40th Conference on
Our World in Concrete & Structures
27-28 August 2015, Singapore

CREATIVE CONCEPTUAL DESIGN OF TALL CONCRETE BUILDINGS – 40 YEARS OF IDEAS

Franco Mola[*], Elena Mola[†], Laura Maria Pellegrini [†]

[*]Politecnico di Milano
Piazza L. Da Vinci, 32, 20133, Milan, Italy
e-mail: <franco.mola@polimi.it> webpage: http://www.ecsd.it

Keywords: tall buildings, historical development, structural systems, formal aspects, materials, concrete technology.

Abstract

The main reasons of the development of tall building in the last 40 years are discussed. After a brief introduction regarding the history of these smarting constructions, from the ancient time to post WWII, the recent works of architects and engineers are examined in detail. Formal aspects, the progress of material technology, in particular of structural concrete and the refinements of structural analysis will be illustrated. With special regard to concrete, a material nowadays more and more employed in erecting tall buildings, some typical problems are pointed out, together with the analytical tools adopted in order to obtain refined and affordable solutions. Referring to particular and iconic tall buildings, the conceptual approach to structural design and the analytical process able to confirm and optimize the ideas deriving from a synergic collaboration between engineers and architects will be finally depicted.

1 INTRODUCTION

Tall buildings are among the most significant and challenging expression of modern engineering and they have always represented a goal towards which designers have passionately devoted their skills.

Even in ancient times, tall buildings have been regarded as landmarks and their memory has been traded down the centuries as a reminder of the ongoing struggle of mankind to get to know the basic laws of creation. The Egyptian Pyramids, the gothic cathedrals, the medieval watchtowers, the bell towers of all the cathedrals and churches, Figure 1, can be regarded as the most significant tall buildings of the past. Their elegant and complex shapes are even more awe-inspiring considering that the laws of mechanics and physics were unknown to the architects who created them. For this reason, they can be regarded as peculiar moments of holistic interaction between architecture, art and natural philosophy.

Many different reasons can be given in order to justify the search and struggle of mankind to reach new heights by means of new findings and the progress of technology and science. Such reasons are varied and keep changing in time: in ancient times, the main motivation was related to religion. Glorifying the gods or leaving perpetual memories of the earthly manifestations of the gods, i.e.the pharaos, which was the case for the pyramids, was one of the first and most powerful motivations for building tall. In more recent times, the reason behind this ongoing challenge mostly remained in the

[†] ECSD Srl, Milan, Italy

pride scientists and architects were starting to take in the fact that they had been understanding and mastering more and more of the laws of physics and therefore mastering the world around them.

Figure 1: a) Egyptian Pyramids; b) Gothic Cathedrals; c) Medieval Watchtowers

A famous and very meaningful example of this newfound pride is represented by the Eiffel Tower, Figure 2, built in Paris in 1889, and the first building reaching the height of 300m. This building, whose shape and architectural features have made it a worldwide renown, timeless masterpiece, was the result of the fertile synergy between modern material science, construction technology, steel production technology, mechanical engineering, and industrialized production and construction processes.

Figure 2: Eiffel Tower

Even if the example of the Eiffel Tower highlights how important the interaction between new, fast developing technologies is in order for meaningful tall buildings to be designed and built, it cannot be maintained that all of the advancements in building tall have been due to this reason. As time goes by, and down to the present day, the motivations for building tall have mostly become related to saving resources, such as urban spaces and energy: the main challenge has now become how to use our resources in the most efficient, environmentally friendly, conscious and sustainable way.

It can thus be concluded that no unique and all-encompassing motivation for building tall can be cited, but rather a number of ever changing reasons, all of which have consistently spurred mankind to reach new heights, up to present day, when we are about to witness the completion of the first building reaching the previously unfathomable 1000m mark.

At this regard, one would come to think that the most sensible reason behind this ever changing but constantly developing challenge towards building tall would be an innate quest for improvement and unquenchable thirst for perfection: men have always struggled to master and forge the world and make it better, more convenient, more suitable for their own needs. This has been going on since the beginning of time and has set mankind apart from animals: in this respect, building tall can be considered one of the best and self-explaining expressions of this human characteristic, which led to some of the most significant buildings of the past 4 decades: such achievements were made possible by the synergic developments of architecture and engineering in the framework of a never ending challenge towards improvement and progress.

The creative approach to the design of modern tall buildings has led to new shapes, whose significance and motivation does not remain in pure aesthetics any more, but rather extends to their functional meaningfulness. The search for a tighter connection between shape and function is one of the main features of modern architecture, together with a focus on sustainability and integration with the urban habitat. On the other hand, the rational approach to the design of tall buildings focuses on conceiving an object complying with a predetermined set of varied performance levels. Among these, the most obvious are static load capacity, earthquake resistance, dynamic load capacity, durability, occupant comfort. In order to achieve higher and higher levels for all of the above-mentioned performance targets, a synergic approach between the creative and the rational approach to tall building design becomes mandatory. This synergic interaction is the basis of the conception, design and construction of the building. In modern engineering, a peculiar branch was thus born in modern times, called the conceptual approach to structural design. This discipline was recently defined as such [1], [2], has become more and more popular and well established worldwide, through specific conferences and forums [3], and has finally been accounted for in the most recent Codes, [4]. The conceptual approach to structural design finds its roots in the classic formulations of structural mechanics and allows a more and more refined use of state-of-the-art analytical and numerical tools in order to provide more and more reliable results and to guarantee that the built objet will comply with a larger set of predefined performance levels. At this regard, the concept of structural robustness must be regarded as one of the basis of the conceptual approach, since providing robustness means preventing highly hazardous failure modes, involving the whole building even as a consequence of only minor local perturbations of the applied loads. In the past four decades, the impressive progress towards taller and taller buildings having increasingly complex shapes and structural behavior can be traced back to a set of circumstances that allowed such remarkable advancements in structural engineering.

