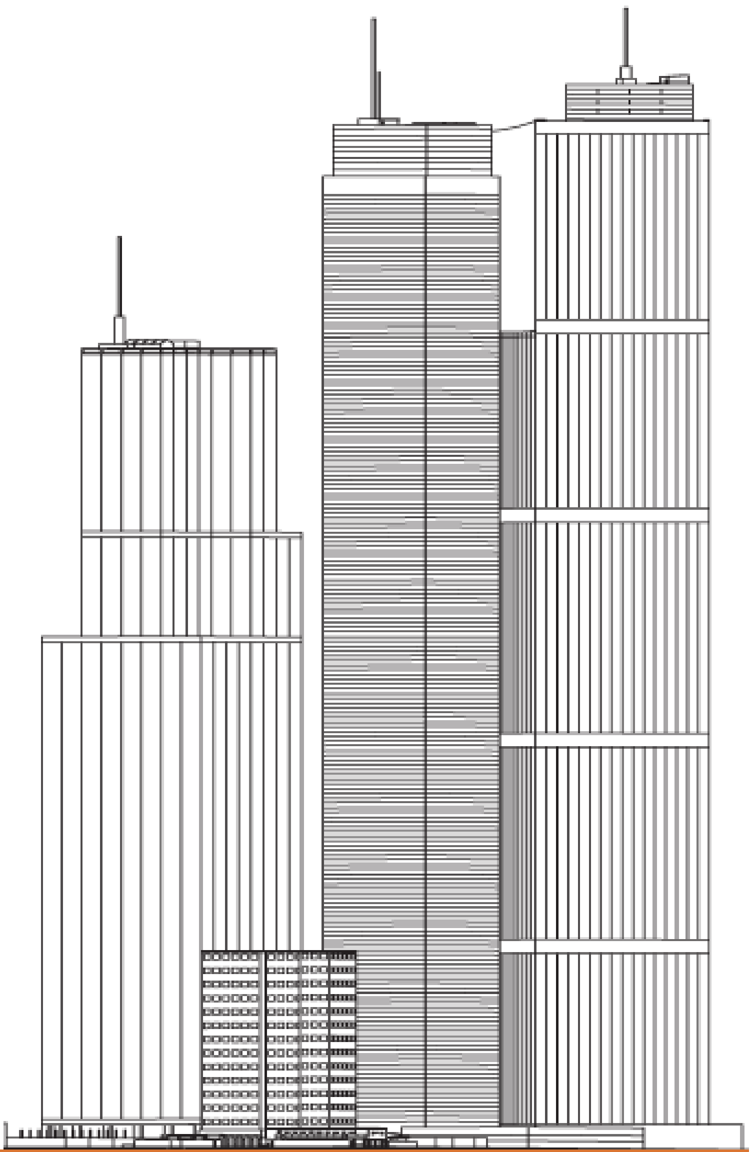
HIGH-RISE BUILDINGS
STRUCTURES AND MATERIALS

ILDA KOVAČEVIĆ | SANIN DŽIDIĆ



SARAJEVO, 2018

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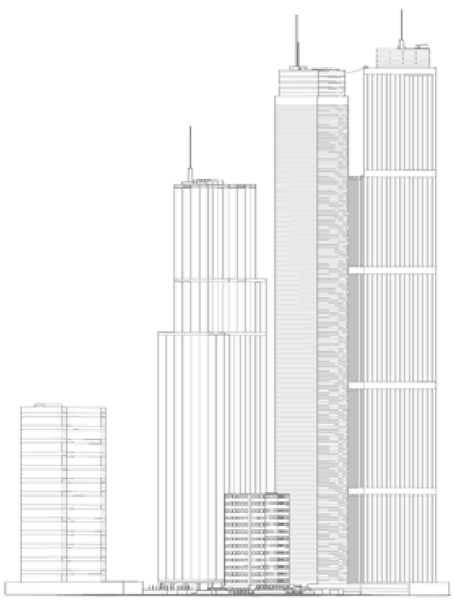

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PREFACE

High-rise buildings present a challenge; they present a challenge for architects, engineers, occupants as well as observers. They attract the viewer's eye. They are our monuments and often become city landmarks and tourist attractions. City views from the tops of the buildings are also extremely appealing. People either praise them or criticize them, but they are indeed an important part of urban landscape in every modern city. They are here, present, and can be found in every metropolis or city that intends to become one. Sometimes they stand in awe, and sometimes they stretch above. For all they are, or for all they are not, their builders are the culprits responsible for these magnificent structures.

This book is the result of a serious research, and it is intended to become a textbook for the "High-Rise Buildings" course held at the Master's Degree Program at the Department of Architecture at the Faculty of Engineering and Natural Sciences of the International BURCH University in Sarajevo. However, students of other architectural faculties or departments of architecture, students of structural engineering, as well as architects and structural engineers in design and construction themselves may find this book helpful. Parts of the book, or the entire book may also be of interest for a common reader.

As the human body is composed of brain, skeleton, muscles, organs, blood and nervous system, all of which have their own functionality and appearance, the organism we call a high-rise building is also composed of load-bearing structure, different materials applied, and various embedded functional systems that allow for comfort and serviceability of these structures. Their appearance catches the observer's eye and causes different emotions; sometimes these emotions are positive, sometimes not so much, but essentially everything that initiates any emotion in a person becomes a truly memorable experience.

This book attempts to simultaneously analyze high-rise buildings from several aspects - form, appearance and beauty, and in the next step, their architectural and structural functionality and comfort. But no project is possible without the actual materialization and functional load-bearing structure. Like a human being, each building has its own requirements and expectations, as well as its needs to properly behave in dangerous situations that may happen in one's lifetime, or in the case of buildings, in a service life. Every high-rise building should adequately respond to common situations, and those that are not so common, but also be prepared to those that are entirely unexpected. This book will try to explain the symbiosis and causative consequential relationships and synergy of architecture, load-bearing structure and applied materials. If this synergy did not exist, it would be difficult to talk about a successful *project, but if it existed, then the story about that building would be shared and passed on.*

Readers of the book will decide if we succeeded in our attempt; if we contributed to the improvement of one's knowledge in this field of expertise, then we succeeded as authors. If we caught up your interest in the subject, we did it again. If not, forgive us, because we had the best possible intention of doing so. However, we will look for the opportunity to improve and redeem ourselves through some other future projects.

We use this opportunity to thank our reviewers for their remarks, recommendations and suggestions. We'd like to thank mr. Elmir Halebić for the design of the book cover, and also to everyone who has in any way contributed to the process of publishing this book, at the mutual pleasure of readers and authors.

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INTRODUCTION

Race and desire in constructing tall and high exist since periods of early civilizations. The architectural heritage and remains from early civilizations, are undeniable evidences that constructing high and massive is not innovation and reflection of the contemporary society. Looking back at Egyptian pyramids, Greek and Roman temples which introduced high, massive columns, human desire to express the power and wealth through building high and tall continued with European churches, towers and castles back in Late Middle Ages and Renaissance period lasting up to the contemporary ultra–high–rise buildings and skyscrapers. However, turnkeys for high–rise buildings we are familiar with, were innovation of the mechanism for safe vertical transportation-elevator and new structural materials in late 19th century. Since late nineties of the 19th century and early twenties of the 20th century, high–rise buildings and structures are becoming daily challenge and new direction for architectural, constructional and material technology development. For contemporary societies worldwide, high–rise structures are becoming common thing and inevitable part of new living style. Whether high–rise buildings function as commercial, residential or educational use of these forms of vertical architecture is becoming more and more popular.

> *"Today it is almost impossible to imagine a major city without tall buildings. As the most important symbols of today's cities, tall buildings have become a source of faith in technology and national pride, and have changed the concept of the modern city along with its scale and appearance. Despite the fact that tall buildings have moved city life away from the human scale, in general it is accepted that these buildings are an inevitable feature of urban development."* [14]

Even though, high–rise buildings occupied architectural and construction scene and do play an important role for solving excessive land consumption problems and problems of accommodation in overpopulated zones, architectural critic are generally describing high–rises as gigantic hazards in urban areas and tools to show off the prestige, power and wealth; which do create environment oversized if compared to human scale and do cause harmful influences on environment. As everything, high-rise buildings do have its advantages and disadvantages, but one is sure, high–rise buildings are accepted by mass population. It is common for every urban area to have structures and buildings which are characterized as high–rise because they outstand among other buildings in surrounding, primarily by height.

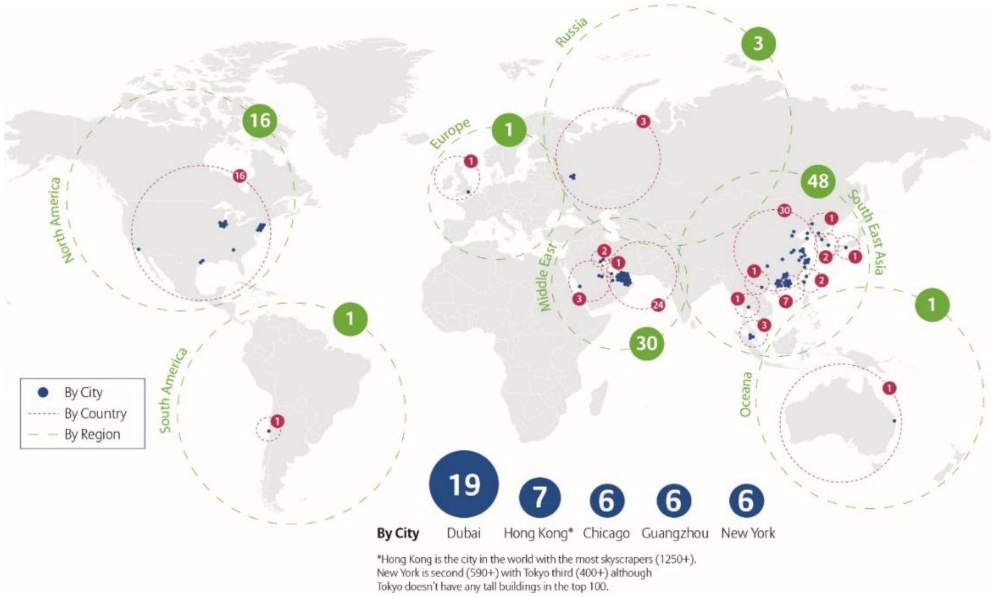

Figure 1 – Around the World in Tall Buildings – Current Location of the Top 100 [94]

High–rise buildings are landmarks of the present and do form urban identity in form of grandiose unique skylines. However, not always high–rise buildings are to be successful, whether failure may happen during construction or service life of the structure. Thus, along with increase in building's height, breath-taking futuristic architectural forms and concepts, awareness of necessity for highly advanced structural systems and materials in order to respond greater loads increases as well. Those advances sought for higher safety, stability, resistance and prevention of possible progressive collapses due to possible accidental occasions.

In terms of these advanced technologies, high–rise buildings were celebrated on the cast iron and steel load–bearing structural elements which were designed to form rigid frame. More slender structural elements, larger spans more open floor plans presented steel as material of future, while concrete as structural material was at the beginning mostly excluded as option in structuring of high–rises. Neither concrete's high fire resistance, nor its high resistance to very aggressive environments, abrasion and corrosion could overcome the problem of large and massive structural elements, in the eyes of the architects, designers etc.

Early advanced technological developments and experimental studies tried to overcome the problem of massiveness of the concrete structures and at the end of the day all efforts resulted in form of material with better properties with focus on compression strength. For better understanding, at that time, the concrete with greater strength, high–strength concrete, referred to the concrete's with compressive strengths up to 35 – 51 MPa. Even though, nowadays, such compressive strength is considered as conventional normal strength concrete, than it was sufficient to initiate use of the concrete in structuring high–rise buildings. Second half of the 20th century, was the period of both structural materials steel and concrete development. In this period upgrading weaknesses of one material with powers of another one, developed new concept of composite steel–concrete structures. Steel, high–strength concrete and composite materials, were three subjects to material technology development in structuring of high–rise buildings. At the same time, keeping up with newest technological achievements of material, structural engineers, architects and designers were developing numerous different structural systems which could relate between desired heights and environmental conditions which causes the most severe loads for high–rise buildings (wind load, seismic actions, etc.). However, real turnover in structuring of high rise buildings whether it is about structure or structural material happened at early 21st century. Unfortunately, fires that affected few of the world's famous and the tallest high–rises in large scale showed weaknesses of steel structures. Rapid progressive collapse, material used which had low fire resistance, insufficient time for secure evacuations resulted in irreplaceable losses. These events, exposed one of the concrete's greatest advantage in high–rise resistance and initiate greater use of the concrete, and high–strength concrete for structuring of high–rises.

Nowadays, around developed urban areas which are living high–rise, there are concrete plants which daily produce concrete with compressive strengths up to 95 MPa.

Bosnia and Herzegovina and Balkan area were undergoing rapid urbanisation and development during late fifties and early sixties of the last century. Sarajevo, Zenica, Tuzla, Bihać, Mostar were enriched with numerous high–rises. Unlike World's scene where the high–rises represented office and commercial blocks, high–rises in former Yugoslavia were strictly functioned as residential with few exceptions, and generally were structured with concrete. For the country at the beginning of industrialisation process, where large migrations were toward urban zones, high–rise residential settlements were logic solution to prevent excessive land consumption and to form urban and spatial plans. The last war (1992–1995) stopped technological development in all fields in Bosnia and Herzegovina, and the years after the war were dedicated to reconstructions and repairs of damaged buildings, infrastructures etc. High – rises suffered many accidental impacts during the war years. However the resistance of concrete structures, largely saved many buildings.

Lately, Bosnia and Herzegovina is being enriched by new samples of the high–rise buildings with more architectural valued high–rises. However, low material technological development is not enabling the possibility for any of futuristic worldwide seen structures. Structural engineers, architects and designers in Bosnia and Herzegovina are still rather choosing the concrete than any other material, but concrete technology is still remaining at conventional–normal strength concrete. Thus, there are numerous rigid frame structures with oversized columns, beams, and overuse of raw material, meaning on aggregate, cement, and superplasticizer while there are domestic materials which are sufficient for the first researches on high–strength concrete and later on productions. Presently, there are numerous easy ways to find out about newest technologies and knowledge. This book is being concerned at the high–rise buildings, from what are the most successful high–rises worldwide, its structural, architectural, mechanical design, its resistance as physical object in different environments, at different loadings and actions to the situation in Bosnia and Herzegovina and ability to catch up with new concrete technologies using domestic materials.

Concepts and forms of the high–rise buildings are under constant change. Specific and detailed analysis of phenomena, high–rise buildings, rises different questions, opinions and understandings, both supportive and those critical ones. Along with the idea of high–rise buildings, there is mostly dose of scepticism after announcement of its primary design due to oversize when compared to human scales. However high–rise buildings are widely becoming accepted as part of the lifestyle and represent great urban development, national pride and construction, which is undoubtedly environmental friendly and efficient at least in decrease of land overconsumption.

Even though this book is concerned on contemporary high–rise building's structures and material technology development, it also includes historical analysis of what, when and how society ended up with these monumental structures.

According to the short documentary published by New York Times "A Short History of the High-Rises" by Katerina Cizek, the historical analysis of high–rise begins back in 2500 BC. This documentary contain four parts "Mud", "Concrete" , "Glass" and "Home", which express the power of vertical living and variety in materials used for high-rise construction from mud and dusty sands in Yemen to advanced high–strength materials (steel and concrete) with curtain glass walls all around the world. Documentary *"A Short History of High-Rises"* gave excellent insight toward phenomena of high–rise buildings.

However, turnkey for high–rise buildings and forms we are familiar with nowadays according to Mark Sarkisian are large fires which burnt large area of the Chicago and initiate diverse thinking in both designs and technologies. In his book, "*Designing Tall Buildings, Structure as Architecture"* he wrote:

> "*The fire of 1871 devastated the city of Chicago but created an opportunity to re-think design and construction in an urban environment, to consider the limits of available, engineered building materials, to expand on the understanding of others, and to conceive and develop vertical transportation systems that would move people and materials within taller structures.*" [33]

To enrich the collected data with situation in the area of Bosnia and Herzegovina, literature includes vision and perception of one of the most important modernist architect of former Yugoslavia, Ivan Štraus. His book, "*The Architecture of Bosnia and Herzegovina, 1945–1991*", [39] informs us about the most successful high–rise buildings in entire area of Bosnia and Herzegovina through this period. However, as the architect and architectural critic, Štraus had chance to choose those building which outstand among the others and represent valuable architectural object partially expressing subjective opinion. Such approach to analysis of architecture in Bosnia and Herzegovina was more than supportive for high–rises, because exactly high–rises were main tool for directing architecture and urbanism for the above mentioned period. Another source, which explains the historical development at the Bosnian territory, is *"Arhitektura Bosne i Hercegovine (The Architecture of Bosnia and Herzegovina)"* [27] by Prof. dr. Amir Pašić, which as the Štraus tended to explain how and in what directions Bosnian architecture and urban areas were developing during the 20th century.

Conducted historical analyses express rapid and advanced development of high–rises. By textual and visual sources, it is possible to analyse how societies worldwide were experiencing taller and taller structures year by year, and how the architects and engineers were pushing the limits of structural, mechanical and material technologies.

Each phenomena interconnected with high–rise building is subjected to *CTBUH, Council on Tall Building and Urban Habitat*. [106] CTBUH in criteria for defining and measuring of tall buildings, evokes the concept and form of the high–rise building, indicates architectural (form, concept and function), structural (structural systems, accent on specific actions on structure, structural material) parameters. Thus, to satisfy world accepted criteria, literature focuses on structural system, new actions and hazards to high–rise structures and as final ability in materialisation of the structure.

Classification of structural systems in high–rise buildings was initiated by Fazlur Khan, which considered height and structural efficiency. Such classification was not supporting rapid classification and variety of new systems. Thus in 1972/3 [1], he modified and delivered new classifications with accordance to the material used.

Unlike Fazlur Khan, Mir M. Ali and Kyoung Sun Moon, in their study "*Structural Developments in Tall Buildings: Current Trends and Future Prospects*" [1] invites the new way of understanding and analysing the structural systems. Key role in their classification was location of main structural system, where the structures can be interior or exterior. In catching up with contemporary trends and futuristic approaches, this classification on exterior and interior structures seems as updated, and shows Khan's classification as highly confusing and hard to incorporate with contemporary advanced material technologies which are more integrating composite structures, than steel or concrete individually.

Due to extreme heights, high–rise structures are to be well designed to give the occupants or inhabitants comfort and safety. Mehmet Halis Günel and Hüseyin Emre Ilgin, worked on book "*Tall Buildings, Structural Systems and Aerodynamic Forms"* [14] where main focus is at the power of the wind forces which are influencing the design and which require complex approaches and design to overcome possible displacements, bending or sway of the building. According to the authors, architectural design approach should be aerodynamic and structure based, structural approach should integrate the structures with mega columns, outriggers, mega come and tube systems as important as this two is mechanical approach which refers to damping systems for additional stability. M. H. Günel and H. E. Ilgin, developed the high–rise structuring with accordance to way of structure's responding to the loads and design ability and approaches to reduce load actions on structure. In their work materials do not play an important role which do not lead the structural development.

Although, statistical data which are mentioned in their book, taken from CTBUH, clearly show that concrete as structural material is overtaking steel's popularity. Such turnover in choosing structural materials happened at the period when steel showed its greatest weakness in fire resistance, at early 21 century. According to report, "*Tall Buildings and Sustainability"* [26], by authors Will Pank, Herbert Girardet and Greg Cox, concrete is leading material in structuring.

> *"Conventional–normal strength concrete which was initially use is extremely harmful for environment and is guilty for 5–7 percent of world's CO_2 emission. For instance 1 tonne of cement uses 4000–7500 MJ energy, and releases 1–1.2 tonnes of CO_2."* [26]

However if high–strength concrete is considered, with use of silica fume, fly ash or slag as substitute for cement then is a concrete much more environmental friendly. At the same time concrete has better properties to answer the needs for structuring of high–rises. As additional literature for deeper study on high–strength concrete is the book "*High–Strength Concrete"* [3], by Michael A. Caldarone, and "*Journal of Mechanical and Civil Engineering" Volume 10* [2], which discusses the high–strength concrete properties, mix and proportioning, constituent materials.

In Bosnia and Herzegovina there is not much interest, researches or studies on high–strength concrete. However there are highly qualified constituent materials which can be used for high–strength concrete, unfortunately those physical resources are still insufficiently used in Bosnia and are waiting on architects, engineers to take their advantageous properties.

HIGH – RISE BUILDNGS THROUGH WORLD ARCHITECTURE

Even in early civilisations, high–rise structures and buildings, represented the power, strength and development of the specific civilisation. Dating back to 2500 BC, high–rise structures originated in Egypt. High, massive structures, such as pyramids, were made for pharaoh's afterlife, in order to show off his greatness and power to his inheritors. Those pyramids, are nowadays taken as the greatest heritage of the Egyptian Civilisation to the field of architecture and they still raise many question about the way they were built and what the construction technologies and abilities Egyptians had in order to support such structures. Another historical and architectural achievement, world known and valued, high–rise readable structure, is the Colosseum, Rome.

Unlike the pyramids, the Colosseum's function was not to worship kings, rulers or God, but to serve and reflect the development of the society. It is also lower than the pyramids, but structural system, construction and architectural principles, are clearly defined, constructed and readable in scale of the Colosseum and are worthy of examining even today.

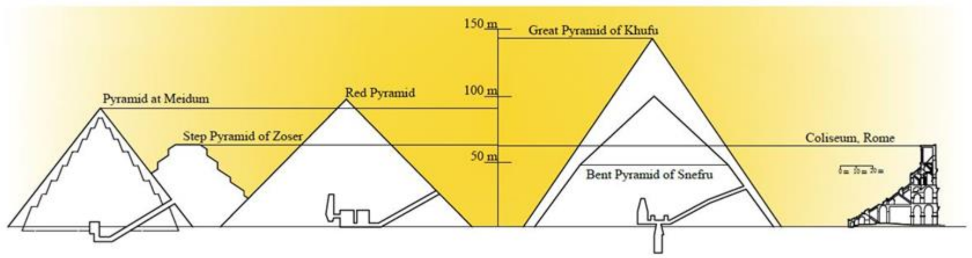

Figure 2 – Comparison of Historical High – Rise Structures, Pyramids of Giza and Colosseum, Rome

As already stated, the Colosseum was built for public use; new amphitheatre was built for public to enjoy the gladiatorial fights. The construction lasted for 10 years, which seems like a short period of time when we consider the building's structural system that has clearly defined columns, precise arches and exceptional openings–doors, with symmetrical and regular repetitions of the same which add a great value to the Colosseum. What makes Colosseum stand out from other structures from that period, besides the mentioned structural values, is its location. Located in Rome, Italy, Colosseum is situated at one of the highest seismic zones in Europe.

The most valued examples of the architecture through history are defined with inherited high–rise structures, which serve as the undeniable evidences that constructing upward, high, nearer to sky presented a mirror image of the greatness, wealth, strength, and the leader position. However, in the Late Middle ages and the

Renaissance, high-rise structures and buildings, were reserved only for the churches, mosques, observatory towers, castells etc. This leads to the conclusion that churches and other specific buildings were focal point, or monument of the specific area which could easily be seen from the distance.

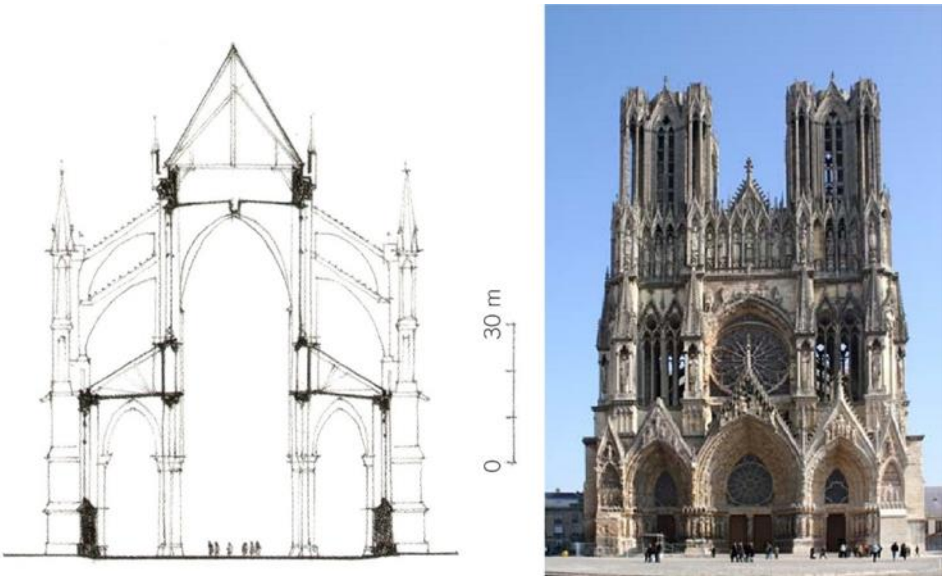

Figure 3 – Notre – Dame Cathedral, Reims, France 1211 – 1311 [108, 5]

While still meeting the accommodation needs, living spaces and business zones were constructed low–rise, and were spreading horizontally. Causes for such development and construction appear to be the lack of construction abilities, the lack of fast vertical communication through buildings, and fast evacuation which was impossible in the case of emergency.

Construction abilities and knowledge of the mid–19th century show the high–rise buildings as very expansive and impractical. Commonly used masonry structures were very rigid, with load bearing walls that were too thick at the lower floors because of the design structural elements that could transfer loads from higher floors. Clustered interior spaces that were produced by these massive structural systems made high rise buildings undesirable places to work in or live in.

Real turnover for the high–rise structures, which became high–rise buildings that humanity is familiar with nowadays happened with the introduction of steel structures. Load–bearing systems became much lighter in weight, and created open, breathable interior spaces, and also made facades of the buildings much lighter and more diverse. Former limits of construction were broken, making a complete shift and creating a new field for the architects, designers and engineers. Experiments with steel structured high–rise buildings started in the United States of America, in the Chicago School of Architecture. Filled with curiosity of what the abilities of this new structural material were, designers, architects and engineers, designed and constructed first high–rise building made entirely out of steel.

By making a brief skim through global history of architecture, it becomes clear that each great civilisation or each period of architecture has some remarkable monumental high–rise structure. It clearly shows that those high–rise structures and buildings are becoming closer and closer to the population as time goes by. Today the overall development of the high–rise buildings, both in design and construction, made high–rise buildings to become a new sustainable living style, solving the problems such as overpopulation, or lack of the horizontal space and area for spreading in the urban, metropolitan areas.

The analysis of the high–rise structures shows that even in distant past humans had a desire to build large and high. It does not matter whether we mention the pyramids in Egypt, thin towers which became focal points of the cities, Roman's amphitheatres, religious buildings such as churches and mosques, mansions of former leaders etc., it is clear that during the history, architects and builders tended to build as high and big as the circumstances allowed for.

The term high–rise building was first used to refer to tall building in Chicago. If we consider the pyramids in Egypt as one of the oldest high–rise structures which made Egypt as motherland of the high–rise structures, United States of America can be considered the motherland of the modern high–rise buildings, skyscrapers and tall skylines of the cities. The Great Chicago Fire of 1871 lasted for two days, burning down the whole city which was built out of wood; this event forced the technological development in construction and introduction of the new material, the one that could have better resistance in such situations.

Owners of the Home Insurance Building in New York City wanted a new office building in devastated Chicago, and they demanded high building that could accommodate numerous offices; the most important and greatest challenge for the construction was to find the material which would have greater fire resistance than timber has. The Chicago School of Architecture and the representative engineer William Le Baron Jenney designed a steel framed building for the contest and won it, primarily for the material's fire resistance properties. With this project and design, Jenney was the first to introduce and welcome steel structure to the world, publicizing the material that supported the first high rise building we are familiar with nowadays.

Home Insurance Building, Chicago, the first high–rise building, was a 10 storey building with steel framed structure. The whole building weighted one third than it would weight if it were made out of stone. In 1884–1885, Home Insurance Building, evoked scepticism with numerous experts, but nevertheless this building serves as the first example of such construction, and its' great design opened and forced a new movement in architecture and construction during the late 19th century and early 20th.

Figure 4 – First Steel Framed Skyscraper, Home Insurance Building, Chicago 1884-85 [155]

Since the high–rise buildings started to develop, the experts claimed Home Insurance Building as the pioneer in upward building; it represents a great achievement, and it is for sure the tallest structure of the period. However questions such as, *What is the high–rise building? What are the parameters?, What are the definitions of high–rise buildings?* remained. While there are different fields of expertise closely connected to this field of architecture and civil engineering, there are also numerous definition of the high – rise buildings with the shortest one stating that the high–rise building is a building that is 23 to 30 m high, depending on the floor height; that is 7 to 10 storeys building, where the height of the building can have a great impact on the evacuation.

The Home Insurance Building could be seen as a great breakthrough in the development of the high–rise structures from the design point of view; however the actual revolution happened with the growth of the construction technology, and with the development of the elevators and their improvement. Thus, the flourishing of the construction of the high–rise buildings may be defined through two main occurrences:

- The first occurrence may refer to the steel structures that replaced the heavy stone structures or the weaker forerunners of steel, cast iron and timber structures, which were thick and massive. Steel proved to be a much lighter material, more durable and more fire–resistant more than any other known material suitable for high–rise constructions. Due to its lightness, and at same time its stiffness, steel as a main structural material enabled buildings to be constructed higher than ever before;

- The second occurrence is the great innovation of the Elisha Graves Otis, the American innovator who invented the first safety elevator. Elevator as a main transportation in vertical direction enabled people to travel safely to upper floors and provided faster communication with higher floors, when compared to using stairs (walking).

Figure 5 – First Safe Elevator in Crystal Palace, E.G. Otis, 1853 [145]

Construction technology and architectural concepts, both in volume of the building and interior spaces, started to flourish after 1885. High–rise buildings became more available to the mass population; rapid and fast growth of the high–rise buildings dramatically changed the urban layouts through the cities of the United States of America, forming new skylines of the city. This period of the late 19th and 20th century, period of Modernism, might be seen as the Renaissance of the high–rise buildings.

North America experienced and forced this trend of high–rise buildings to the fullest, while Europe still tried to keep their traditional and historical landmarks.

Figure 6 – New York (up) Compared to Paris (down), Period of 1915 [69, 93]

While Europe tried to keep skylines and landmarks of their cities, few great European modernists were developing the idea of ideal cities; their concept included new designs of the cities filled with vertical buildings, and they were taking any chance they could to experiment and realize all the potentials of the upward building.

Le Corbusier, Swiss–French architect, created a hypothesis according to which buildings were nothing but sleeping machines. This meant that buildings were in a way like cars, whose main function was to transport people from one place to another, and to reduce time needed for travel.

Also, the buildings should not take up much space, but rather spread vertically and still serve their function. Le Corbusier, in his concept of Ideal cities designed the buildings as high–rise units, serving different functions, but strictly separated hotels, and business and residential buildings. This idea was different from what was actually happening in the cities of the United States and the Ideal city would have taken bigger area between the high–rise buildings, while across the ocean, high– rise buildings were growing uncontrollably, creating forests of the high–rise buildings.

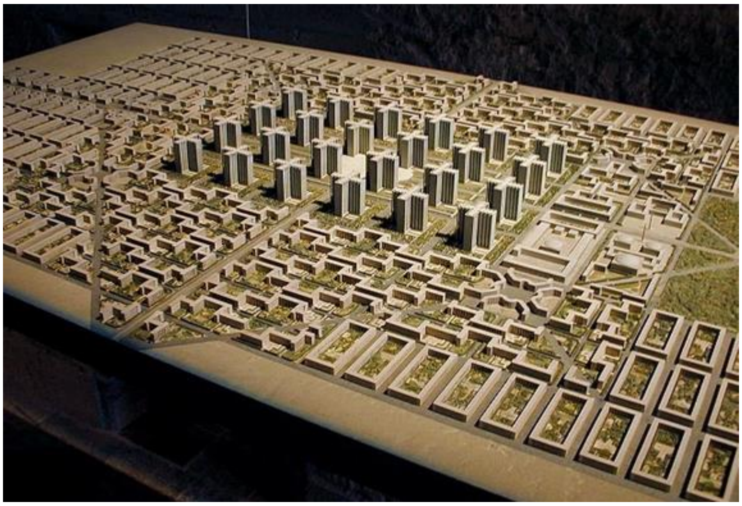

Figure 7 – Le Corbusier's Radiant City [162]

On the other hand, majority of modernists were traveling to the United States of America, exploring the abilities for new designs, new technological development and new building materials. The early 20th century was marked by the steel frame construction and steel tubular construction, where the main focus was to use the steel and to use all the advantages of one material. Thin structural elements made out of steel were leaving the elevations of the buildings opened for free design, including openings which could be filled with glass, or in the early 20th century, non load–bearing brick wall. Chrysler building, located in Midtown of Manhattan, is the tallest steel–framed brick building, with total height of 319 m, with 77 storeys. Construction of the building was finished in 1931, showing how perception of high–rise building changed during the period of 45 years. Construction technology development in the next 45 years showed huge improvement, and the buildings nowadays can achieve seven times the height of the pioneering high–rise building. With the development of high–rise buildings, new materials and systems developed as well; glass facades, glass walls, or the system of enveloping the building's structures etc.

Figure 8 – Chrysler Building, Manhattan – Steel Frame [112]

Larger spans of steel columns wrote the parameters of the modernist period, such as open floor plans, multifunctional areas, movable wall systems, free positioning of the partitioning walls, opening the opportunity for easier and more usable space. Steel and development of steel structures, played the greatest role in the construction of high–rise buildings. Steel as a material was new and unexplored, opening the opportunities for engineers, architects and designers to experiment with it.

