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252-263 **Tomaž Slak, Vojko Kilar**

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UDC 721.550.3: 624.042.7

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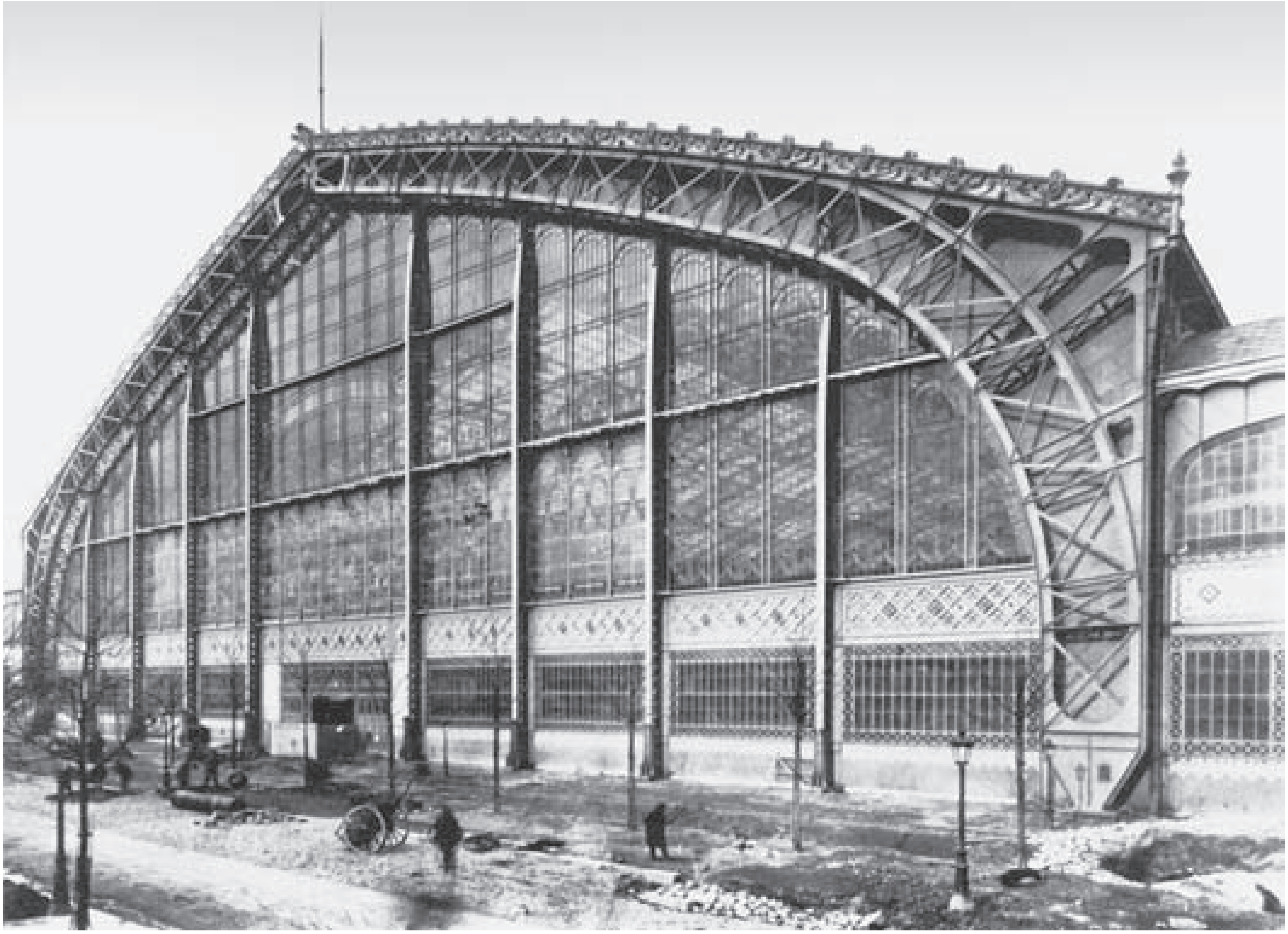

Fig. 1 Gallery of Machines: first three-hinged arch used for a building structure
Sl. 1. Galerija strojeva: prvi puta korišten trozglobni luk u konstrukciji građevine

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Development of Earthquake Resistance in Architecture from an Intuitive to an Engineering Approach

Razvoj potresne otpornosti u arhitekturi – od intuitivnog do inženjerskog pristupa

Development of structural systems
Earthquake engineering
Earthquake resistant buildings
Structural logic

Razvoj konstrukcijskih sustava
Seizmičko inženjerstvo
Građevine otporne na potrese
Konstruktivna logika

The paper examines the development of earthquake resistant design in relation to architecture in earthquake prone areas, from the first mainly intuitive measures for ensuring horizontal stiffness of buildings up until the 20th century, when influences of earthquakes on buildings began to be included in standards and regulations for the design of contemporary earthquake resistant structures. Through the prism of earthquake resistance the paper studies and chronologically presents the influence of building structural systems from the period of the labour division of architecture and engineering until today.

U članku se istražuje razvoj projektiranja arhitektonskih konstrukcija otpornih na potrese u potresnim područjima u rasponu od prvotnih, uglavnom intuitivnih, mjera poduzetih radi postizanja horizontalnog ukrućenja objekata sve do 20. stoljeća, kada utjecaj potresa na građevine biva uključen u standarde i propise za projektiranje suvremenih konstrukcija otpornih na potrese. U članku se kroz prizmu potresne otpornosti proučava i kronološki prezentira utjecaj konstrukcijskih sustava građevina od razdoblja podjele na arhitektonske i građevinske poslove do današnjih dana.

Introduction

Uvod

Tectonics – Architecture as a science incorporates the structural aspect in the notion of tectonics – the natural logic of composition. The rules and principles of architecture are based on natural laws, on the structural logic of construction and on the tectonic logic of construction materials.[1] With the development of architecture this logic transformed into "the art of composition" or as Kenneth Frampton expressed himself in the title of his monograph "Poetics of Construction".[2] With the development of architectural art and with the separation from structural engineering, architecture was becoming an increasingly independent discipline.

Earthquake engineering as a science – Earthquake science is relatively young and it is still developing, and its beginnings do not go back more than 100 years.[3] With increasing awareness of the need for horizontal stiffness (Fig. 3) and with the increasing knowledge on the effects of earthquake forces, earthquake engineering[4] has gradually developed over the last two centuries. It began its rapid development only in the middle of the last century, and today independently presents specialized knowledge that is summarized in modern standards and codes (e.g. Eurocodes).