Among those circumstances, some are worth listing:

- The exponential progress of numerical analysis tools and state-of-the-art software and the availability of low-cost hardware;
- The marked progress in material technology, with a particular focus on concrete;
- The progress in research in the field of structural behavior;
- The development of new construction technologies and highly specialized machinery. In the following, the above mentioned issues will be discussed in detail.

2 THE VERTICAL CHALLENGE

Tall buildings typical of modern engineering were designed starting at the end of the XIX century in the United States, in particular in the city of Chicago, reaching a height of 61m with the Reliance Building, Figure 3a). In 1900, in New York, a height of 95m was reached with the Flatiron Building, Figure 3b), in which the synergy between architecture and engineering is apparent in the triangular shape of the floor plan and in the use of steel frames to provide lateral load capacity and stiffness.

In the years 1910-25, the so called first New York Era flourished, and iconic buildings such as the MetLife Tower Building, Figure 3c), were born. The Metropolitan Life Insurance Company Tower, 213m tall, was shaped after the bell tower of the San Marc Cathedral in Venice, which had collapsed in 1902 and had been rebuilt in 1912.

Figure 3: a) Reliance Building, Chicago; b) Flatiron Building, NY; c) Metropolitan Life Insurance Company Tower, NY

Another building belonging to the first New York Era is the Woolworth Center, Figure 4a), which set the new height record to 243m in 1913.

Figure 4: a) Woolworth Center, NY; b) Chrysler Building, NY

The years 1925-1937 span the so-called Second New York Era, during which some of the most charming and beautiful tall buildings ever conceived were built: the Chrysler Building, Figure 4b), 321m tall, which was the first building higher than 300m, the RCA Building, Figure 5a), 259m tall and built in 1933, and finally the Empire State Building, Figure 5b), built in 1931 and setting the height record to 381m for the following 40 years. This building was finally passed by the Willis Towers, formerly known as the Sears Towers, built in Chicago, Figure 5c), in 1973 and reaching the impressive height of 443m.

Figure 5: a) RCA Building, NY; b) Empire State Building, NY; c) Willis Tower, Chicago

From that moment on, i.e. in the past forty years, tall buildings have become a landmark not only of American cities, but of the most important cities worldwide: record setting buildings in recent years have been built in other continents, with the USA ranking nine in 2012 as for tall building height. In order to better represent the progress of tall buildings, in Figure 6, the worldwide height records for the years 1900-2015 are reported, whereas, in Figure 7 - Figure 8 - Figure 9, the heights in Asia, Europe, Italy, starting from the year 1970 to 2015, are reported. It is interesting to observe in Figure 6 that the challenge for new height has involved essentially the USA until the 1970s, with a height increase of about 10m/year in the period 1900-1930, from the 95m of the Flatiron Building up to the 381m of the Empire State Building. Following to that, an increase of about 1.5m/year was achieved in the period 1930-1973, starting from the 381m of the Empire State Building up to the 443m of the Willis Tower.