The tallest building in the world from 1931-1972 was Empire State Building in New York. Originally, it was 381 m high, but in 1951, a broadcasting antenna was added to the building, increasing total building height to 443 m. It is steel framed structure with masonry infill. Excavation began on January 22, 1930 with actual construction on March 17, 1930. Construction took just over 18 months. The building incorporates 10 million bricks, 1,886 kilometers of elevator cables, 6,400 windows, and weighs 331,000 tons. It was constructed with 60,000 tons of structural steel. The facade is composed of more than 200,000 cubic feet of Indiana limestone and granite, and utilizes several setbacks to offset the optical distortion of its 102-story height. [186]

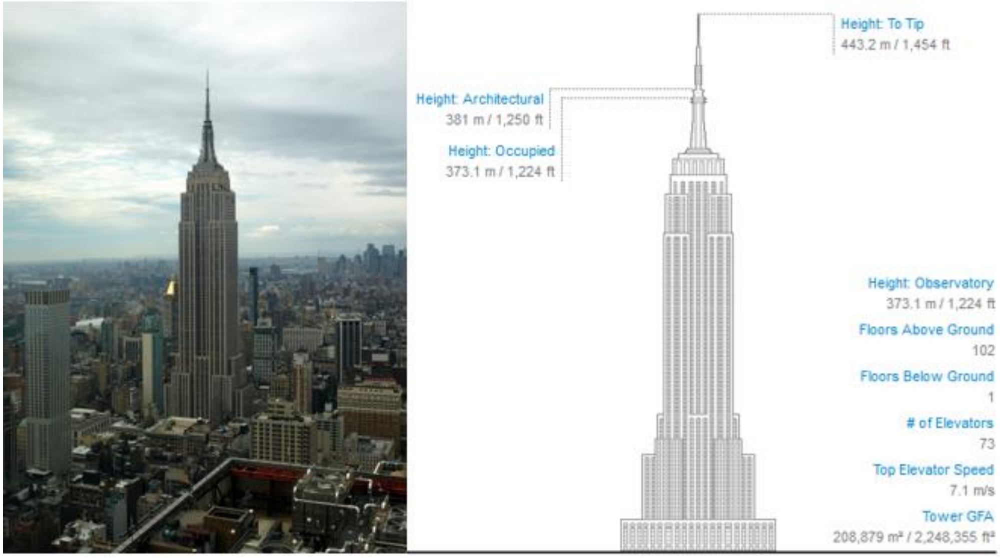

Figure 9 – Empire State Building [186]

In 1973, it was completed a construction of the World Trade Center in New York. The World Trade Center was more than its signature twin towers: it was a complex of seven buildings on 6.5 ha. The towers, One and Two World Trade Center, rose at the heart of the complex, each climbing more than 30 m higher than the silver mast of the Empire State Building. Architect Minoru Yamasaki was selected to design the project; architects Emery Roth & Sons handled production work, and, at the request of Yamasaki, the firm of Worthington, Skilling, Helle and Jackson served as engineers. Yamasaki and engineers John Skilling and Les Robertson worked closely, and the relationship between the towers' design and structure was clear. Faced with the difficulties of building to unprecedented heights, the engineers employed an innovative structural model: a rigid "hollow tube" of closely spaced steel columns with floor trusses extended across to a central core. The columns, finished with a silver-colored aluminum alloy making the towers appear from afar to have no windows at all. When complete, the Center met with mixed reviews, but at 417 and 415 m and 110 stories each, the twin towers were the world's tallest, and largest buildings until the Sears Tower in Chicago surpassed them both in 1974 by approximately 30 m. [135]

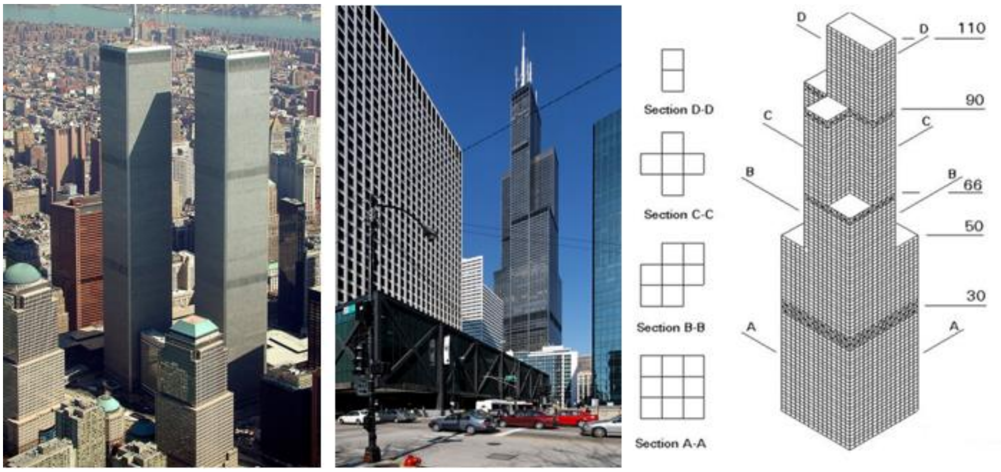

Figure 10 – World Trade Center (left) and
Sears Tower (Willis Tower) (in the middle and right) [135, 146]

However, the reinforced concrete was another option for high–rise structures. Construction technology development of steel was faster than the development of the RC structures due to fact that steel structural elements (columns and beams) were pre–made, and more accurate for load designs, but also steel had better capacity for tension forces, than RC structures.

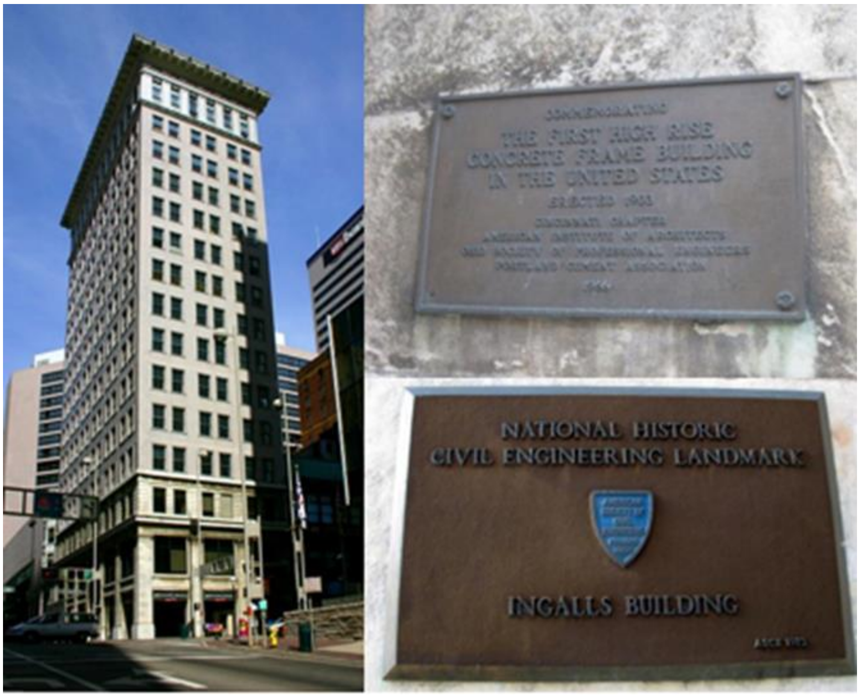

Figure 11 – Ingalls Building, Cincinnati – Concrete Structure [11]

While the first steel high–rise building was built in 1885, the first concrete high–rise building was built in 1903. The Ingalls Building in Cincinnati, Ohio was a 16 storeys tall building, which was constructed out of concrete columns, beams, floors and stairs; it was suspected both by public and engineers alike, that the removal of the supports, the wind load or just its weight, would lead to its collapse. The architect of the building, Alfred Oscar Elzner, received a reward for this building (for the concrete structure of the building), which surpassed the steel frames in fire resistance and cost savings.

The Ingalls Building was declared a National Historical Civil Engineering Landmark in 1974 and was added to the National Register of Historic Places in 1975 in USA. [11]

Number of high–rises worldwide are being created, the highest one at the moment being in the development process and construction may last for another year. Even though high-rise buildings were "born" in the United States, Asian countries are becoming leaders in the high–rise construction. The centres and urban areas in Asia are undergoing a transformation into vertical expansion rather than the horizontal.

Figure 12 – Petronas Towers, Kuala Lumpur, Malaysia, 452 m [163]

The greatest example of such expansion is Shanghai. There are currently 141 completed high rises buildings and eleven under construction with height above 150 m, and five constructed and one under the construction above 300 m.

Figure 13 – Shanghai, China, Landscape [113]

The analysis [187] on high-rises above 150 m in Shanghai shows that structures of high rises are dominantly made of concrete (54 percent) and composite structures (38 percent).

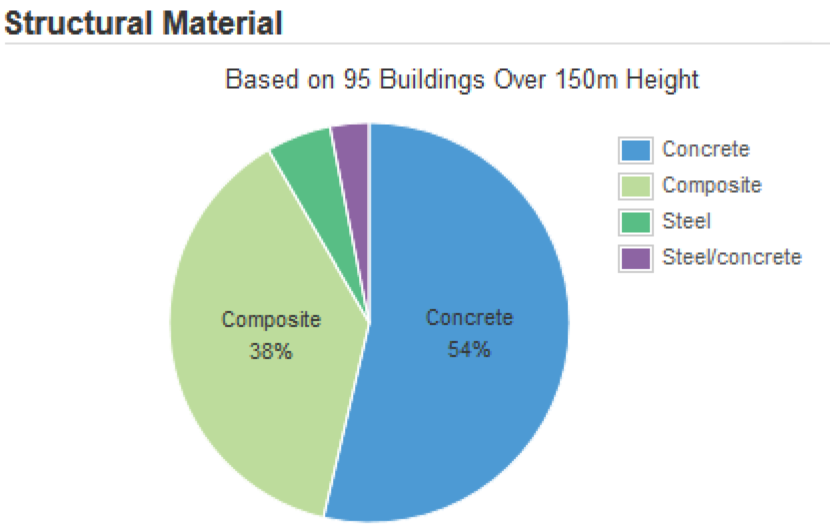

Figure 14 – Structural Material for High-Rises in Shanghai [187]

The Shanghai Tower is currently the highest building in Shanghai and Asia and second tallest in the world (632 m).

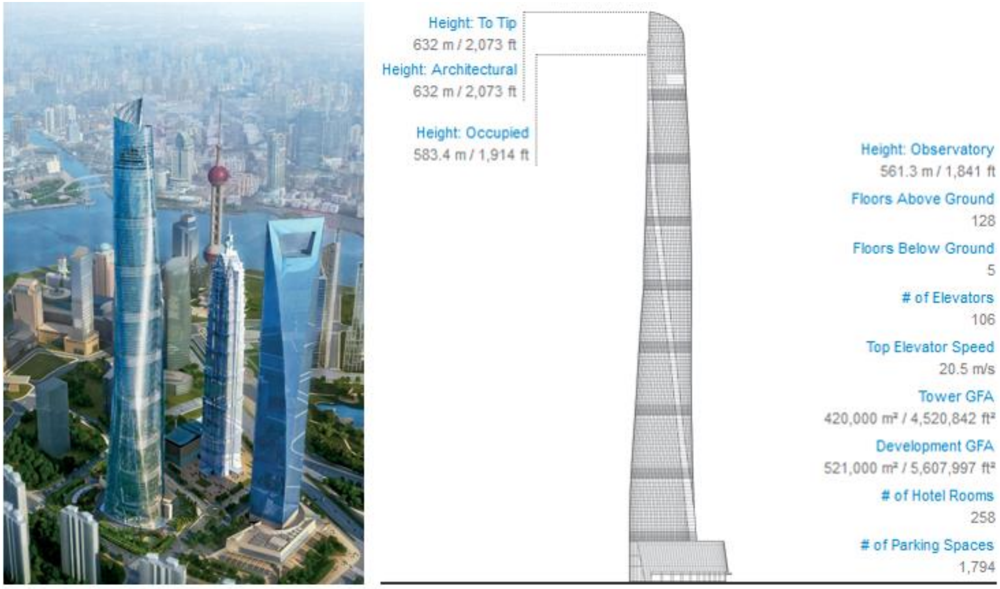

Figure 15 – Shanghai Tower [187]

Another undeveloped area, with infrastructure, and construction, but with no defined zones of urban areas, such as Singapore or Dubai are designed to function with high–rise buildings.

Figure 16 – Dubai – 1991(left) and Dubai – 2016 (right) – with World's Highest Building Burj Khalifa (829,9 m height) [90]

Since their beginnings up to today the high-rise buildings can be classified into three categories, based on the material used for their construction or the abilities of the construction technology:

- *The first category, is the high–rise building with exterior walls built out of bricks or stone, with columns and beams cast out of iron and steel, and were mostly unprotected. Floors were wooden, with unenclosed elevators. Most* *of these buildings were demolished due to lack of standards for steel and iron protection which made them, a risk to use;*

- *The second category of high–rises are frame structures, where the skeleton of the building is made out of steel. The steel columns and beams are protected, by casting them in concrete, which makes them different from the first category. This created a higher level of structure's protection. These high–rise structures, used non-combustible materials, and greatly reduced the possibility of collapse in case of an impact action on structure, or in case of fire.*
- *The third category of high–rises was developed after World War II. In the case of structure, there are steel–framed constructions, reinforced concrete construction, as well steel–framed concrete constructions or composite structures. Numerous standards created a normative in order to serve and bring new level of safety for high–rise uses.* [6]

To be precise, demand for high–rise buildings is constantly growing; desire to build upwards is going to be a necessity for the humanity. High–rise buildings are becoming more of a living style, than the modernist experiment. The constant growth of population and economic growth of urban areas made humanity to face problems of the horizontal spreading of the constructed areas, be it for accommodation, business or industries, and infrastructures brought the rapid destruction of the natural environment, at same time causing natural disasters and climate changes. Thus, contemporary architecture and engineering within futuristic conceptual designs are creating new ways of vertical living and working, where high–rise buildings and skyscrapers, are entering a new era, and where sustainability is becoming the new parameter that has to support the vertical expansion rather than horizontal one.

Vertical cities, also called the sky cities, in their simplest definition refer to high–rise buildings and skyscrapers. On one hand, some people are stunned by this attractive living style, while others are still debating about these ideas, deeming them unideal and do not support this way of development. However, the global community is confronted with problems of overpopulation and destruction of natural environment in order to accommodate growing population on daily basis, and the only solution seems to be in the form of vertical living.

European countries haven't faced such problem yet, and haven't felt necessity to build upwards; on the other hand, certain areas of America and Asia have already been opening, creating and exploring the conceptual designs of vertical living. High–rise buildings are already becoming multi–functional, defined by their verticality. So it is not rare to have buildings that function as offices, retail or hotels, with underground garages, and safe storages etc. But just how safe this environment is in the case of an emergency? And are these buildings sustainable and energy efficient? Do they have positive sociological impact on humanity?

Figure 17 - Illustration: "Would you like to live in a vertical city?" [197]

If consider the urban planning, high–rises take as little square meters of the ground as possible, leaving the open space or keeping the natural environment. Phenomena of Vertical Cities, with detailed spatial planning is clearing infrastructures of the urbanized area.

Figure 18 - Low – Rise Settlement in Less Developed Areas of Shanghai (left) and Shanghai – Pudong District (right) – Vertical Living [149, 153]

Also, we have to take into consideration that structure of such buildings is built out of the material which may resist various loads depending on the area where it is located; buildings that were built in the last few years, have used the best and the most developed technology in order to meet all the needs of the construction. Turnover for the use of such material for construction of these structures happened because of the incidents which took place in New York, USA; the World Trade Centre on 9/11 showed that, steel structures were not sufficient enough to resist impact loads and fire, and completely collapse. All this lead to the switch from steel material to concrete, and with rapid technology development of concrete’s variations which proved to be more economic, sustainable and most importantly more resistant or with higher resistance to intruded loads.

In other words, the importance of safety for the inhabitants grew with technological development of the materials, which also lead to the development of structural design, into core hybrid structures which had the capability to transfer lateral loadings.

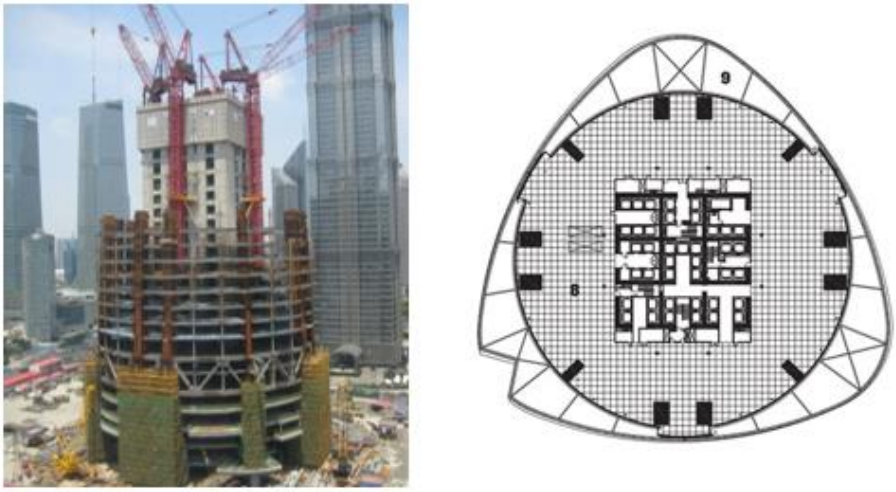

Figure 19 - Shanghai Tower – during Construction Phase – Showing the Structure of the Building (left) and Characteristic Floor Plan of Shanghai Tower (right) [133, 97]

Technology has, more or less, developed material and structures that are well designed for constructions of vertical cities, but have they taken sustainability or energy efficiency into considerations? To construct a high–rise that could function as a city inside the building, it would have to consume more energy than a low – rise building would. High-rises are under the impact of strong winds on the upper floors, and instead of strengthening the structure, wind serves as a natural source of ventilation; also, wind turbines are being built, to get renewable energy which can sustain the building.

With this safe and sustainable way of working and functioning, vertical cites, apropos high–rises, are becoming the new way of living.

Figure 20 - Wind Turbines at the Top of the Residential Building, Indigo Building, Portland Oregon – Renewable Energy Source (left) and Breathable Double Elevation on Shanghai Tower Enables Natural Building's Ventilation, Saving Costs and Use of Electric Energy (right) [141, 168]

In Asia and America this is a living style that has certain tradition, and where we can talk about some super high buildings, ranging from 300 up to 500 m in height, with the highest example being Burj Khalifa, Dubai, 829.9 m.

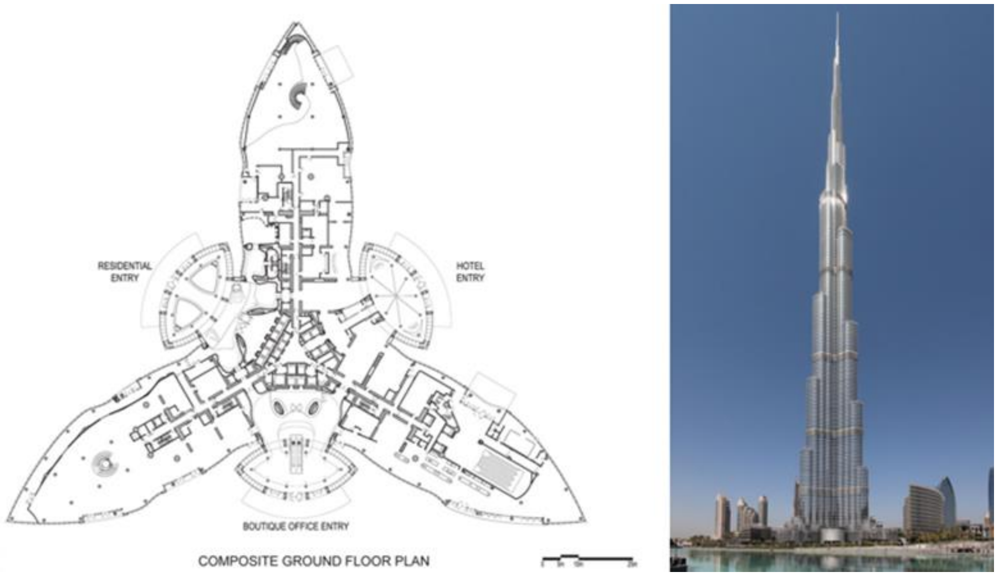

Figure 21 – Burj Khalifa, Dubai, [148, 159]

In these areas, sociological impact is not something that plays a great role nowadays; almost all living population have experienced the vertical living since their childhood. On the other hand Europe, one of the more developed continents, does not have the culture of vertical living in such scale; buildings in Europe range from 150 to 300 m in height, and still requires the safety and sustainability in order to give and to receive positive sociological aspect to their inhabitants.

Despite the initials and constant scepticism of the public and expertise towards the high–rise buildings, the construction technology development has brought high–rise buildings to a new level, where it is not the one building in question, but the entire system of liveable cities. This rough history of the high–rises had numerous turnovers in the use of structural materials, systems and vertical communications, and they were basically all leading to constructing a safer environment for tenants, providing more resistant structures that were well designed, variable, impact and wind loads resistant, and seismic and fire resistant.

HIGH – RISE BUILDNGS IN BOSNIA AND HERZEGOVINA

By the time world got its first high–rise building, Bosnia and Herzegovina was going through fundamental changes in urbanization, taking the principles of urbanization and construction technology of Austro–Hungary (1878 – 1917), and inhabitants of Bosnia were slowly abandoning the way of living of the previous years. It was previously mentioned that Europe lagged behind the United States of America in terms of high–rise construction due to European politics that wanted to preserve landmarks from early periods and the cities skylines. This politics lead to high–rise buildings being still unfamiliar in Bosnia and Herzegovina. However, it is important to mention that Austro–Hungarian period in great measure created overall skyline of Bosnian cites by constructing mostly residential buildings up to four, five storeys high, infrastructures and numerous monumental buildings in the cities. Flourishing of Austro–Hungarian plans for development of Bosnian territory was stopped by escalation of the World War I. Urbanized and constructed areas of Bosnia and Herzegovina were not devastated in great scales, but poverty of the after World War I period stopped development of any new buildings or technology in Bosnia and Herzegovina, and this situation remained for the next two decades ending together with the World War II.

Figure 22 - Capital City of BiH – Sarajevo 1900 (above) and Sarajevo (1950) (below)
[72, 166]

After the World War II, Bosnia and Herzegovina became one of the six republics in The Socialist Federal Republic of Yugoslavia (SFRY). With development and strengthening of the SFRY, Bosnia and Herzegovina became a place of opportunities in various fields, where architecture and engineering took high position in terms of development interests. Such situation, and new opportunities were extremely interesting for numerous highly educated professionals from European schools of architecture.

The capital city of the Republic of Bosnia and Herzegovina, Sarajevo, was the centre of new technological achievements, and it is not surprising that the first high–rise building was constructed in Sarajevo. Reuf Kadić, assisted by Muhamed Kadić, both architects that brought modernism in Bosnia from the Prague Academy, were designers of the first Bosnian high–rise building. The first high–rise building, named “Vakufski neboder”[1], was 12 storeys high building, with underground level that served as a foundation of the building.

Figure 23 - First High – Rise Building in BiH, “Vakufski neboder”, after Last Renovation [129]

Despite the concrete construction, outer walls were in large scale enclosed with large windows, which introduced new interior spaces than those inhabitants of Bosnian buildings were used to. Even though the building was designed in 1930, the construction of the building was completed in 1947, and it was 40 meters tall.

[1] Endowment Skyscraper–Investor of this building was Endowments Directorate of Bosnia and Herzegovina, and the building was named after directorate, Endowment Skyscraper/ Vakufski Neboder, commonly known by name JAT – ov neboder.

Period of the late fifties and early sixties of the 20th century was period of the great expansion of architectural achievements, both in terms of horizontal and vertical constructions. This period is best perceived through residential blocks at the Miljacka river bank dating back to 1962; the group of 4 residential buildings, cubic in shape, with clear white facade were 13 storeys high, with concrete structures, and to a great degree, they introduced the new culture of living in apartment blocks in this area.

Figure 24 - Apartment Blocks at the Miljacka River Bank in Sarajevo, 1962 [39]

The first 12–storey high–rise buildings in this area that served a specific function was a Faculty of Natural Sciences and Mathematics of the University of Sarajevo in Sarajevo; the construction of the building was finished in 1966.

Figure 25 - Faculty of Natural Sciences and Mathematics in Sarajevo, 1966 [76]

Shortly after, the culture of high–rise living was accepted by the inhabitants of Sarajevo, and it proved to be the only possible way to accommodate all the new population that was migrating from the rural areas to Sarajevo. The demand for high–

rise buildings in Sarajevo continued with the expansion of city which continued to create a neighbourhood of high-rise buildings; the area of Čengić Vila, with residential block of four high-rises, each being 17 storeys high, pushed the limits and improved the technology of the construction in the period of the late sixties.

Figure 26 - Residential Block of High – Rise Buildings, Čengić Vila [119]

However, the analysis of the functions of high–rise buildings in Sarajevo, showed that they were mostly used as residential blocks. This situation lead to restrictions in the SFRJ laws, where high–rise building could be designed or built only with a purpose to accommodate the influx of population. Such trend continued throughout the next decade in Sarajevo, and by the early eighties, new settlements or forests, of high–rise buildings were constructed in Sarajevo. Winter Olympic Games in 1984, were also one of the stimulating factors for rapid high-rise construction, and this rapid construction and large demand for high-rises, resulted in a great number of similar buildings, with variation ranging from 12-18 storeys, built as concrete structures, or prefabricated concrete structures.

Figure 27 - Prefabricated High – Rise Buildings – Alipašino Polje [77]

Just before the Winter Olympic Games in 1984, previously mentioned government restriction were cancelled in order to build and design remarkably important buildings to represent modern Sarajevo to the world. One of the most successful designs is building of National Parliament of Bosnia and Herzegovina and the building of State Administration in Sarajevo, 1980, where the complex was designed by an architect, academic and professor, Juraj Neidhardt back in 1955. Even though the building was designed with horizontal volume and vertical as unity back in 1955, construction was disposed in two parts, where vertical volume was constructed in first. With 21 storeys, it is still at the top ten highest high–rises in Bosnia and Herzegovina.

Among all these examples of high–rise buildings built in the period of SFRY, it is impossible not to mention UNITIC Office Block building in Sarajevo, designed by the academic Ivan Štraus.

UNITIC Office Block, known as "Momo and Uzeir", is designed as two equal high–rises. It's design showed great protection for the future actions undertaken on these buildings; it is also enclosed by reflective glass envelope facade and it changed city's skyline making it unique. Even though UNITIC Office buildings were constructed in 1986, its technological achievements and designs of modern architecture, as well as its height, can compete with the new generation of high–rises in Bosnia and Herzegovina.

Figure 28 - National Parliament - J. Neidhardt (left) and UNITIC Office Buildings - I. Štraus (right) [80, 101]

Despite the evidence that Sarajevo was the centre with the highest rate of development in the period of SFRY, other cities like Zenica, Tuzla, Bihać, and Banja Luka also resembled a large construction site and deserve to be mentioned for the examples of high–rise constructions that can be seen in these areas. All these cities were under different forces that required fast and rapid development in short periods of time. The strict law restriction in spatial planning and construction of SFRY, could be a reason why the architecture in these cities didn't have examples of notable architecture. Numerous high–rises buildings, mostly had accommodation function for the arriving labour population that was migrating during the industrial development.

At the list of Bosnian largest cities, Banja Luka, is immediately after Sarajevo as Bosnian second largest city. However, there aren't many examples of high–rise construction; even in the period of the great expansion of the cities in SFRY, Banja Luka was primarily oriented toward low–rise buildings. That phenomena was unique for Banja Luka and surrounding areas due to the location of the city on the very seismic area. Back in the late sixties, when the rest of the country was developing, Banja Luka was damaged by two devastating earthquakes. Fifteen people lost their lives and more than thousand were injured in the earthquake in 1969, and significant number of the buildings were damaged or destroyed.

Figure 29 - Banja Luka after Devastating Earthquake in 1969 [110]

Newer buildings were concrete structured which proved to have more favourable transfer of the lateral forces. This was a case with "Incelov neboder" or "Čajavčev neboder" constructed in 1967 in very close urban core, 14–storey tall. Besides its height, this building located at "Krajina Square," outstands in its surrounding with characteristic architecture of socialist period.

Figure 30 -”Incelov neboder” or “Čajavčev neboder”, Banja Luka [152]

However, Banja Luka recovered and rebuild fast, but as a low-rise city, where nature has proven more powerful that the current technological capabilities.

Another urban core in Bosnia and Herzegovina is Zenica, where all high-rises still resemble those examples of the residential blocks in Sarajevo, from the same period. Cubic shaped towers with openings in one vertical line with nothing striking to show, but already seen and recognizable architecture. Also, the construction principles were those that were already seen with the concrete structure, designed as a frame system. However, high–rise named “Lamela”, served the inhabitants and local government as a representation of their power and strength. The building was designed as a complex of six cubic vertical forms, set one next to another from the lowest to the highest.

In the initial project the highest cubic was designed to be 30 storeys high, but the lack of construction technology and problems with water supply and other mechanical systems, reduced the number of storey to 27, with final height being 101.9 m. Building was designed by an architect Slobodan Jovandić, and it took five years to finish the construction (1971-1976), due to the utility problems of the building, but not the structure itself.

 

Figure 31 - Zenica – Residential Blocks at River Bank (left) and Lamela – Highest High–Rise Building in Zenica (right) [131, 125]

Along with Sarajevo and Zenica, Bihać and Tuzla also had large income; Tuzla as the industrial city, and Bihać as military city were developing rapidly. Even though both of these areas had problematic load bearing soil in terms of quality and strength, urban cores still have examples of high–rise structures. Like Sarajevo, Tuzla experienced birth of new high–rise buildings growing as new defined settlements, where high–rise buildings formed group of detached high–rises with courtyards, which served as gardens and parking lots. What is Alipašino Polje and high–rises for Sarajevo, Sjenjak settlement is for Tuzla. Structure and function of both settlements are not much different, but variation of the storeys constructed exist. However, in the psychological perception of the people living in these cities, Sjenjak was and still is an elite settlement, while Alipašino Polje, for most architectural critics represents an area of the sleeping units.

Figure 32 - Tuzla's Settlement of High–Rises – Sjenjak [73]

The centre of the northwest of the republic Bosnia and Herzegovina was Bihać. Construction of the largest military airport in SFRY and industrialisation of Bihać, were turnover for new investments in construction in order to accommodate the influx of population, military and otherwise. Bihać, unlike other cities, was not one of the cities with newly constructed high – rise settlements. Somehow, most of the buildings were up to 5 storeys high, which shows awareness of former architects and engineers about the quality, strength and stability of the load bearing soil, as well as their attention to seismic forces, due to the fact that Bihać lied at very seismically active area.

Figure 33 - Bijeli neboder (White Skyscraper), Bihać's Highest High–Rise [120]

In spite of this, there are examples of the high–rises in Bihać, but in smaller scales than those in other Bosnian cities. Highest high-rise in Bihać reaches 16 storeys, and it functioned as residential building with commercial at the first two floors, commonly known as Bijeli Neboder (The White Skyscraper), and it is recognizable for its finishes on the outer walls and its facade, where the whole solid area of the facades is cladded with "Bihacit[2]" stone tiles, which was an unusual example during this period.

The period of constant development, rapid construction and acceleration in the development of construction technologies in this areas was stopped in the early nineties when war broke out in the area. Period of devastating war and vandalism lasted from 1991 to 1995. During this period, that what was built in the era of rapid

[2] Bihacit is a clean granular, gravelly and cavernous limestone, created at the tertiary freshwaters basin around Bihać

development was under daily destruction and bombing. Sarajevo was the city with the longest siege of the modern period. During this period, buildings that were valued as greatest achievements, became military targets.

Neither the building of the BH Parliament, nor UNITIC Office Building, among numerous others were spared. Reason for the survival of pre–war high–rises was their solid structure that actually resisted devastating fires and preserved the high–rises in their volume. July 7, 1992 was the day when images of the twin high–rise on fire spread as sun light worldwide, and the day when architect Ivan Štraus wrote in its diary the best description of that period:

> "*…Tonight, barbarian burned one of two glass towers of UNIS Office Building, at Marijindvor. Both of them were already damaged in large scale, but now one of them is burning. With immeasurable sadness, I was watching it being helpless with flames breaking out of its windows, while my minds were filled with memories of construction days and how actually I was proud of them. The rest of the night I spent in basement, sleepless, lying at improvised bed, watching game of black cobweb pieces and their shadows at cracked off – white ceiling, counting latticework and span between them. However image of the tower burning as torch, I could not expel"* [39]

After the last war, Bosnia and Herzegovina was devastated in large scale; there was not a single building that was not damaged. Most of the country's infrastructure, roads and bridges, were highly destructed or demolished, so was the economy. Reconstruction of everything that was built before the war was set priority and inevitable for rehabilitation of the whole country.

Figure 34 - UNIS Office Building in Sarajevo, Burning, Last War (1992) [138]

While the years after the war were mostly cited as the period of stagnation, it would seem unfair to dismiss efforts that were done to bring back the old shine of great and fast development. However, early 21st century for high–rises in Bosnia and Herzegovina represented a new generation of high-rise buildings.

Pioneer of the new generation of high–rises in BH is Bosmal City Centre, conceptually designed as a city within a city, or more precisely, a city within a building. Bosmal City Centre consists of two buildings, used for residential, commercial and other functions.

Figure 35 - Bosmal City Centre Sarajevo [156]

Construction of the BCC started in 2001 and lasted for 5 years, the predicted and designed height of the Centre was 118 m, which would give it a title of the highest residential building in the area of Balkans. Shortly after Sarajevo became birthplace of another high–rise building that would become the highest among high–rises at the area of south–east Europe.

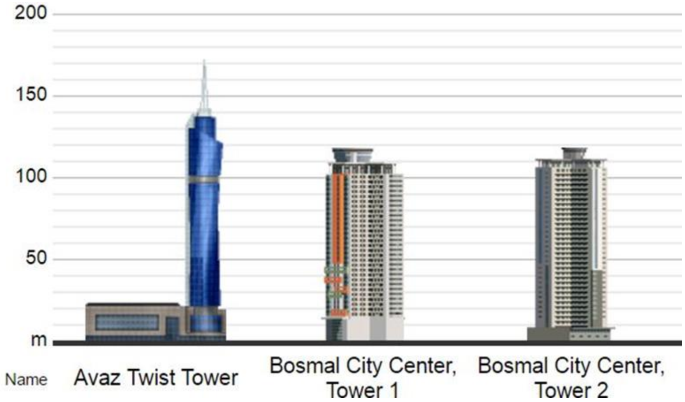

Figure 36 - New Generation of BH High – Rises in Sarajevo [188]

Located at Marijindvor, by 2006, the construction of high–rise Avaz Twist Tower had started. Avaz Twist Tower was designed as a concrete high–rise, 40 storeys high, with final height of 175 m, enveloped with twisted glass curtain wall.

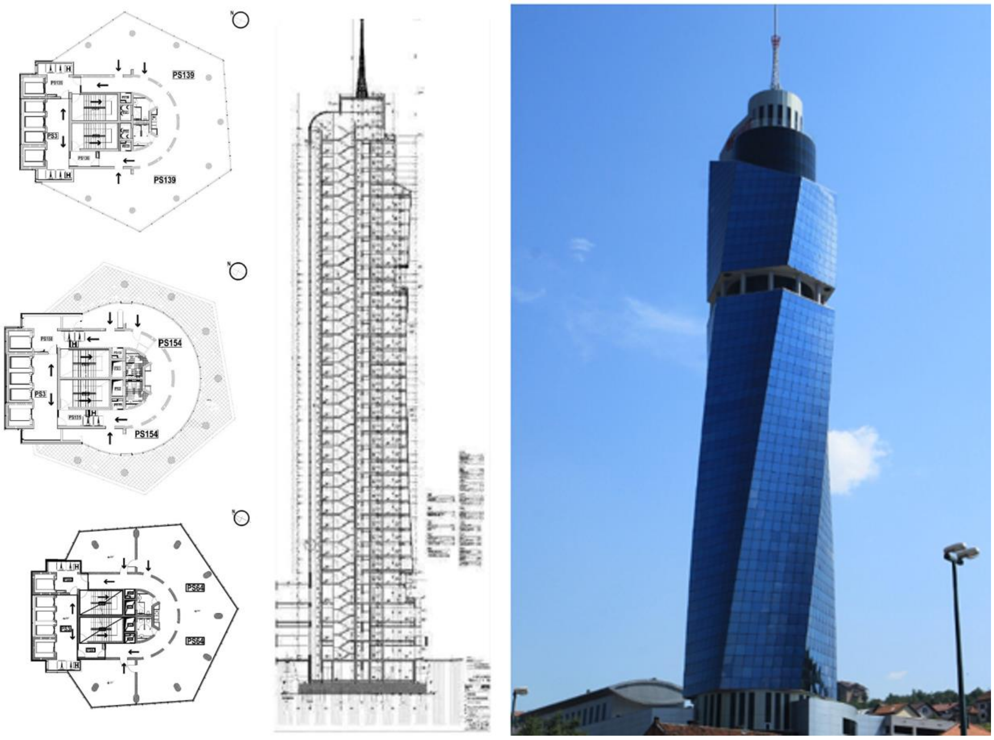

Figure 37 – Avaz Twist Tower [124, 150]

Few years later, Marijin Dvor hosted construction of new business and commercial complex. Sarajevo City Centre (SCC) with two tall volumes, was promising remarkable piece of tall architecture. With 74 meters SCC for sure did not reach the heights already seen in Sarajevo, but rather expressed playful forms with strongly defined broken lines which states for unique example of high–rise architecture in Sarajevo and wider area. Its exterior construction was completed in 2013, however interior of the towers is still under construction. And nowadays if observed Marijin Dvor appears to be neighbour of the most representative high–rises in Sarajevo including, UNITIC Office Blocks, National Parliament, Avaz Twist Tower and Sarajevo City Centre.