Development of structural knowledge – Traditionally an architect was anyone with the ability to conceptualize, describe geometry, draw, and construct a structure without subsequent collapse.[5] It is true that architecture without structure is non-existent, which could lead us to presume that due to this dependence, structure is more important than architecture.[6] But on the other hand, structure is merely one layer of otherwise a very complex system represented by architecture. By the adequate understanding of tectonics as the basis of architectural work, connections between architecture and structure become more logical. The engineering part forms a realistic basis of architectural work, which is of a constitutive meaning for architecture, but can in no way be compared to it as a uniform work of art.[7] In dealing with a special field of structural engineering such as earthquake resistance, we need to be aware of all the possible significant (positive and negative) consequences and influences on architecture, as C. Alexander claims in the chapter *Order as mechanism - the destructive impact of mechanistic thought on the art of building*: "... so, in works of art, the mechanistic view of order always makes us miss the essential thing ...".[8]

An Overview of the Development of Architecture in the Context of Earthquake Resistance from an Intuitive to an Engineering Approach

Pregled razvoja arhitekture u kontekstu potresne otpornosti – od intuitivnog do inženjerskog pristupa

Intuitive assurance of horizontal resistance – Prior to the occurrence of the first seismologic researches in the 19th century,[9] earthquakes were not consciously taken into account in construction of buildings. Awareness of the threat of an earthquake, if it existed, was merely intuitive. Earthquakes, as such, were treated as an uncontrollable destructive power of nature, the consequences of which could not be prevented. Despite this we can infer that masters/builders intuitively or subconsciously ensured lateral stiffness of buildings and better resistance to horizontal forces. Buildings constructed before the 19th cen-

1 Vodopivec, 1993

2 Frampton, 1995

3 Bubnov, 1986

4 Seismology has long contributed to engineering and architecture. The founders of seismology, defined as the scientific study of earthquakes, were Robert Mallet [1810-1881], a civil engineer, and John Milne [1850-1913], a mining engineer. They were first stimulated by their field studies of great earthquakes, and then posed some basic questions, such as "What is the mechanical explanation for the damage (or lack of it) when structures are subject to seismic strong ground motion?" and "What are the essential characteristics of seismic waves that affect different structures?" (*** 2006) These nineteenth century links between seismology, engineering, and architecture have continued ever since.

tury were mainly built according to the principles of classical tectonics, which was developed mainly through experience and was passed on within the guild from masters to apprentices – future masters. In the analysis of buildings of that time we can notice elements of the so-called lateral thinking[10] of all architects, builders and engineers.

Classical tectonics of construction in wood, brick and stone started to lose their primacy in the mid-18th century with the division of the building process into architecture and civil engineering. Old knowledge was giving way to new principles and the use of new materials (iron, steel, concrete) in architecture at that time. The structural over-achievements of the 19th century (e.g. the Eiffel Tower or the Crystal Palace) as well as the period of the so-called Chicago school and skyscrapers at the end of the 19th century in the USA, first required more reliable assurances of their adequate horizontal stiffness. The period of modern architecture started in the 20th century, and was the precursor of the later International style and postmodernism, when entirely new principles of construction were established, which radically interfered with the treatment and understanding of structures and their horizontal resistance.

Before the 19th Century – the Classical Tectonic Building Approach

Razdoblje do 19. st. – klasični tektonski pristup

Classical principles of tectonics[11] – Cross-shaped vaults, arches and domes working primarily in compression, conditioned spans and structures up until the occurrence of iron, steel and concrete, and the first reinforced concrete in the 19th century. From the earthquake safety viewpoint, up to this period buildings were constructed distinctively on classical tectonic principles (Fig. 2). Due to the heavy weights, short spans and the use of arches in combination with thick walls, tension and bending stresses practically did not occur due to horizontal wind or earthquake loading.

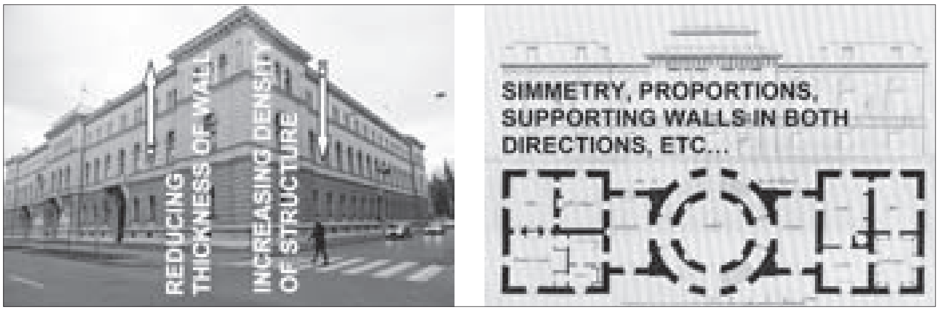


Fig. 2 Examples of classical principles of tectonics: symmetry, mass concentrated as low as possible, thickness of walls is increased in the bottom storeys, etc.

Sl. 2. Primjeri klasićnih principa tektonike: simetrija, koncentriranje mase što je niže moguće, debljina zidova pojačana u donjim katovima, itd.

Until the end of the 18th century earthquake resistance of buildings was achieved mainly by following the principles of classical tectonics:

– masses were concentrated as low as possible,

– walls had a significant thickness at the bottom of the building which was reduced in the upper storeys,

– regularity was strictly enforced (symmetry, the direct transfer of loads to the foundations, height to width ratios rarely exceed 1:4),

– buildings were limited in height depending on the material used and were rarely higher than 4 or 5 storeys,

– floor plans were usually regular with walls running in the two orthogonal directions and show significant structural density,

– during an earthquake, the most common occurrence is the shear transfer of horizontal forces,

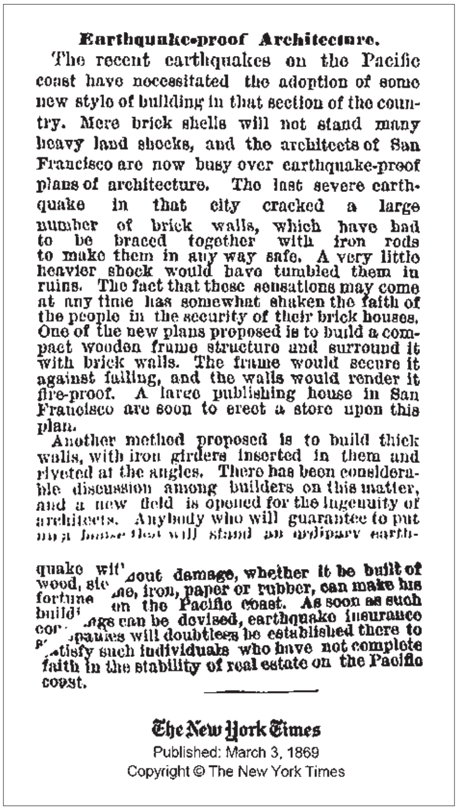
– building elements were mostly loaded in compression and due to the large self-weight, axial and bending stresses were minimized.

Structure was limited mainly to masonry or stone buildings. Though concrete and iron were known materials, their usage for structural purposes until the mid 19th century remained limited in ways that did not have a significant influence on architecture.

With the occurrence of new materials which enabled technically more advanced design, taller and more slender buildings and structures which allowed a better use of space by moving the structure to the building's circumference, earthquake loading was becoming an increasingly important factor.[12] Structure was no longer limited to the basic principles of classical tectonics. Light, metal, frame and also truss structures emerged. The development of structural systems and materials started with the use of iron, without which construction until the end of the 18th century was, except for exceptional monumental buildings, limited to low-rise masonry buildings. The exceptional characteristics of the "new" materials were the main reason for the rapid breakthrough of iron and later steel and reinforced concrete structures.