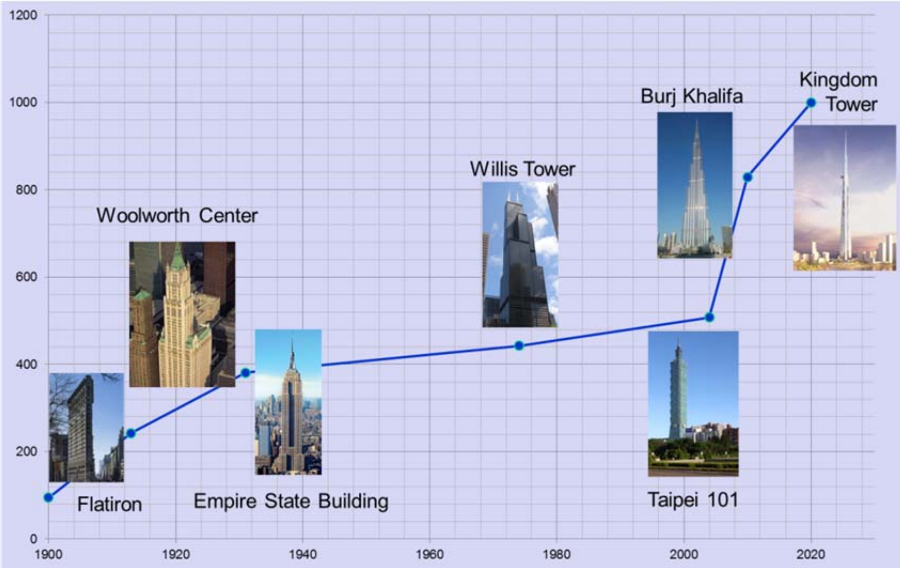

Figure 6: The Worldwide Height Records

Starting from the 1970s, the trend is slightly increased up to 2.1 m/year, with the Taipei 101 building, 508m tall, breaking the 500m record in 2004. Starting from this date, the growth become exponential, with an increase of 40m/year, so that in 2012 the Burj Khalifa, in Dubai, reaches a height of 828m, and the Kingdom Tower is currently under construction, in Jeddah, and expected to reach the heigh of 1000m in 2018. When observing Figure 7, reporting the heights of Asian tall buildings, it can be derived that the increase in their heights, starting from the 1970s, is of about 16m/year, starting from the 156m of the Kasumigaseki Building, built in Tokyo in 1973, up to the 828m of the Burj Khalifa. In Europe a different scenario can be observed, Figure 8, with much lower heights: in the 1970s the tallest building in Europe was the Tour Pleyel, 129m tall and built in Paris in 1973, whereas the current tallest building in Europe is the Mercury City Tower in Moscow, reaching a height of 339m, which makes for an increase of 5m/year.

Figure 7: The Asian Height Records

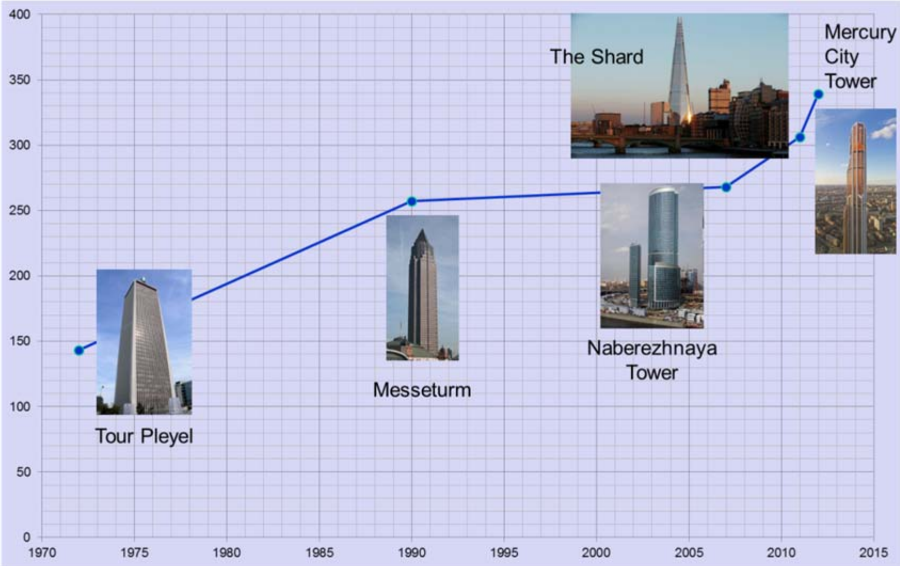

Figure 8: The European Height Records

Even lower heights can be observed as for italian tall buildings, Figure 9: from the 127m of the Pirelli Tower, built in Milan in the 1960s, the current record has now been set to 214m of the New Regione Piemonte Headquartes, currently topped out in Turin, with an increase in height of 1.6m/year.

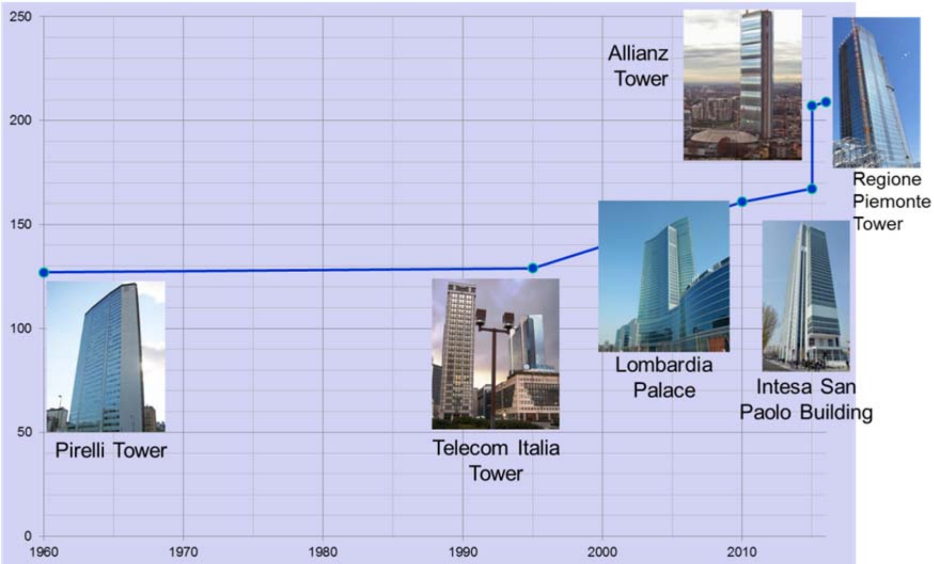

Figure 9: The Italian Height Records

From a comparative examination of the above mentioned figures, it can be concluded that starting from the 1970s, tall building design has been characterized by:

- the progress in height has become more and more marked;
- the lead in the challenge to building tall has moved from the USA to Asia;
- formal and aesthetical aspects have become increasingly important;
- a range of high performance materials have become available, so that a number of different structural systems for tall building have been conceived.

Starting from the 1970s, tall building engineering has developed more and more refined tools to deal with complex problems whose solution, informed by the principles of conceptual design, has allowed the construction of important and iconic buildings, achieving goals that even just a few years ago sounded irrational and impossible to pursue.