Besides the mentioned buildings, there are other newly constructed or under construction high–rises filling the contemporary Sarajevo's skyline.

Figure 38 – Sarajevo City Center (SCC) [158]

On the other hand other cities that were trying to catch up with the capital city in pre–war years, in terms of rapid high–rise construction, in the following years and nowadays were dealing with dramatic reduction in demand for high–rises.

However, positive example of the new generation of high–rises in BiH, besides Sarajevo is the administrative building of Government of the Republika Srpska, located in Banja Luka. In comparison to the previous periods, this was a greatest step forward in high–rise construction in this area. Previously mentioned area of Banja Luka is marked as intense seismic zone, which makes it obvious why there are not many examples of high–rises in Banja Luka as there are in other cities in Bosnia and Herzegovina.

Figure 39 - Administrative Building of the Government of the Republika Srpska [99]

Administrative building of the Government of the Republika Srpska was constructed in 2007, 18 storeys high (ground floor + 17, 70 m high), enveloped with glass facade, cubic shaped tower, and was nothing new worth of high praise for architecture in Bosnia and Herzegovina, due to the fact that period of 2005/7 was marked with the highest building in the Balkan area, Avaz Twist Tower. However, this high–rise is worth mentioning in the analysis of high–rises in BiH due to its location in intense seismic zone, if nothing else.

Besides Sarajevo and Banja Luka, other BiH cities Tuzla and Mostar also have examples of new–generation of high–rises. Tuzla recently became a place of few new high–rises, the most impressive being Mellain building; large scaled, massive complex of four attached buildings, where three of them are high–rises. Building is designed as multi–functional, where the design of volumes was used to enhance each function. When observed from the main street, this complex seems as three united high–rises. Focus was added to the central high–rise, whose function reflects in hospitality, and at the same time this is the highest part of the complex with the height of 96.45 m, and 21 storeys high. Facade design differs, from the previously mentioned buildings, glass curtain walls were used to enhance the main entrances and to add a touch of glamour.

Other two high–rises, are identical residential blocks, one on the left, and other on the right side of the complex, resembling as wings of the strongly stated central high–rise, which is 19 storeys high.

Figure 40 - Mellain Complex, Tuzla under Construction (left) and Constructed (right) [125, 130]

Mostar’s skyline is enriched with high–rise building that serves a unique function, unlike other cities in Bosnia and Herzegovina, Mostar’s highest building serves to religious purposes, as well as touristic attraction. As celebration of the new millennium in Mostar, an idea to design and construct a bell tower as part of the reconstructed Franciscan Church was born. Cubic, pure concrete tower, with 107.20 meters height, was designed by an architect Davor Smoljan. The tower was defined as a symbol of peace, and its design was divided in two phases. First phase was to construct the height of 75 meters which is used as an observation tower of Mostar’s landscapes and natural environment. In order to reach the observation floor, vertical communication was designed as elevator and stairs, which was however finished in 2016. Second phase, was to establish International Art Gallery of “Peace”, from the ground level up to the observatory. After the construction was completed, it became obvious that compared to this building all other Mostar’s high–rises buildings looked like dwarfs.

Figure 41 - Franciscan Church and its Bell Tower – Symbol of Peace, Mostar [140]

Even though BIH scene of high rise buildings and their construction, started some 50 years later than the rest of the world’s scene, it is more than obvious that architects and engineers in Bosnia and Herzegovina achieved great success in the last 70 years. In the beginnings, high–rise buildings in this area were mostly defined as sleeping units, with few exceptions. Increased number of rural population migrating to urban zones required fast solution in accommodation. High–rise buildings in this case proved to be as the best solution for fast construction and low land consumption. As main structural material, architects, designers and engineers chose reinforced concrete structures, or prefab concrete structures, rather than other materials, which proved to be one of the greatest advantages in the design of high-rises. Era of constant, rapid and mass development of Bosnia and Herzegovina as part in the SFRY was all of a sudden interrupted and stopped by the war. It was impossible to find a building in Bosnia and Herzegovina that was not partially of fully damaged both by heavy artillery or fires. High–rise buildings were “easy targets”, and what saved most of them from complete demolition to the ground was high–fire resistance of concrete. In large scale, the war slowed down the construction of new high rises; after the war, a period of restauration, conservation and reconstruction of demolished and damaged buildings followed. First years of the 21st century, brought new ideas and attempts of construction of new high-rises.

Pioneers of the new–generations of high–rises in Bosnia and Herzegovina, still kept concrete structures, while breaking the limits of previous heights. Also, the function of the new high-rises was not reserved only for residential purposes anymore; with few exceptions, new high – rises in Bosnia and Herzegovina followed new living style, and most of the buildings are multifunctional, accommodating residential zones, hospitality, business etc.

STRUCTURES OF HIGH - RISE BUILDINGS

Architecture depends on many factors, which greatly vary from initial concepts, functionality of designed spaces, its proportions both to human perception and urban context, and structural support and technological capabilities to support desired concept. Thus, any analysis of the above stated factors that architecture depends on, as its final result shows that crucial factor among these is structural support, which has to maintain the stability of the building.

Scholar proficiency in architectural structures mostly focuses on basic structural systems which are common within different structural materials and within different volumes of the buildings, however reality is more than complicated, especially if we consider high–rise buildings, or buildings designed by architects such as Frank Gehry, Daniel Libeskind or Zaha Hadid. However, high–rise buildings are completely another and specific field with longer technological development history than those new contemporary buildings that show futuristic designs and which are defined with curved volumes and elongated elements. In high–rises, increased safety for the inhabitants of the building, greater resistance of the structure to various actions, and necessity for decreased overuse of structural materials and overdesigned load-bearing structural elements, as well as economic benefit, forced the development of structures of high-rise buildings since their beginnings. Structures of high–rise buildings are analysed and grouped by different approaches, focusing on structural material or the composition of the structural elements.

However numerous divisions and subdivisions of structures of high–rises and an an excellent start for understanding complex issue of high-rise structures might lay in the definition approved by many critics and The Council of Tall Buildings and Urban Habitat, which states that high–rise is: “A building whose height creates different conditions in the design, construction and use than those that exist in common building of a certain region or period.”

As an example that supports this statement is a remarkable contemporary high–rise Burj Khalifa, which rises 829.9 meters above Dubai. Even its urban context is created by numerous high–rise buildings, the height of Burj Khalifa creates a vision that the rest of the high–rises are just common buildings in this area. Opposite to this, one of the highest building in the area of south–east Europe, Avaz Twist Tower, rises 175 meters above Sarajevo, where achieved height is outstanding compared to other buildings in this urban context. So it is more than obvious that these two buildings required different treatments, different structural systems and technological requirements, even though they were built around the same period, and both have the title of the highest buildings in their areas.

Despite various contemporary requirements and technological developments of high–rise building's structural systems, history and beginnings of high–rises were less complicated and simple when compared to nowadays technology. During the period of the first–high rise building, widely in use and best known were massive load bearing masonry structures, rigid thick shear walls with small perimeter openings with low resistance to lateral forces which are crucial for structural design of high–rise buildings. Masonry structures were replaced with an iron and steel structures which created larger spans between columns, creating more open areas at the building's perimeter for the windows, and it also facilitated the construction. At that time, terms such as load–bearing systems, in shape of rigid steel frames and non–load bearing structural elements, such as separation walls, or fill–in brick non–load bearing walls between the columns at the perimeter of the buildings that were not glass surfaces, were introduced to structural design. Non–load bearing elements and cladding materials were carrying nothing but self–weight and lateral wind load in their areas. Development in this range was more than sufficient for designers and investors to start racing for expansion in vertical dimensions. High rate in increase in height of the buildings was not equally accelerated with technological development of the structural systems and designs.

With tendency to go higher, while keeping the same steel frame systems braced to resist wind loadings, made high–rises of the late 19th century and early 20th century were very expensive due to overuse of structural materials in order to construct overdesigned structural elements.

At this point, initial forces that created an idea of high–rises, reflected in economic benefits of the investor, expecting that desired height could reduce cost on low land consumption, proved to be pure imagination. However, a turnover for fast development occurred in the second half of the 20th century; strong economy forced and supported technological developments, and even the new generation of computers and software helped in the development of more efficient structural systems. Innovative structural systems, enacted use of tubular forms, outriggers, diagrids and megastructures, reduced the overuse of material and low scaled the dimensions of the structural elements. Each of these structures had to satisfy four primary structural requirements, and in following order: static equilibrium, stability, strength and rigidity of the structure. Static equilibrium, as the first requirement is to test the structure in order for it to respond to designed loads acting at the structure, which should go without major displacements of the structure, where sum of forces in the foundation could resist the designed loads. Stability refers to the structure in equilibrium which has to avoid major changes in shape of the structure. In the case of high–rise buildings the structure is more exposed to strong lateral forces, wind and seismic loads; in this case, static equilibrium and stability of the structure are strongly connected. Structure of the high–rises requires adequate treatment to exclude possible sway of structure or even collapse. In the figure below, in the left scheme we can see rigid frame of high–rise structure, in static equilibrium but deformed, while the scheme on the right side shows braced frame of high–rise structure, where bracings added axial respond to lateral load providing static equilibrium and stability.

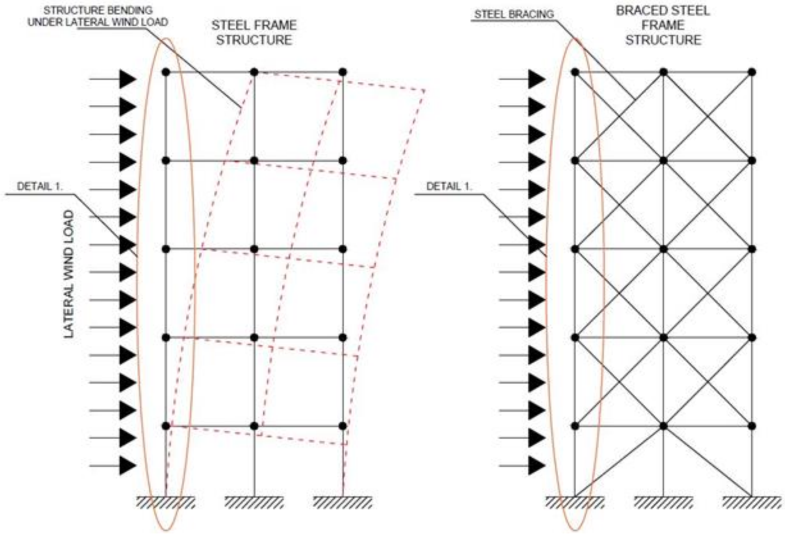

Figure 42 - Frame (left) and Braced Frame (right)

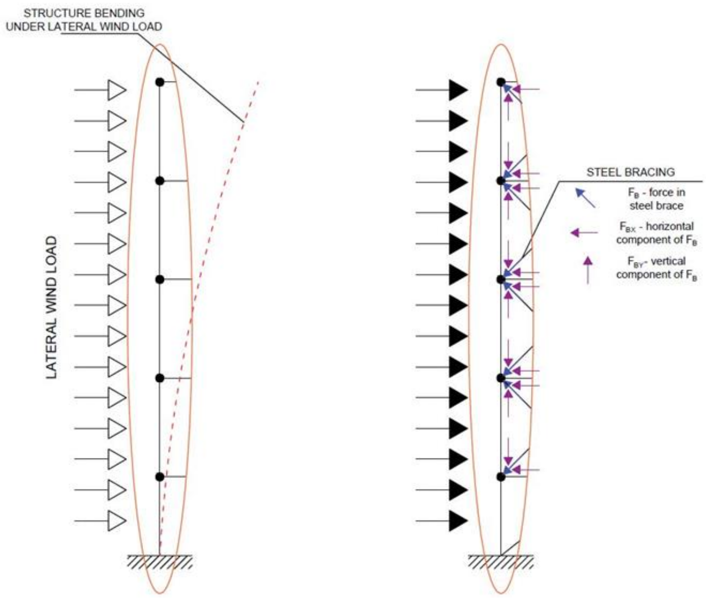

Figure 43 - Detail of Figure 42

Figure 43 on the left shows sway of the high–rise frame structure upon lateral wind loads which disturbed the stability of the building, while the right side shows distribution of the axial forces in braces, which improved the stability remaining with in static equilibrium. Once the static equilibrium and stability are satisfied, the question of required strength of the elements comes to the table, which has to determine the internal forces, the best material for the structure depending on its strength and to design the structural element, the element sufficient enough to respond to internal forces.

Last requirement for the structure is rigidity. The first two requirements are closely connected, the last two are also, both strength and rigidity depend on the material used and cross sections of the structural elements. Elements designed in such way are supposed to exclude excessive deflection in respond to loadings.

Notwithstanding fact that major requirements crucial for the structure are to meet equilibrium, stability, strength and rigidity, which should not tolerate any other design requirements, structures itself are nevertheless in architectural sense becoming an additional aesthetic value for a building supporting the concept. Structural diagrids, tubes, braces of the frame system, space trusses etc., commonly represent structural systems that bring an additional aesthetic value to high–rise buildings.

An excellent example of the high–rises with an exposed structures (megastructures) is Hearst Magazine Building, tower designed by Norman Foster in New York City.

Figure 44 - Hearst Magazine Building - 2004, NYC (left), Hotel de las Artes – 1992, Barcelona (right) [87, 100]

It is an outstanding high–rise in neighbourhood of high–rises, due to the specific exposed steel structure–diagrid, which even reduced the structural material consumption, due to its geometrical disposition of the structural elements, when compared to the braced steel frames.

Unlike the Hearst Magazine Building whose diagrid is full–filled with glass walls, structure of the Hotel de las artes was practically attached to the building volume; an exo–structure was attached by design at the building perimeter in order to resist lateral forces. Being hidden or exposed, it is more than obvious that evolution and development of structures contributed to the overall architectural expression. Also, the structures are not heavy anymore; there are no massive barriers in interior spaces, but there is a variety of aesthetic forms of architecture.

CLASSIFICATION OF THE STRUCTURES OF HIGH – RISE BUILDINGS

Architectural structures of the high–rise buildings have been a new field for various scientific researches, analysis and classifications ever since their rapid developments in the sixties. Structures were classified according to the use of structural material in ratio with economic benefits and heights, whether they were visible (at the perimeter of the building, supporting architectural expression, exterior structures) or invisible (such cores, or structures hidden in interior of the building, interior structures).

However, each of the classification is greatly upgrade of the previous one, in an effort to find a place for a newly developed structural system of the high–rise.

According to F.R. Khan, back in 1969, high–rise structural systems were classified according to the efficiency relating to their height. As a final result of such attempt to classify structures upon these factors, diagrams “Heights for the Structural Systems” were created. [20]

However, this era of rapid development in order to catch up with desired heights and economic benefits brought necessity for upgrade of the existing diagrams. In 1972/73, new schematic diagrams were created for classification of structural systems, based on the structural material used, concrete or steel. With these diagrams, Khan enhanced the close relationship between progressive demand for height and economic benefits, while the decision not to use steel structures in buildings under 20 storeys, in order for it to be the most sufficient, is not surprising. According to Khan, doable systems were frames, shear walls, framed trusses and tubular forms.

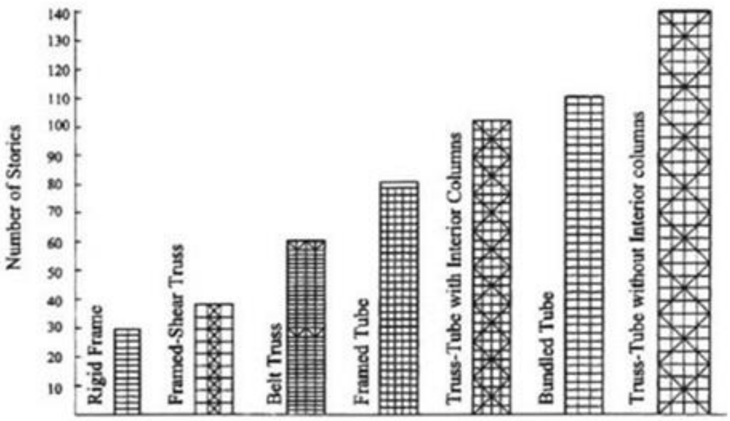

Figure 45 - Classification of the Structures of High–Rise Buildings according to F.R. Khan (steel structures) [1]

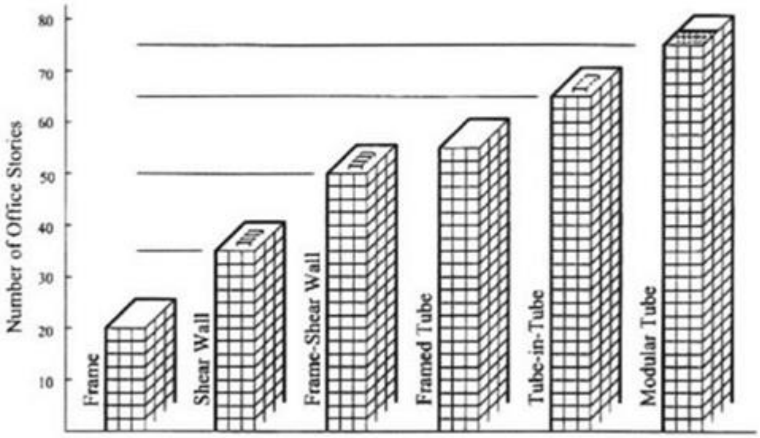

Figure 46 - Classification of the Structures of High–Rise Buildings according to F.R. Khan (concrete structures) [1]

With such accelerated evolution of the structural systems, high–rise structures required more updated classification. In 2007, Mir M. Ali developed new classification guided by lateral load resisting capabilities. According to Mir M. Ali, each structure had a major structure which was capable to resists lateral actions (wind and seismic actions), and minor one which was not as dominant as major, but did have capacity to resist lateral actions.

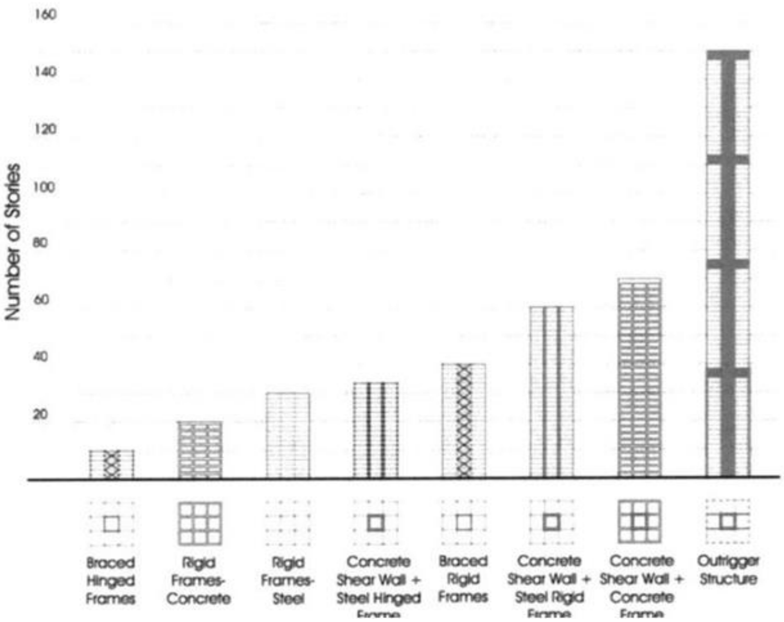

Figure 47 - Classification of the Structures of High–Rise Buildings according to Mir M. Ali (interior structures) [1]

If the major structure was placed at the inner part of the building, while minor structural elements were positioned at the perimeter of the building, structure was classified as interior structure. If the major structure was positioned at the perimeter of the building and minor at the interior, structure was classified as exterior structure.

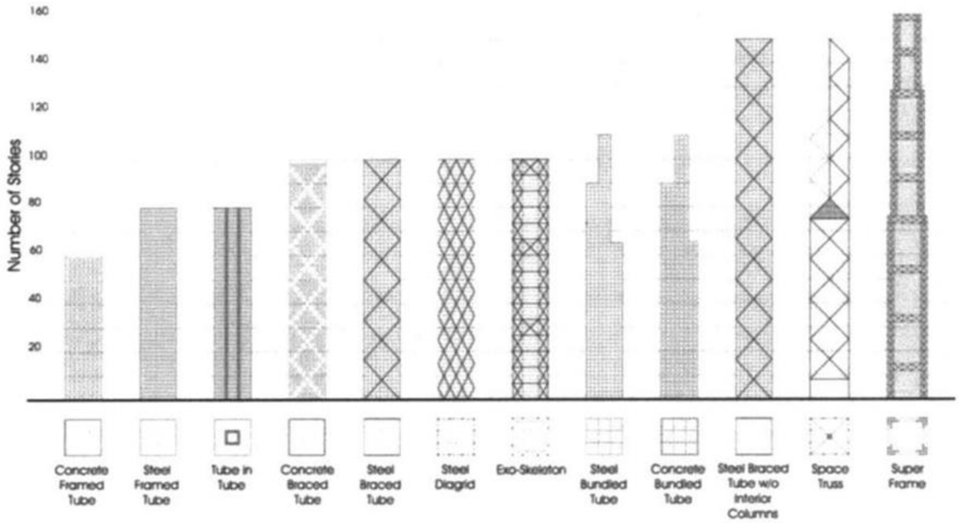

Figure 48 - Classification of the Structures of High–Rise Buildings according to Mir M. Ali (exterior structures) [1]

FRAME SYSTEM

Frame system was pioneering system in structuring and maintaining the concept of high–rises as physical objects. The first generation of high–rises were structured with rigid frames. Such system appeared as regular grid, with girders as horizontal elements and columns as vertical elements, rigidly connected. Rigid frame structure, primarily resisted loadings through flexural stiffness of the members, where vertical members of the frames were designed upon the gravity actions (permanent and variable actions), while the girders, horizontal members were designed to withstand possible deflection under permanent and variable actions, and were also designed to resist lateral sway of the structure under lateral actions.

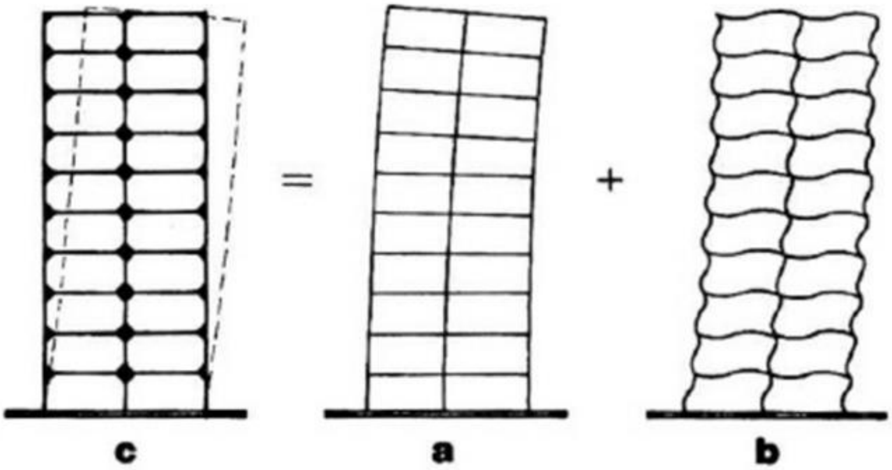

Figure 49 - Rigid Frames of High–Rises
Combination of the Displacement due to Sway and Bending [177]

However, if the span between the columns was larger, which was the actual case due to necessity for more open space, girders and columns were respectively increasing in cross–sectional dimensions in order to ensure overall stability of the structure. The same goes with the height increasing, where the columns that were close to the ground or foundation was wider in cross section than columns at the upper floors. Rigid Frame System can be made out of both structural steel and concrete. However, prevalent material for these structures is structural steel, which accelerates the construction and proves as very efficient for the high–rises up to 30 storeys, while the concrete is efficient up to 20 stories but high fire resistance of concrete is what made concrete the number one choice in structural material for rigid frame systems.

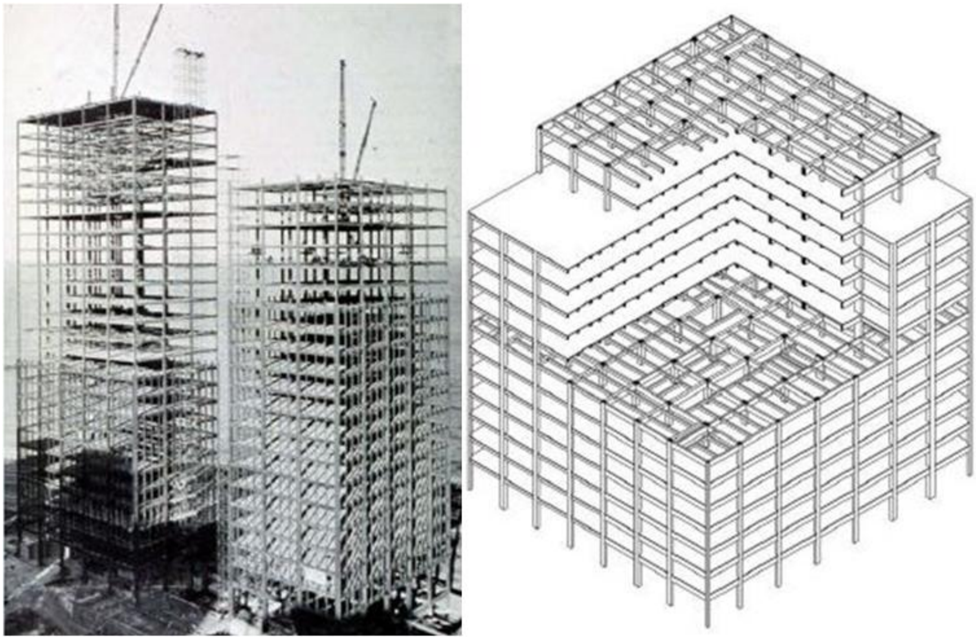

Figure 50 - Lake Shore Apartments – Rigid Steel Frame Structure (left)
and Stanhope Building – Rigid Concrete Frame Structure (right, axonometric) [179]

The subcategory, described as developed method of rigid frame is braced rigid frame system. Unlike rigid frame, braced frame system was more economic and efficient steel structure; bracings minimizes or exclude bending of the columns and beams in such a way that, axial stress in bracings mimics the rest of the lateral forces. By bracings the structural elements such as girders and columns became more slender and overall structure got a geometry of vertical trusses, where columns appeared as chords. There are various ways of bracing systems, most common being: single diagonal, double diagonal and bracings in appearance of letter "K". Such structural system might be used for building up to 40 storeys high.

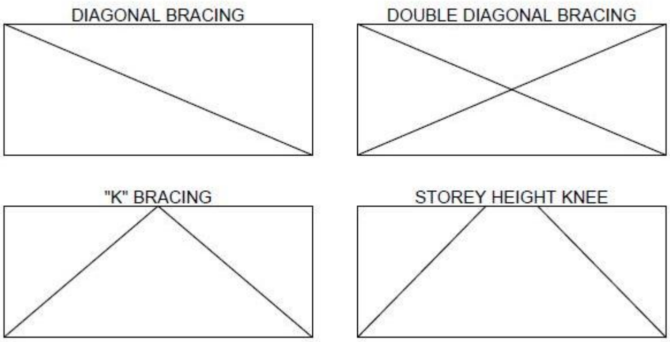

Figure 51 - Common Type of Bracings

SHEAR WALLS SYSTEM

Even though load–bearing walls, forerunners of shear wall system, were main break for high–rise construction, development and change to a more efficient structural material such as reinforced concrete (and other strengthened types of concrete) resulted in development of shear wall system. Shear walls, plane structural elements extended from the foundation to the final height, proved to be the greatest advantage in bracing of high-rise buildings that could resist lateral actions (wind and seismic). Large in plane, shear walls had great stiffness and strength. However if the shear walls were interrupted in order to build windows or doors, stiffness of the overall structure respectively decreased in ratio of solid to void areas; similarly, if two shear walls were connected with a beam, two walls acted as one unit, and such system was named coupled shear walls.

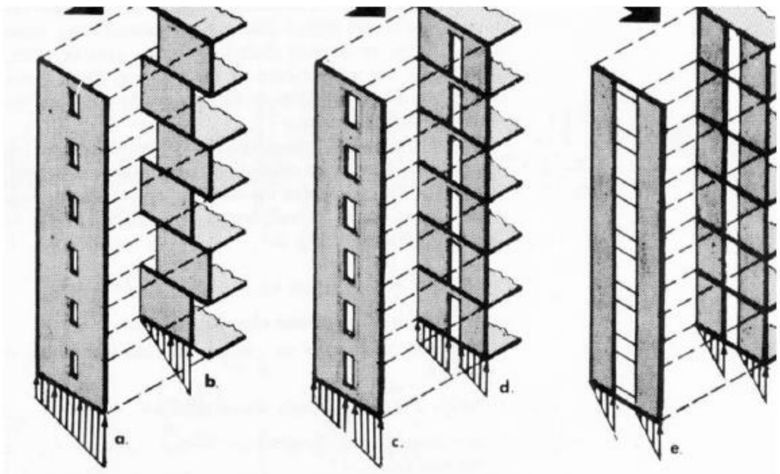

Figure 52 - Variations of Interruptions in Shear Walls [176]

Figure 52, shows different percentage of shear wall interrupted, the first version shear wall is interrupted with small openings, not largely affecting the stiffness of the wall, the second however has larger opening which in ratio of solid void decreased overall performance of the shear wall–coupled shear walls, and the third figure shows the void area that fully separated wall to two smaller plane areas noticeable decreasing overall structural stiffness. In statics, shear wall might be described as cantilever beam, fixed at the foundation, extending up to the final height of the building. Such system is chosen when constructing in highly seismic zones, due to its greater stiffness because "cantilevered" vertical beams transfer seismic lateral loading to the foundation.

Arrangement in the plan of shear walls, in any case, should be symmetrical; if not, the structure can undergo torsion. Such proposal for symmetry of the shear walls arrangement imposes mirrored floor plans, and debatable flexibility of the space. This might be additional plus in the design of hotels, dormitories or residential buildings in terms of creating shafts for the rooms, or apartments; otherwise in architectural design, shear walls system is considered highly inefficient and creates various limitation. However use of the shear walls to create cores, and shafts for stairs and elevators, mostly located in the centre of the floor plan axis, partially solves problem of the space's flexibility. With such approach, a new sub category was developed as structure of shear walls + frame system.

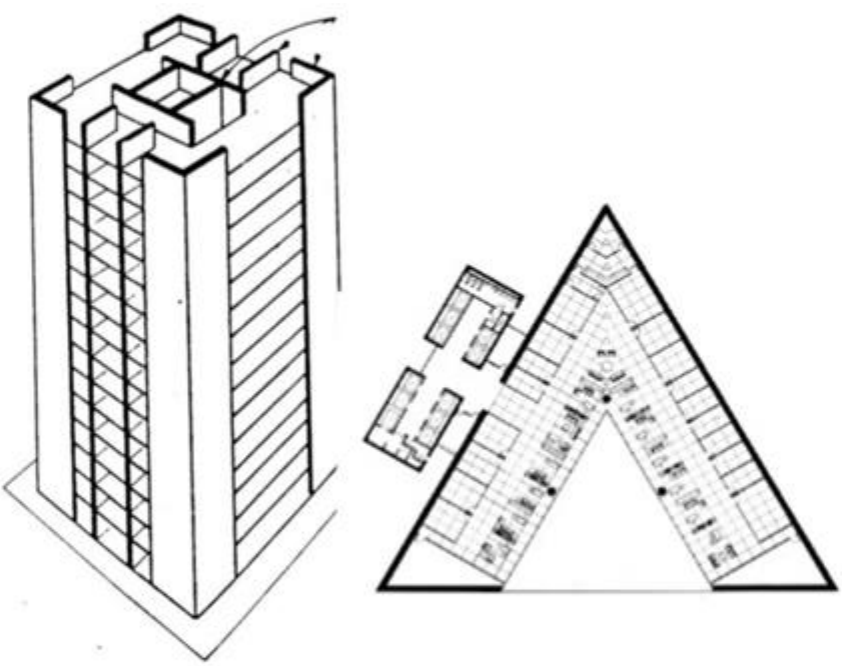

Figure 53 - Axonometric View of Shear Walls System, Example (left) and Characteristic Floor Plan of the National Commercial Bank, Showing the Symmetry in Arrangement of Shear Walls (right) [180]

In terms of height, shear wall system can reach the height of 35 storeys in order for it to be economic, while the use of reinforced concrete will still be used effectively. On the other hand, when combined with a frame system, possibility of steel or concrete framing of shear walls lead to more storeys, but also proved to be more economic and efficient, which means that concrete shear wall and steel rigid frame can reach up to 60 storeys, while concrete shear walls and concrete frame systems goes up to 70+ storeys high.

Figure 54 - Casselden Place, Melbourne – Concrete Shear Walls + Steel Frame, 43 Stories (left) and 311 South Wacker Drive – Concrete Shear Walls + Concrete Frame, 75 Stories (right) [102, 104]

OUTRIGGER SYSTEM

Outrigger structures are generally a unity of the core, outriggers, belt trusses and mega columns. Shear cores are mostly designed at the axial centre of the floor plan; however it is not impossible for it to be located at either one side of the building. Commonly in a form of concrete cores or rarely in a form of steel trusses, shear cores do act as vertical cantilevered beam fixed at the foundation. Outriggers, might be in a form of steel trusses or concrete walls, and depending on the design the outriggers are approximately 1 to 2 storeys deep. Depending on the position of the core, outriggers may extend from both sides if the core is centrally positioned or from one side if the core is placed on one side of the building. The role of the outriggers is to reduce moment in the structure's core by acting as the stiff headers that transfer the moment from the core, to the mega columns generally located at the perimeter of the building by stimulating a tension–compression couple in mega columns. Belt trusses connect the mega columns at the perimeter of the building, reducing the elongations in tensile zone and shortening in compression zone of mega columns, while also being capable to resist a shear load, which can cause bending. Even though, the columns and belt trusses are capable of taking over lateral actions, the design of major structure is interior core and outrigger, which classifies this structure as interior structure.

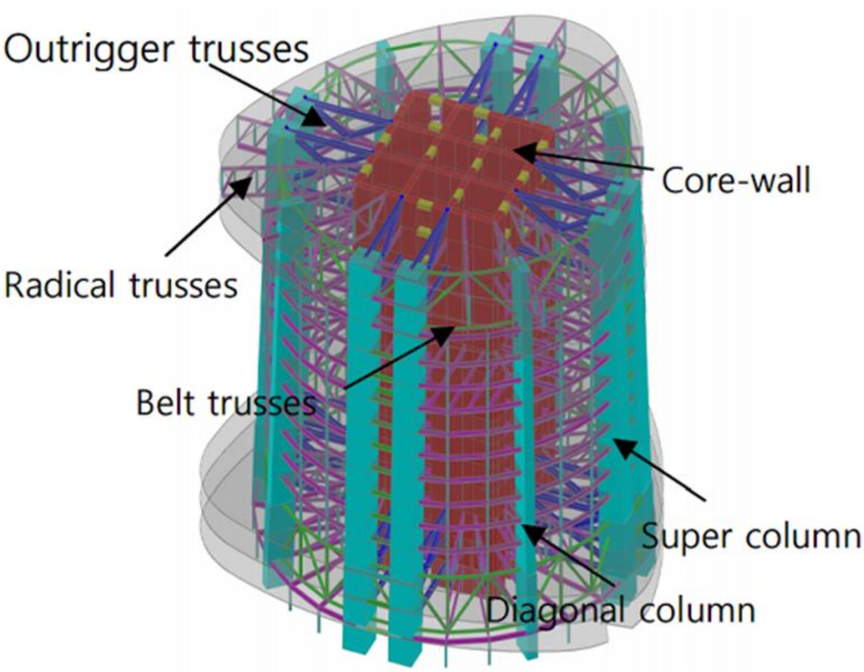

Figure 55 - Shanghai's Tower Structural System [139]

Outrigger structures are lately becoming very popular in super high-rise buildings, where outriggers trusses or walls advance shear wall/core system in resisting lateral actions in a form of re–distribution of shear forces. With outriggers in buildings higher than 70 storey, bending caused by overturning is highly resistant.

