. Concrete has long been, and continues to be, a significant building material that provides a full range of structural, architectural, and sustainability options. The science and technology of concrete has advanced notably to allow for a range of uses and capabilities that have been proven in countless buildings as well as industrial and infrastructure projects. Combining these capabilities with advances in computerized building information modelling allows entire design teams to work together to achieve designs that are truly representative of 21st century thinking and possibilities. Further, the longevity of concrete means that these constructed designs will likely endure for generations to come. The collaboration of architect and structural engineer is needed now much more than ever, because the vision of entire men surrounding starts to be close to science fiction ambiance and needs to be realised safely and sustainable.

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