Fig. 3 Probably the first time the mention of earthquake-proof architecture was published

Sl. 3. Vjerojatno prvi objavljeni spomen arhitekture otporne na potres



Earthquake-proof Architecture.

The recent earthquakes on the Pacific coast have necessitated the adoption of some new style of building in that section of the country. Mere brick shells will not stand many heavy land shocks, and the architects of San Francisco are now busy over earthquake-proof plans of architecture. The last severe earthquake in that city cracked a large number of brick walls, which have had to be braced together with iron rods to make them in any way safe. A very little heavier shock would have tumbled them in ruins. The fact that these sensations may come at any time has somewhat shaken the faith of the people in the security of their brick houses. One of the new plans proposed is to build a compact wooden frame structure and surround it with brick walls. The frame would secure it against falling, and the walls would render it fire-proof. A large publishing house in San Francisco are soon to erect a store upon this plan.

Another method proposed is to build thick walls, with iron girders inserted in them and riveted at the angles. There has been considerable discussion among builders on this matter, and a new field is opened for the ingenuity of architects. Anybody who will guarantee to put up a house that will stand an ordinary earthquake without damage, whether it be built of wood, stone, iron, paper or rubber, can make his fortune on the Pacific coast. As soon as such buildings can be devised, earthquake insurance companies will doubtless be established there to satisfy such individuals who have not complete faith in the stability of real estate on the Pacific coast.

The New York Times
Published: March 3, 1869

5 Lewis, 2001

6 e.g. Saint, 2008

7 Slak, 2010

8 Alexander, 2002

9 *** 2006

10 Reitherman, 2005

11 Here the word *classical* can be interpreted in the sense of the classical in architecture in general, since the classical discipline is based on natural laws. Classical principles of tectonics are normally more or less present in every building and cannot be completely avoided (Vodopivec, 1993).

12 Slak, Kilar, 2008

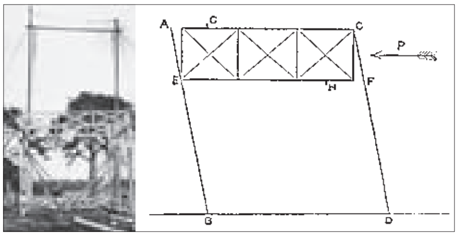


FIG. 4 THE FIRST 24-FOOT HIGH STRUCTURAL PART ERECTED IN HYDE PARK, LONDON 1851 AND A DIAGRAM SHOWING THE STATICAL CONCERNS RELATED TO STABILITY UNDER WIND FORCES

SL. 4. PRVI KONSTRUKCIJSKI DIO VISINE OD 7,4 METARA PODIGNUT U HYDE PARKU U LONDONU 1851. GOD. I DIJAGRAM KOJI POKAZUJE VAŽNOST STATIKE PO PITANJU UTJECAJA VJETRA NA STABILNOST OBJEKTA

Architecture as a separate discipline – With the developments in building practice it became too difficult for one individual or an organization to master every facet of building design and construction. Specialization became inevitable. Architecture thus became a separate, independent, legitimate, professional discipline. We can also infer that the initial more serious thinking about the horizontal stiffness of buildings appeared precisely during the period of the division of building into architecture and engineering, which is also confirmed by the findings in different sources.[13]

THE HISTORICAL SEPARATION OF STRUCTURAL ENGINEERING AND THE ARCHITECTURAL PROFESSION

HISTORIJSKO ODVAJANJE KONSTRUKCIJSKOG INŽENJERSTVA I ARHITEKTONSKE PROFESIJE

The end of traditional guilds – From antiquity and the Middle Ages until the renaissance period in the 17th century, an architect was treated as a universal builder who unified an artist and a scientist in one person. In 1756, the foundation of the *Ecole des Ponts et Chaussees* initiated the separation of the two disciplines of engineering and architecture.[14] Emphasis on the use of technical knowledge further encouraged the separation of the profession into architecture and engineering. This period was also approximately the time of the widespread use of new structural principles and iron, steel and reinforced concrete.

Engineering structures – The first more daring structural solutions in the 19th century were in this way suggested by structural engineers. Buildings that were up to then designed from experience became the object of scientific research and economy. At that time, architecture was running out of ideas and innovations, and architects found new materials and structural systems too demanding for them to use. Among the multitude of eclecticism and neo-... styles, when the development of advanced architectural thought nearly came to a standstill, engineering boldness and also new structural aesthetics presented the development of architecture and created the basis for the formation of modern architecture at the beginning of the 20th century. The 19th century is thus also called the period of modern structures. Due to entirely different construction principles, also horizontal stiffness became much more important. Of course at that time it was not in relation to earthquake resistant design, but more in the sense of wind loads and the stability of buildings with their mass at a certain height. When a building no longer takes into account the principles of classical (massive) tectonics, the effect of horizontal forces becomes completely different, and the behaviour of structures changes in such a way that the knowledge which was sufficient to control classical tectonic buildings was no longer adequate.

First research on earthquakes – The first research of earthquake loads took place in the mid 19th century after the earthquake in Naples,[15] but it took at least another half a century before the first written anti-seismic rules occurred in the form of building recommendations (in Slovenia that occurred after the Ljubljana earthquake by Building Orders issued in 1906 and 1909[16] and in Croatia in 1911[17] when a pioneer of earthquake engineering Andrija Mohorovičić published the book "Impact of seismic action on buildings", which appears to be one of the first analytical approaches to seismic design in the world). The intuitive and experience based approach to ensure horizontal stiffness used up to that point, now started to be complemented by the first concrete research discoveries. The occurrence of diagonals, cross-ties, external reinforcement and strengthening joints in the structures of these new buildings is a consequence of studying the problem of horizontal loading on vertical elements, which became very slender and, in certain cases, entirely in contradiction to the principles of classical tectonics.

In the 19th century, engineers presented the leading factors of development in the field of the built environment and the use of new technologies in architecture. Earthquake resistance was not yet systematically considered (e.g. as a standard), however, it can be seen from the construction recommendations of the time that builders and more advanced societies were aware that the method of construction could significantly alleviate the consequences of an earthquake. This is precisely the reason why measures of earthquake resistance can to a certain extent be found in quite a large number of buildings from the end of the 19th century.