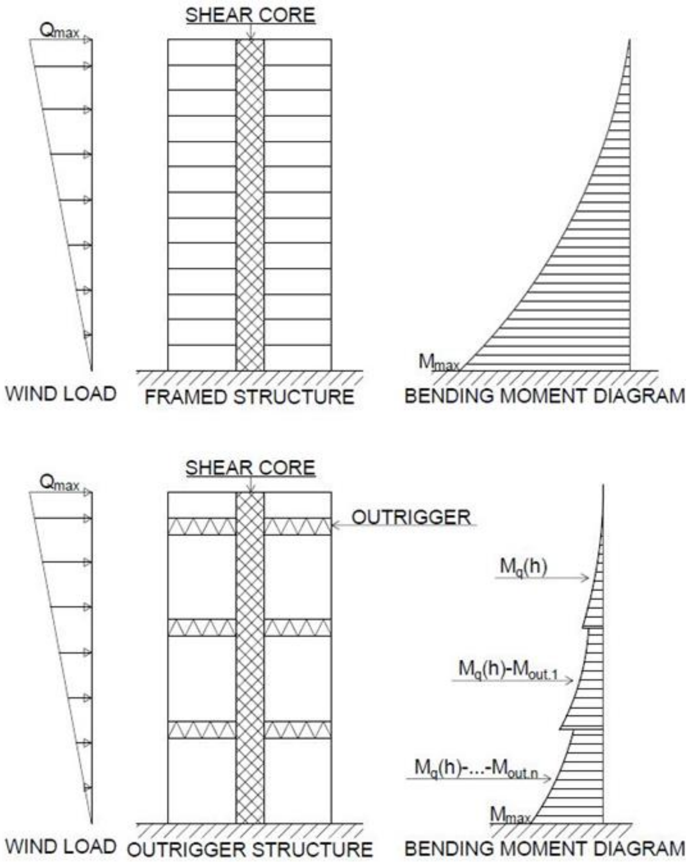

Figure 56 - Bending Moment Diagram under Applied Wind Load on Shear Core and Frame Structure (above) and Bending Moment Diagram under Applied Wind Load on Outrigged Structure (below)

Besides valued advantages, in terms of additional stiffness, stability, higher resistance of the structure to crucial lateral loads, high performance and efficiency in use of the materials and design, the main disadvantage is perceived in occupied rentable space reserved for outriggers. If consider that 1 or 2 storeys are required per one outrigger, it becomes obvious that the greater height leads to the percentage of occupied stories respectively increasing as well. However if well planned and designed, outrigged stories can be used as mechanical floors; such approach excludes “waste” of space. Considering structural material, this structure might be designed as steel structure or concrete, or in most cases as composite structure. Due to the high fire resistance requirements, cores are mostly designed in concrete, which adds to the safety for occupants of the building in the case of emergency. However, lightness of structural steel makes steel preferable in comparison to heavy concrete for outriggers and belt trusses, such structure and relation between materials and structural elements, is showed as efficient when constructing 150 storeys high buildings.

TUBE SYSTEM

One of the most spread exterior structures of high–rise buildings is tube structure. Lateral actions in such structure are resisted with the structural element positioned at the perimeter of the building. As one of the greatest innovation in the sixties, tube structure was designed by F. Khan back in 1961. It was delivered as an actual structure with De Witt Chestnut Apartment Building in Chicago. Construction was finished by 1963, with 43 storeys height, and in arrangement of framed tube.

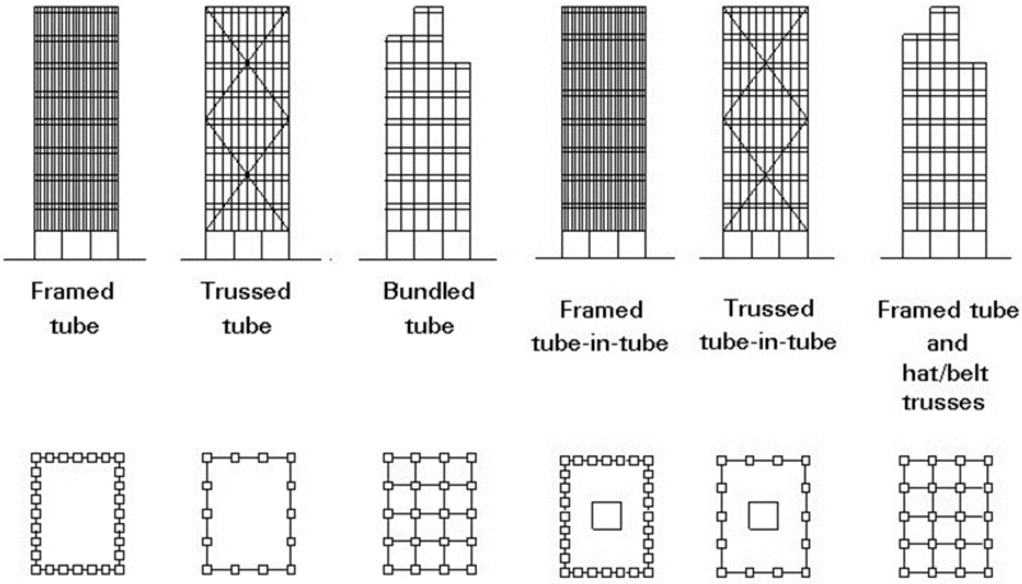

Figure 57 - Variation of Tubular Structures

Frame tube structure was the first example of tubular approach for construction of in high–rise buildings. It is designed as hollow cantilever, fixed at the foundation to the ground, in order to resist lateral loads. It consists of closely arranged columns, while the span between central axes of columns' cross section is approximately between 1.5 to 4.5 meters and spandrel beams being rigidly connected. The depths of beams vary between 60 and 120 cm. Term framed tube structures is closely related to, shear lag effect, which means that within this type of structure corner columns experience the largest axial forces, which are not distributed linearly along the direction perpendicular or parallel to the wind.

Frame tube can be designed both out of, steel or concrete, with efficiency up to 80 storeys.

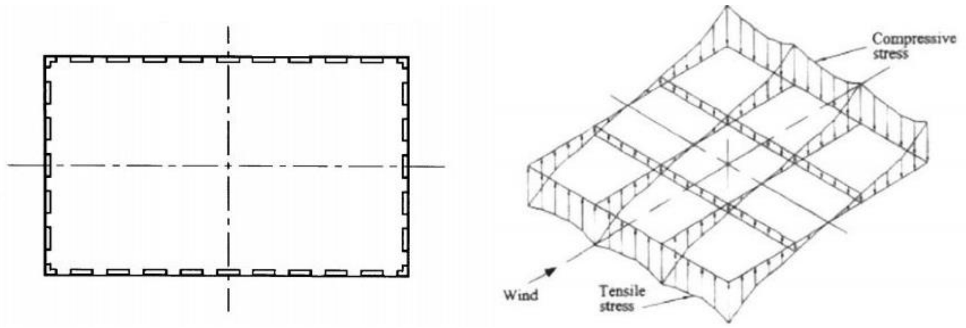

Figure 58 - Characteristic Arrangement of the Structural Elements for Framed Tubes in Plan (left) and Diagram of Shear Lag Effect (right) [1]

For architectural functionality or aesthetics such system strongly leads the overall composition, dynamic and geometry of the elevation, while at the same time decreases costs for the additional curtain wall or fill in walls, but also reduces daily light penetration to the building.

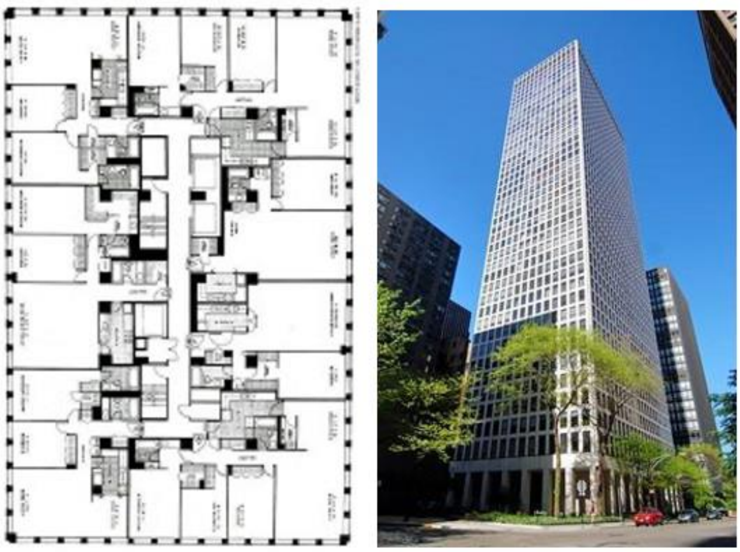

Figure 59 - De Witt Chestnut Apartment Building in Chicago, F. Khan, Characteristic Floor Plan Showing Perimeter Column Arrangement (left), and De Witt Chestnut Apartment Building Constructed (right) [178, 137]

A type of tube structure, braced tube, also called truss tube, was first used back in 1970 in Chicago, at John Hancock Centre. Such structure developed as newly evolved frame tube. Instead of closely arranged columns, required structural stiffness was achieved by diagonal bracing. Braced tube overcame the problem of progressive inefficiency in over 60 storey high buildings which was the case with frame tube. With bracing, perimeter frames acted as stiffener and the braces overtook floors' gravity actions. Each joint of the diagonals and columns, in structure of braced tubes, eliminated effect of shear lag by being tubular in framework. Besides structural advantages of braced truss tubular structure, larger spans between columns that were provided by bracings, created larger areas for the openings glass areas increased the interior quality and at the same ratio, the glass areas increases themselves. Also, the braces which were left as visible by design, enhanced and gave a character to each elevation.

Figure 60 - John Hancock Centre, Representative Example of Braced Tube Structure [79]

Unlike other tubular structures, bundled tube system, made high–rise buildings structured with this system a vertical play of the various volumes, which differentiated it from the cubic shaped towers. In this variation of tube structural system, couple of tubes were interconnected and acted as one unit. Back in 1974, Sears Tower was the first bundled structure, with 9 tubes at the base level, which created regular grid of 3 rows and 3 columns, while still following the principle of bundled structure; as the final storey was not cubic. Approach of the bundled structures, concept and the overall design of structure reduced the elements of the lower storeys, slandering lower structural elements, when compared to those that would be required for other type of structure.

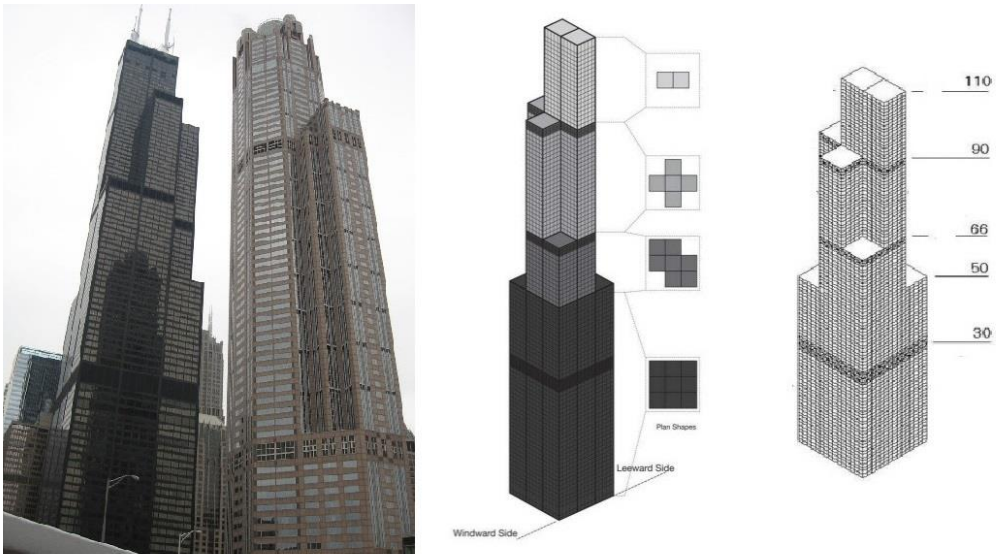

Figure 61 - Sears Tower, Chicago (left),
Schemes of Modular Floor Configuration (mid and right) [67, 181]

Bundled concept, unlike others structure's concepts gives variety of characteristic floor plans in areas, with greater lower storeys and those smaller at the upper storeys. There are different geometrical shapes in grid plan, such as: rectangular, triangular, hexagonal etc., which mould vertical volume of the high–rise tube. Bundled tube structures, efficiency is up to 110 storeys, with possibility of steel or concrete as main structural material. Even though such composition reduces shear lag and enables slenderer structural elements, the configuration of tubes may have created limitation in arrangement of the interior space.

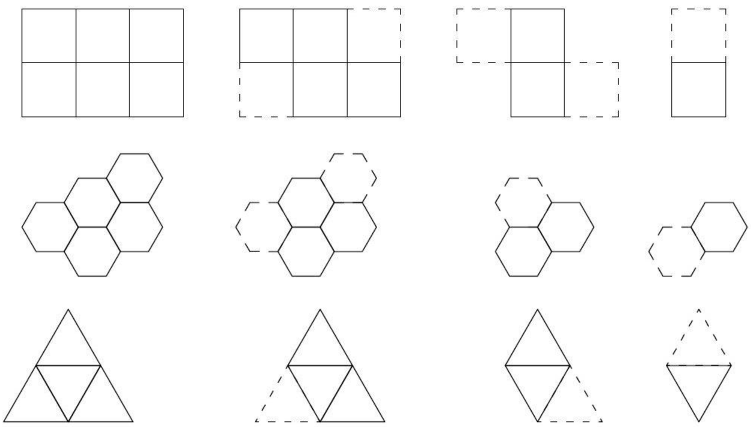

Figure 62 - Different Plan Configuration for Bundled Tube Structures

One of the safest tubular structures due to resistance to the impact loads, besides its high stiffness of structure in resisting lateral and gravity loads is tube in tube structure. It is usually composed of two tubes, one larger at perimeter and smaller inside perimeter of building, however it may be designed with more tubes within a tube if it is required due to higher safety and if such attempt and concept shows as efficient. An example of tube in tube structure is 181 West Madison Street in Chicago, which has 52 storeys.

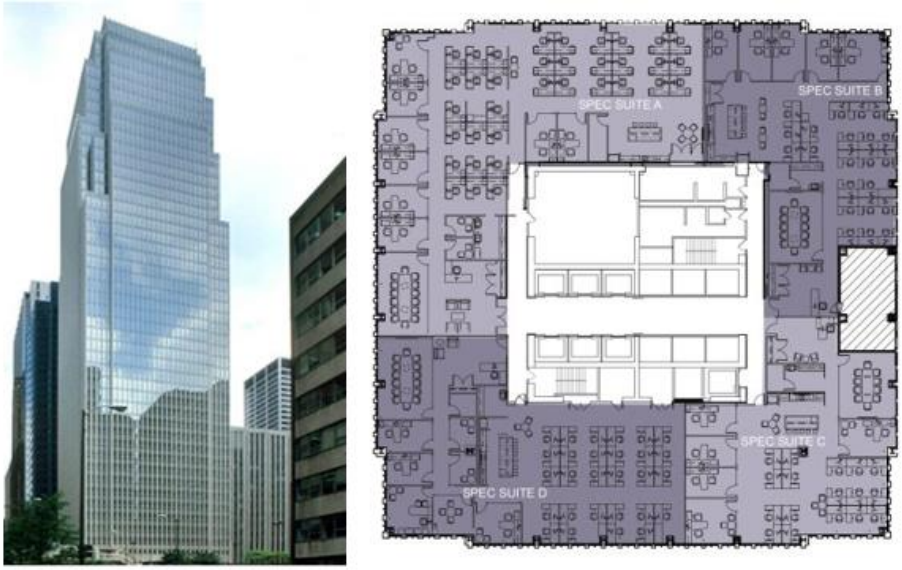

Figure 63 - 181 West Madison Street, (left), Characteristic Floor Plan (right) [144, 143]

Such structure effectively resists lateral actions with both tubes due to its system that inner core (inner tube) and outer tube with slabs, which makes both core and cube able to resist lateral actions. As far as the structural material is concerned, both exterior and interior tubes can be designed as concrete or steel cores or frame tubes. In terms of height, tube in tube system is efficient up to 80 storey high buildings. However, such structures excludes a high demand for numerous columns in interior design, inner core if not used with specific purpose as elevators, stairs, mechanic installations core, can develop limitation in arrangement of interior space.

DIAGRID SYSTEM

Diagrid is an exterior structural system used in high–rise buildings, which is even though entirely exposed at the elevation, both in architectural and structural fields of science and art, defined as extremely aesthetic. Unlike, diagrid braced tubular structure, which may be seen as a forerunner of diagrids, it is mostly degraded by expertise and critics. Entirely braced John Hancock Centre in Chicago, was one of the pioneers in braced tube structures; despite the improved structural efficiency, new aesthetic style, innovation, structure exposed through all four elevations was not welcomed. However, a decade later, newly named form of diagrid, gained full attention. Dating back to 1980's Sir Norman Foster, proposed diagrid solution for the Humana Headquarters composition. Even though diagrid was not a best solution for Sir Norman Foster, Hearst Headquarters Centre in New York and 30 St. Mary Ave in London received praise and become monuments of Sir Norman Foster, and were closely related to diagrid structures.

Figure 64 - Hearst Headquarters Centre in New York (left), and 30 St. Mary Ave in London (right) [170, 96]

In diagrid structures, the whole structure depends on diagonal members. Due to stored shear by axial forces in diagonal members diagrid structures reduces and minimize shear deformation.

Diagonal members of diagrid were also capable of carrying gravity actions, and its triangulated configuration of diagonals could resist for lateral actions. As structure, diagrid did not seek for shear rigidity cores, because diagrid had high bending and shear rigidity at the perimeter's diagonals.

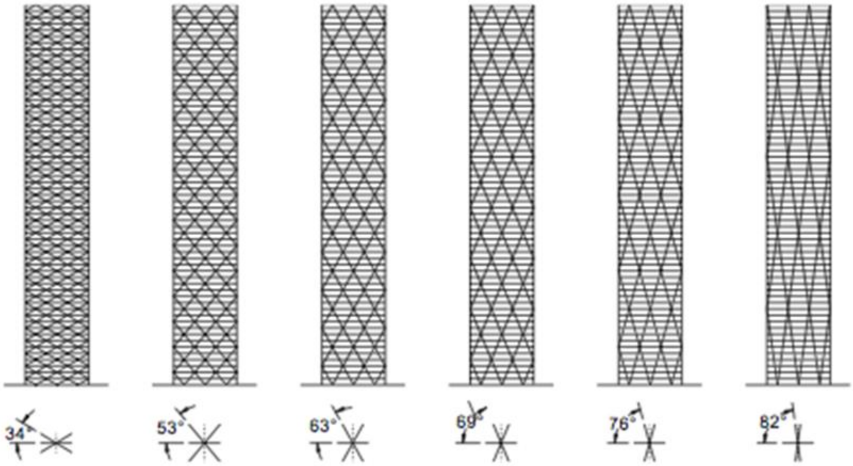

Figure 65 - Variations of Diagrid Geometry [62]

Diagrid structures are commonly steel structures, with very complicated joints of the diagonals, however they are efficient in up to 100 storeys buildings, and represent regular geometry in diagrids. Lately diagrids are designed and constructed out of concrete, as main structural material, which is far different from steel diagrid, with more irregular and organic shape, which lead to the new futuristic architectural aesthetics. Concrete diagrid structures, require expensive formwork and the construction. An example of such design is reflected in O–14 Building in Dubai.

Figure 66 - Concrete Diagrid, O-14 Building Dubai (left)
and Construction of Diagrid (right) [161, 167]

SPACE TRUSS SYSTEM, EXO–SKELETON SYSTEM AND SUPER FRAME STRUCTURES

Besides Tube and Diagrid, exterior structures that resist lateral actions and structures that supports high–rise buildings in physical world include, Space Truss, Exo Skeleton and super frames.

An example of Space Truss structure can be seen in China Tower of 1990, in Hong Kong. In appearance, space truss is described as braced tube with modified diagonals that penetrates from the exterior to the interior of the building. That is at the same time greatest difference between the two, braced tubes diagonals and chords members are connected in plane areas, while space trusses diagonals have third direction toward to the interior space. Axial forces of the space truss members, resist lateral actions, while space trusses are steel structures which are efficient up to 150 storeys. Diagonals that penetrate the interior of the building are one of the crucial elements for structure's resistance, however if not well designed they might appear as obstacle in interior of the building.

Figure 67 - China Tower of 1990 (left)
and View on Buildings Structure from Interior of the Building (right) [160, 64]

Unlike all other structural systems, Exo–Skeleton is located on the outside of the building, which means that the actual lateral load resisting structure is located outside of the building and its elevation plane. An example of this structure is Hotel de las Artes, in Barcelona, Spain. Due to such exposed structure, buildings volume and elevations are catchy and act as identifiers. Main structural material for this structure is steel. However, fire proofing for this exterior structure is not highly demanded as for the other structures, because it is solely responsible for resisting lateral actions, and its failure should not initiate progressive collapse of the entire building. However, due to ever–lasting exposure of the structure to weather conditions, corresponding thermal bridge should be carefully designed. This structure hasn't got any obstacles in interior space and it is efficient for up to 100 storeys high buildings.

Figure 68 - Hotel de las Artes, Exo – Structure at Main Structural System (left) and View on Detail of Elevation, Structure Connection to the Buildings Volume (right) [128]

Super frame structures are ideal for the concepts of skyscrapers or ultra–high buildings. Super frames are efficient for up to 160 storeys, but there are buildings structured with super frames, with lower numbers of storeys, and example of such structure is Parque Central Tower (Caracas, Venezuela), which has 56 storeys, while an even higher buildings structured with the use of super frames, is designed but still not built – the Chicago World Trade Centre, with 170 storeys.

Figure 69 - Parque Central Tower, Caracas, Venezuela, Concrete Super Frame Structure, under Construction (left), on fire (mid), Renovated (right) [91, 134, 132]

Super frame building reacts as tubular structure in order to resist lateral actions. Such structure consists of vertical structural truss in a shape of mega columns, arranged at each corner, where this position of the mega columns imposes that highest efficiency for resisting wind actions is at the corners.

Unlike vertical, horizontal like trusses are linking mega columns, after every 12 to 14 storeys respectively. The major disadvantage for architectural design and form of the high–rise with this structure, is that the structure is actually leading the form of the high–rise. Super frames could be both steel and concrete, where more efficient material is steel, with efficiency up to 160 storeys, unlike concrete where efficiency stops at 100 storeys.

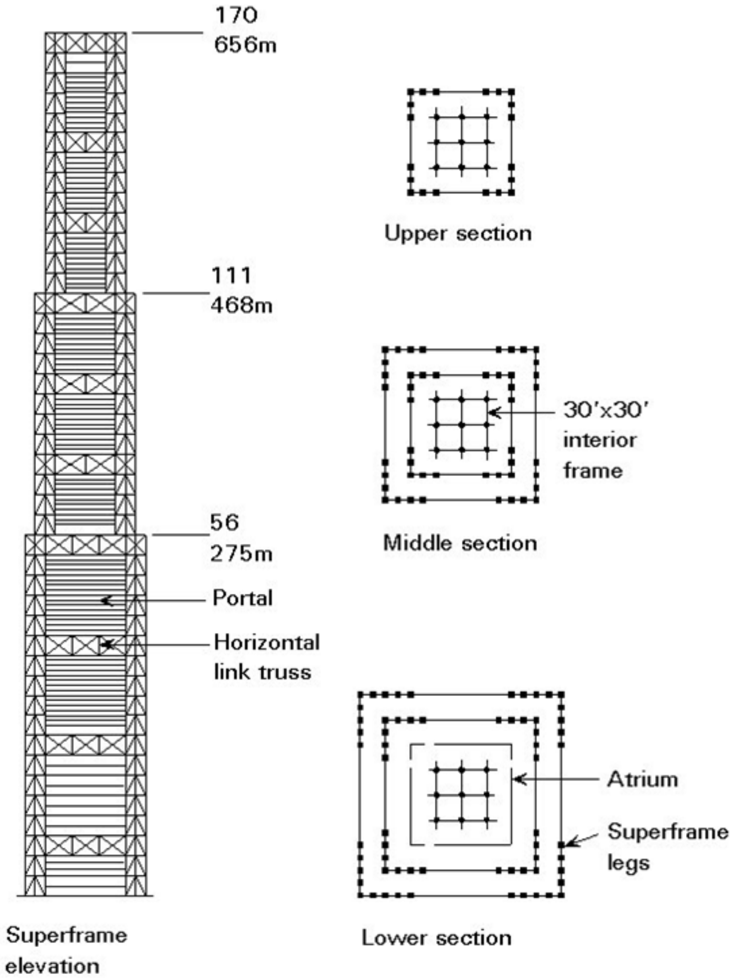

Figure 70 - Chicago Ultra – High Building, Proposal for Steel Super Framed Structure, Elevation (left) and Characteristic Floor Plans (right) [71]

HYBRID STRUCTURES

After the period of modernism, architectural aesthetics imposed more irregular shapes, conceptually designed as unity of more different geometrical volumes, with more curved lines, inclined elevations, bridges, buildings etc., which made none of the previously known individual structures able to support such volumes. As a solution for this concept, an idea of hybrid/mix structural systems in form of combination of advantages of different structural systems and materials, and in order to maximise structural efficiency of the building. Such structures, were mostly mix of a composite structures and materials, however it is important to distinguish these two structures, because of their difference in load resisting capabilities.

While the composite materials, present two or more materials combined in order to form a new material, more efficient one, in hybrid structures, structural materials may perform their properties individually, or together in order to get the highest performance and efficiency of materials. As long as hybrid structures engaged variations of different structural systems, principle of the load bearing and resisting was hard to explain with the unique principle. However evolution in the production of the concrete, in form of innovative HSC (High-Strength Concrete), certainly reduced deformation of the columns, increased axial load capacity of the material, and in same time decreased self –weight when compared to conventional concrete.

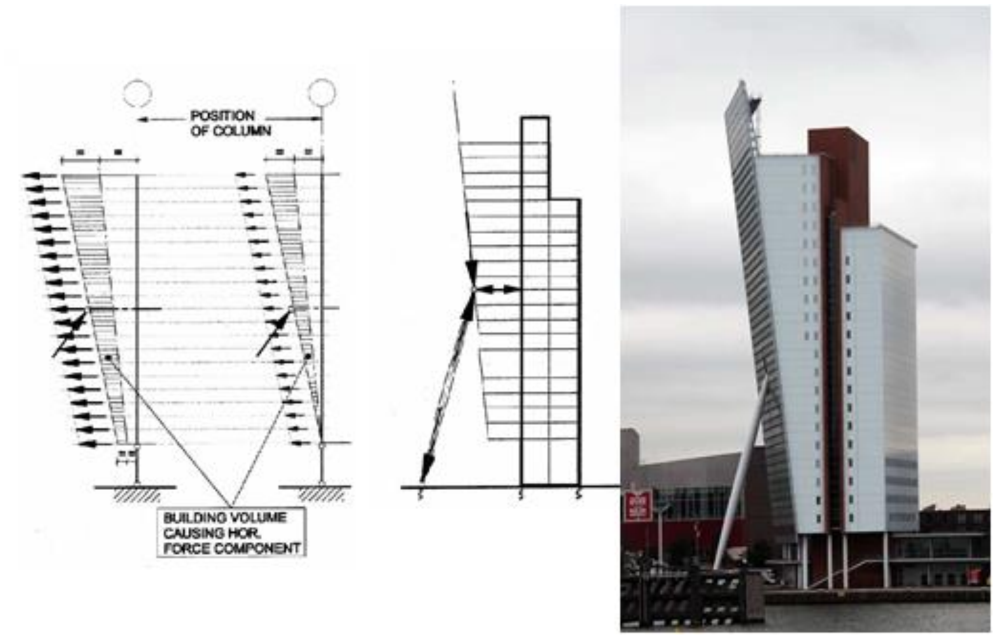

Figure 71 - Belvedere Building, Rotterdam - Horizontal Forces Scheme (left), Inclined Strut (mid), Constructed Building (right) [41]

Sloping tower “Belvedere” in Rotterdam, designed by an architect Renzo Piano is one of the most representative example of hybrid structures. Inclined design of the eastern elevation represented great challenge for structural design. Even though, columns were positioned in optimum arrangement, horizontal forces were too high to be resistant by any of the ordinary structural systems, like core, tubes, or shear walls. Strut, which was actually part of the overall building’s concept, became part of the structural system in case of an emergency and in order to resist horizontal forces. [41]

STEEL AS STRUCUTURAL MATERIAL FOR HIGH–RISE BUILDINGS

Steel, as structural material has dominated worldwide for a long period of time, enabling various achievements in both architecture and construction. Due to its mechanical properties and construction abilities, steel encouraged development of high–rise buildings, bridges, towers and other structures, which required lighter material, but with at least the same or higher bearing capacity than masonry structures allowed. Steel, an iron alloy, is basically manufactured in steel factories in high–advanced conditions; that way it is more predictable in its behaviour than materials such as concrete or other manmade materials. Strength, uniformity, light weight, ease of erection and prefabrication, in demand for rapid construction made the steel a material of the future.

It could be said that the history of steel can be traced back up to 4000 years in the past. Due to its strength being greater than that of a bronze, iron started to replace the use of bronze for weapons and various tools. However in the 6th century B.C., Chinese were the first to use blast furnace in order to work with cast iron. What Chinese started doing in the 6th century B.C., Europe developed in the Middle Ages; their attempts and experiments almost clarified most of the iron properties, with one of the main explanation being that carbon is affecting iron's workability.

Cast iron in that period was in great measure strong material, despite high level of carbon varying from 2.5 to 4.5%, which lead to the problem of brittleness. Although this was an obvious problem, solution wasn't developed until few centuries later.

Solution was an innovation of puddling furnaces offered in the 18th century by Henry Cort. Despite efforts of different metallurgist, puddling furnace and cast iron were the greatest achievement in the development of technology. Higher interest for the development of steel was evoked by 19th century. In 1856, Henry Bessemer introduced process of inducing oxygen into iron in order to reduce the amount of carbon. Process was named after Bessemer but it did not succeed as it was planned due to the portion of induced oxygen, which was not easily defined, creating iron with too much reduced carbon, containing overdosed remains of induced oxygen. Shortly after, in 1860s, new process of steel production and carbon reduction was disclosed with success, known as Open Heart Process.

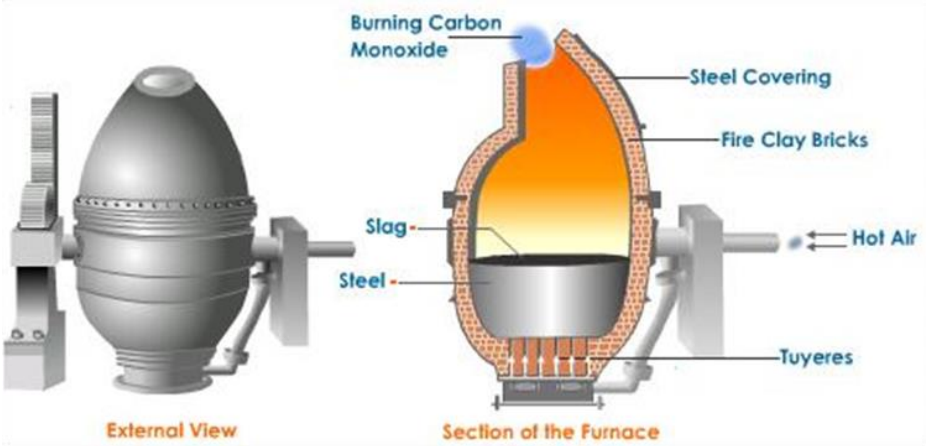

Figure 72 - Bessemer Steelmaking Process (illustration of furnace) [142]

After these innovations, vast iron or earliest steel were a turnover for spread of steel structures. With the development of steel, idea of high–rise structures and high–rise constructions was born. Along with that, Chicago became place of the world's first high–rise building. Home Insurance Building, 1884/85, the first worlds' high–rise constructed with cast iron and pioneering steel.

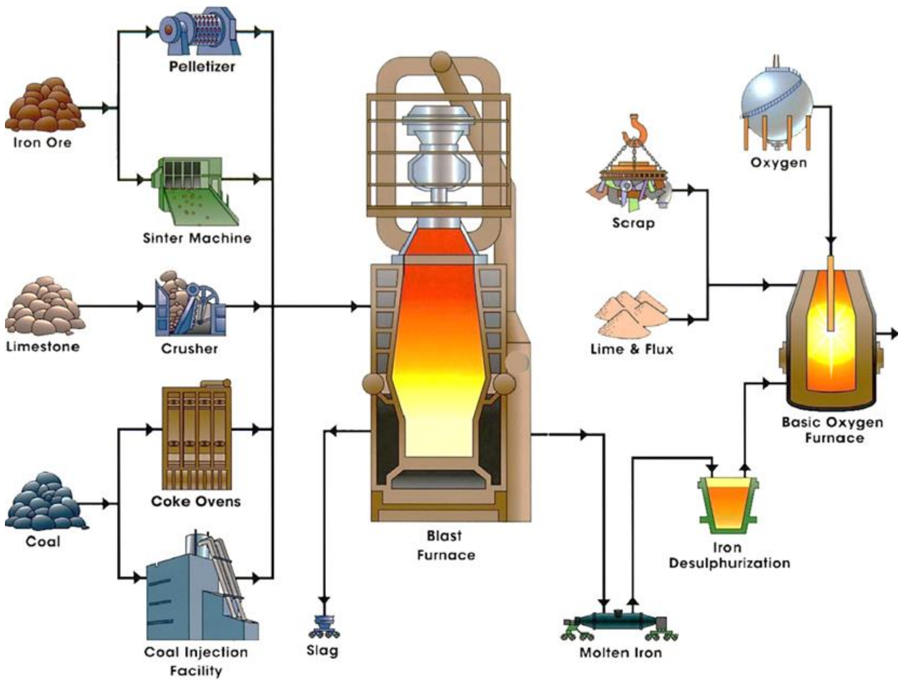

Figure 73 - Contemporary Steel Making Process, Combination of Blast Furnace Top Gas Recycling and Blast Oxygen Furnaces, Highly Reduces Steelmaking Emissions (illustration) [151]

After the first high–rises, it is hard to separate whether the development of material was rapid due to the necessity for high–rise constructions, or high–rises were designed and constructed in order to achieve and push the steels' abilities and limitations. However, it was sure that the world was undergoing a revolution of steel industry, parallel with the race for high constructions. Different requirements developed new steel manufacturing processes, Electric Arc Furnaces and latest oxygen steelmaking. The latest widely used steel manufacturing process is oxygen steelmaking, with the basic oxygen furnaces being developed back in 1960, and is still remains one of the 66% of world production of steel.

Although steel has been used in various ways, and has many representative achievements in construction, its low fire resistance and high maintenance costs, are reasons why steel is taken with reserve, and reasons why there are more composite structures rather than single steel structures.

Steel's properties as structural material are mostly taken as its advantages. As a material that can answer most of the architectural requirements on its own, with wide range of shapes and excellent properties, steel was declared as a material of future architectural concepts and future high–rises, long span constructions. However, steel weaknesses were not treated well in earlier buildings, so events of collapses, damages or maintenance issues with buildings made steel less desirable as major structural material.