3 THE FORMAL ASPECTS OF TALL BUILDINGS

Formal aspects of tall buildings include both structural features, related to the geometrical configuration and the construction methods, and the architectural features, related to the aesthetics of the building, to its function and its interaction with the urban habitat.

In the 1970s, the shapes of tall buildings were essentially regular both in plan and in elevation. The structural material of choice was steel and the structural systems were mostly frames with hot bolted riveted joints placed along the main axes of the building and at the sides. Only after WWII, bolted and welded connections were used because of their increased efficiency and reliability, reducing global deformability under lateral loads.

A fully tridimensional structural behaviour was achieved, by enforcing full collaboration between the main frames and the concrete stairway cores through the slab systems: the latter were assumed to acts as fully rigid in-plane restraints, distributing the horizontal actions among the vertical elements according to their relative stiffnesses. This solution allowed new heights to be reached, but only if the lateral actions applied to the cores were those deriving from wind loads, with a known distribution along the height of the building. These assumptions excluded the presence of any other lateral actions on the cores, i.e. those due to second order effects or accidental eccentricities: these actions were reduced by means of severe limitations on the global lateral displacements and on the interstorey drifts. In order to achieve this, axial symmetry of the geometrical shape of the buildings was generally maintained along the whole height in order to avoid torsional effects inducing lateral actions under vertical loads. This approach led to a limited variety of shapes, because vertical regularity and symmetrical planwise configuration had to be maintained as much as possible, as can be clearly observed in the Empire State Building, whose height defines the acceptability limits, in terms of lateral displacements, for building having this kind of resisting system made of 3D frames.

In order to reach new heights, new structural systems had to be conceived: to this goal, a fundamental contribution was provided by F. Khan, who, in the 1970s, conceived a new resisting system, consisting of one or more central r.c. cores coupled with perimeter structural steel frames or trusses, such perimeter structures were clearly exposed under the glass facades, thus becoming a very meaningful and representative architectural features of the buildings that he designed, Figure 10a).

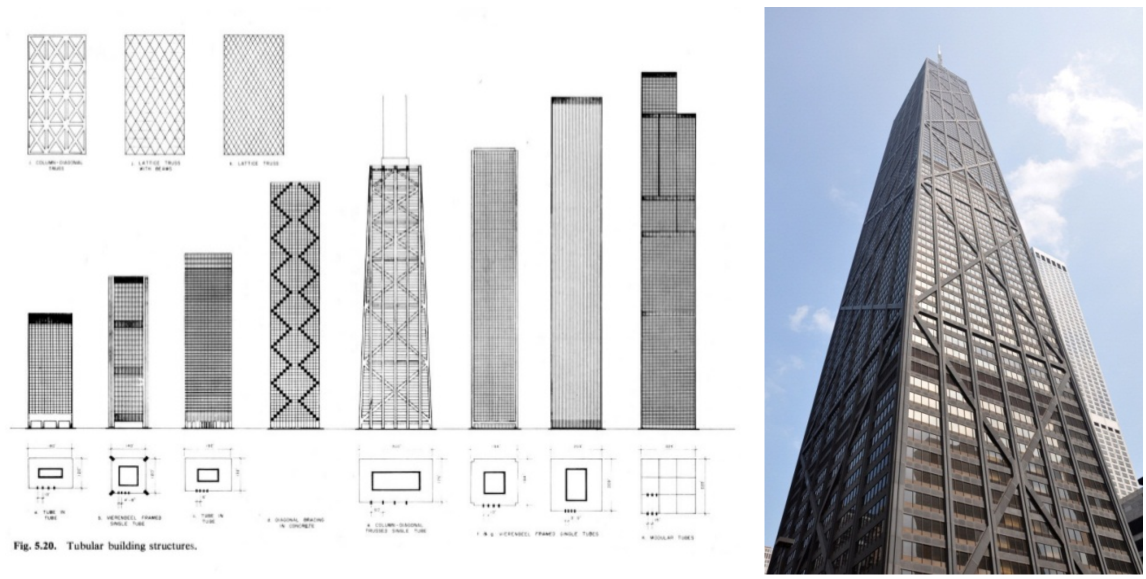

Figure 10: a) Shear resisting systems in tall buildings; b) John Hanckok Center, Chicago

This structural arrangement allowed the 400m threshold to be passed, but, eve more importantly, it introduced a new architectural feature that would later be developed by other designers into new shapes. In the John Hancock Center, Figure 10b), the external structure is a steel truss, whereas in the Willis Towers it is made of steel frames arranged differently along the height. In this case, it can be observed that the approach by Khan achieved both improved static efficiency and innovative architectural shape: the need for axial symmetry in this case is overcome by the increased global lateral stiffness provided by the arrangement of the frames.

Figure 11: a) Torre Avalanz, Mexico; b) Jongno Tower, Seoul

This so-called tube in tube system by Khan is now recognizable in a large number of the tall buildings designed in the past 40 years. The systems has been further developed and improved with the use of additional elements such as outriggers and belt trusses, which increase global stiffness of the system in case of high lateral loads due to heights or high seismicity and extreme wind conditions.

The introduction of outriggers and belt trusses generally requires the use of one or more floor for the structural system and for plants only, but at the same time provide the designer with increased creative freedom in the architectural design. Outstanding examples of this systems can be observed in Figure 11.