THE PERIOD OF STRUCTURAL DEVELOPMENT IN THE 19TH CENTURY

RAZDOBLJE RAZVOJA KONSTRUKCIJA U 19. STOLJEĆU

New materials and technologies – In structural thinking, the 19th century presents a

13 e.g. LEWIS, 2001; SAINT, 2008 or *** 2006
14 HARTOONIAN, 1994; FRAMPTON, 1985; SAINT, 2008
15 *** 2006
16 VIDRIH, GODEC, 1995
17 ANIČIĆ, 1998
18 WALTER BENJAMIN, 1930
19 Earthquake resistance was probably not included in the thinking about structures in England, which is an area of low seismic activity. However, structural achievements made possible by a high standard of this influential coun-

FIG. 5 GALLERY OF MACHINES DURING ERECTION, BEHIND IT THE ERECTION OF THE EIFFEL TOWER CAN BE SEEN

SL. 5. GALERIJA STROJEVA TIJEKOM GRADNJE, IZA GRAĐEVINE SE VIDI PODIZANJE EIFFELOVOG TORNJA

milestone. Structure was no longer limited to the basic principles of tectonics. Light, metal, iron and steel truss three dimensional structures emerged.[18] Among many revolutionary achievements we draw some attention to certain buildings where horizontal stiffness was introduced more or less on the basis of experience and/or intuitive perception of the problem.[19]

The first over-achievements made of metal structures – The most influential example of a metal structural system composed of cast and wrought iron was the Crystal Palace, built in 1851 by J. Paxton for the first international exhibition to be held in London.[20] It is interesting that the construction of the Crystal Palace presented such a novelty that many assumed the structure was unstable and might collapse under the impact of the first strong wind (Fig. 4). The reason was the high positioned centre of gravity and slender columns on small foundations. The Crystal Palace was, looking at it technologically, the most advanced building of that time.[21] It influenced the rest of the world to build in a similar way, regardless of the seismic activity of the local ground.

From the viewpoint of structures, the most important among the next world exhibitions was the one in 1889 in Paris, when the Galerie des Machines (F. Dutert and V. Contamin) and the well-known Eiffel Tower[22] (Fig. 5) was built.

The span of the Gallery of Machines was 30% longer than the spans of all structures known before. The project was made possible by using steel as a new building material that replaced wrought iron.[23] For the Gallery of Machines, the engineer Contamin used a three-hinged arch founded on simple foundations, which was until then used only for bridges. (Fig. 1).

The Eiffel Tower is essentially a 300m tall supporting column (pylon) of a viaduct, whose typical shape is a consequence of the interaction of horizontal (wind, earthquake) and vertical loads. The concept of the tower as a parabolic curve is a sensible solution for an extremely tall building. The centre of gravity is positioned very low, and earthquake forces reduce rapidly with height and reduced mass (Fig. 6).

The first tall steel frame structure – a skyscraper, which does not yet show its special and revolutionary character on the outside, was the Home Insurance Building built in Chicago in 1883-85 and designed by William Le Baron Jenney (Fig. 7).[24] From a structural viewpoint this was still a traditional, massive, brick building that was already a result of the so-called Chicago School.[25] He also designed the first real steel frame building Fair Store in Chicago in 1892. The main horizontal loading in designing these buildings was the wind force and a suitable horizontal stiffness was achieved with moment resisting frames arranged in both orthogonal directions of the building, although in early skyscrapers, designers relied mainly on the brick perimeter

FIG. 6 GUSTAVE EIFFEL: A TOWER OF 300 METRES AND THE SUPPORTING PYLONS OF THE VIADUCT – THE BASIC SHAPE OF THE TOWER

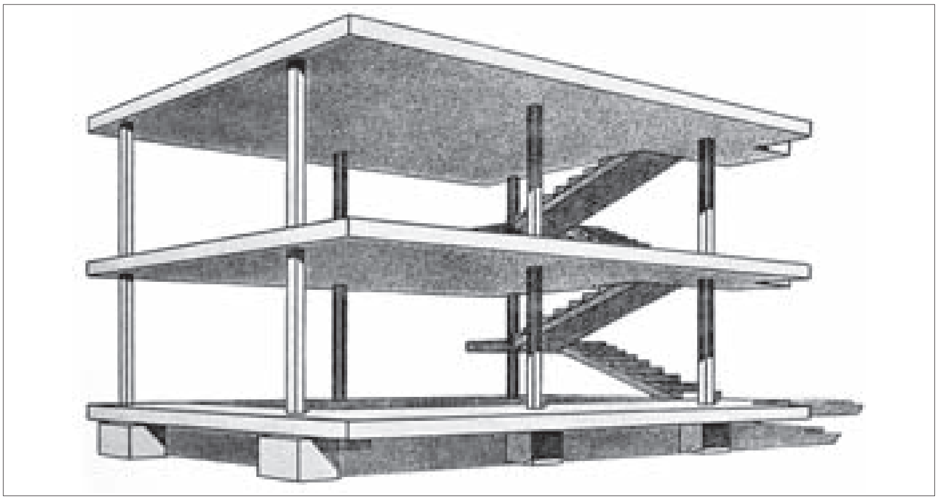
SL. 6. GUSTAVE EIFFEL: TORANJ VISOK 300 METARA I POTPORNI PILONI VIJADUKTA – OSNOVNI OBLIK TORNJA

try were also the starting point for the further development of structures all over the world (also in seismic areas). They presented the foundation for later structural solutions that present the most successful concepts of earthquake resistant buildings.

20 TIETZ, 1999
21 MCKEAN, 1994
22 LEMOINE, 1988
23 DURANT, 1994
24 FRAMPTON, 1985
25 HATJE, 1998

FIG. 7 W. L. B. JENNEY: HOME INSURANCE BUILDING – FIRST STEEL FRAME BUILDING
SL. 7. W. L. B. JENNEY: ZGRADA HOME INSURANCE – PRVA GRAĐEVINA S ČELIČNIM OKVIROM

FIG. 8 LE CORBUSIER: DOM-INO HOUSE – ”PATENT” OF PRIMARY STRUCTURE, 1914
SL. 8. LE CORBUSIER: KUĆA DOM-INO – „PATENT” PRIMARNE KONSTRUKCIJE, 1914.



walls, which were supposed to withstand horizontal loads.

The behaviour of frames in the event of an earthquake had not been researched at the time, and the ductility (by then an unfamiliar term) of joints or structure as a whole was not intentionally increased – rather it depended on the realization of the connections and fixing elements (rivets, screws etc.). However, after the widespread acceptance of the skeleton framed skyscraper form in Chicago the use of steel as a building material became widely accepted. Later protagonists of the Chicago School (Sullivan, Adler, Burnham, Root, Richardson etc.) stressed, as far as structure was concerned, mainly two standpoints: the use of a steel skeleton as a load-bearing structure and the wish that the structure should be clearly expressed in the structure of a building or on its façade, which often meant the introduction of simple and new forms. The Chicago area is not very prone to earthquakes ($a_g < 0.1g$) but again these principles uncritically spread all over the world regardless of the local seismic activity.

Concrete structures – Reinforced concrete developed very fast between 1870 and 1900, after the introduction of the first calculation method in 1866. The period that followed was the period of large monolithic concrete structures. Auguste Perret is considered the first architect to use the technique and the possibilities provided by reinforced concrete and promoted it as a noble and widely usable material. The structural characteristics of concrete were extremely suitable for the upcoming architectural directions and movements which can be seen in the 1930s in the approaches developed by architects such as Le Corbusier and by the famous architectural school Bauhaus with Walter Gropius. The principles of ”architecture as a volume” developed through skeleton structures on columns in contrast to massive structures. Storeys supported by steel or reinforced concrete columns enabled the floor plan flexibility of space [Khan, 1998]. In the sense of earthquake resistant design, a correctly designed frame structure with ductile frame joints could provide adequate safety during a strong earthquake. However, if vertical continuity is not enforced, such systems might introduce a weak or a soft storey, which could be a potential threat during a strong earthquake. Such structures have been widely used from the beginning of the 20th century up to today, although they have been developed mainly in non-seismic regions.