However, steel as a structural material has significant advantages and are as follows:

- High–strength material, with equal resistance both in tension and compression stresses;
- High–strength/ weight ratio declare steel suitable for high–rise structures, long span bridges due to slenderness of structural elements compared to concrete structures;
- Prefabrication – factory made material with the best conditions and high quality control of the production and processing of steel elements;
- Time – schedule of the structure erection;
- Predictable material in its behaviour;
- Ductile material, steel can undergo large plastic deformation before failure; and
- Fatigue strength.

Steel disadvantages are also important for consideration:

- Unlike concrete rigid connection, in steel structures weakest point may occur in joints/ connections;
- Cost of steel structures – in general steel structures are much more expensive than other structural materials;
- Fireproofing costs – steel has low fire resistance which is mostly one of the weakest point in steel structures, especially if there is word about high–rise buildings with no sufficient time to evacuate the building; however, there are different fire proof coats which highly increase total cost of structure, but elongate time for fire resistance;
- Maintenance costs – maintenance may request same or even higher costs in time. Besides fireproofing coatings, steel structures require additional coatings to prevent corrosion; due to different environmental conditions, constant humidity may cause corrosion which reduces cross sections and durability;
- Buckling as much as the slenderness of steel element is one of its greatest advantages and desirable in architectural expressions, steel columns are subjected to the buckling of steel columns due to columns slenderness, which explains why steel columns are mostly avoided and replaced at closest composite concrete steel columns.

Steel sections used in construction are classified according to the way they are formed, or manufactured. However steel is also classified according to its chemical compositions, that is, according to the percentage of carbon present, type of the alloys or stainless.

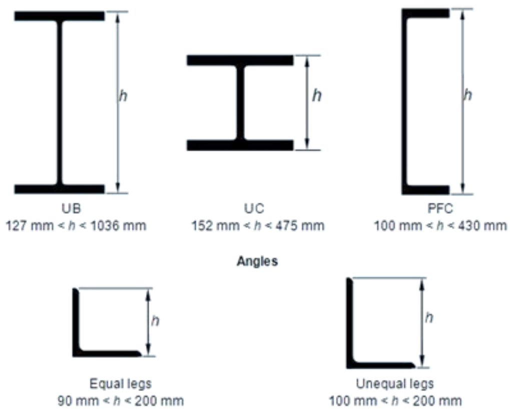

Figure 74 – UK Hot – Rolled Steel Open Sections [191]

What lead to some of the newly developed ways of classification of steel is development of steels with highly increased strengths, so classification of steel based on its physical strength is now also a common thing.

Numerous types of steel section are produced by hot rolling, with different shape, weight or size. For instance, open sections in UK are defined as universal beam (UB), universal column (UC), and parallel flange channel (PFC) or angle section.

Tubular hollow sections have circular or rectangular shape (CHS and RHS), and proved to be a better solution for buckling resistance of structural elements. There are two types of steel hollow sections and they are distinguished by the method of production: cold formed hollow sections and hot formed hollow profiles.

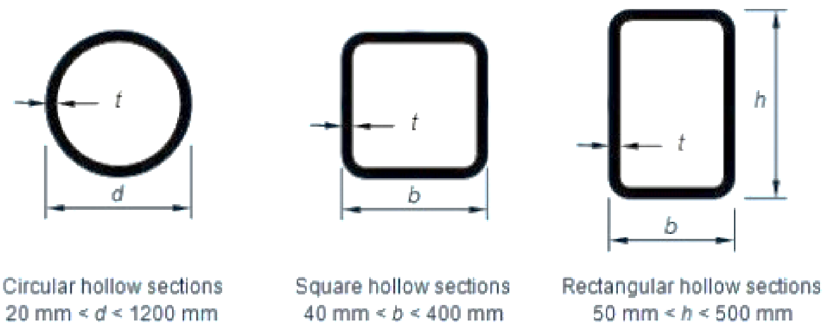

Figure 75 – Tubular Steel Sections [191]

There are also so called European Steel Sections with appropriate tables for all the steel sections, with their dimensions, properties, classification, resistance and buckling resistance values according to Eurocode 3, EN1993-1-1:2005. The tables are extended to welded section with dimensions. The designers can select section type e.g. IPE, HE etc.

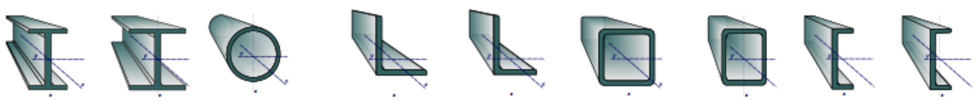

Figure 76 – European Steel Sections [123]

On the other hand, cold formed sections are mostly used as secondary elements in structures or in light steel frames. Typical cold formed section are C and Z sections, produced by cold rolling from galvanized strip steel, with 1.2 to 3.2 mm in thickness.

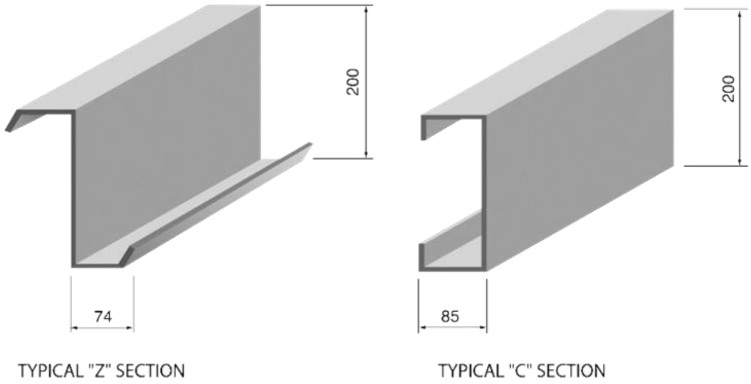

Figure 77 – Standard Z and C Cold Rolled Steel Sections [117]

Another important classification of steel is also in accordance of steel's chemical compositions, which influences its properties and dedicates its purpose.

Table 1 - Steel Classification according to Carbon Percentage Presence

CARBON STEEL TYPE	**CARBON PERCENTAGE**	**APPLICATION**
Low – carbon steel (Mild steel)	0.04 % - 0.30 %	• various shapes from flat sheets to structural beams • other chemical elements are added or increased to achieve desired properties.
Medium – carbon steel	0.31 % - 0.60 %	• manganese 0.06% - 1.65 % • stronger than low carbon steel • more difficult to form, cut and weld
High – carbon steel (Carbon tool steel)	0.61 - 1.50 %	• once threated with heat becomes very hard and brittle

Alloy steels are reserved for pipelines, car parts, electric motors, power generators etc. They contain elements such as silicon, copper, chromium, titanium, nickel, aluminium in order to improve steel's properties. Although not used as structural steel, stainless steels is an important category itself, which contains 10-20 % of chromium, and is valued for high corrosion resistance. However, its costly production is not economical for construction of building's structures.

For structural steel, the most important strength property is its yield stress (f_y). However it in great measure depends on steels' chemical constitutes, among which carbon and manganese increase yield stress. For yield stress, the heat treatment and amount of rolling process in production and shaping is important for instance, thinner plates, which were more processed, have higher yield stress than thicker ones.

The minimum yield stress is identified individually for different steel classifications, depending on chemical compositions and heat treatments, where yield stress is defined in accordance to the results of a standard tension tests. Howsoever, yield stress allowable for design is listed in different tables, with specific characteristics of specific steel.

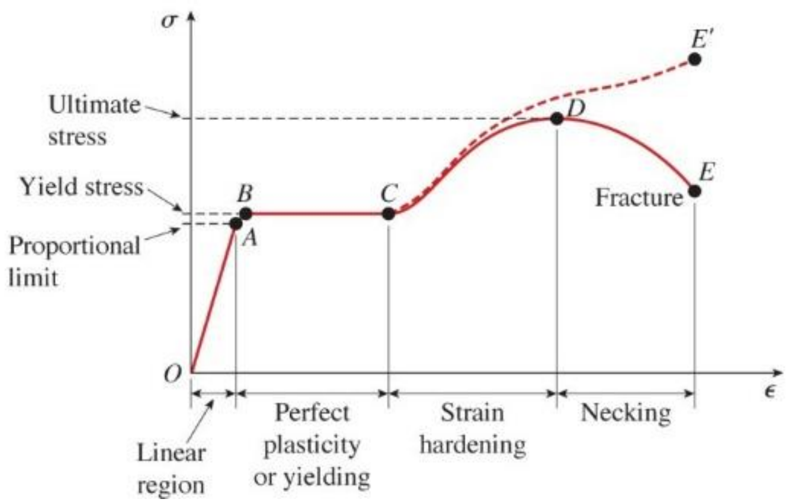

Figure 78 – Stress – Strain Diagram for a Steel in Tension [85]

Steel's yield stress determined for uniaxial tension is usually also accepted for uniaxial compression. This means that tensile strength of the steel is also referring to compression strength.

Another steel property is very important for the behaviour of structures and elements, particularly for resisting the shock loadings, such as seismic or impact load. This is ductility. Steel ductility is responsible for avoiding brittle fracture, meaning that steel can undergo great plastic deformation before failure.

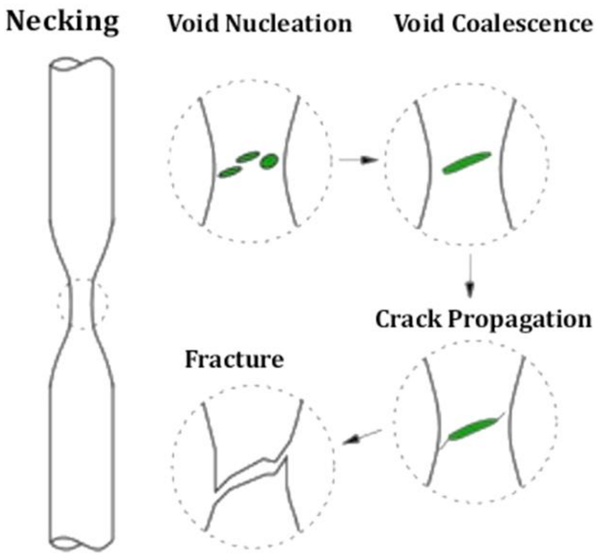

Figure 79 – Schematic Expression of Steel's Ductile Failure Phases [183]

Steel's minimal ductility is expressed by:

- Elongation after fracture at the measurement length of $5.65\sqrt{A_0}$ (where A_0 is the initial surface of cross section). According to Eurocode 3, the elongation after fracture should not be less than 15 %; [35]
- f_u / f_y ratio of a specified minimum strength, f_u, and a specified minimum yield strength f_y. According to Eurocode 3, the minimum value should be $f_u / f_y \geq 1.10$. [35]

According to this, steel with greater yield stress is limited to the smaller elongation.

There is a possibility for all materials to develop some defects during a production, curing and erecting time, or during its service life. Such defects may take any forms, but in case of steel, the smallest crack is sufficient to result in brittle fracture of structure, due to its acceleration in spreading through the specific element. Brittle fracture stands for undesirable sudden failure, without expresses the plastic deformation of material. Risk of steel's brittle fracture increases with thickness of the element, tensile strength, or cooler temperature.

Steel toughness is its ability to resist brittle fracture after loaded, and is defined as quantity of energy pre unit volume. This is determined by means of the Charpy test, where energy–temperature curve is derived. Due to this, steel toughness is influenced by temperature, loading speed, cold–forming and thickness of material.

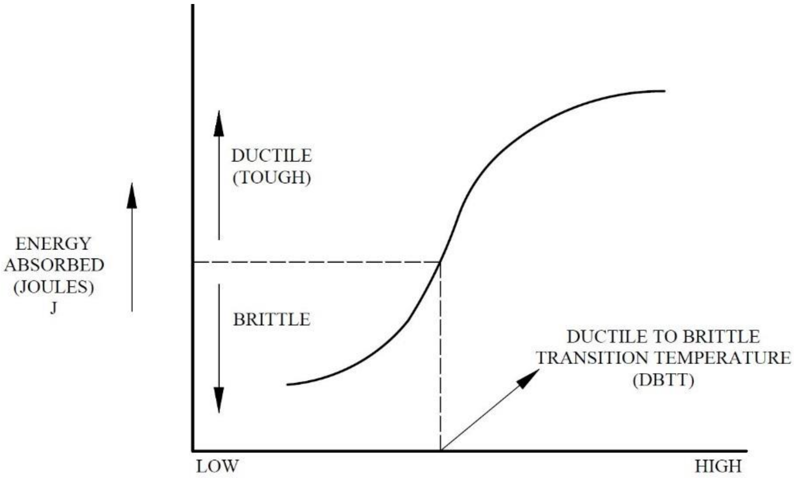

Figure 80 – The Influence of Temperature on Loss of Toughness [154]

Steel celebrated the phenomena of high–rise construction, where structural properties of steel enabled larger and higher buildings than those structured with timber or stone. So without any overstatement it is safe to say, that steel structures are foundation of high–rise structures.

Figure 81 – Home Insurance Building, Chicago, World's First High – Rise Building Steel Structured [192]

The Home Insurance building, in Chicago was entitled the first high–rise building in 1885. Cast iron and steel were the only materials used in structure which framed this 10–storeys high–rise. The building gained a lot of attention and succeeded as new architectural concept, which initiated a race of high–rise construction. All steel high–rises and buildings, were also characterized with large open surface of the facades, which indicated the role of steel in large spans and slender elements, columns and beams, which was innovation for the earliest high–rises. To express the earliest success of steel in high–rise buildings, according to the researches of CTBUH, in 1930, 96% of the world's highest high–rises were steel structured. Sears Towers, World Trade Centre I and II, Empire State Building, Chrysler Building, John Hancock Centre are the examples of World's highest high–rise buildings, although it is interesting that all these building were constructed before 1990.

Evidence of a great decrease in high–rise buildings constructed of steel is repeated CTBUH researches in 2000, where among world's 10 tallest high–rises only 4 of them are steel structured, along with devastating data of researches from 2011, where among 10 tallest buildings there is only 1 steel structured buildings, Willis Towers (Sears Tower, 1974). So, it is hard to see these results and not to raise a question of why steel structures lost their role in structuring of the high–rise buildings.

Figure 82 – World Trade Centre I and II, Results of the Attack High Fire – Demolished or "Burnt" Steel Structure of High–Rises, September 11, 2001 [194]

The answer certainly lies in steel's weaknesses, among which its low fire resistance is crucial for the decrease in demand for steel structures. In the late nineties and at the beginning of the new millennium, few high–rises were attacked and/or caught by fire. Unfortunately, steel's low fire resistance did not provide enough time for evacuation of the many people that were inside the building, so the results and losses were huge, and the human lives were irreplaceable.

One of the most known and valued steel high–rises is John Hancock Centre in Chicago. The 100–storey building was designed by Bruce Graham and F.R. Khan. Trussed–tube steel system, with tough integration of architectural aesthetics, entitled J. Hancock Centre as one of the most recognizable and unique high–rises. J.H. Centre, became an icon of Chicago. Its sloping form, narrowing as it rises and its continuous mega cross bracings of trussed–tube system, enhanced harmony between architecture and structure created, an outstanding piece.

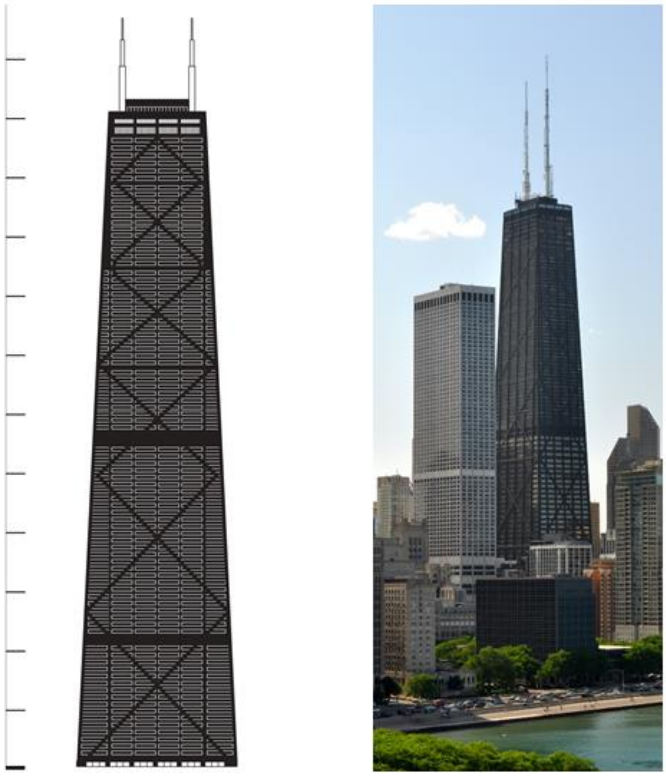

Figure 83 – John Hancock Building - Elevation (left) and in Urban Context (right) [109, 88]

Mega X–braces on facades are designed as truss element with 45° angle, which support large percentage of wind load, while sloping structure and volume of the high–rise also reduce wind effect at higher storeys.

CONCRETE AS STRUCUTURAL MATERIAL FOR HIGH–RISE BUILDINGS

Concrete, the name of the artificial stone, is one of the most spread structural material worldwide. Even though it is the most valued for construction of buildings (structural systems, slabs, walls and foundations), it is not fair to neglect its merits in the construction of bridge decks, piers, grandstands, chimneys, pipes and also urban furniture. The most common definition of concrete states that concrete is a mixture of sand, gravel, crushed rock or other aggregate held together in a rocklike mass with a paste and water. Besides these basic materials mentioned in the definition above, technological and chemical development of concrete industry created various admixtures that worked to improve concrete’s properties and its main strengths compared to other structural materials, such as durability under hostile environments, high resistance to water etc.

The first appearance of concrete is often thought to be many centuries ago, which in one hand may be true. Dating back to the Roman period, their approach in design and material mixing technology may take a role of contemporary concrete’s forerunner. Romans used domestic material, pozzolana–sandy volcanic ash, found near volcanic areas in Italy. Pozzolana was mixed with water and quick lime, sand and gravel, and when it hardened, it was used as a building material. Most of the Roman’s impressive buildings were built with this material. Even though from this point of view such mixture may be equal to very weak contemporary concrete, Roman buildings still remain intact, with one of the most outstanding being Pantheon with its impressive great dome, located in Rome.

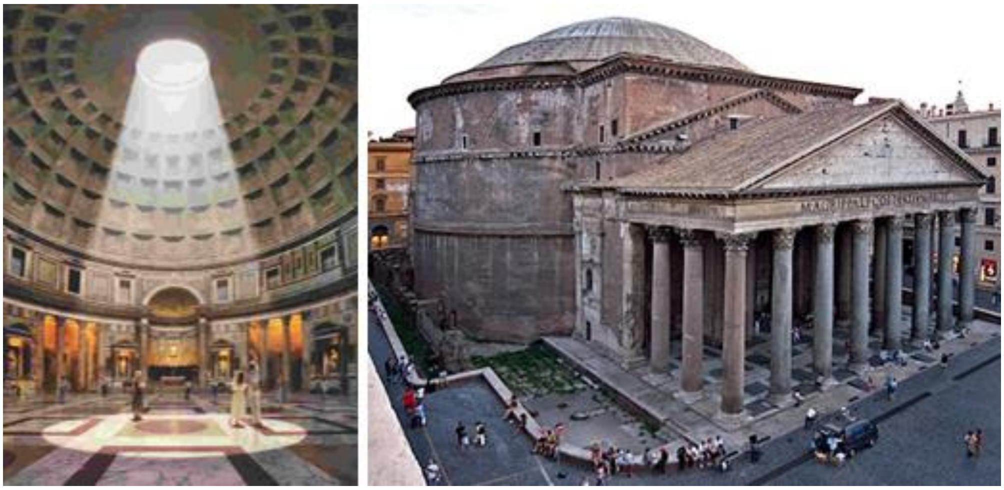

Figure 84 – Pantheon, Rome, Interior (left) and Exterior (right) [193, 81]

After, to say, Roman's pioneering in this building material, concrete technology was stagnant until the late eighteenth century. In 1796, natural cement rock named after the Roman cement was discovered in England. Similar cement rock was found throughout Europe and America and was used for several decades. Patent for Portland cement was received by Joseph Aspdin in 1824, in England. Cement was produced through long and various experiments of pulverizing clay and limestone into a fine powder. Even though Portland cement was accepted in Europe and America at a slower rate, it could be seen as a turning point for further development of concrete.

Francois Le Burn, Joseph Lambot and Joseph Monier were the first to present concrete to mass public. Le Burn built concrete house (1832), school (1834) and church (1835). Lambot introduced concrete boat, reinforced with wires and bars back in the middle of the 19th century. However, back in 1867, Monier invented widely known reinforced concrete. Along with these three names, great credits should be given to Francois Coignet for publishing a book on the application of concrete, with conclusion that too much water greatly reduces concrete's strength together with designing ribbed iron bars as reinforcement and patenting. In early 20th century, rediscovered and improved concrete was used to build the first high–rise building. Back in 1903, Ingalls building was the first high–rise with 16 storeys in Cincinnati that was built out of concrete. Besides high – rise buildings, various engineering infrastructure and facilities were constructed with concrete due to its high water resistance and the most magnificent example is Hoover Dam, with height of 221 meters, finished in 1936.

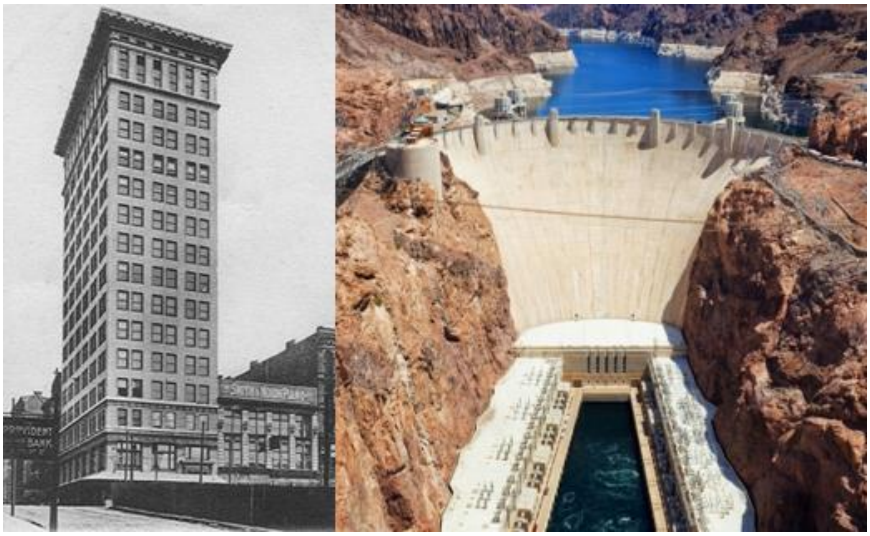

Figure 85 – Ingalls Building, First Concrete High- Rise (left) and Hoover Dam right)
[105, 111]

Thus, concrete similar to the contemporary one, dates back to the 19th century. Since then, concrete became structural material that underwent constant technological development and improvement in its greatest advantages and its physical properties, and concrete became applicable everywhere, becoming the "universal material", suitable for low–rise and high–rise buildings, megastructures, architectural aesthetics, tubes, grandstands (stadiums) etc.

As any other material concrete has it strong and weak points, advantages and disadvantages; high compressive strength of a widely known concrete is its one of the greatest advantages, while its tensile strength is just approximately 10% of its compressive strength. Due to its weakness in tension, concrete is combined with steel reinforcing, where steel upgrades concrete's weakness. Concrete advantages are:

- High compressive strength;
- High fire resistance and water resistance – during the fire, it suffers only surface damages, and in constant touch with water concrete proves to be as almost immutable material;
- Compared to other materials, concrete requires lowest maintenance;
- Concrete structures are very rigid;
- Concrete has long service life, without decreasing in bearing capacity;
- Concrete can be produced almost everywhere out of domestic materials (sand, gravel, water);
- In demand for footing, pillars, basement walls, concrete becomes the only economical solution;
- Cast in situ concrete, does not require highly skilled labour;
- Prefabricated concrete may be derived in any desired shape and volume, creating shells, arches, domes etc.

Concrete disadvantages are as follows:

- Very low tensile strength;
- Necessity for formwork, whose costs can go from 1/3 to 2/3 of total cost of the structure, however forms are in most cases reusable, where if handled correctly may be economically profitable;
- Properties of concrete may vary, due to different proportions od used material;
- Placing and curing cannot be controlled as for other materials, such as steel;

- Weak in large spans, where structural elements requires large cross sections, so it can create situation that self-weight of concrete elements become one of dominate loads on the structure.

Portland cement is one of the concrete’s main components, where cement paste influences concrete’s workability. Raw materials that are crushed and blended at high temperatures in a rotary kiln are: lime, silica, alumina and iron oxide. When cooled, clinker is mixed with gypsum in order to get fine powder cement. There are many types of cement, whose use depends on the environmental conditions.

- Type 1 – Common type, all purposes cement;
- Type 2 – Rapid hardening Portland cement
- Type 3 – Low heat Portland cement
- Type 4 – Sulphate – resisting Portland cement.

Cement mixed with water creates cement paste, which has function to bind, or in other words to glue other components of the concrete to form a unique mass. Cement paste, or in other words, the water/cement ratio is the important property of concrete, where w/c ratio role influences compressive strength, permeability of concrete and other characteristics. Meaning, the lower w/c ratio is, concrete appears to be more durable and much stronger.

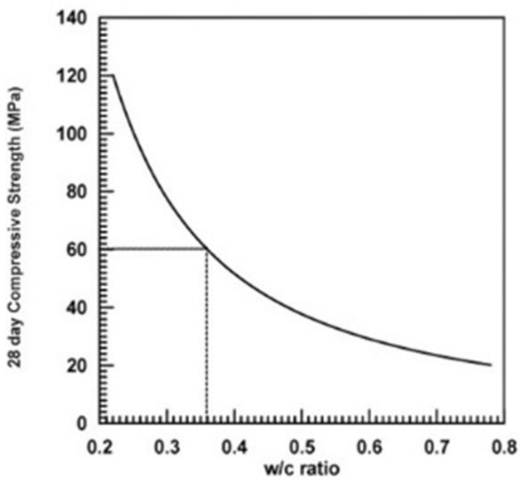

Figure 86 – Concrete Compressive Strength in Relation to W/C Ratio [165]

In concrete volumes, aggregates occupy about three thirds. Aggregates are much cheaper than cement, and due to economical profitability, there is a need for as much of aggregates as possible. In concrete production, coarse aggregates, gravel - 4 mm and larger in sizes crushed rocks, and fine aggregates, sand less than 4 mm in diameter are used.

Rock types classify as natural aggregates, such as limestone, quartz, dolomite, granite etc. whereas they should be clean, hard and durable. In the case of fine aggregates used in concrete production, it is important to avoid sea sand due to the high percentage of salts which may react with reinforcement and create corrosion.

Well graded aggregates, lead to a better compressive strength and low permeability. Besides the grade of aggregates, aggregate shapes and surfaces, fine/coarse aggregate ratios, and aggregate/cement ratio are crucial. For higher concrete workability, spherical shaped aggregates with smooth surfaces showed as a better choice, while angular shaped aggregates with rough surfaces resulted with lower control, but with better mechanical properties and bonds in the concrete mixtures.

However, if the cohesiveness needed to be increased, it appeared that the most effective, way was to increase fine/coarse aggregates ratio. On the other hand increased aggregate/cement ratio provided higher stiffness, compressive strength and at same time improved concrete's stability due to the reduction of shrinkage and creep.

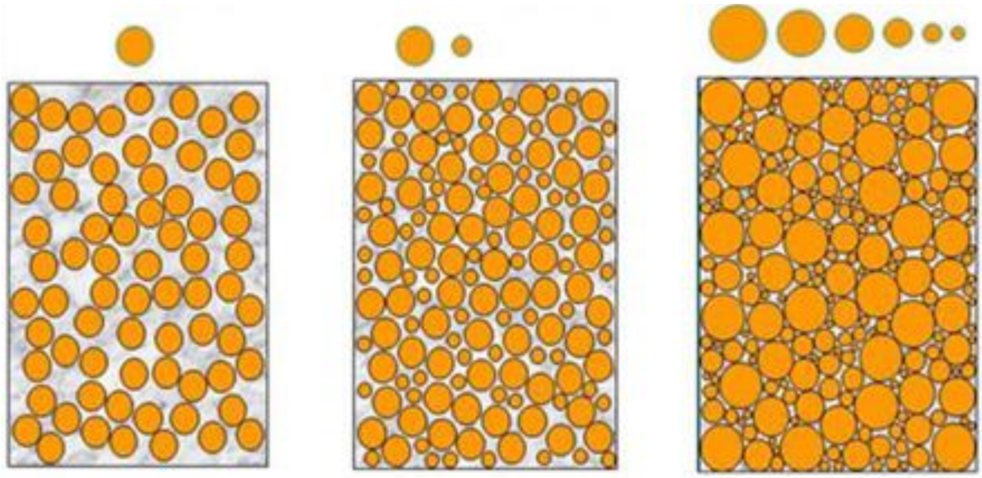

Figure 87 – Importance of the Aggregate Grading – Single Sized Aggregates (left), Poorly Graded Aggregates (middle) and Well Graded Aggregates (right) [175]

Indispensable part of the contemporary concrete technology are various admixtures. Being added to concrete during or before mixing, admixtures improve concrete's performance, both in fresh or hardened state. For example, concrete workability may be affected by air entraining agents, or fly ash, while the strength may be improved by silica fume. Most common admixtures are:

- Accelerating admixtures, accelerate concrete's early strength development, reduce time of curing with earlier removal of formworks. An example: calcium chloride;
- Air – entraining admixtures, used to increase concrete's resistance to freezing and thawing and decrease its damage;
- Retarders, retarding admixtures, prolong the plasticity of concrete, slow the setting of concrete and retard temperature increases. An example: various acids, or sugar and sugar derivatives;
- Superplasticizers are used to keep water – cement ratio constant, while using less of cement. They are mostly derived from organic sulfonates;
- Waterproofing materials, exclusion among other admixtures due to their appliance to hardened concrete, but might also be in fresh concrete, to assist retard the penetration of water into concrete. An example: various soap or petroleum products.

Plain concrete is material with high compressive and very low tensile strength; therefore plain concrete does not have major role in building construction. Reinforcement in concrete overtakes tensile forces and presents a revolution in the success of Reinforced Concrete (RC). Most common reinforcement material is steel, whose characteristic yield strength (f_y), ultimate tensile strength (f_u), ductility, bendability and weld ability are design requirements in RC structures.

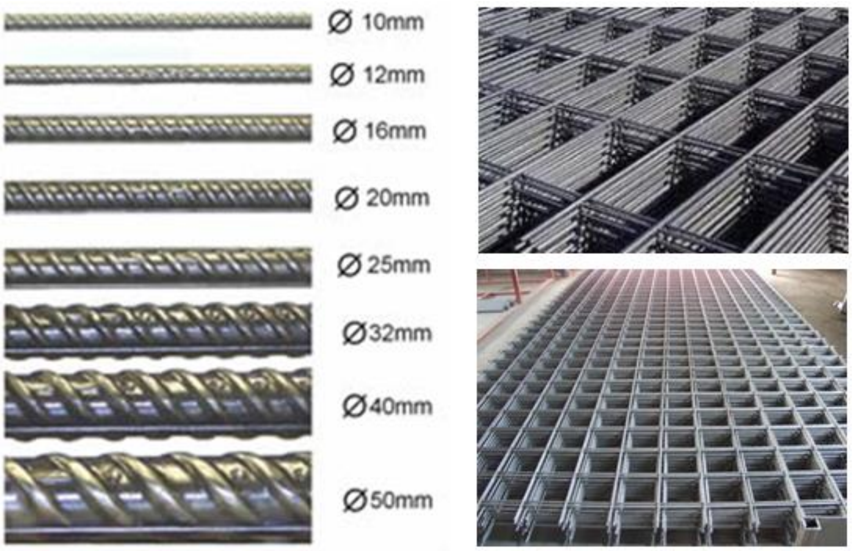

Figure 88 – Reinforcing Steel – Textured Rebar and Meshes [121]

Steel reinforcement for concrete is available in two forms: steel rebar and steel meshes, all with f_{yk} = 500 MPa (N/mm^2) in Europe, which are manufactured in three grades due to different ductility. Manufactured steel rebar are textured in order to achieve better bond between rebar and concrete.

As composite material with various mix designs, wide range of application and high technology development, concrete is classified according to different criteria. Concrete is classified according to the construction technology applied, on cast in situ concrete and prefabricated concrete and at the chosen way of reinforcing the concrete, conventionally reinforced concrete (steel bars, meshes) and pre–stressed concrete elements.

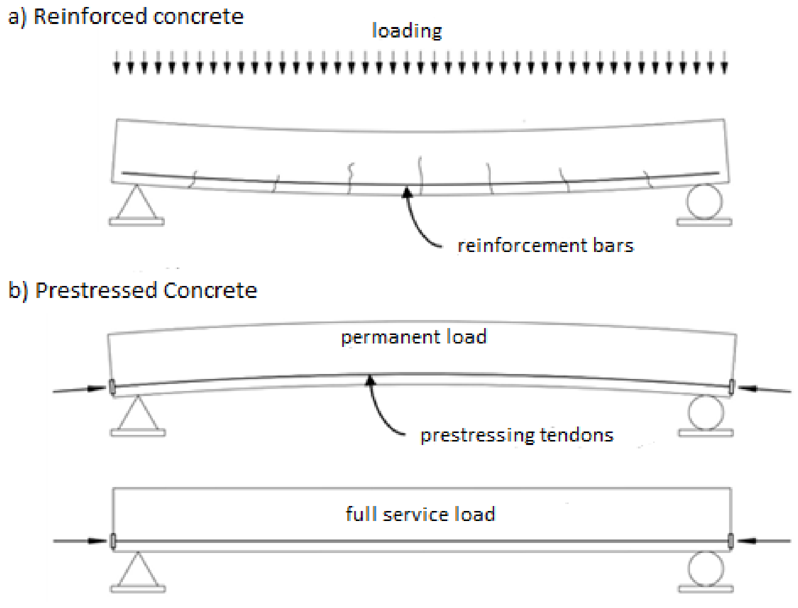

Figure 89 – Difference in Behaviour of Reinforced Concrete and Prestressed Concrete under Applied Load [11]

Generally, concrete can be classified based on its properties in compressive strength, unit weight or according to concretes admixtures and additives.

One of concrete's greatest advantage lies in its compressive strength. Concrete's primary property, characteristic compressive strength (f_{ck}) is affected by various factors: water/cement ratio, cement type, type of aggregate, age of concrete and curing time and type of admixture, if used.

Table 2 - Concrete Classification according to Compression Strength of Concrete

CONCRETE TYPE	**COMPRESSIVE STRENGTH f_{ck} (MPa)**	**APPLICATION**
Low – strength concrete	< 20	• mass concrete structures • subgrade of roads • partitions
Moderate – strength concrete	20 < MSC < 50	• buildings • bridges
High – strength concrete	50 < HSC < 150	• high – rise buildings • bridge towers • shear walls
Ultra – high strength concrete	150 < UHS	• not widely used, only few foot bridges and some structural segments, girders

Table 3 - Concrete Classification according to Unit Weight of Concrete

CONCRETE TYPE	**UNIT WEIGHT (kg/m^3)**	**APPLICATION**
Ultra – light – weight concrete	< 1200	• non–structural members
Light – weight concrete	1200 < LWC < 1800	• non–structural members • structural members
Normal - weight concrete	~ 2400	• infrastructure • buildings
Heavy - weight concrete	> 3200	• special structures • laboratories • hospitals • nuclear plants

Table 4 - Concrete Classification according to Admixtures Used in Concrete

CONCRETE TYPE	**ADMIXTURES**	**APPLICATION**
Fibre reinforced concrete	include steel, glass, polymers and carbon fibers	• improve tensile property, to enhance toughness shrinkage control and decoration
MDF – Macro defect free	incorporate large amount of water soluble polymer	• improve tensile and flexural properties of concrete
DSP	large amount of silica fume	• provide an excellent abrasion resistance to produce machine tools and industrial moulds
Polymer concrete	polymer	• polymer–binder • polymer–impregnated into Portland cement concrete members • polymer–admixture in Portland cement concrete

In almost entire Europe and some other parts of the world, concrete is designed based on rules of Eurocode 2. The characteristic compressive strength refers to uniaxial compressive strength measured by compression tests, done on test samples being concrete cylinder 15 x 30 cm or cube 15 x 15 x 15 cm, 28 days of age. Test samples are conditioned in a room temperature with high specified humidity level.