The new, freely creative approach to architectural design, without any formal or functional restraints, has grown very popular in the past decades, and has explored new paths, with no end in sight. This has led to such varied and even bizarre shapes in tall buildings that even a classification is somehow difficult to make, considering the variety and the complexity of such architectural features. The first approaches towards a totally free creative architecture ignoring limitations of structural nature can be traced back to the 1980s and early 1990s, with examples such as the 'Puerta de Europa' in Madrid, Figure 12, the Bank of China, Figure 13a), in Hong Kong and the Torso Tower, Figure 13b), in Malmo.

Figure 12: Puerta de Europa, Madrid

Figure 13: a) Bank of China, Hong Kong; b) Torso Tower, Malmo

These buildings have different features representing the free architectural approach: the Puerta de Europa gives up verticality, so much so that an extensive use of prestressing is needed in order to reduce long term lateral displacements induced by vertical loads. In the Bank of China Building, the peripheral truss structures exposed in the façade are a spatially complex 3D systems, as opposed to the John Hanckock center, in which they are two dimensional truss systems. Finally, in the Torso Tower, the lack of verticality of the peripheral structures introduces significant torsional effects. These buildings can be regarded as pioneering examples of an approach to architectural design later developed into a specific discipline, with the use of complex mathematical algorithms for the creation of new shapes or for the optimization of predesigned ones [5]. Moreover, such buildings brought about a broadened creative horizon, as can be observed today, to an extent where sensation and bizarre features are sought after, Figure 14.

Figure 14: a) CCTV Headquarters in Beijing, China; b) Ocean Heights, Dubai; c) Capital Gate, Abu Dhabi

Another interesting aspect regards the use of special floors, characterized by stiffness and capacity, able to counterbalance the effects of the modifications of the location of vertical elements along the height. A first important example is the Citycorp building, Figure 15a), in which the need for large surfaces at the first floor led the designers to chose an alternate solution, i.e. the use of a complex, heavy duty floor at the first floor, able to carry all of the above floors and only supported by the central core and four perimeter columns. The case of the Banca Intesa Building, Figure 15b), in Turin is also interesting: an auditorium was located at level 2÷6, which was made possible by the use of large steel trusses able to counterbalance the actions originating from the rest of the building above and to transfer them to six perimeter mega columns.

One last interesting case is the Velasca Tower, Figure 15c), in Milan, in which the top seven floors are wider than the rest of the building: in this case, the deviation of the vertical loads is made possible by tilted concrete struts restrained by the slabs, in which tension and compression stresses will be developed, respectively in the slab above and below the struts.

Figure 15: a) Citycorp Building, NY; b) Banca Intesa Tower, Torino; c) Velasca Tower, Milano

Apart from some architectonically meaningful examples, such as the Citycorp Building and the Velasca Tower, both of which still maintain axial symmetry, the most complex and bizarre architectural shapes have been conceived in the past twenty years, as a consequence of the wide availability of high performance software for structural analysis. This circumstance has allowed engineers to thoroughly investigate the new shapes conceived by architects, but at the same time it has reduced their conceptual design skills, through which numerical analyses need to be interpreted and validated in order to define their applicability limits.

In other terms, in order to achieve a balanced and fruitful interaction between architecture and engineering, the availability of very efficient numerical analysis tools must not be used to achieve a blind validation of architectural shapes, but rather as a tool to enhance conceptual design skills as a reference point to establish a synergic interaction between architecture and engineering.

The former is one of the key issues of modern engineering and its solution is not a unique one: it can only come from a balanced relationship between architecture and engineering, and from a conscious use of numerical tools, which will be embodied in tall buildings characterized by beauty, value, capacity, efficiency and harmonically interacting with the urban habitat.

4 MATERIALS AND THEIR STRUCTURAL PROPERTIES

The materials usually employed to erect tall buildings are structural concrete and structural steel. These two materials reached high performance levels in different times, so that the materials and the constructional techniques adopted in tall building design significantly changed from the first applications up to the present time. Before the ‘60s concrete technology and the related techniques of transportation, and placing were not feasible to guarantee values of compressive strength sufficient to construct buildings exceeding 100m. Besides the poor strength, the randomness affecting the results was so large to discourage the use of concrete in tall building design. However, observing that a large number of buildings of the II NY Era exceeded 200m, with maximum height 381m, it is easy to derive that structural steel was the only material used at that time. Structural concrete was introduced at the end of the ‘50s to erect the Pirelli Tower in Milano, 127 m high, the tallest building in the world with the structural skeleton totally in reinforced concrete. From that time, as shown in Figure 16, structural concrete has been more and more frequently used and nowadays it has been adopted for the construction of the Kingdom Tower, tallest building in the world, 1000m high. The impressive growing of the mechanical properties of structural concrete is the result of the correspondent growing of concrete technology, which started in the ‘70s. The use of plasticizers and superplasticizers dramatically enhanced the material workability reducing the water/cement ratio and the introduction of fine materials such as fly ash and silica fume reduced the material porosity, increasing durability and strength. In the ‘70s, the rheological behavior of concrete was widely explored regarding the structural effects generated by creep and shrinkage, and with respect to the properties related to the behavior in the fresh state.