The beginning of the 20th century represents a period when the classical approach to architecture still prevailed; however, new materials and structural systems were often hidden behind lavish decoration. During this period, architects such as Gaudi, Horta, Berlage, Sullivan, Perret and others tried to do pioneer work in promoting new materials and knowledge, and in doing so their work indicated an entirely new period – modernism, which established itself a decade or two later. Thus their work can be called proto-modern.

With the development of seismology the first rules for construction in seismic areas started to be formed. This development took place in the shadow of the upcoming progress in the architecture of modernism as it can be seen from the realizations of the most important and influential architects of that time: F. L. Wright, Le Corbusier, Mies van der Rohe and others.

THE BEGINNING OF THE 20TH CENTURY (MODERN ARCHITECTURE AND INTERNATIONAL STYLE)

POČETAK 20. STOLJEĆA (MODERNA ARHITEKTURA I INTERNACIONALNI STIL)

The period of Modernism substantially changed the existing principles in architecture and art as well. The emerging architectural style brought clearly expressed structural aesthetics into force, which were based on a structural logic. We mention a few architectural and structural principles of the period, which express a special approach and control over structural design.

Le Corbusier – Columns and flat slabs without any beams were accepted as a new struc-

26 BOESIGER AND GIRSBERGER, 1999

27 This is a frequent principle in his works, where he condensed the bearing elements, fireplace, staircase etc., at the centre of the floor plan, and arranged rooms around this ”core” many times as long consoles (e.g. Waterfall House).

28 BLASER, 1993; FRAMPTON, 1995

29 In architecture the expression ”internationalism” was first used by Walter Gorpius in the work entitled ‘Interna-

tural form, which played a dominant role as a major element of architectural expression.[26] This kind of simple structural logic was first used by Le Corbusier in his patented Dom-Ino house in 1914 (Fig. 8).

Le Corbusier triggered a revolution by designing the first free/open floor plan that did not include any walls or other elements to sustain horizontal loads. The concrete slab supported only by concrete columns offers very low load carrying capacity for horizontal loads, since the joint rotational capacity is crucial for sustaining the horizontal loads. Furthermore, if walls are added only in the storeys where they are needed due to architectural functionality (usually the upper storeys), the building system becomes a soft storey building that might generate excessive damage during a strong earthquake (Fig. 9). This system was later frequently and uncritically transferred to all regions all around the world regardless of the seismic risk in a particular location.

Le Corbusier, who was devoted to the concept of "volumes bathing in light", designed buildings with free ground storeys, where all the loads were supported by specially designed single-storey frames, as can be seen in the building *Unite d'Habitation*, built in 1946, where he achieved the effect of a transitional ground floor with an extremely powerful transverse structure, which also follows the shape of moments induced by horizontal loading (Fig. 10).

F. L. Wright – The American architect F. L. Wright in his projects often created the principle of structure with a central core,[27] which offers adequate horizontal stiffness of a building in the case of a symmetric arrangement of structural elements. The wish for a wide, low and horizontal division of the façade made it necessary to reduce vertical elements along the outer edge of a building, which he then moved towards the inside (e.g. Johnson Wax Building – Fig. 11). Very long cantilevers might result in a torsionally weak structural system that can experience large torsional rotations and damage on the perimeter as well as in the core shear walls during a strong earthquake. Even though his buildings were erected in areas with a low earthquake risk, they represent extremely influential architecture which should not be copied (or transferred in principle) to earthquake prone areas.

L. Mies van der Rohe – Special treatment of structural logic which explicitly defines architecture is also typical of Ludwig Mies van der Rohe.[28] He was also fond of free floor plans; with skyscrapers (e.g. Seagram building) he used steel columns with concrete encasing (better compression characteristics) in combination with strong central cores, as in the example in Fig. 12. Horizontal stiffness is also often questionable with these buildings, since there are practically no transversal stabilization elements. All horizontal forces are sustained by the flexural capacity of the fixed based columns.

International style – Architecture of the modern period and its derivative, the aforementioned International style,[29] favours a technologically clear approach and structural logic, where the elegance of the buildings is assured with slender columns and massive, clear horizontal slabs, which create the effect of a floating storey. Unfortunately, these principles in many cases completely contradict regular earthquake resistant design. The International style still has a strong influence on the architecture of today. C. Arnold establishes that "in much everyday commercial architecture, evolved forms of the International Style still predominate".[30] The International style which originated in the concept of modernism has preserved its legitimacy until today, presented in many forms or newer styles (high-tech, minimalism, critical regionalism, new complexity etc.).

Le Corbusier, Mies van der Rohe and many other architects of the last century (Perret, Gaudi and Wright and also Loos, Wagner, Gropius, Saarinen, Aalto, Kahn, Niemeyer etc.) had a significant influence on the architecture of modernism and all later periods until today. It is important that new generations of architects are aware that many structures of great architects of the last century

Fig. 9 Le Corbusier: Swiss pavilion at Cite universitaire in Paris with a passage in the ground floor as an example of a potential soft storey building

Sl. 9. Le Corbusier: švicarski paviljon u Cite universitaire u Parizu s prizemnim prolazom kao primjerom zgrade s potencijalnim mekim katom

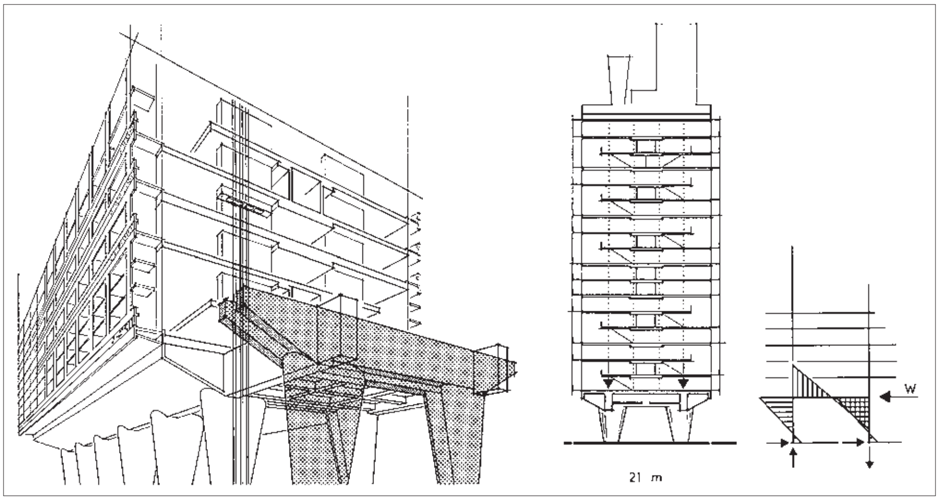


Fig. 10 Le Corbusier: Bending moments and structure of a residential house with a ground passage – the structure follows the moment shape due to horizontal loading

Sl. 10. Le Corbusier: moment savijanja i konstrukcija stambene kuće s prizemnim prolazom – konstrukcija prati oblik momenta zbog horizontalnog opterećenja

tionale Architektur', which he edited for Bauhaus in 1925. This work presents an extensive overview of the architecture of that time, and the author separately treats the characteristics of modern architecture, as international and not connected to space or culture. According to the definition, the international style lasted from 1925 to 1965, however, it continued to be used as a model for modern architecture until the late 1980s (Khan, 1998).