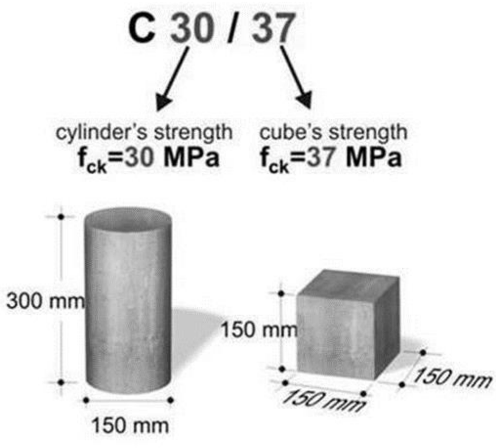

Figure 90 – Concrete Cylinder and Cube Test Samples [75]

Conditioning of the tests samples significantly affects the concrete compressive strength as presented in *Figure 91*.

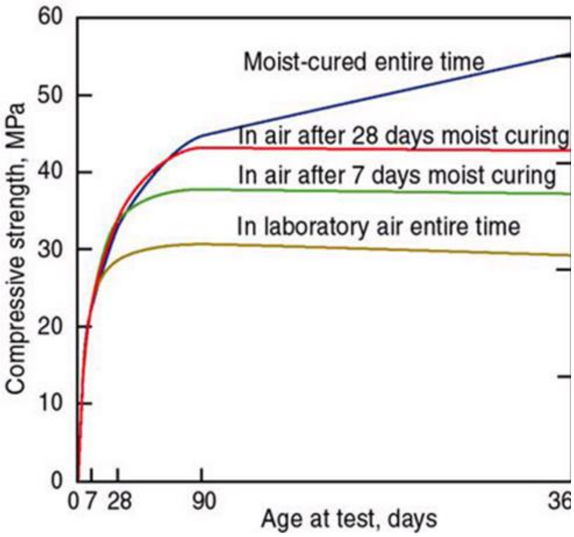

Figure 91 – Concrete Compression Strength Development in Relation to Conditioning of Test Specimens [164]

Modulus of elasticity is an important property of concrete used for stiffness and deflection determination; however concrete does not have unique and clear linear modulus of elasticity. It varies due to the age of concrete, different compressive strength, stress level, type of loadings, characteristics and properties of cement and aggregates, whereas it's important to point out aggregate type in high–strength concrete where type of coarse aggregates is crucial. Concrete is characterized as non–linear stress–strain curve, where modulus of elasticity is defined by being tangent or secant to stress–strain curve in range of elastic strain.

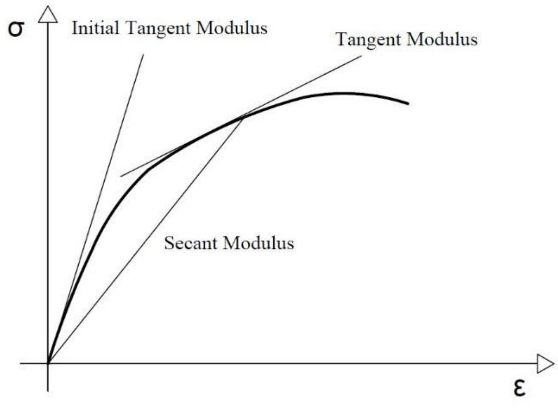

Figure 92 – Tangent and Secant Modulus of Elasticity of Concrete [126]

Concrete will continually keep deforming during time and under continual compressive load. The additional deformation that comes after the initial one is called creep or plastic flow. In other words creep refers to plastic time dependent deformation that occurs under continual stress.

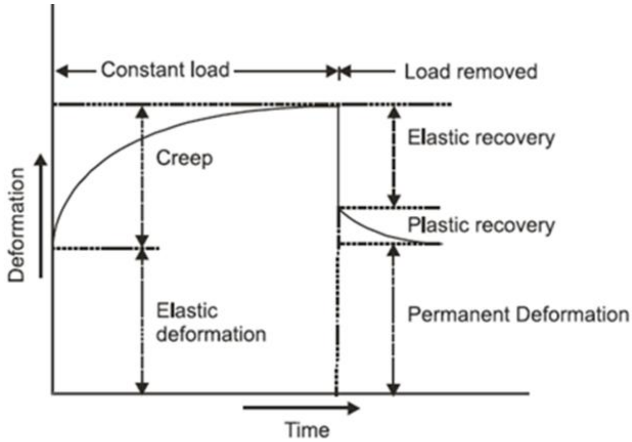

Figure 93 – Creep of Concrete [89]

Creep is related to hydration process in cement paste; therefore, concrete with the highest percentage of cement paste ratio (water/cement ratio) will have the highest creep. This leads to the conclusion that high–strength concrete with lower w/c ratio will undergo decreased or very low creep compared to normal strength concrete.

Once concrete is cured and starts to dry, excess of chemically unbounded water starts to evaporate; the result of this leads to the shrinking and cracking of concrete. Such cracks reduce shear strength and tensile strength and that cracking may leave reinforcement unprotected which can start to corrode due to different environmental factors. Even though shrinkage occurs during a long period of time, 90% of it happens during the first year.

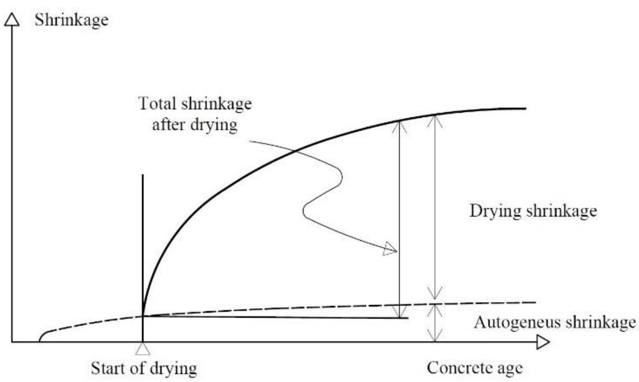

Figure 94 – Concrete Shrinkage Development in Ordinary Concrete [38]

During construction of structures of high–rise buildings almost any structure may be derived and erected out of reinforced concrete; with strong, durable and highly resistant, rigid concrete structures, if well designed, it may overcome all the struggles in high–rise construction. Use of concrete in construction of high–rise buildings has been rapidly increasing in the last few decades, where the main factor includes chemical industry admixtures in concrete mix design, better curing abilities, and better technology for concrete pumping to higher storeys in high–rise buildings.

Back in 1903, the first idea for concrete high–rise building, was not widely accepted. For most experts, critics and public, such idea evoked doubtfulness. However, 16–storey concrete high–rise was constructed in Cincinnati. Ingalls building was designed as very rigid structure, enveloped by the 20 cm thick walls, structured with rigid concrete frame of 76 x 86 cm columns up to the 10th storey, and 30 cm x 30 cm for the rest of the storeys, connected with concrete beams. In Ingalls building, slabs and stairs were also made of concrete. Such massive elements were not welcomed by architects and designers. Unfortunately, during that period concrete technology was only familiar with types of concrete of lower strength, and large cross sections of the elements were a necessity. When concrete was discovered as a material with high potentials in various fields, the reinforced concrete technology quickly started to develop concrete with high–strengths, improved by various admixtures which also upgraded properties of concrete.

In high–rise buildings, safety and time of evacuation is one of the most important factors, which follow immediately after its load bearing design. High fire resistance of concrete was also one of the encouraging factors for the further use of concrete in high–rises.

In favour of reinforced concrete application of the structures of high–rises are Petronas Twin Towers. Back in 1998, the world’s highest buildings were Petronas Twin Towers in Kuala Lumpur, two identical towers with heights of 452 m and diameter of 46.3 m. Mega structure of these towers consists of 16 perimeter columns varying in diameter from 2.40 m from the ground to 1.20 m on the top of the towers. With the decrease in columns cross section, reinforced concrete core is respectively decreases from the bottom from 22.9 x 22.9 meters to 18.9 x 22 meters, while beams are about 79 cm in depth. Petronas Twin Towers were developed with high–strength concrete of 80 MPa in compressive strength of the columns of lower floors, however middle floors had the compressive strength of 60 MPa and upper floors of 40 MPa.

As latest achievement in reinforced concrete structure of high–rise building is definitely Burj Khalifa, Dubai. Burj Khalifa, was designed in shape of Y; such form of the building maximises the exterior view, but also derives a newly supported core named buttressed core.

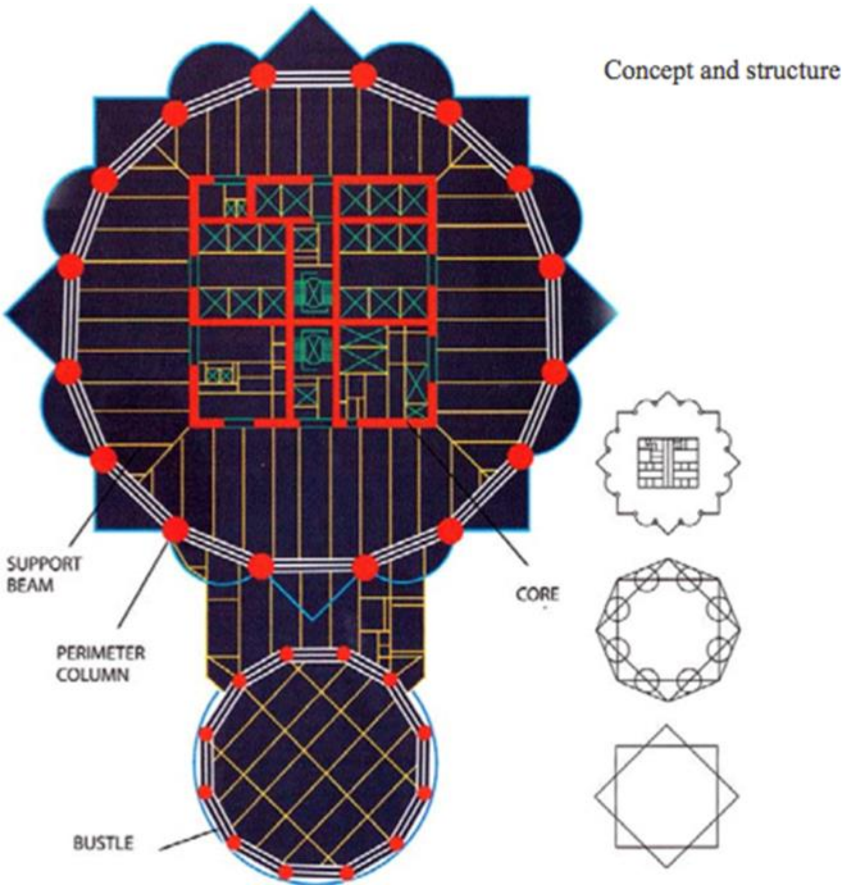

Figure 95 – Petronas Tower- Characteristic Floor Plan Showing Concept and Structure [66]

The material used for structure materialisation was high–strength concrete, varying from 60 MPa to 80 MPa. Although use of steel in this 829.9 meters high building was not fully excluded, major structure is erected out of high–strength concrete.

The Ingalls Building, Petronas Twin Towers and Burj Khalifa are chosen as representative examples of reinforced structures, with different aesthetics, volumes achievements in vertical direction due to the period of their designs. However, all of these structures are in a way key points for the development and achievements of reinforced concrete, despite the fact that the only common point for these buildings is their RC structure. To summarize, an imposing fact is that with contemporary technology, concrete excluded the adjectives massive, clustered and large structural elements for RC structures in high–rise buildings and became more desired material in construction.

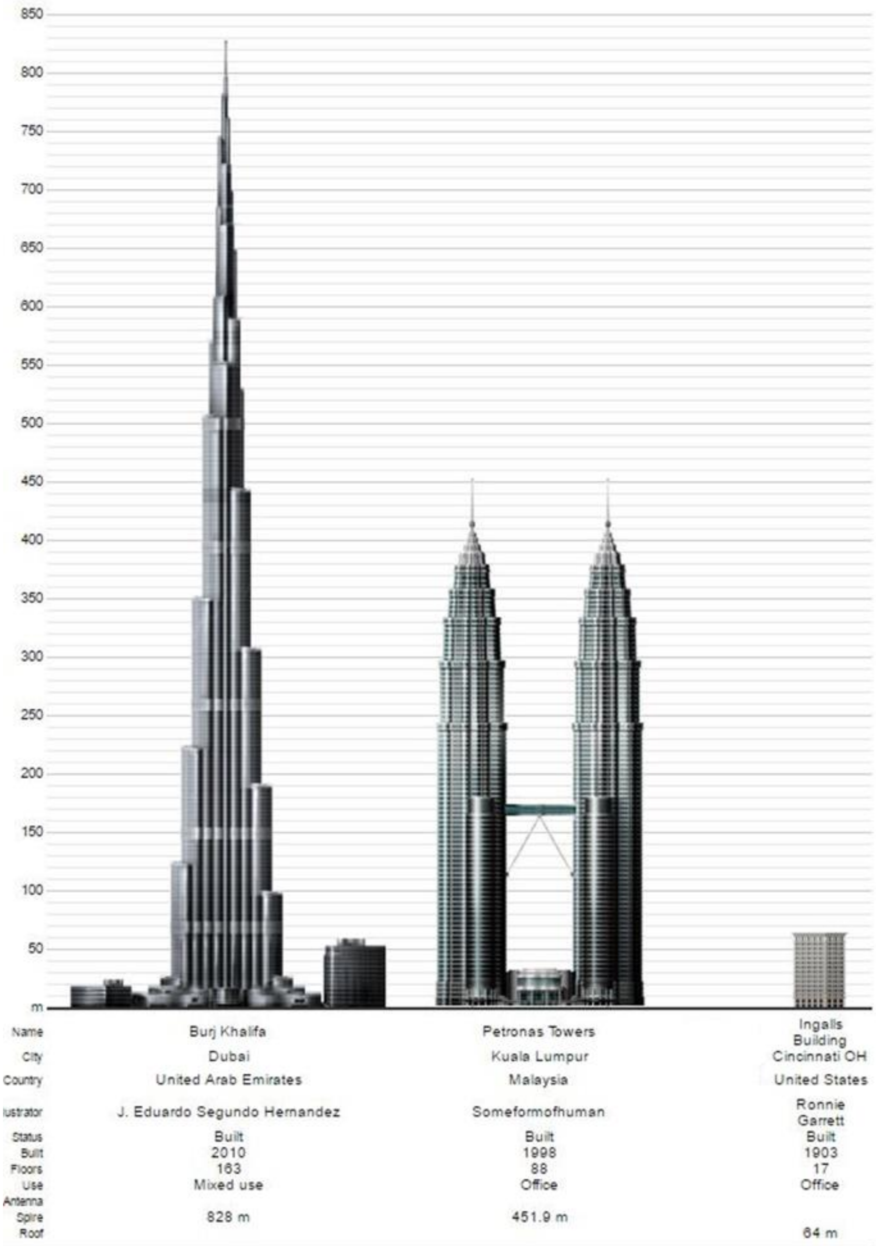

Figure 96 – Burj Khalifa (left), Petronas Twin Tower (mid) and Ingalls Building (left) [82]

HIGH STRENGTH CONCRETE (HSC) AS STRUCUTURAL MATERIAL FOR HIGH–RISE BUILDINGS

It is hard to define high–strength concrete (HSC) with one unique number, or create any strict border between conventional normal strength concrete and high–strength concrete. As long as achieved concrete or target strength is about the same quality as the local material, curing conditions, size and age of testing specimens, it imposes the fact that nor unique nor unified definition of high–strength concrete is neither possible nor necessary. Another factor in defining ranging lines of high–strength concrete is also a demand for specific strengths or performances of concrete. In the specific case of the USA or some rapidly growing Asian country or city, 95 MPa high–strength concrete is available in most of concrete plants, and at same time it is economically and cost efficient.

On the other hand, situation in Balkan area is totally opposite. Abilities to use high-strength concrete in this area is not even adequately researched, and the top limit of concretes' strength may appears to be up to 60 MPa, which corresponds to weak economical and cost efficiency. However, in different standards there are some differences in classifications of concrete up to the characteristic compression strengths. According to EN 206:2013, normal–weight and heavy–weight concretes are divided into sixteen classes according to their compressive strengths; high–strength concrete is in range between C55/67 and C100/115.

Terms high–strength concrete and high–performance concrete were commonly used as synonyms, which was acceptable at the early beginnings. However, in the contemporary concrete technology, this interchangeable use of the two terms is not acceptable.

High–strength concrete commonly refers to the increase in compressive strength of concrete, while high–performance concrete refers to the increase of all concrete's properties, with accent on mechanical properties, durability, workability, permeability etc. which is more than just increase of strength.

Commonly, the periphrastic high–strength concrete is introduced as new material or as a result of new technological development. Although such periphrasis may be taken as correct, term high strength concrete and practice of creating high–strength concrete occurred many decades ago. Dating back to 1950s, concrete with compressive strength of 34–35 MPa, was considered to be high–strength concrete. However, when compared to contemporary daily routine in concrete solutions, designed compressive strength of 34–35 MPa, at 28th day of age is one of the most common examples of conventional or so called normal strength concrete.

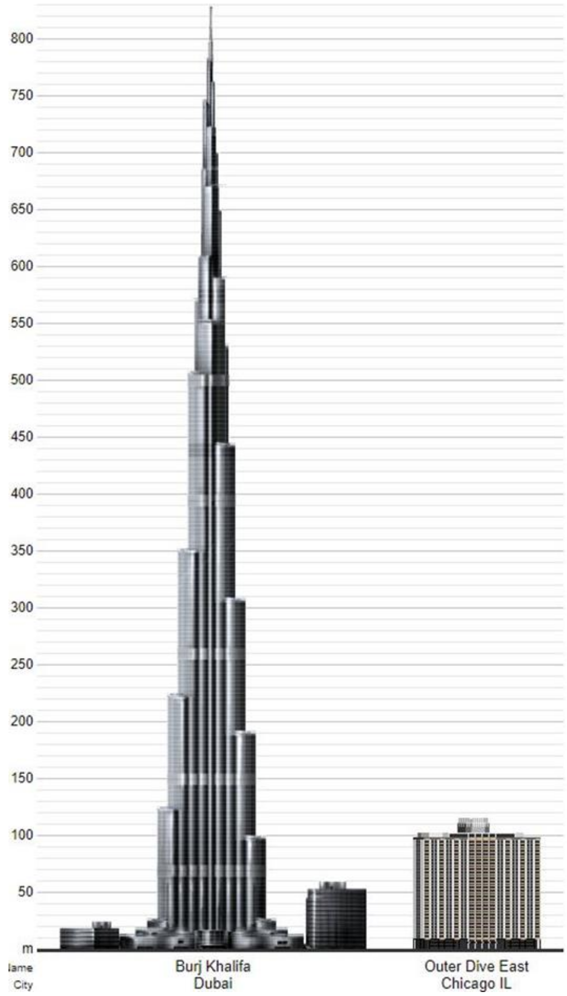

Figure 97- The Last Completed Super High–Rise, Burj Khalifa, 2010 (left) and the First Completed High- Strength Concrete High–Rise, Outer Drive East 1963 [83]

More specific and more scientific approach to the subject of high strength concrete occurred in the 1960s. Newly developed high–strength concrete with compressive strength of 41 to 52 MPa, rapidly spread through the construction sites across the USA. For high–strength concrete technology, sixties of the last century were crucial turning point because all experimental studies of technological development were aiming for the achievements of the desired results.

In the early sixties, Japan was a place where the first superplasticizers were developed. Formaldehyde condensates of beta naphthalene sulfonates, were developed by Dr Hattori. These superplasticizers had primary function to reduce water demand in production of high–strength concrete. Product created was named Mighty 150, which could decrease water usage up to 30 percent. Along with superplasticizers, use of another supplementary material for high–strength concreting developed in this period was silica fume or so called microsilica; micro–filler in between cement particles, a by-product of Ferro–alloy industry was first introduced by German Doctor Aignesberger.

Although invention of superplasticizers and silica fume took place in Japan and Germany, most of the credits in HSC development for wide use went to Chicago, United States. During the early sixties, Chicago was a place which accelerated development of high–strength concrete and increased that day available concrete's compressive strength of 35 MPa to 41 MPa for 40–storeys high–rise buildings. An engineering step forward pioneered the use of high–strength concrete in Chicago on the Outer Drive East high–rise building

The USA, also constructed numerous bridges, river dams, marina piers and terminals; however their main focus was on structuring of high–rise buildings, multi–storey garages, shopping malls etc. For instance, it was almost mandatory for high–rise buildings in Chicago to be structured with high–strength concrete. In 1972, from previous 41 MPa, concrete's strength already increased to 52 MPa for structuring of 52–storey Mid–Continental Plaza. It is important to mention that production and application of high–strength concrete used to structure Mid-Continental Plaza, was more of an economical choice rather than a solutions. Achievable strength of concrete and all performances of concrete were increasing year after year with correspondence to cost efficiency, and due to the development of chemical admixtures and other supplementary materials; the result was of 74–storeys Water Tower Palace, in 1976. Water Tower Palace, was the world's highest high–rise structure in that period, designed as concrete structure reaching compressive strength of 62 MPa.

After all, American Concrete Institute can take all credits for the rapid development of high–strength concrete and actual exposing of high–strength concrete to a wider market for application in most of the high rise buildings worldwide.

Nowadays, high–strength concrete is in wide use all around the developed world, and it is more than common to find concrete plants which can catch up with the production of concrete with compressive strength of 95 MPa, on daily basis.

High–strength concrete was developed as better and as structural material of higher quality when compared to normal strength concrete. Therefore it has many benefits, both in performance and cost efficiency, so HSC advantages are as follows:

- Reduction in structural element size;

- Reduction in amount of longitudinal reinforcement and compression members, focusing on slenderer columns;
- Higher strength and better performance leads to larger spans and decrease of total number of beams, columns etc.;
- Decreased time necessary for concrete's formwork due to early strength development;
- Decrease in concrete cover due to lower permeability;
- Long performance under the most critical action combinations;
- Lower creep and shrinkage with higher resistance for freezing and thawing;
- Increased resistance to very aggressive environments;
- Decreased axial shortening, buckling of supporting elements;
- Increased rentable space, due to slenderer and thinner elements, but also decreased number of supporting elements due to larger spans;
- Decreased permanent action of self–weight of structure;
- Decreased maintenance and repair costs;
- Greater stiffness due to higher modulus of elasticity with high compressive and flexural strengths.

Although high–strength concrete has many advantages as a material, it also has disadvantages which may occur due to some impurities or even as a consequence of some advantages mentioned above. High strength concrete disadvantages are:

- Bond strength between cement paste and aggregate does not increases with the same acceleration as compressive strength;
- High–vibration are required for better compaction, and to exclude possible segregations;
- Minimal concrete cover for reinforcement protection may prevent the use of maximum benefits in reduction of element sizes;
- Available prestressing may be inadequate for the maximum use of high–strength concrete's strength;

- High–strength concrete requires very detailed, precise and careful material selection and does not accept any impurities;
- Due to low W/C ratio, high–strength concrete requires special curing and installation or placement;
- There is a possibility of decrease in stiffness, whereas modulus of elasticity does not respectively increase with concrete's strength, therefore use of high–strength concrete may provide slenderer elements but with lower stiffness which may lead to stability problems, whereas solution lays in very precise choice of structural systems.

Like a conventional normal–strength concrete, HSC also contains constituents, or in other words raw materials. Materials which participate in high–strength concrete proportioning are: supplementary cementitious materials, fly ash, silica fume and some other mineral admixtures, aggregates of the best quality, and of high compressive strengths which include dolomites, granites, quartz etc., as well as superplasticizers or some other types of chemical admixtures.

It is important for high–strength concrete to have raw materials of the highest quality without any compromises for marginal or lower qualities. If raw high quality materials are well proportioned and combined, it is possible to produce high–strength concrete with long lasting compressive strength and other mechanical properties.

Generally, all types of Portland cement proved to be suitable in production of concrete of compressive strength up to 60 MPa at the 28th day of age. However, to achieve higher strength with respective increase in performance and workability it is necessary to design and study reactions between additional chemical and mineral admixture.

Along with Portland cement, use of Blended hydraulic cement in production of high–strength concrete is common. Blended hydraulic cement is mixture of Portland cement and other supplementary cementitious materials, also named mineral admixtures. Benefits of Blended hydraulic cements lay in lower rate of heat development, higher strength, lower permeability, increased durability and overall performances.

Credits for accelerating the development of high strength concrete technology go to the mineral admixtures, usually denoted as supplementary cementitious materials (SCM). These are the materials which developed and increased concretes' performance and strength of both fresh and hardened concrete. Generally, mineral admixtures are siliceous and alumina siliceous materials which with the addition of water chemically react with calcium hydroxide in order to perform cementitious properties.

The most common types used in preparation of high–strength concrete are fly ash, cement slag and silica fume, while less in use are ultra-fly–ash, volcanic ashes, met-kaolin, diatomaceous earths and calcined natural pozzolans. Benefits of blended hydraulic cement in lower permeability, higher strength, and lower heat of hydration are also benefits of mineral admixture (SCM).

Figure 98 - Common Mineral Admixtures – Supplementary Cementitious Materials for High-Strength Concrete [103]

Fly ash is the most common type of SCM and by–product of combustion of pulverized coal; it is spherically shaped and glassy residue. Fly ash is commonly added to all concretes for higher performances. When combine fly ash and slag cement with Portland cement, it may create concretes with compressive strengths of 70 MPa.

Silica fume or micro silica is a by–product of silicon metals and ferrosilicon alloys, generated during reduction of quartz in the production of silicon metals and ferrosilicon alloys. This ultra–fine non–crystalline by–product, enabled widespread of high–strength concrete and the ability to produce ultra–high–strength concrete at all.

Generally, silica is described as grey to black dust. Silica fume is available in forms of raw powder, water based slurry, densified or palletized. Silica fume in form of densified powder is the most common practice of adding silica directly to concrete mix. Silica fume grains are approximately 100 times smaller than Portland cement grains with sizes of 0.1 to 0.3 μm. Although silica fume or micro silica has numerous advantages, its fineness may require higher percentage of water which may cause a decrease in workability and other desired properties if high–range water reduction admixtures are not added.

The principle of micro–filling with silica fume benefited in strengthening the bond between coarse aggregate and concrete paste, with the ability of achieving compressive strength of over 105 MPa. Silica fume also tends to be efficient in reduced demand of other cementitious materials, for instance 1 kg of silica fume may replace 2 to 5 kg of cement, while the remaining content of water.

Production of high–strength concrete would be impossible without superplasticizers such as high–range water reducers, retarders etc. As SCM (supplementary cementitious materials/ mineral admixtures), chemical admixtures improve both fresh and hardened concrete. Without chemical admixtures, even the ability for transport, placement and curing of conventional normal–strength concrete would be questionable, and therefore lack of chemical admixture in high–strength concrete would make high–strength concrete impossible.

High–range water admixtures as more common superplasticizers (HRWR) decrease W/C ratio, but it is important to determine correct dose and type of the admixture. Thus, HRWR increase strength, with decrease W/C ratio, while maintaining slump constant, but also increase slump while maintaining W/C ratio.

When compared to conventional normal–strength concrete, W/C ratio in high–strength concretes is lower varying from 0.22 to 0.40. However, it is important to analyse whether the certain decrease in W/C ratio is necessary and whether it leads to the requested increase of concrete's strength and performance.

The highest percentage of concrete's volume goes to aggregate volume. Selection of the appropriate aggregate is very important; in high–strength concrete, the best quality and the strongest aggregates are required. What effects aggregate is its density, grain size composition, shape and texture of the aggregate surfaces. In high–strength concrete rough textured and angular aggregates increase mechanical cement paste–aggregate bond and therefore such aggregates are more workable in high–strength concrete. Trap rock, granite, dolomite and quartzite are mineralogy types of aggregates, suitable for high-strength concrete.

Although high–strength concrete has lower fire resistance than normal strength concrete, it still has higher fire resistance than any other structural materials' and becomes economically efficient solution able to improve its fire resistance.

According to the most of the nowadays standards, high–strength concrete and ultra–high-strength concrete are leading concretes with compressive strengths of above 50 MPa and 150 MPa respectively. Many countries are somehow limited to maximum concrete strengths up to 50–60 MPa due to lack of demand for higher performance and higher strength concretes or because of the lower rate of development. However, areas under rapid and constant construction and development in vertical directions, routinely produce concretes with compressive strengths of over 80 and 100 MPa. The USA, Canada, Singapore, China, Malaysia, UAE are countries and areas with the highest usage of high–strength concrete. Such fact is not surprising because these are the areas with the largest construction sites dedicated to high–rise construction and way of living. In circumstances, where daily human habits are lifted way above the ground, safety comes first. High–strength concrete showed its power in ensuring necessary safety in high–rise buildings, providing safety and comfortable living environment, with its high rate of resistance to any possible structure's daily displacements due to wind actions, seismic actions, or high–rate of resistance in cases of emergencies such as fire or progressive collapse, where the structure itself enables sufficient time for safety evacuation.

Possibilities in structuring of high–rise buildings out of high–strength concrete are best described on examples of Burj Khalifa, Petronas Twin Towers, Taipei 101 (composite structure–steel and high–strength concrete), etc. Magnificent architecture and breath-taking heights were enabled without any concessions by virtue of high–strength concrete. High–strength concrete in these examples showed limitless abilities in concrete technology, and at same time provided sufficient safety to occupants and inhabitants. Besides mentioned, there are numerous examples of high–rise buildings which represent great examples of concrete technology development.

Eureka Tower in Melbourne, Australia, a 91–storey tall high rise building is structured as outrigger system, and entirely erected with high–strength concrete. It is designed with central core, perimeter columns, shear walls and continuous outrigger with thickness of 30 cm. This choice of high–strength concrete as structural material, decreased cross sections of structural elements and increased rentable area of floor plans.

Core walls for the first 15-storeys are 75 cm thick, made of high–strength concrete with compressive strength of 80 MPa, while perimeter columns were erected with concrete of compressive strength of 100 MPa. As the height of the building increased, characteristic compressive strength of used concrete decreased. Thus, structural elements near the top of the building were made with concrete of 40 MPa for shear walls, and 60 MPa for perimeter buildings.

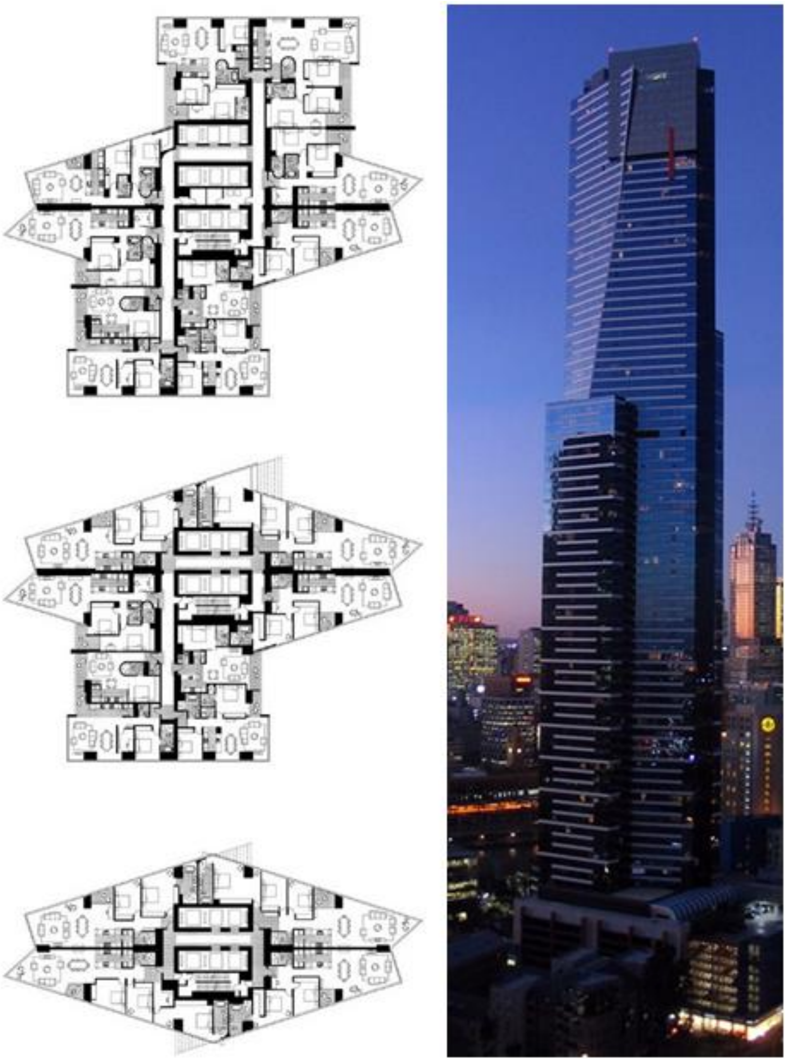

Figure 99 - Eureka Tower Characteristic Floor Plans
26-52 Storeys(left – top), 53-65 Storeys(left – mid), 66-88 Storeys(left – bottom),
Black Hatch Stands for High–Strength Structural Elements and in 2006 (right) [78]

Another example is Baiyoke-2 Tower in Bangkok, Thailand, a 90–storeys high–rise building which was designed with the desire to break the world record as the tallest hotel and the tallest high–strength concrete building. This 90–storeys structure was constructed with high–strength concrete, and represented turning point in concrete technology seen up to that day in Thailand. Concrete columns, and concrete central core, as well as concrete slabs, were built out of high–strength concrete with compressive strength of 60 MPa up to 65–storey. Final 25 storeys were constructed out of concrete with compressive strength of 50 MPa.

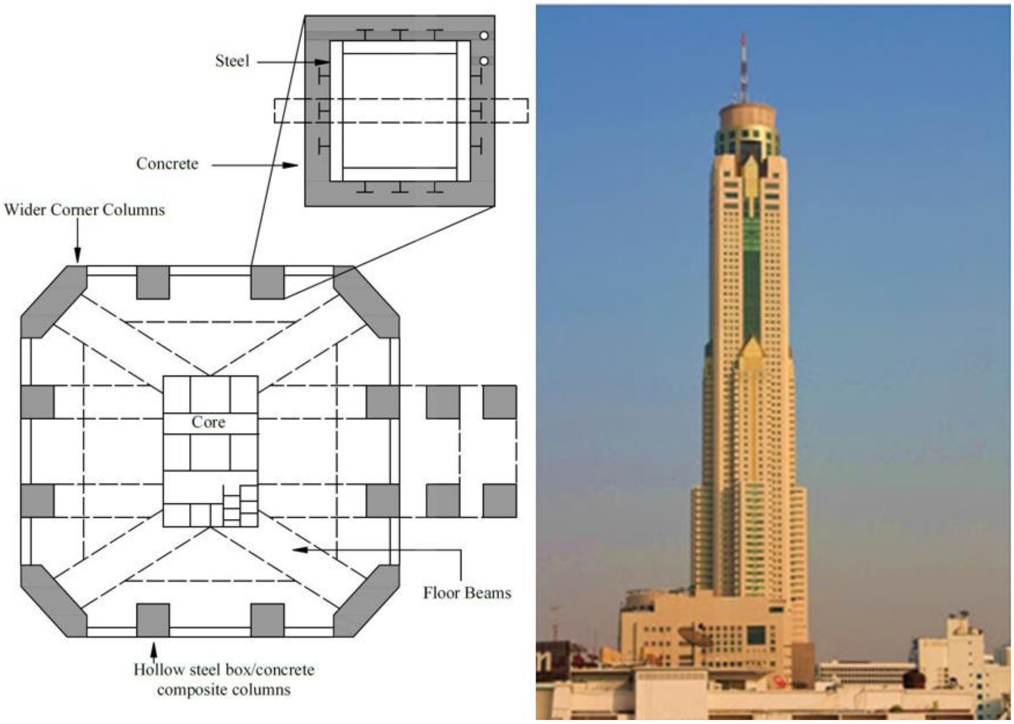

Figure 100 - Baiyoke Tower 2 [118, 60]

Although Europe is a few steps behind the USA, Canada, China and others in vertical expansion, Holland, Finland, Germany, Denmark and Norway are European countries which have practice in production and use of high–strength concrete for specific purposes in construction of high–rise buildings.