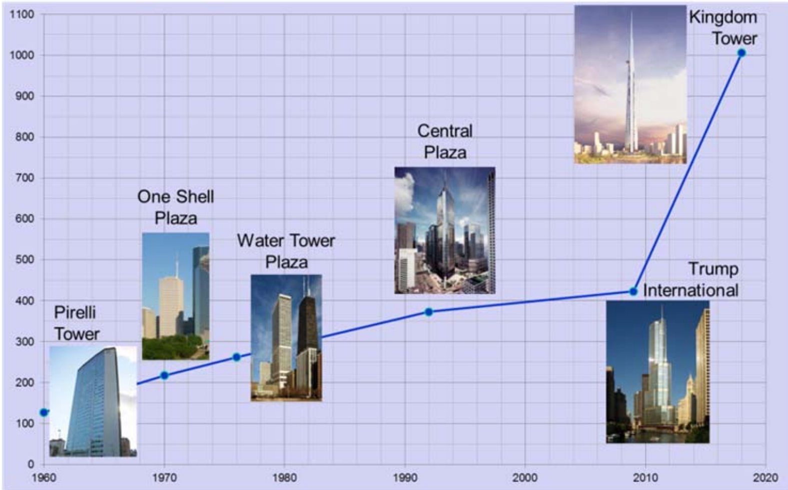

Figure 16: Evolution of concrete tall buildings

Other outstanding results were achieved from the application of fracture mechanics in order to define the intrinsic levels of ductility and brittleness of the material to be introduced into consistent constitutive laws. The theoretical refinements and the modern semiprobabilistic methods adopted to control structural safety led, at the end of the ‘70s, to set up a very sophisticated material and to define analytical models able to foresee the mechanical response of structural arrangements subjected to static or dynamic actions. In the ‘80s, the progress of concrete technology allowed high strength and successively high performance materials to be produced, able to compete with structural steel. The development of concrete technology is briefly summarized in Figure 17, where the static efficiency of the material, defined by the ratio h_0 between strength and specific weight is expressed in km on the vertical axis, as a function of the cylindrical compressive characteristic strength f_{ck}, expressed in MPa. We observe that for a concrete with f_{ck}=90MPa, coinciding with the maximum strength class at present time allowed by Eurocode2, the static efficiency is 3.6km, while the one pertaining to S355H steel is 4.52km. The difference is not very pronounced, anyhow, as we can see in Figure 18, for building with height 1km, the use of concrete appear undoubtedly profitable, allowing to reach a sufficiently large structural mesh in front of reduced dimensions of the column section.

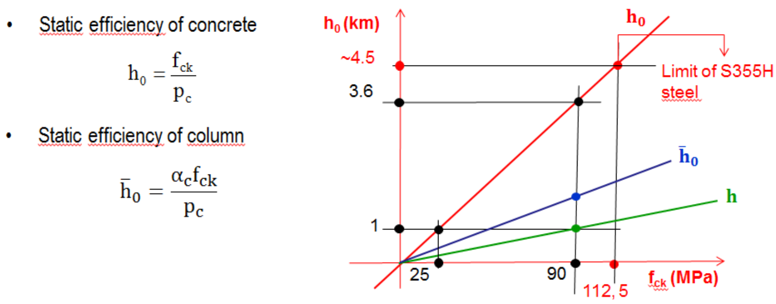

Figure 17: Static efficiency of concrete

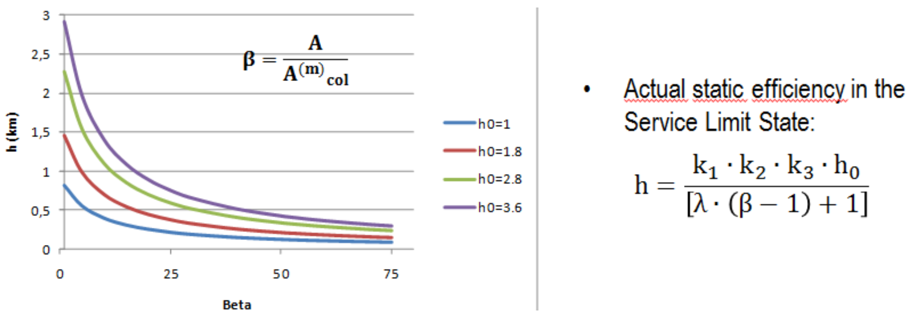

Figure 18: Concrete actual efficiency

In the ‘90s the production of self compacting concrete, allowed to reduce the time of placing without recurring to vibration techniques and to carry out massive volumes of strong consistency and durability. Taking into account that the concrete cost is largely lesser than steel and observing that the carbon dioxide emission to produce 1kg of cement is about 0.6 respect to 1kg of steel, we can conclude that the construction of tall buildings can be profitably operated by using structural concrete. This is a typical trend of modern engineering observing that tall and super-tall concrete buildings are more and more frequently erected worldwide. Besides the intrinsic properties of concrete we have to mention the continuous refinement and enhancement of the constructional techniques by which a profitable and convenient use of concrete can be achieved together with a consistent reduction of the construction time. Two aspects are of great interest: the possibility of placing concrete by means of pumps and the use of self –climbing scaffoldings. At present time, pumps with heads of the order of 600m are at our disposal and systems of self-climbing scaffoldings can be used to cast cores of complex geometrical form. The construction of cores, which generally preceeds that of the floor slabs requires to set up joining techniques between cores and slabs, which are particularly complex for cantilever slabs of significant span. In these cases, prestressing becomes determinant as it allows to join two different parts exploiting the contribution of friction to achieve connections exhibiting high structural capacity. Furthermore, the introduction of prestressing unbonded single-strand cables is very profitable as it can reduce the structural depth of the slab and increase the flexural stiffness by avoiding cracking. In this way, it becomes possible to design sound and efficient structures reducing the total weight of the building. Some applications of these techniques are shown in Figure 19, Figure 20, Figure 21.