30 Arnold, 2001

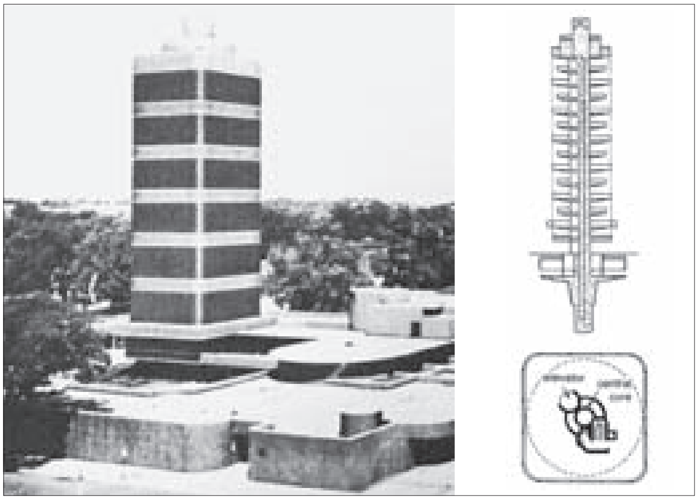


Fig. 11 F. L. Wright: Johnson Wax Building, 1939

Sl. 11. F. L. Wright: Zgrada Johnson Wax, 1939.

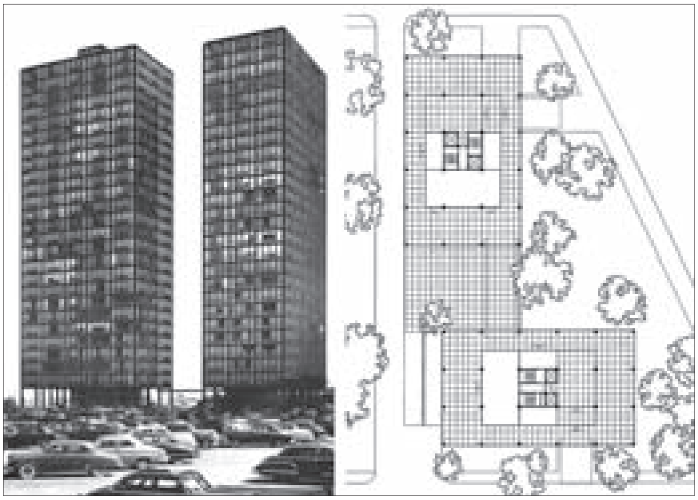


Fig. 12 Mies v.d. Rohe: North Lake Shore drive apartments in Chicago (1948-51) and plan of the ground floor with symmetrically positioned shear walls

Sl. 12. Mies v.d. Rohe: stanovi u ulici North Lake Shore Drive u Chicagu (1948.-51.) i tlocrt prizemlja sa simetrično postavljenim posmičnim zidovima

are built in areas with no earthquake activity and at a time when earthquakes and their impact on buildings had not been researched as well as today. The controlled ductility of a structure as a whole was in most cases not ensured. Horizontal stiffness of buildings was suitable mainly to resist wind loading, which presents significantly less powerful forces and completely different frequencies of oscillations and accelerations. With the first recommendations for construction and with the regulations which started to appear as late as the mid 20th century, the design of buildings to withstand earthquake forces became an obligation required by law.

The 20th Century and Post-Modern Periods

20. stoljeće i razdoblje post-modernizma

The period after the Second World War was the time of the renovation of society and the built environment in general, which was characterized by rapid progress in the methods of structural engineering analysis and the development of computer technology and computer programs that enabled the analysis and design of much more elaborate structural systems with greater accuracy and trust level. This was also the time of the rapid development of building codes and when the first codes for earthquake resistant design were issued. Though it seemed that the roles of an architect and structural engineer were further apart than ever, this period gave rise to building design geniuses that unified the role of an architect and structural engineer in one person. Architect-engineers, such as P. L. Nervi and later F. Otto, O. Arup, S. Calatrava and others prove that the unification of engineering skills and a sense of architecture is possible or even inevitable.

Post-modernism – Aesthetic rules of international style – especially glass-steel cubic buildings – faced harsh criticism in the mid 1970s. Later, in the 1980s, this criticism was realized in the architectural style more widely known as 'post-modernism'. Among other characteristics, the post-modern period typically used classical structural forms, such as arches, decorative columns, pitched roofs in non-structural ways and generally in simplified variations of the original elements and a return to symmetry in configuration. In seismic terms, these changes in style were, if anything, beneficial.

As S. Lyall established; towards the end of the 20th century constructors became more than just "under-acknowledged servants of the art of construction".[31] Analysing and solving complex non-orthogonal structural forms

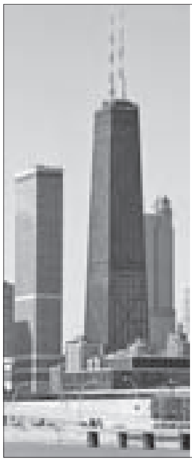


Fig. 13a John Hancock centre in Chicago (1966); architecture: B. Graham, structure F. Khan

Sl. 13a. Centar John Hancock u Chicagu (1966.), arhitektura: B. Graham, konstrukcija: F. Khan

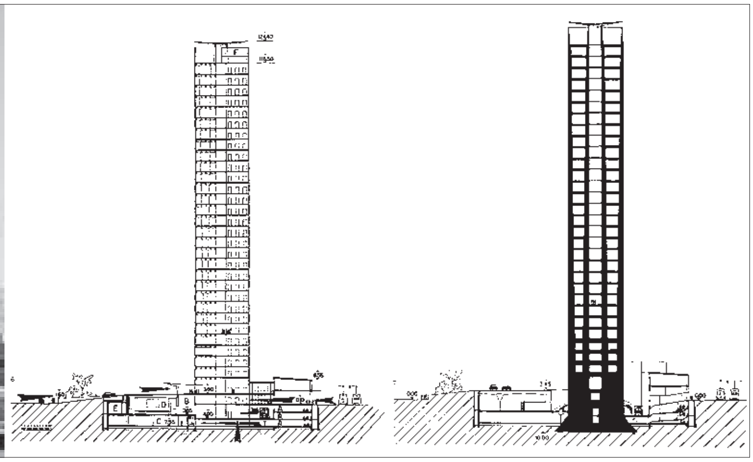


Fig. 13b Pirelli building, (1955-59); architecture P. L. Nervi and Ponti & Rosselli. The increase of structural "density" towards the base of the building is clearly visible

Sl. 13b. Zgrada Pirelli (1955.-59.), arhitektura: P. L. Nervi i Ponti & Rosselli. Vidljivo povećanje „gustoće" konstrukcije prema temeljima građevine

31 Lyall, 2002

32 i.e. Kilar and Koren, 2009

became usual and familiar for them. The trend turned towards non-orthogonal shapes such as 3D trusses, thin shells, thin membranes, curved surfaces and inflated and geodesic structures. New and unusual materials were used: wooden fabric, cardboard tubes, titanium, high-quality materials, polymers and also glass. The result was a complex structural typology, often free in shape, which could be analysed only with the help of computers and with tools developed particularly for this purpose.