Germany pioneered the use of high–strength concrete through the Trianon, high–rise building in the Westend of the Frankfurt am Main, in 1992. This high–rise building with final height of 186 meters has 47 storeys above and 4 storeys below the ground level. High strength concrete B 85, was used for four main columns 54 cm wide and partially for shear walls. The rest of the structure was erected with concrete B 45. The use of the high–strength concrete proved to be very economically efficient due to reduced dimensions of structural elements and reduced demand for the further use of reinforced steel. Concrete mixture for Trianon building contained fly ash, superplasticizer and retarders. These concrete cube specimens taken for the compression tests showed that average compressive strength of B85 after 56 days was 112 MPa.

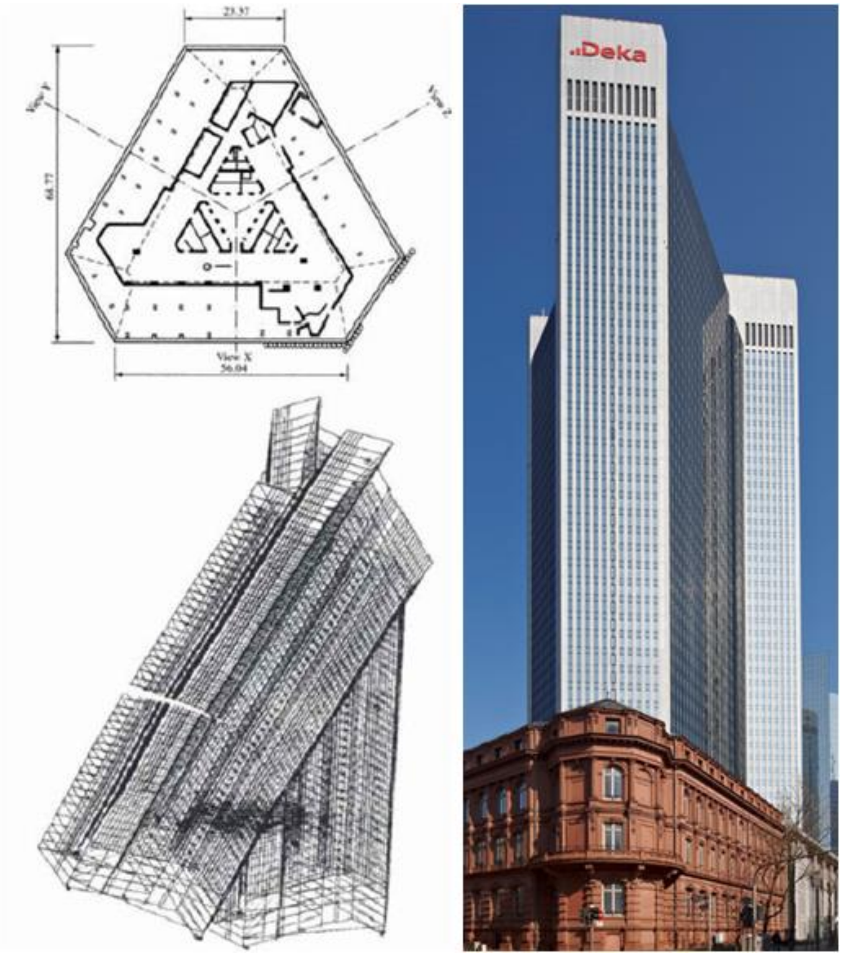

Figure 101 - Characteristic Floor Plan of Trianon Building (left–top), Schematic Scenario of Possible Collapse (left–bottom) and Trianon Building, 1992, completed (right) [199, 200]

Altieri Spinelli Building, formerly called D3 building with its 24 storeys represents remarkable achievement in concrete technology in Europe; Altieri Spinelli Building is part of the complex of the parliament buildings in Brussels. High–strength concrete was used as a material for prefabricated columns in storeys that were reserved as garaging space. Target strength for these columns was 80 MPa, which was achieved by the addition of superplasticizers, reduced W/C ratio and the use of fly ash. Such concrete mixture and ability for prefabrication, resulted in accelerated construction and higher economic efficiency, smaller structural elements in this specific case of columns, left more free space than it would have if any other material was used.

Figure 102 - Altieri Spinelli Building, Brussels, Belgium [157]

To summarize, successful examples of high–rise buildings mentioned and described earlier are obvious evidences that the use of high–strength concrete is nowadays reality in construction worldwide. Whether focus on high–rise buildings up to 15– 24 storeys, or the super tall high–rise buildings that are few hundred of storeys high, high–strength concrete of different qualities is the unavoidable choice in search for structural material. If technology development and economic efficiency opened up a gate to high–strength concrete towards wider market, high–rise buildings for sure enhanced benefits and abilities of high–strength concrete as commonly available structural material. Use of such environmental friendly, structurally safe and very resistant material enabled previously mentioned idea and concepts of vertical cities and vertical living.

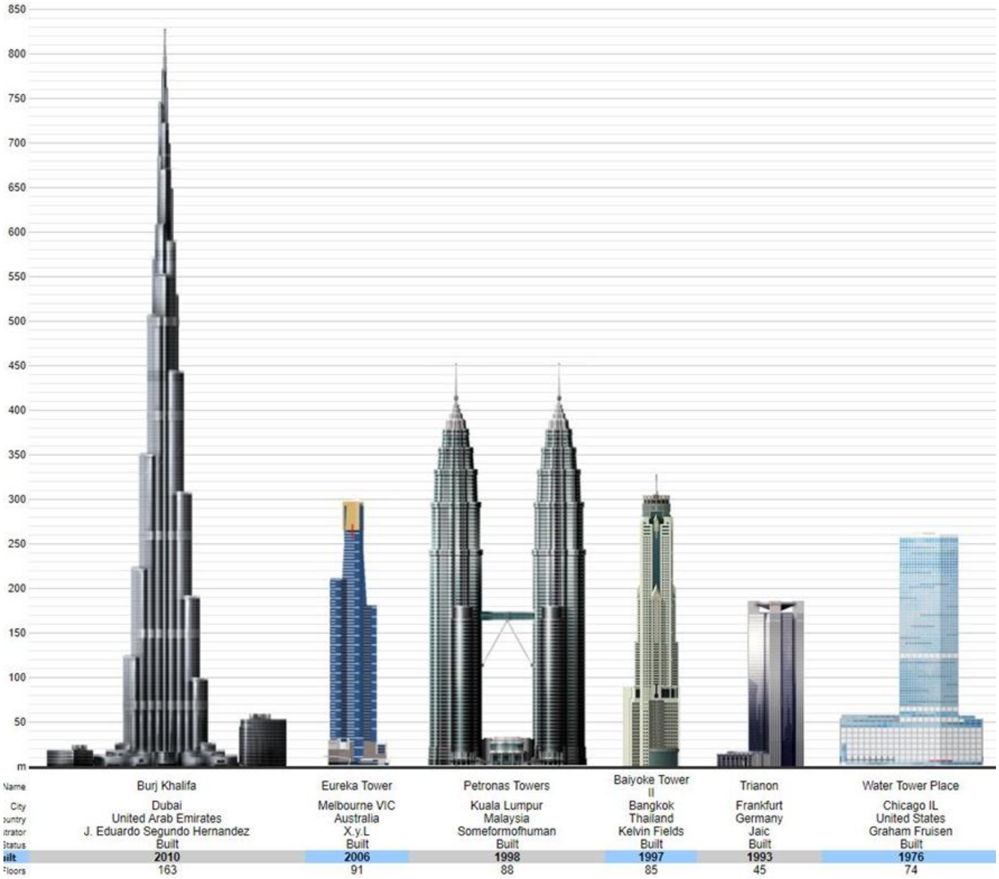

Figure 103 - Summary of the Representative HSC High–Rises [136]

COMPOSITE STEEL–CONCRETE STRUCTURES FOR HIGH–RISE BUILDINGS

Composite structure is term which refers to the use of different materials within one structural element, where these two materials act as one material. Even though composite structures may refer to composition of any two or more structural materials, due to common use in composite structures it generally refer to the steel–reinforced concrete structures. Composite elements might be beams, columns and slabs, where it is important to enable composite acting of two materials with sufficient shear connection between materials' bonding surfaces. Philosophy of composite materials seeks for enhancement of single materials' strength and cutting down of its weaknesses and disadvantage, by combining it into new material.

Back in the late 19th century, earliest form of composite structure referred to the composite material commonly known as reinforced concrete. However, it did not take long until the advantages of combining steel sections with reinforced concrete defined new way in construction of buildings, bridges, urban garages structures etc. Early 20th century introduced steel and reinforced concrete in composite structures as flexural members, although lack of shear connection between the two materials resulted in lateral slipping of one material from another.

In 1911, O. Kommerell was the first to use transversal steel bars for his bridge design to connect steel beams and concrete in order to prevent lateral slipping; although he solved the problem of the lack of shear connection between the two materials, the function of shear connectors were still not explained. However, few decades later, L. Combournac was the first to explain the function and design principles with shear connectors.

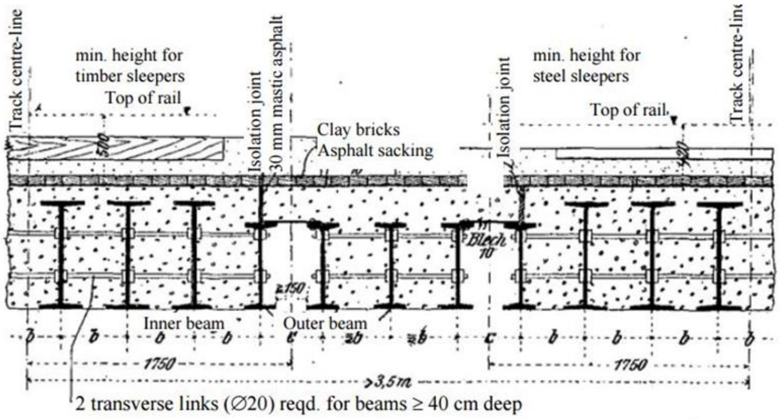

Figure 104 - Rolled Beam Enchased with Concrete, Section through Railway Bridge (Kommerell) [28]

In composite structures, earliest forms were composite beams or span girders for the bridges, with low application for high–rise buildings. In composite beams, steel section and reinforced concrete shear were connected and worked together to resist bending moments. Next ability in composite structures was in the shape of composite columns, where steel's slenderness and concrete's fire and buckling resistance resulted in more economical and structurally efficient element.

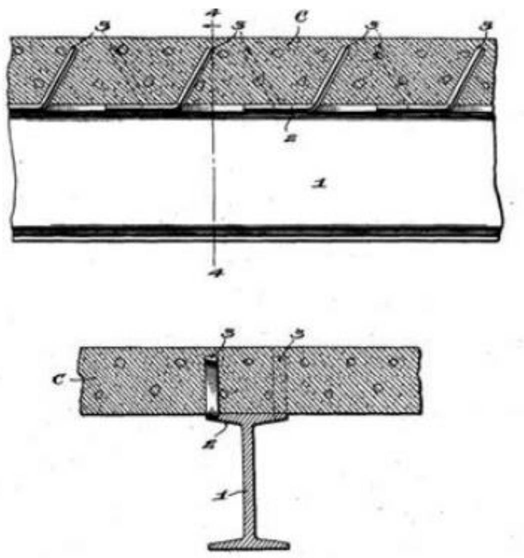

Figure 105 - Composite Steel Beam Patented by Julius Khan, 1926, USA [28]

Such columns were used for high–rise buildings. In the eighties, composite structures were enriched, combining steel sections and cast in situ concrete deck. Main advantage of composite deck was reduction of formwork, and more efficient and faster construction. Nowadays, composite structures are commonly used, especially for bridges and high–rise buildings, with same working philosophy, just following the innovative technology of steel and reinforced concrete as hybrid material, while taking all its advantages.

Design philosophy of composite structures is to use advantages of both steel and concrete, while enhancing them in order to provide higher resistance, strength and durability of the structure. Besides utilization of both individual material advantages, composite structures reduce or exclude material's disadvantages and weaknesses.

Advantages of composite structures:

- Ability for larger spans, creating more usable space;
- Reinforced concrete appears in compression and steel appears in tension zone, taking the best of both materials;

- Shorter construction – schedule due to fabricated steel elements;
- Coating steel with concrete adds protection layer toward environmental conditions, which prevents corrosion and increases fire resistance;
- Greater stiffness is achieved, with the decrease in bending and deflection of structural beams and columns (buckling);
- Better resistance to seismic forces;
- Lighter structure when compared to the RC structures due to smaller cross section of structural elements;
- Reduced cost for the formwork; and
- Shallower beams, which can reduce building's height.

Disadvantages of composite structures are:

- If not well done, low strength of shear connectors or any deformation of shear connectors may enable sliding between concrete deck and steel girder;
- Additional subcontractor needed for shear connector installation; and
- Time consuming due to installation of shear connectors.

First composite elements were composite beams, designed as steel beams with shear connectors at the top flange, encased with reinforced concrete slab, or lately composite slabs. Crucial for composite beams are shear connectors, which exclude the possibility for the two materials to behave independently with lateral slipping. When shear connectors unify steel beam and RC or composite slab, the structure acts as composite structure. For the analysis of the structure's behaviour, composite beam is taken as the behaviour of the cross section of T shaped beams. Concept of composite beams lays in the use of concrete in compression zone in order to achieve better stiffness of the structure, and in order to prevent deflection and buckling, while steel takes place in tensile zone to behave elastically and prevent brittle failure.

Composites are more economical for the same span and combination of actions, where composite beams weight and depth are reduced when compared to steel structures.

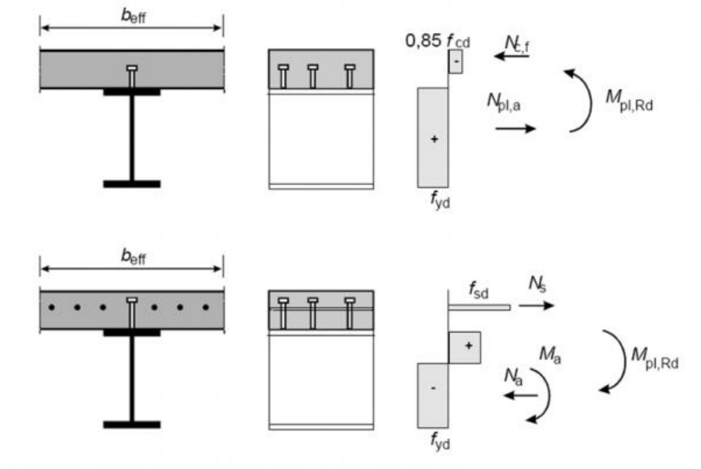

Figure 106 - Composite Beam with Shear Connection between Steel Beam and Concrete Slab, with Diagrams of Stress Distribution in Cross Section [68]

Composite columns overcome the problem of intensive buckling of steel columns, as the RC column's large cross section. Composite steel–concrete column is erected by two principles; the first steel sections are fully or partially enchased with concrete, while other principle lies in filling steel's hollow sections with concrete.

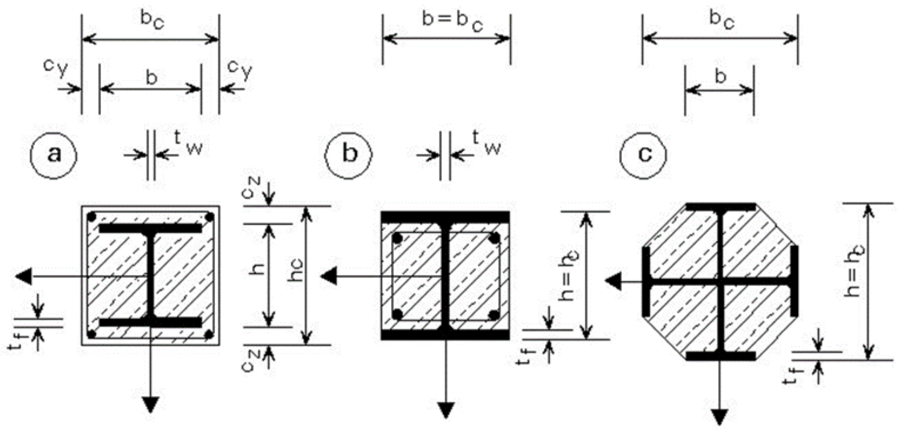

Figure 107 - Composite Columns Types, a) Steel Section Fully Enchased with Reinforced Concrete, b) Steel Section Partially Enchased with Reinforced Concrete, c) Steel Section Partially Enchased with Concrete [70]

An important difference lies in the lack of need for the additional reinforcement of filled hollow steel section, unless there is a necessity for higher fire resistance of the reinforced concrete. The greatest advantage of the composite columns lies in greater fire resistance compared to the steel's fire resistance, as well as in better corrosion protection of enchased composite columns. Another advantages is in the reduced use of formwork, because filled hollow steel sections' formwork is excluded, it increases stiffness of the columns, reduces slenderness and increases buckling resistance.

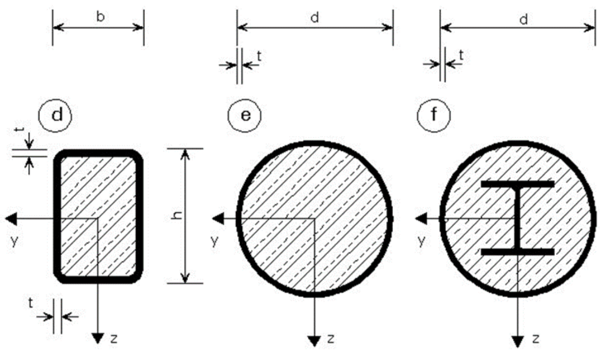

Figure 108 - Composite Column Types, d) Rectangular Hollow Steel Section Filled with Concrete, e) Circular Hollow Steel Section Filled with Concrete, f) Circular Hollow Steel Section Filled with Concrete with Embedded I Steel Section [70]

Composite columns are mostly used for construction of high–rise buildings, where the reinforced concrete structures require large cross section elements, using much of the rentable space and where steel column require high maintenance cost and high cost of fire and corrosion protection, which isn't economical, while composite columns proved to be a more economical solution.

Composite slabs consists of steel decking shear connected with concrete slabs. Technology of composite slabs developed new, stiff, light weight and economical slabs. Metal decking in composite slabs exclude necessity of formwork and also acts as a tension member. Steel decking is available in various shapes, with various surface textures and may vary in decking thickness.

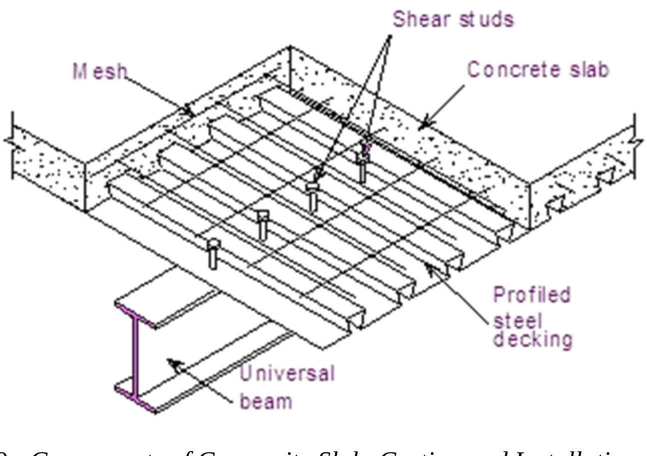

Figure 109 - Components of Composite Slab, Casting and Installation Principle [190]

The most commonly used is decking with deformed ribs, which results in stronger bond between metal decking and concrete, however, composite slabs, as other composite elements, require shear connectors. Number of shear connectors per surface area and its installation, along with the type of shear connection is designed according to the principles of Eurocode 4 (EC4) – Design of composite steel and concrete structures.

In composite structures, a natural bond between concrete and steel exists, however, required bond is not available without any other strengthening method. Shear connector, in shape of steel bars or sections is installed at steel decking or section to achieve desired strength. This leads to the role of the shear connector, which is to resist horizontal slipping between the steel and reinforced concrete, and in the same time, to prevent vertical separation of concrete between steel sections. Dimensions, shapes, types or numbers required to resist horizontal movement are designed according to the design rules of EC4. Composite structures have three types of shear connectors: rigid type, flexible type and bond or anchorage type connectors.

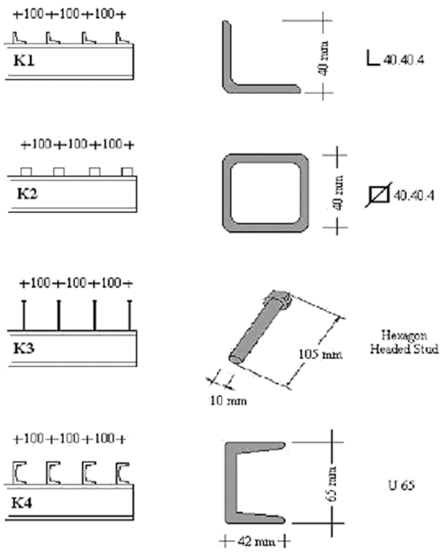

Figure 110 - Shapes and Common Dimensions of Shear Connectors, Angle, Circular, Hexagonal or Circular Headed and Channel Section [174]

Rigid type of shear connectors can be found in various shapes, short bars, angles or tees welded on steel girder or steel decking. Failure of such connectors occur in terms of cracking of concrete.

Flexible type of shear connectors appears in the shape of studs, channels welded to structural beam or decking. As long as these connectors resist bending of the connectors, failure occurs when yield stress in the connector is exceeded.

Bond or anchorage type of shear connectors consists of inclined bars with one end welled to the steel's top flange, while other is bent and enhanced with concrete.

High–rises structures, besides concrete and steel as main structural material, are also constructed as composite structures. Composite structures in case of high–rises strictly refers to steel and concrete, where advantages of both materials are utilized to create one new, high resistant and stiff material. Use of composite structures in high–rise buildings varies from entirely composite structure to specific use of composite columns, beams or slabs. Even though philosophy of composite structures and its advantages in favour of high–rises, composites were not a choice for high–rise buildings until 1970. After the seventies, composite structures took an important role in construction of high–rises and multi–storey buildings, however, the focus was on composite columns, whose principle was to overcome disadvantages and weaknesses of steel and concrete columns. According to the CTBUH, Franklin Centre–North Tower (1989, Chicago) and Bank of China Tower (1985, Hong Kong) were placed among world's ten tallest high–rises up until 1990. However, the first composite structured high–rise that was entitled the world's tallest high–rise is building Taipei 101, 2004, with its height of 508 meters. In addition the success of composite structures in terms of high–rise buildings is shown in the latest CTBUH's researches, where among top ten world's tallest structure in 2011, six of them were composite structures, Taipei 101, Shanghai World Financial Centre, International Commerce Centre (ICC), Zifeng Tower, Kingkey 100 and Guangzhou International Finance Centre.

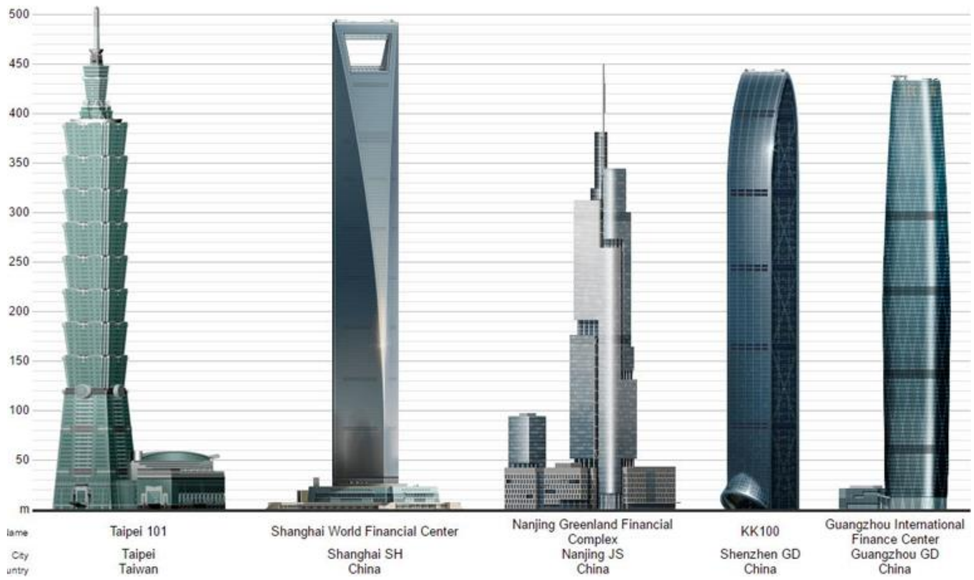

Figure 111 - Composite Structured High–Rises on the List of the World's Tallest High–Rises in 2011 by CTBUH [188]

According to the design philosophies, the most critical elements for high–rise buildings have to correspond to wind and seismic actions, where seismic actions are increased with buildings' weight and height. When compared to RC structures, steel structures acted better in terms of dimension of the cross-section of the structural elements, weighing less and having slenderer elements, making them more resistant; on the other hand concrete had better stiffness and higher resistance to any deflection and buckling of columns.

As solution to such problem are composite structures as they remain the best option for structuring of high–rises. Composite structures have better bending and buckling resistance than steel structures, but also weigh less when compared to RC structures.

World's tallest building of 2004, and at the same time the first building that is over half the kilometre tall and has 101 storeys, is Taipei 101, designed by C. Y. Lee and Partners.

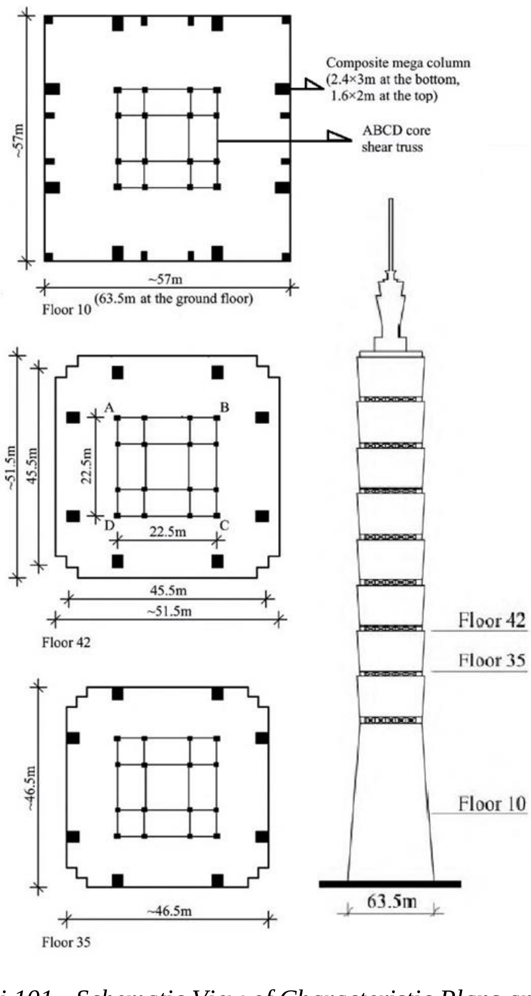

Figure 112 - Taipei 101 - Schematic View of Characteristic Plans and Elevation [14]

This composite structure is conceptual interpretation of bamboo, where volume is divided following vertical axis. The first part is pyramidal shaped volume with height of 25 storeys, and the last part of vertical division is rectangular shaped 12 storeys, while the rest of the inner storeys are divided in inverted pyramidal shape and have 8 storeys.

Located in windy area, structure of this tall building had to be designed to resist constant wind action, whose velocity achieves 156 km/h. Overall building design had to correspond to large wind actions, and the use of composite structure together with volume concept made it able to resist strong winds without suffering any serious deflection or damages.

Building is enclosed with 8 perimeter composite columns and 16 core columns, all composed of rectangular steel hollow section, filled with high strength concrete of 70 MPa, where the ground columns are 2.4 x 3 meter in cross section.

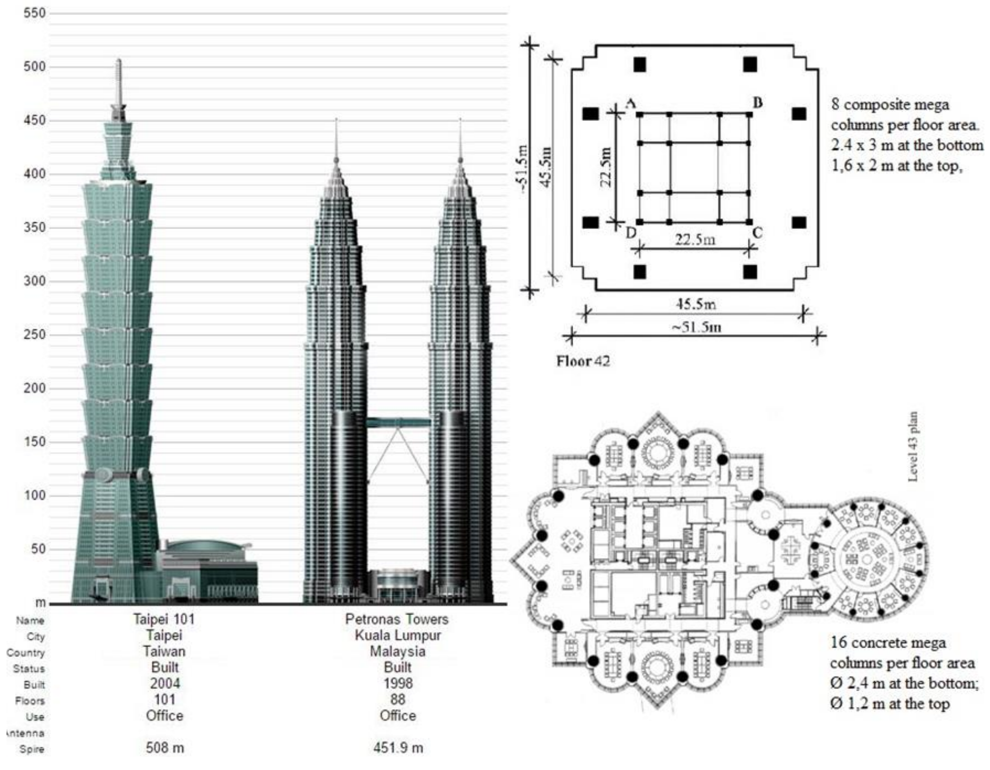

Figure 113 - Taipei 101–Composite Structure Compared to the Petronas Towers–Reinforced Concrete Structure in Terms of Perimeter Columns [189, 14, 98]

If compare concrete structure of Petronas Towers, where the height of 452 meters is achieved, and which has high strength concrete columns with diameter of 2.4 meters (80 MPa), but also located in less windy environment to composite structure of Taipei

101, it is evident that composite structures are more efficient. Being taller, located in much windier environment, meant greater lateral actions on structure happened, and the use of high–strength concrete of lower strength, 70 MPa, than it was used for pure concrete structure enhanced the success of composite structure in the case of Taipei 101, when compared to RC structure of Petronas Towers.

RISK OF PROGRESSIVE COLLAPSE IN HIGH–RISE STRUCTURES

Architectural design focuses on aesthetics and functionality of designed spaces in accordance with anthropological measurements in order to satisfy users and inhabitants. Following this philosophy buildings', structures fit right into architectural design and concepts as well. It is possible to apply this philosophy due to its greatest aim in providing comfortable and rentable spaces. Structures following the architectural plans, concepts and ideas represent a common design principle in any type of buildings, low-rise buildings allow fast and secure evacuation in cases of emergencies accepting this as proper practice.

However, in the specific case of high–rise buildings, structures don't compromises on architectural design, but rather combine its advantages to preform unique aesthetic values of the high–rise volume concepts. Main responsibility of the structure is to be capable to resist failure or collapse of building under various and the critical combination of actions, meaning that the structure should have efficient performance as long as the building's service life.

In high–rise structures, vertical elements columns and walls are designed to resist and transfer all actions to the foundation ground. Design process of high–rise buildings is important in order to provide efficient structure and in resisting various actions with efficiently designed composition of structural elements which would provide rentable and functional space. Structural design should be economical in selection of structural material and required time of the erection.

Worldwide accepted design method for building's structural design is limit states design method, where limit states refer to the structure's behaviour at different limit states, providing necessary safety against all limitations. Such design is based on probability that a structure will not collapse or become unusable due to various deflection, cracking, etc.; in other words that structure will not reach any limit states under the critical combination of any action. In the mid–20th century, previously working stress method was replaced by the limit states design method. With more precise and more economical designs, and increased safety of the building, limit states design method became worldwide accepted method in structural design. Working stress methods (WSM) follows Hook's law, considering that stress–strain diagram is linear. In WSM, stresses in structural elements are received through working loads when compared to permissible stress. For WSM, ultimate load carrying capacity is not accurate, as it is for ULS, so generally working stress method is uneconomical due to structural elements being overdesigned than it is actually required. On the other hand, limit states design considered stress–strain diagram as non–linear and more acceptable principle, with stresses received from designed loads in comparison to designed strength.

Partial safety factors appear to be crucial for limit states design, which varies up to action type and action predictability and refers to material type. With partial safety factors, possible errors in constructional inaccuracies, design assumptions and stress redistribution are covered in structural design.

There are two limit states:

- Ultimate limit state (ULS) – state for the structure in which it must not collapse under maximum design loads up to which it is designed. This means that it must satisfy ultimate state criteria for flexure, compression including stability, tension, shear or combined stresses; and
- Serviceability limit state (SLS) – which focuses on governing building service life, most importantly refers to deflections, durability, crackings and fatigue.

Limit States Design is defined in Europe in Eurocodes. Basis of design explains the definition classification and principles of limit states designs. This means that limit states designs, according to Eurocodes are in correspondence to structural material type and design of the structure, or in other words, they are in correspondence to a building type.

In Eurocodes, term load is practically replaced with the term action, which refers to a load but with wider meaning, where actions are being classified as:

- Direct actions, forces or loads applied to the structure; and
- Indirect actions, deformation imposed on structure, by temperature change shrinkage, settlement of foundation etc.

In structural design, there are three types of design situation; persistent situation which corresponds to a normal design use, transient situation which happens during the construction phase, and accidental situation which occurs in case of earthquake or fire which is also greatly influenced by structural system and material type. According to Eurocodes, along with these three designed situation there are also three main types of actions:

- Permanent action (K), self–weight of a structure, or so called dead loads;
- Variable action (Q), wind snow or any imposed load, including live load;
- Accidental action (A), impact from vehicle, explosion, fire etc.

Besides Eurocodes' classification of actions, actions may be classified according to direction of acting on gravity actions, lateral actions and special action cases. Gravity actions include permanent actions, variable actions and snow loads, while lateral actions are crucial for high–rises and include seismic and wind actions, which respectively increase with the buildings' height requiring more precise analysis in estimating them, and special action cases which include impacts, blasts, fire etc.