Figure 19: Self climbing scaffoldings and preassembled steelcages

Figure 20: a) Prestressing of slabs; b) Cantilevered slabs

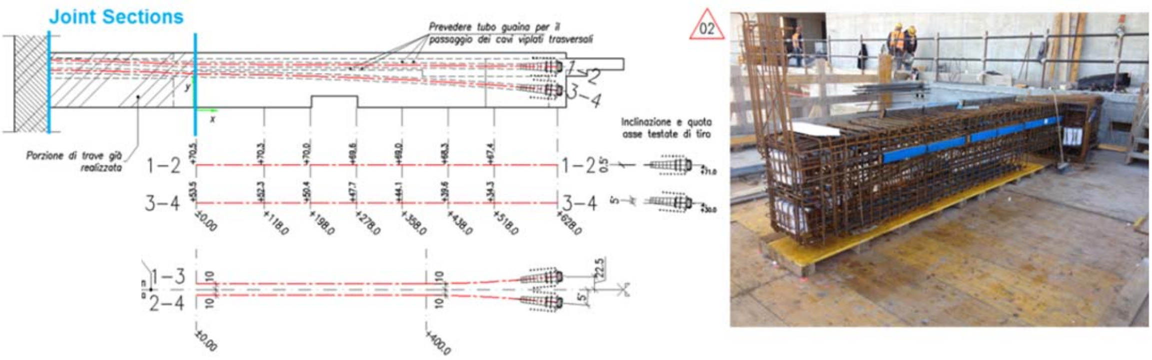

Figure 21: Prestressing details in cantilevered slabs

5 PECULIAR ISSUES IN TALL BUILDINGS DESIGN

The impressive height reached by some tall buildings recently erected and the more and more frequent use of concrete have pointed out specific structural problems. We have indeed to take into account that the vertical bearing structures i.e. columns and cores, exhibit different geometry and strength and are subjected to different stresses, gradually applied during the construction process. Therefore, the long-term deformations due to shrinkage and creep are not uniformly distributed and differential vertical settlements between columns and cores take place. Differential vertical settlements can generate unfavorable interaction between the bearing structures and the façade from which local damages can derive. They can also increase the bending moments acting in the slabs, to an extent depending on their bending stiffness.

Different situations can generally take place depending on the rheological properties of the materials. Regarding this point, we remember buildings formed by internal concrete cores and peripheral steel frames or columns. In these cases the differential vertical settlements are more pronounced as long term deformations do not affect steel structures. Finally, we have to take into account that the long-term permanent loads are applied following the construction process so that we can recognize a transient phase, associated to the building construction, in which the differential settlements can be compensated, thus strongly reducing the related effects, and a final phase, after building completion, in which the displacements cannot be compensated. The structural problem connected to the computation of the long term structural effects in tall buildings is rather complex and requires refined analyses to be controlled and validated by means of the general concepts and theorems of linear viscoelasticity. The problem was firstly approached by Khan and Fintel [6,7], in the years when the design of buildings exceeding 400m was in progress. The pioneering works of Khan and Fintel, even though oversimplified, allowed to the basic aspects of the problem to be highlighted and simple algorithms to be devised, able to derive useful indications about the order of magnitude of the various quantities and about the possibility of reducing the related negative effects. At present time, this kind of analyses can be approached by means of general methods implemented in specialized software. At this regard, good accuracy can be found in Midas Gen general purpose software, which has been accurately validated in many typical cases by the authors [8]. Some results of the analyses performed for the Regione Piemonte building are reported in Figure 22, Figure 23.

Besides long term deformation, the height of tall buildings makes them markedly sensitive to horizontal actions, either ordinary or exceptional. Regarding this point, the analyses under seismic actions are of paramount importance together with the formulation of a consistent strategy oriented to enhance the structural behavior in terms of ductility and bearing capacity. Referring to the tube-in-tube structural arrangement, the recent approach based on the introduction of special fuses in the joints of the peripheral steel structures is of significant interest and the so called Eccentrically Braced Frames (EBF) system has been conceived.

These special components can increase the structural efficiency by reducing the seismic action by virtue of the energy dissipation provided by their plastic deformation [9]. At present time, the theoretical and experimental research oriented to set up special devices of prescribed performance and the development of methods for non-linear analyses necessary to evaluate the related effects represents one of the most interesting fields in tall building design. In Figure 24a), some basic aspects concerning these elements are concisely illustrated. Analogous remarks can be made regarding the systems of dampers introduced in order to make the building less sensitive to wind-induced vibrations, increasing occupant comfort. Dampers were firstly introduced in the City Corp Building and from that innovative experience many other applications have been operated, up to the one, also characterized by significant architectural meaning, of the Allianz Tower, Figure 24b),designed by A. Isozaki for the Cytilife complex in Milan.