Computer aided design (CAD) – For certain new structural systems engineers discovered in the middle of the last century that the existing methods of analysis and dimensioning were not reliable enough. Novelties in construction and structures required expert studies or research on actual models which were used to create or check suitable analytical methods.[32] The result of computer generated design is usually a three-dimensional unique structure, which follows the transmission of loads and tectonics. Such an approach became a reality with all more or less complex achievements and presented a vision of the future development of architecture and structures (Fig. 14).[33]

Today, the separation between a structural engineer and an architect has moved the professions even further apart. A combination of both kinds of knowledge is the rare and special quality of certain individuals or well-coordinated teams. The most prosperous seem to be the formations of teams of designers, who together with constructors harmonize structural solutions, taking into account the regulations and requirements of earthquake safe design (e.g. Eurocode 8).[34]

Conclusions

Zaključci

The article quotes certain examples, authors and general architectural practices from individual periods of the last two centuries to present the development of structures and architecture through the prism of earthquake resistance. Increasingly more daring and slender structural designs have also conditioned an increasingly consistent and rational approach to the stability and firmness of buildings. Earthquakes as a loading on buildings have only been dealt with scientifically in approximately the last hundred years; before that, builders first intuitively and later through experience and with simple observation of the behaviour of structures under horizontal loading, already introduced certain measures for ensuring the horizontal stiffness of buildings. Earthquake safe design with an adequate degree of reliability was only possible with the development of seismology and later, through adopted standards and regulations in the mid 20th century, and also with the development of earthquake engineering.

It is obvious from the analysis of the relationship development between architecture and earthquake engineering (and also engineering in general) that a special earthquake-engineering aspect was formed with a considerable delay and with its own specific dynamics, which to a large extent suited the development of building regulations and standards. Exceptional examples of realized buildings, which presented novelties from the viewpoint of structure and architecture, had a strong influence on the development of earthquake resistant structures and architecture in the context of seismic resistance. Historically this aspect was not consciously and systematically defined until the middle of the last century, but we can nevertheless notice in these periods many intuitively introduced measures for increasing lateral stiffness and resistance to earthquake forces.

We can conclude that the period of intuitive, experience-based approach to designing earthquake resistant structures ended in the first decades of the 20th century, when earthquake engineering started to be developed together with the development of seismology. Despite scientific and rational approaches to designing earthquake resistant structures and with the use of powerful computer tools, intuitive perception of the problem together with the treatment of experiences from earthquakes is still the key element in designing adequate earthquake resistance in architecture. Tectonic design with an essentially regular structural system and unambiguous loading paths is still the basis of quality architecture in earthquake prone areas.

An important additional conclusion of the article is also that the most effective structural solutions together with quality architectural realization are most often a consequence of good cooperation between architects and engineers. Due to the mere complexity of construction and architecture, we need to focus on improving cooperative skills among engineers and architects and deepen experiences which enable engineers to understand the essence of architecture, and which bring the meaning of structure closer to architects in such a way that it remains the basis of their tectonics and with it architecture itself.

[Proofread by: Peter Waller]

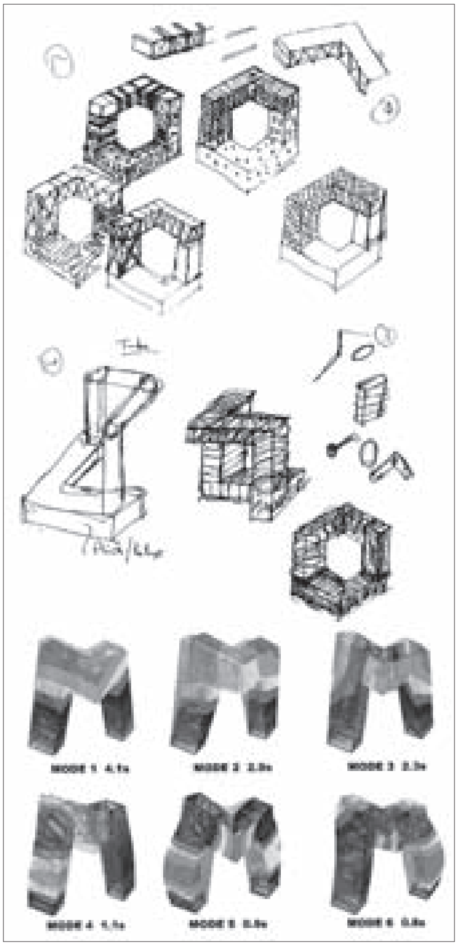


Fig. 14 Computer based design enables the transfer from a simple sketch to the structural model. Building CCTV, Beijing; architecture: Rem Koolhaas, structure: ARUP Group

Sl. 14. Računalno arhitektonsko projektiranje omogućuje prijelaz od jednostavne skice do konstrukcijskog modela. Zgrada CCTV, Beijing; arhitektura: Rem Koolhaas, konstrukcija: Grupa ARUP

33 Zaera-Polo, 1993
34 Slak, Kilar, 2007

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Sources

Izvori

Illustration sources

Izvori ilustracija

Fig. 1	New York Times, March 3rd, 1869
Fig. 2	Left: T. Slak; right: Middleton, Watkin, 1980
Fig. 3	Saint, 2008; Peters, 1996
Fig. 4	Durant, 1994
Fig. 5	Hix, 1996
Fig. 6	Lemoine, 1988
Fig. 7	Hatje, 1970; http://hi.baidu.com/rouni/blog/item/751a890117c013d2277fb533.html
Fig. 8	Boesiger, Girsberger, 1999
Fig. 9	Boesiger & Girsberger, 1999
Fig. 10	Sandaker, Eggen, 1992
Fig. 11	Sandaker, Eggen, 1992
Fig. 12	Blaser, 1993
Fig. 13a	http://www.skyscraperpicture.com/chicago16.jpg
Fig. 13b	Rogers, Joedicke, 1957
Fig. 14	Glancey, 2007

Summary

Sažetak

Razvoj potresne otpornosti u arhitekturi – od intuitivnog do inženjerskog pristupa

Konstruktivna logika predstavlja čest izvor inspiracija arhitektima svih stilskih razdoblja. No, osim vertikalnih opterećenja, potresima, kao vrsti opterećenja na građevine, znanstveni krugovi se bave tek posljednjih stotinu godina. Prije toga su građevinari uglavnom izvodili mjerenja kako bi osigurali horizontalno ukrućenje objekata, prvotno uglavnom intuitivno, a kasnije iskustveno i putem jednostavnih ispitivanja ponašanja konstrukcije pod poprečnim opterećenjem.