Figure 114 - Types of Structural Loads on High-Rise Structure [185]

Generally, no structure is designed to respond to one single action, but up to the critical possible combinations of estimated actions. What differs high–rise buildings form low–rises is necessity for high quality wind control and tests due to the increase of wind actions which happen along with the increase of height. Basic principles of action combinations are reflected in taking permanent actions in any action combination at any structure, and that each variable action is the leading action depending on building's service type and function. Even though limit states design in analysis takes the critical combinations of all loads and the critical distribution combinations, accidental actions, such as impact loads, explosion and fire, can cause reaching of the structure's limit state, or in other words failure of the structure will occur. Another issue that structure is dealing with is localisation of that specific failure and prevention of progressive collapse. Progressive collapse is collapse of the whole structure or large part of it, initiated by failure of one or more structural elements or part of the structure. Such failure or damage of one structural element or part of it initiates chain reaction, comparable to domino effect and failure of other structural damages resulting in total collapse of the structure.

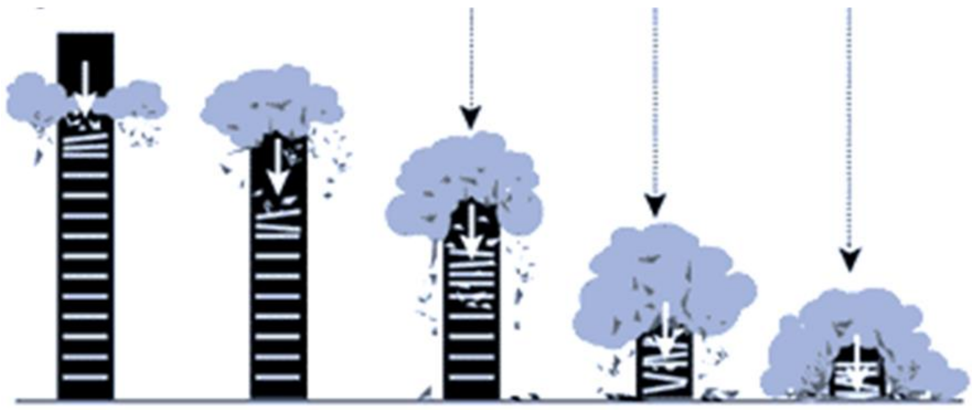

Figure 115 - Progressive Collapse, Schematic Presentation of the Progressive Collapses of World Trade Centre (9/11) [61]

Few decades ago design for progressive collapse was taken into account only partially or was entirely neglected; however, recent happenings in the USA and Asian countries, whether discuss the attacks or gas explosion, forced accelerated and more detailed structural design to prevent progressive collapses. The regulations of high–rise buildings mostly require addition of redundant members and additional tie of structural elements in order to provide more robust structures, strong, ductile and capable of redistributing accidental loads. In such design requirements new high strength and high performance materials greatly assist, whether it is the case of concrete structures or composite steel and concrete structures. Both of the mentioned materials provide more slenderness, and with slenderness lighter structures with higher resistance to fire and explosions, which are main actuators of progressive collapse when compared to normal strength or conventional concrete.

Gravity actions are group of possible actions which act perpendicularly to the slab surfaces, including all actions which are induced by gravity. In high–rise buildings, gravity actions do not differ from those acting on low–rise buildings. Exceptions occur in addition of permanent actions from increased number of storeys, therefore permanent actions of high rises when compared to those form low–rises increase as many times as the number of storeys increases.

Gravity actions are permanent loads such as self-weight of structure, densities etc., variable actions – which include service actions, actions during execution, various of vibrations and snow load, where the environmental characteristics define average degree of snow loadings.

Unlike any other action types, permanent action may be precisely determined and designed. Permanent actions remain constant and in the same position throughout buildings' service life, including weight of the structure and weight of the various attachments which are permanently attached. For the design of permanent action, it is important to have a defined type of the structural material and its density, where exact sizes and weights of the structural elements are derived through presumption and structural analysis.

Permanent actions include structural system, frames, walls, floors, slabs, ceilings, stairways, elevators roofs and plumbing, which can be constructed and made from various materials. All of possible materials have specific and characteristic approximate weights required for the design of permanent actions. In limit states design due to high accuracy of permanent actions design and calculation, safety factors are lower than those of other action types.

While structural materials in high–rises structures are mostly concrete, steel or composite materials; concrete with greater density seeks for larger structural elements such as columns, beams etc., while on the other hand very light and slender structures can be achieved with steel.

Variable actions vary in their value and position of acting on structure. Variable actions include actions during execution, service load such as furniture, users, inhabitants, equipment, and many others with shearing property of being movable and being induced by gravity to the structure.

Figure 116 - Illustrative Presentation of Permanent and Variable Actions [122]

Variable actions, besides these occupancy weights, include traffic vibration of the vehicle movements in garages, car ramps etc., in the specific case of high–rise buildings, but also the accelerations of elevators has to be well calculated as type of variable action

However, practice of the Eurocodes declares specific action values for various occupancy of the buildings. For instance, National Annex to Eurocode 1, BAS EN 1991-1-1 in Bosnia and Herzegovina [49] specifies service load for residential, office, commercial, hotel and university buildings from 2 kN/m^2 for residential buildings, to 3-5 kN/m^2 in office buildings, and finally to max. 7 kN/m^2 in department stores and commercial buildings.

Different global climate conditions develop different environmental impacts and actions on structure. All of the environmental actions are considered to be variable actions due to constant change in climate conditions. Among environmental actions, snow and rain loads are the ones that are being induced by gravity to the structure.

Areas with long winter season, where the snow remains for few months, require specific roof designs up to the snow load. Snow load is defined in national annexes to Eurocode 1 – Part 3, from country to country with correspondence to data of average snow amounts during the last few decades, nevertheless roof design and type (flat, gable, hip etc.,) play an important role with the degree of roof slope, windy areas or areas with no wind, snow type, single or multiple snow. Single snow refers to the areas where snow remains for few days, and thaws before the new cycle of snow in following days, however multiple snow refers to the areas where first snow does not thaw before the new cycle of snow arrives, causing multiplicity of the load acting on structure. For multiple snow type, presence of wind and direction in specific environment is also important, which dictates whether the snow load is uniformly distributed, or it accumulates on one side of the structure.

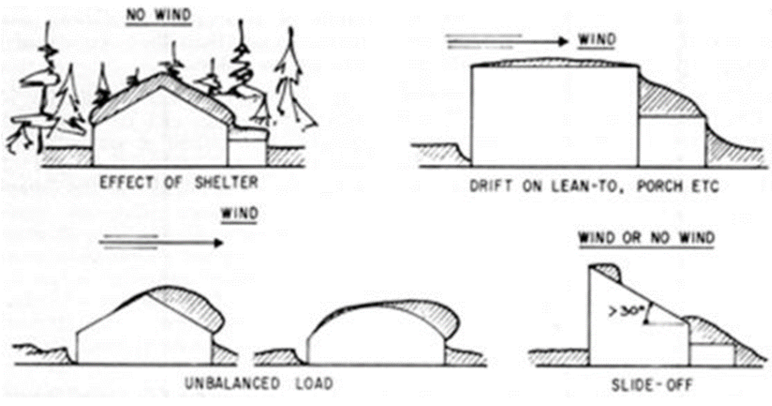

Figure 117 - Effect of the Wind on Snow Load Distribution on Roof Top [115]

Cases of high–rises showed that practice in roofing reflects on flat roofs, or slightly sloped roofs, which indicates another issue of snow remaining until it is being physically removed or until the sun solves the problem, which happens due to lack of slopes and possibility of snow sliding down.

Along with the common issues of snow remaining, on the top of the roofs, there is high possibility of rainwater accumulation on flat roofs which can also create problems, commonly called ponding. Ponding however, may be caused by accelerated snow melting on flat roof types. Nevertheless, problem of ponding can be solved by proper drainage systems, but in case it is missing, problem of ponding may be solved by installation of water tanks at the roof of the high–rises which have a capacity to collect rainwater at the rooftop area. Amount of value of this kind of load is also defined according to the data of national meteorological institutes of specific environments and areas, which shows the average rainwater fallen per square metre in the last few decades. Collected water is later recycled and reused in water supplies of the higher floors, due to natural fall which excludes the necessity for strong pumps to pump the water from the ground to the top floors.

Figure 118 - Flat Roof with Ponding Issue [116]

When discuss the lateral actions, their effects are major factors for high–rise structures. Lateral actions, such as wind and seismic actions increase with buildings' height and become main problem which may make building unstable, unusable, with the critical case scenario of building's collapse or over turning. Design of the buildings up to 10–storeys high, is affected by lateral actions with diminished effect, but also capable to cause deformations, cracking, deflections etc. However, with buildings over ten storeys high, lateral actions become crucial in structural and architectural design. In such cases, structural elements increase in cross sections, and design requires additional redesigning and arrangement of structural elements. At the early beginnings of high–rises in the late 19th century, wind actions and seismic actions were not the main focus of design, due to large, massive and stiffened structural elements and structures. However, with the development of high–strength structural materials, lighter and slenderer structures, possibility of deflection and sway became daily problems for engineers. Such situation enhanced the necessity for wind and seismic design in order to prevent collapses, loss of money, economy destruction and prevention of loss of numerous lives.

One of the most important issues of high–rise structures is wind action. Lighter, slenderer and more flexible structures are prone to sway, movement, and shake due to wind loadings. As the building's height increases, importance of wind load design increases respectively. Under the effects of wind high–rises might have different motion and direction of movements, such as, motion along wind, motion across wind and torsional motion. Due to excessive heights and great wind actions, high–rise buildings can be tested in wind tunnels, which determine intensity and nature of wind acting upon a building. Wind tunnel test actually represents behaviour of the structure's scaled model with its urban context in specific environmental loading, wind. Usually, scale is 300–400 decreased, where the case of the Burj Khalifa required scale was 1:500.

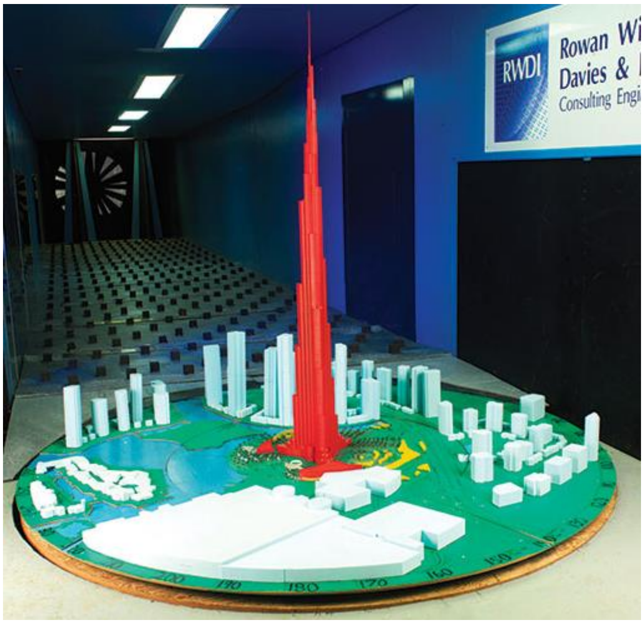

Figure 119 - Burj Khalifa, Model for Wind Tunnel Testing, Scale 1:500 [84]

Ever since wind became one of the most important factors in high–rise structures, techniques, methods and approaches multiplied and different categories were discovered, which had different focuses in order to achieve better resistance to wind actions. Approaches for wind design include architectural design approach, structural design approach and mechanical design approach.

Architectural design approach has its foundations in aerodynamic based designs and structure based designs. Aerodynamic architectural design is based on various factors such as: building's position–orientation, plan variations/modifications in height, aerodynamic forms and aerodynamic tops. Each of these approaches may decrease wind effect up to 50%. Effective design, if considering building positioning or orientation at the site is prevailing wind direction. However if the shape or urban context of the site itself allows the correct positioning, effects of wind upon structure may decrease up to 20 per cent. Burj Khalifa, one of the masterpieces in aerodynamic approach to high–rise design, where successfully the building with its butterfly structure resists six types of the wind.

Plan variation, as it says, is a variations in characteristic floor plans and height, and it may reflect in reduction of floor plan area or changes in geometrical shapes. In 1973, F. Khan [21] proved in his studies that at the high–rise, which has 40–storeys, and sloped facade of 8 per cent, reduced lateral drift for 50%.

Along with plan variation, aerodynamics may be developed through architectural modification, which refers to the modified rectangular in plan of high–rises, whose corners may appear to be notched, slotted, rounded, recessed etc., all in order to reduce across wind motion on the high–rise building.

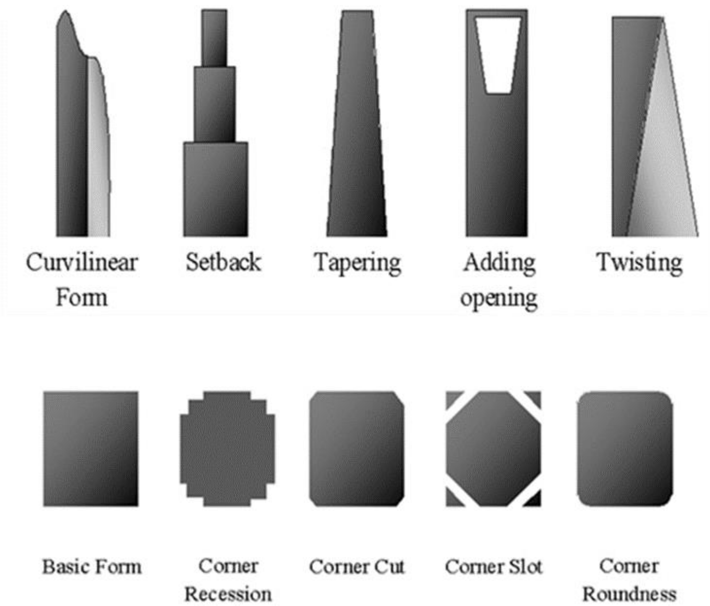

Figure 120 - Schemes of Possible Aerodynamic Solutions in Architectural Forms of High–Rise Buildings Caused with Drastic Plan Variations from Floor to Floor [65]

Aerodynamic form, mostly refers to various cylindrical, conical, twisted or elliptical forms, proved to be the most efficient forms and methods in reducing wind loadings. For instance, choosing circular plan form, rather than rectangular form at the initial phase of the design decreases possible wind actions by 20 percent. However, aerodynamic volumes are still perceived as the monumental in architecture and uncommon for high–rises; the most common of the aerodynamic forms lays in aerodynamic top approach. Such design is based on tapering the structure's upper part, following the practice of creation of the openings in between 80 and 90 percent of buildings total height; such example may be seen in Shanghai World Financial Centre, Shanghai.

Along with aerodynamic based design, structure based design is also important for architectural design approach. In such design symmetrical, circular, elliptical and triangular plans have high structural efficiency and higher response to wind action.

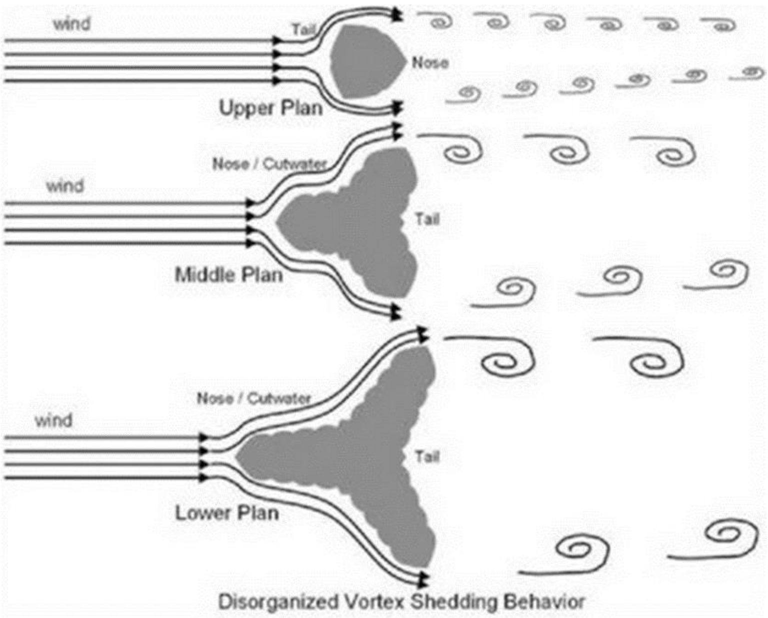

Figure 121 - Wind Behaviour on Characteristic Floor Plans of Burj Khalifa [159]

Structural design should respond to resist any wind displacement which makes building undesirable and uncomfortable for use. Shear frame systems, core systems, mega frames, tubular systems, mega columns and outrigger systems are structural approaches in resisting wind.

Within mechanical design approach, engineers usually take some inherent damping in order to estimate serviceability under lateral actions, which are induced by both seismic and wind actions. Structural systems, structural materials, non–structural materials, soil structure connection and its interaction, all affect damping which makes it difficult to measure. The installed damper reduces wind or seismic effects.

Figure 122 - Taipei 101's 728 Ton Tuned Mass Damper, World's Largest Tuned Damper, and the Only One Visible to the Public and Opened for Visits [95,127]

Dampers are divided into four groups: passive and active systems, semi–active and hybrids. In the case of high–rises, passive dampers are generally used and may be installed initially or later as retrofit, in order to upgrade buildings with low design for wind or seismic actions.

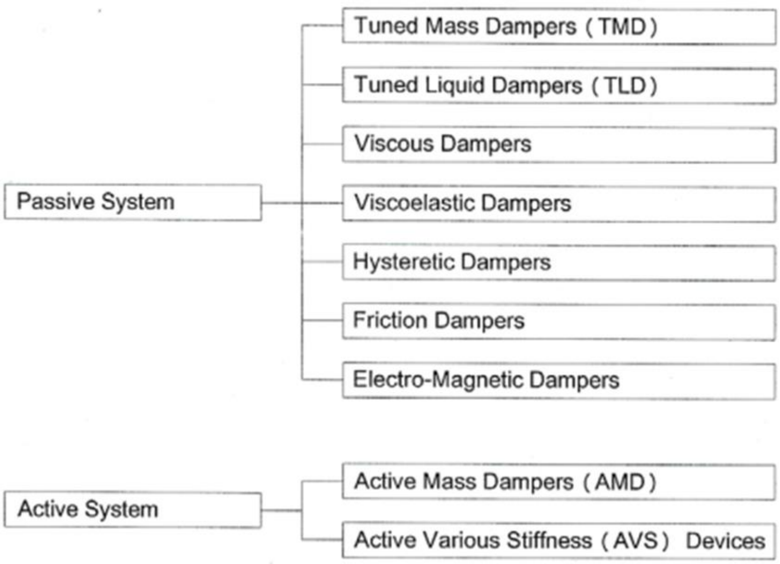

Figure 123 - Damping System Types for High–Rise Buildings - Classification [1]

There are many territories worldwide which are described as seismic zones, with different degree of seismic actions. Seismic actions are result of the buildings' dynamic response to the shaking ground. As rule for lateral actions is that it increases with the height of the structure and seismic action as class of lateral action has the same impact on high–rise structures. Until the mid 20th century, most of the buildings and infrastructural constructions were not adequately designed for seismic actions due to lack of technology and scientific approaches.

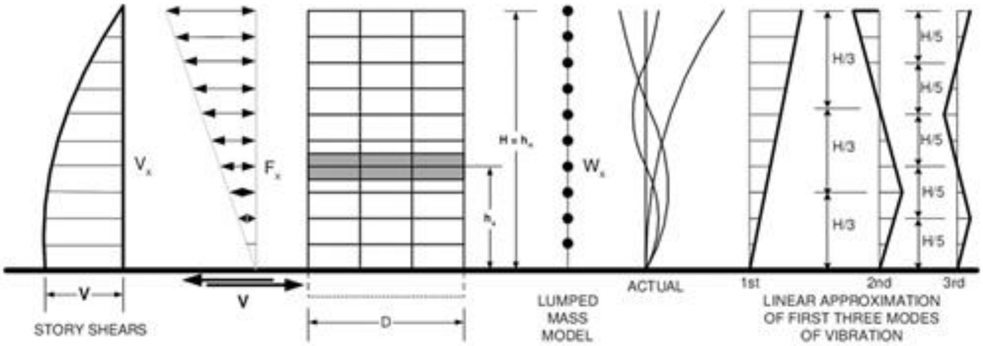

Figure 124 - Diagram of Seismic Action Distribution, with Respective Increase of the Buildings Height [184]

There are evidences worldwide how even a low earthquake may cause damages or even collapse of structures. One of the latest case of progressive collapse of high–rise building due to earthquake took place in Taiwan, in February 2016, on 17–storeys high residential building.

Figure 125 - Progressive Collapse of Residential 17-Storey High–Rise, Caused by the Earthquake in Taiwan, February, 2016 [173]

Commonly, the main issue of collapses reflects in weak structural design and inadequately designed structures. The seismic action depends on building’s mass, ground acceleration, type of foundations, structure, and also load–bearing soil.

So far, high–rise structures, showed that accidental actions are the hardest to predict and toughest to resist if they occurs. In structural design, accidental actions refer to all possible actions which are the result of accident, impact or blast which can occur in exceptional circumstances.

Accidental actions include blasts such as explosions, detonations and bombs etc., impacts which take vehicle into consideration such as aircraft impact etc., and include fire incidents, which are the possible result of previously mentioned two load types, but is also possible to be caused by anything else. Such actions are not commonly treated and considered within structural design, but rather with variations of passive protection systems.

Impact happens at the moment when a body with known velocity hits structure and applies impact action. This kind of dynamic effect is mostly short but inflict a hit that causes further damages, cracking etc. When discuss the crucial impacts, those include aircraft impacts in the air and vehicle impacts on the ground.

Figure 126 - World Trade Centre – 9/11 [107, 172, 92, 86]

Aircraft impacts, became one of the greatest hazards for high–rise structures in the last decade. Because of their height, high–rise structures are easy targets. The most known recent aircraft impact on high–rise structures is impact on World Trade Centre, where the possibility of progressive collapse and fast fire expansion happened with the worst case scenario. Although, if we exclude aircraft attacks that happen on purpose, chances for any aircraft impact is reduced to the minimum.

Figure 126 shows how an aircraft impact and bomb attack at the World Trade Centre, Manhattan, New York City, initiated fire with progressive collapse of the whole structure, where the attack did not demolish only the targets, World Trade Centre twin towers, but surrounding buildings as well; this case proved the necessity of designing the structure able to resist such or similar impacts.

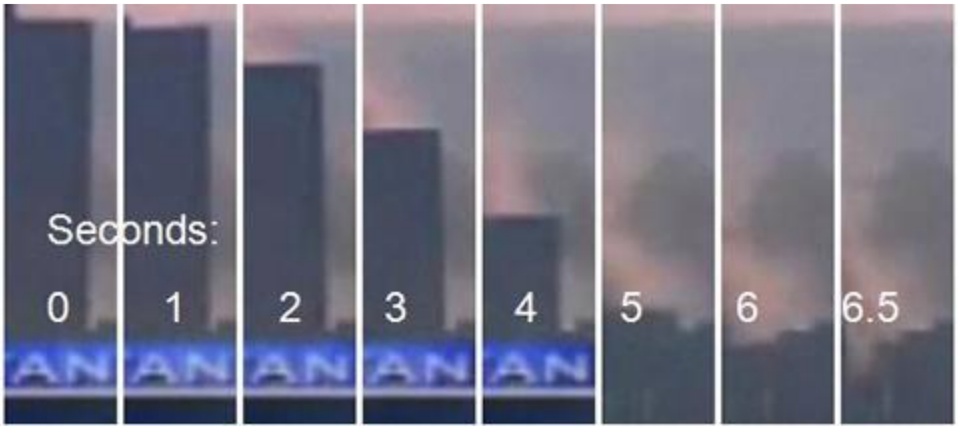

Figure 127 – Progressive Collapse of the World Trade Centre in 6.5 seconds [171]

Along with the aircraft impacts, urban areas have to deal with issues of vehicle impacts as well, which cause less destructive load for structures with partial or local damages. Lower velocity achieved by the vehicle is crucial for decreasing the possibility of great injuries on the structure. However, other factors which can be taken into consideration in order to reduce the risk of vehicle actions are distance of the building from the traffic road, direction of the impact, weight of the vehicle as the velocity at the moment of impact. If location and urban context of the structure require design for accidental actions, impacts are generally analysed through modelling of possible impact, evaluation of structural safety after the impact, and rate of fire expansion after the impact if there is any possibility of fire.

Blasts include bomb and gas explosions, which refers to blast with condensed high explosive of hot gasses with maximal pressure of 300 kilo bars and temperature of 3000˚ C. Such pressure and expansion form waves with greater velocity than the velocity of sound.

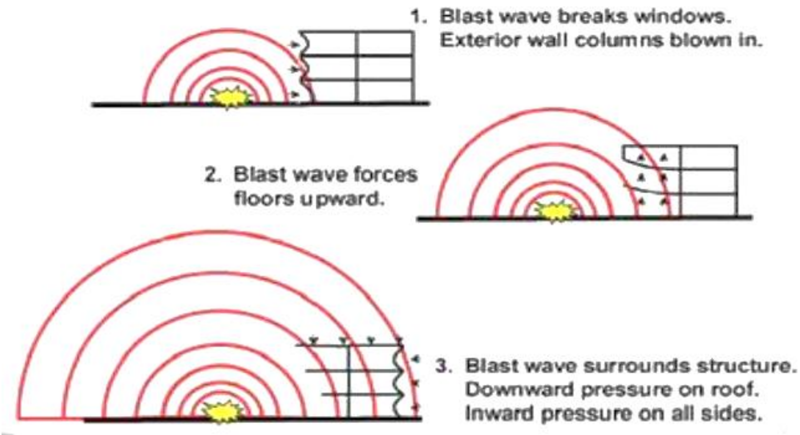

Figure 128 - Exterior Blasts– Explosion Next to the Building [182]

Bomb and gas explosions are difficult to take into design consideration and it is almost impossible to erect the structure which is immune to their effects. Some special laboratories and other buildings that deal with hazardous materials are constructed with special techniques and materials which are not cost efficient for wider use in construction of residential buildings, offices, commercial buildings, etc.

Gas explosions, as weaker type of blast load, generally happen due to weak and improper installation of gas pipeline in building's heating systems or mishandling of gas appliances. At the same time the most common accidents are caused by gas explosions, which is not surprising due to the fact that gas is most common fuel used for building's heating system and that there are other auxiliary necessities that run on gas. Even though gas explosions are localised and cause small damages, they may also initiate fire or grater damages and cracking.

Blast that initiates the worst case scenario is caused by bomb explosions which are created on purpose to injure, devastate and demolish a target. Such actions have their targets, but to design a building able to resist such power is questionable. Bomb detonations create shock waves, which expands with velocity of 1 km/s. Bomb explosions may happen next to the structure (exterior) or inside the structure (interior).

Common exterior explosion scenarios includes, broken windows and wall or column failure on the buildings' perimeter due to the pressure waves acting upon it, waves than move further into the building where ceilings and floors become borders, which are also under pressure. Floor generally falls due to large area being under excessive pressure. However, in the case of high–rise structures, losing floor and beams means losing the lateral stiffness and support which indicates collapse.

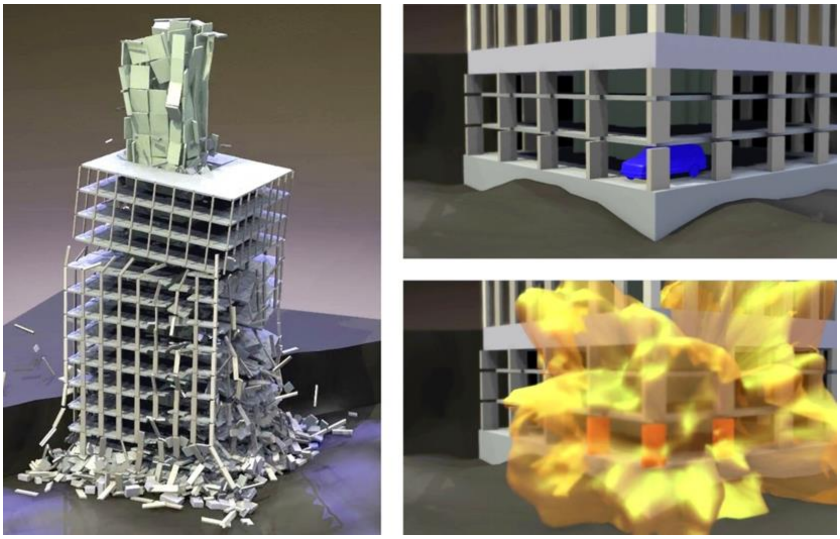

Figure 129 - Collapse Simulation, High–Rise Building Exposed to Interior Explosion, where the Structure does tot Resist for the Applied Blasts, and Continues with Progressive Collapse [198]

On the other hand, interior explosions may be localised due to floor systems above the detonation, with load bearing walls made of concrete or masonry, which results in some local damages and possible failure of non–structural elements; however it still depends on the amount and strength of the bomb explosion.

Fire has been a main problem for construction, since the beginnings of the first more complex buildings and structures. Along with all the merits that fire enabled, there were much more damages and injuries that happened accidentally or on purpose. It is almost impossible to find a city or any urban zone, with high concentration of buildings and infrastructure that did not undergo at least partial fire expansion through city. Fire was and still is one of the greatest weapons one can have. Lately, fire became mankind's weapon with purposes to resolve disagreements; however a fire may be caused by an earthquake or any other natural disasters.

Bosnia and Herzegovina and Sarajevo witnessed many of the pre–war monumental buildings and the greatest achievements from many different periods in architecture caught fire in the last war (1992-1995). However, almost all of the reinforced concrete structures remained and resisted fires, most of the reinforced concrete buildings that were on fire were reconstructed after the war. On the other, hand steel structures that were affected by fire during the war, collapsed and were demolished in most cases, with remains relocated and locations still waiting for their new purposes. World Trade Centre and many other builidngs indicate that structural engineers should be more responsible for fire protection and structures' resistance to fire, which unfortunately was not the case previously.

Figure 130 - Mandarin Oriental Hotel, 2/9/2009, Beijing, 44 Storey, Composite Concrete and Steel Framed Structure, was Entirely Affected by Fire Remained without Structural Collapse [195, 63]

First design for fire safety were prescriptive–based designs, where the whole design was based on fire resistance of materials used in structure, while new design is based on the performance design, including evaluated strength and stiffness for a fire safety design, coupled stress–thermal analysis, specialized design for fire effects and use of fire retardants. In addition, new design for fire safety deal with advanced structural analysis in the shape of temperature–time curves, which derive structural responses during heating or cooling phases during fire.

The most terrifying recent fire which affected high–rise building, was Grenfell Tower, in London. Scenes from Grenfell Tower over flooded world, with scenes of 24–storey high–rise building disappearing in oversized flame, spreading through the entire height of the building's elevation.

Figure 131 - Grenfell Tower, the Most Recent Fire Incident on the High–Rise in Such Large Scale, June 15, 2017 [102]

Building was built in 1974, designed as concrete residential high–rise structure. Initiator of fire and architectural and mechanical failures in fire protection on one side, besides structural design, structure's resistance to high fire and its concrete structure prevented progressive collapse. It can be seen in characteristic floor plans that this tall high–rise had only one staircase down the centre of the building, with two elevators which didn't seem helpful in the case of fire. One staircase unfortunately, showed insufficient for fast and secure evacuation, as well as lack of fire–resistant doors on staircase's entrance, and lack of building's firefighting equipment, and maintenance of the existing resulted in loss of many lives.

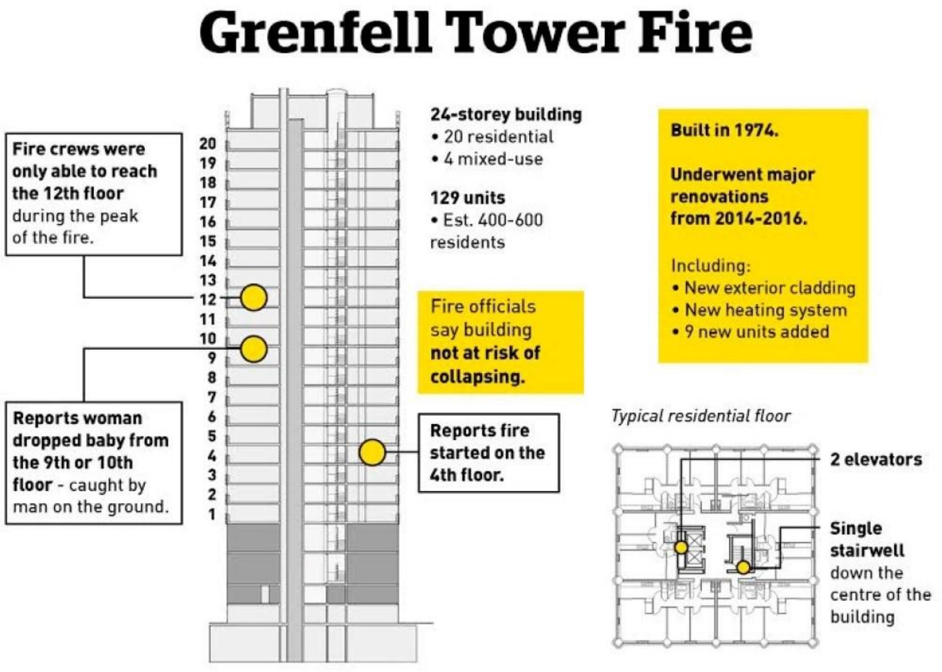

Figure 132 - Grenfell Tower, Cross Section Pointing on Place of Fire Start, with Characteristic Floor Plan Pointing out the Only Staircases Down the Centre of the Building [74]

In conclusion, constructing building that are able to resist fire does not only mean to have right choice of the structural material and structure, which indeed are crucial and which is the case with Grenfell Tower, but also an integration of fire–resisting mechanical and technical equipment, active and passive fire protection measures, relying on fire resisting doors, sprinkler systems, early smoke detector etc., all play a crucial role. Well planned architectural design takes in consideration all fire compartments, with correspondence to the maximum number of inhabitants or occupants at any given moment, because accidental actions are not planned and not predictable.

Studies on structural systems defined up to date classification of structures, with systematic approach based on exposure of major structures which were conducted by Mir M. Ali. [1] In general, all of the structures have their advantages and disadvantages, but commonly opens up a possibility to choose the main structural material, depending on many factors such as domestic material, ease of erection, time required, accessibility and safety both during construction and during service life.

Table 5 - Classification of Structural Systems of High–Rises Interior Structures [1]

CATEGORY	SUB CATEGORY	MATERIAL AND CONFIGURATION	EFFICIENT HEIGHT LIMIT
Rigid Frames	-	Steel	30
		Concrete	20
Braced Hinged Frames	-	Steel Shear Trusses + Steel Hinged Frame	10
Shear Wall/ Hinged Frames	-	Concrete Shear Wall + Steel Hinged Frame	35
Shear Wall (or Shear Truss) – Frame Interaction System	Braced Rigid Frames	Steel Shear Trusses – Steel Rigid Frames	40
	Shear Wall/ Rigid Frames	Concrete Shear Wall + Steel Rigid Frame	60
		Concrete Shear Wall + Concrete Frame	70
Outrigger Structures	-	Shear Cores (Steel Trusses or Concrete Shear Walls) + Outriggers (Steel Trusses or Concrete Walls) + (Belt Trusses) + Steel or Composite (Super) Columns	150

Table 6 - Classification of Structural Systems of High–Rises Exterior Structures [1]

CATEGORY	SUB CATEGORY	MATERIAL AND CONFIGURATION	EFFICIENT HEIGHT LIMIT
Tube	Framed Tube	Steel	80
		Concrete	60
	Braced Tube	Steel	100 (with Interior Columns) – 150 (without Interior Columns)
		Concrete	100
	Bundled Tube	Steel	110
		Concrete	110
	Tube in Tube	Ext. Frames Tube (Steel or Concrete) + Int. Core Tube (Steel or Concrete)	80
Diagrid	-	Steel	100
		Concrete	60
Space Truss Structures	-	Steel	150
Superframes	-	Steel	160
		Concrete	100
Exo – skeleton	-	Steel	100

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