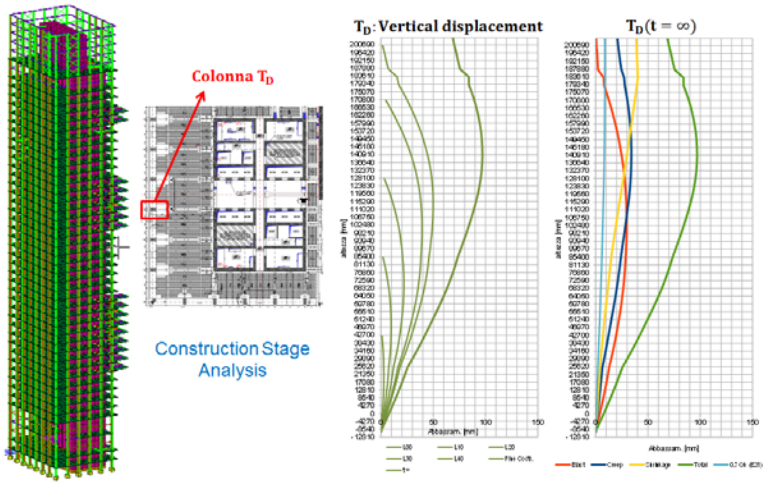

Figure 22: Column shortening due to creep and differential shrinkage

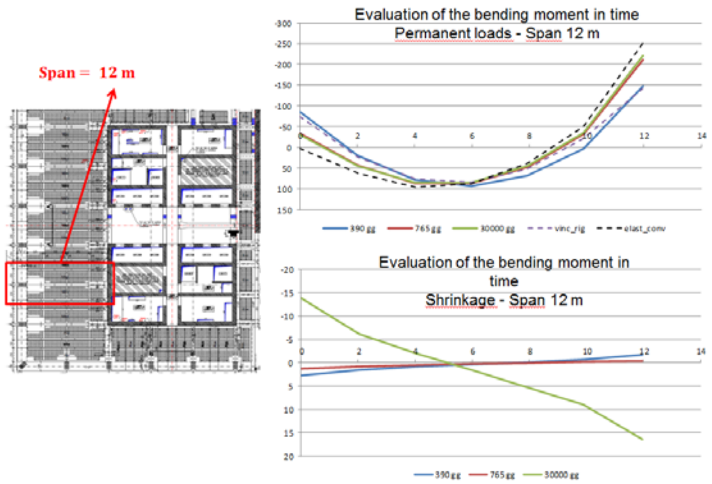

Figure 23: Effect of column shortening on bending of slabs

Figure 24: a) Structures with series of EBF; b) Damping devices in Allianz Tower, Milan

6 CONCLUSIONS

The long-lasting history of tall buildings, developed throughout the XX Century, is still evolving and nowadays very outstanding buildings are under construction worldwide. From the Seventies, when the limit of 400m was exceeded, the height of high-rise buildings has strongly increased up to one kilometer, and preliminary projects for higher buildings are in progress. The challenge of building higher and higher and the quest for more and more complex and sophisticated forms requires a strong and synergical collaboration between architects and engineers in order to design beautiful and efficient buildings. The structural issues brought about by tall buildings design are very complex, therefore refined analyses in the frameworks of a reliable conceptual approach are required to obtain sound and safe results. Only in this way it becomes possible to affordably foresee the structural behaviour and to design all the devices necessary to guarantee a reliable response even when exceptional actions are involved. From the previously discussed issues, we can so retain that tall buildings are very complex and delicate structural systems, whose response is dependent either on long term rheological phenomena and on short term dynamic ones. Furthermore, the form, which is the result of a creative act of the architect, plays a basic role in defining the structural behavior and the complex interactions that take place between the various structural elements. We can thus conclude that form, design, analysis, conceptual approach, material properties, construction techniques are the main factors defining a field where architects and engineers involved in the design processs need to interact with each other, with a productive spirit of cooperation. This is a very engaging perspective, enlightening the way of designing beautiful, out of time buildings, which can become landmarks able to change the city skyline enhancing it with an artistic, technological and cultural connotation.

REFERENCES

[1] J. Schlaich, *On the Conceptual Design of Structures*, Proceedings of the Int. Conference on Conceptual Design of Structures, Stuttgart, (1996).

[2] L. Kollar, *Problems of Conceptual Design in Engineering Structures*, Proceedings of the Int. Conference on Conceptual Design of Structures, Stuttgart, (1996).

[3] *Proceedings of the Int. Conference on Conceptual Approach to Structural Design*, CI Premier Ltd Singapore Ed., Milan, (2003), Singapore, (2005), Venice, (2007).

[4] *fib Model Code for Concrete Structures 2010*, Ernst & Sohn, Berlin, (2013).

[5] S. Khajehpour, *Optimal Conceptual Design of High-Rise Office Buildings*, PhD Thesis in Civil Engineering, University of Waterloo, Ontario, Canada, (2001).

[6] M. Fintel, F. Khan, *Effects of Column Creep and Shrinkage in Tall Structures – Prediction of Inelastic Column Shortening*, ACI Journal N.66, (1969).

[7] M. Fintel, F. Khan, *Effects of Column Creep and Shrinkage in Tall Structures – Analysis for Differential Shrinkage of Columns and Field Observation*, ACI SP27, (1971).

[8] F. Mola, L.M. Pellegrini, *Effects of Column Shortening in Tall R.C. Buildings*, Proc. of the XXIX Int. Conf. on Our World in Concrete & Structures, Singapore, (2011).

[9] W.F. Baker, *Energy Based Design of Lateral Systems*, Structural Engineering International, (1992).