U članku se istražuje razvoj projektiranja arhitektonskih konstrukcija otpornih na potrese u potresnim područjima u rasponu od prvotnih, uglavnom intuitivnih mjera poduzetih radi postizanja horizontalnog ukrućenja objekata sve do 20. stoljeća, kada se utjecaj potresa na građevine uključuje u standarde i propise za projektiranje suvremenih konstrukcija otpornih na potrese. Autori su člankom pokušali predstaviti razvoj konstrukcija i arhitekture kroz prizmu potresne otpornosti.

Namjera je autora analiza razvoja odnosa između arhitekture i građevnih konstrukcija otpornih na potrese u vrijeme kada je potresna otpornost počela igrati sve veću ulogu u arhitekturi. U članku se također proučava utjecaj konstrukcijskih sustava i upotreba materijala poput željeza, čelika i armiranog betona na razvoj građevina otpornih na potrese. Daje se kronološka analiza i prikazuju odabrani istaknuti primjeri graditeljstva koji svjedoče o konstruktivnoj i/ili arhitektonskoj novini važnoj za daljnji razvoj odnosa između arhitekture i gradnje koja osigurava potresnu otpornost. Posebno su istaknuti primjeri u kojima su arhitekti ili građevinari bili u mogućnosti odrediti arhitektonsku strukturu samo na temelju principa konstrukcijske logike. Važnost tektonike u oblikovanju konstrukcije i kompozicije u potresnim područjima se razvijala kroz dugi niz godina prvenstveno putem iskustva i proučavanjem oštećenja nastalih nakon jačih potresa. Početna, najvećim dijelom intuitivna i podsvjesno razmatrana potreba za logičnim tektonskim projektiranjem i horizontalnim ukrućenjem dovela je do logičnih rješenja, koja su se kasnije proučavala tijekom potresnih aktivnosti te su prihvaćena kao opći principi potresnog inženjerstva, a danas se još uvijek koriste u graditeljstvu. Autori se u članku bave arhitekturom poglavito s pozicije osiguranja od potresa i projektiranja, koje (iako predstavlja posebno područje) naglašava inženjersku komponentu arhitektonske djelatnosti i pokazuje odnos arhitekta i konstrukcijskog inženjera.

Člankom se dokazuje da je osjećaj konstrukcijske stabilnosti usavršavan tijekom dugog razdoblja putem iskustva i da je na isti način rasla važnost i osjećaj za tektoniku kao umjetnost konstruiranja. Proučavanjem horizontalnog ukrućenja i otpornosti objekata autori su ustvrdili da je adekvatnost tektonike kao temelja svake arhitektonske djelatnosti bez obzira na faze gradnje (što znači od samog početka gradnje) uvijek dobrodošla te da u arhitekturi uglavnom nastaje iz intuitivne, te stoga iracionalne težnje, koja, unatoč tome, daje konkretne rezultate: stabilne konstrukcije bez posebnih nepravilnosti i/ili slabosti. U prvim desetljećima 20. stoljeća potresno inženjerstvo je započelo razvoj paralelno s razvojem seizmologije. Unatoč znanstvenim i racionalističkim pristupima projektiranju konstrukcija otpornih na potrese i upotrebom utjecajnih računalnih pomagala, intuitivno uviđanje problema, zajedno s iskustvom dobivenim tijekom potresa i dalje ostaje ključni element adekvatnog arhitektonskog projektiranja građevina otpornih na potrese. Tektonika u arhitekturi i projektiranju konstrukcija s više ili manje pravilnim prijenosom (potresnih) sila na temelje još uvijek čini osnovu za kvalitetna arhitektonska djela u potresnim područjima.

Člankom se također želi pokazati da je u odnosu na konstrukciju razdioba profesije na građevinsko inženjerstvo i arhitekturu stvorila nove odnose čija se karakterističnost posebno vidi kod potresne otpornosti budući da je profesija bila podijeljena od samih početaka proučavanja potresa. Posebni primjeri moderne arhitekture koji su primijenili potresnu otpornost u osnovne arhitektonske principe i dalje su istaknuti primjeri koji dokazuju da u potresnim područjima osjećaj za odgovarajuće projektiranje arhitektonskih djela otpornih na potrese sve više jača, zajedno s razvojem potresnog inženjerstva. Danas se, dakle, trebamo usredotočiti uglavnom na unapređivanje sposobnosti suradnje i produbiti iskustva koja omogućavaju građevinarima da razumiju suštinu arhitekture, i koja značenje konstrukcije približava arhitektima na način da tvori temelj njihove tektonike, a time i same arhitekture.

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Biographies

Biografije

Tomaž Slak, Dipl.Eng.Arch., graduated in 1998 on the Faculty of Architecture in Ljubljana, where he attained his Master's degree in 2004 and his Ph.D. in 2010. Since 2000 he works on the Faculty of Architecture in Ljubljana. His research is primarily oriented on architecture and earthquake engineering, with emphasis on the problematic of earthquake resistant design of structures in architecture. Since 2004, he investigates the special interdisciplinary field: earthquake architecture.

Vojko Kilar, Dipl.Eng.Arch., graduated in 1988 and was given the Fulbright grant in 1994/95 in New York, USA. He received his Ph.D. in 1995 at the University of Ljubljana, Faculty of Civil and Geodetic Engineering. Since 1995 he works on the Faculty of Architecture in Ljubljana, since 2005 as associate professor. His research is primarily oriented on earthquake engineering and nonlinear static/dynamic analysis of building structures. Since 2000, he focuses his research also on the problematic of inclusion of earthquake resistant design rules in preliminary design of structures in architecture. Since 2005, he investigates also the effects of seismic isolation and other technological systems for general increase of building safety in earthquake-prone areas.

Tomaž Slak, dipl.ing.arh., diplomirao je 1998. na Arhitektonskom fakultetu u Ljubljani, gdje je magistrirao 2004. te doktorirao 2010. godine. Od 2000. godine radi na Arhitektonskom fakultetu u Ljubljani. Poglavito se bavi istraživanjem arhitekture i seizmičkog inženjeringa s naglaskom na problematiku projektiranja arhitektonskih konstrukcija otpornih na potrese. Od 2004. godine radi na istraživanju posebnoga interdisciplinarnog polja seizmičke arhitekture.

Vojko Kilar, dipl.ing.arh., diplomirao je 1988. godine te boravio u New Yorku 1994/95. god. na Fulbrightovoj stipendiji. Doktorirao je 1995. na Građevinsko-geodetskom fakultetu Sveučilišta u Ljubljani. Od 1995. radi na Arhitektonskom fakultetu u Ljubljani. Izabran je u zvanje izvanrednog profesora 2005. Istraživanja su mu orijentirana ponajprije na seizmičko inženjerstvo i nelinearnu statičko/dinamičku analizu građevinskih struktura. Od 2000. fokusira se na istraživanje problema uključivanja pravila projektiranja objekata otpornih na potrese u idejne projekte arhitektonskih konstrukcija. Od 2005. također se bavi proučavanjem djelovanja seizmičke izolacije i drugih tehnoloških sustava za općenito povećanje sigurnosti građevina u potresnim područjima.