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Super-Tall Buildings Forms Based on Structural Concepts and Energy Conservation Principles

Katayoon Taghizadeh[1,*], Seyedpooya Seyedinnoor[2]

[1]PHD in Architecture, Associate Professor, School of Architecture, Faculty of Fine Art, University of Tehran
[2]Master of Structural Engineering, Young Researchers Club, Islamic Azad University South Tehran Branch

Abstract The term sustainability refers to both structural form and energy efficiency, especially for high-rise buildings. In this paper at first, structural systems appropriate for super-tall buildings are described. Structure-architecture interactions that are necessary to achieve a conceptual design are discussed. Shape strategies and global forms appropriate for high-rise buildings subjected to wind load are illustrated. The paper aims to show how efficient structural forms and energy conservation and generation principles could be blended together with considering architectural expression of high-rise structures. Innovative configurations for super-tall buildings based on the principles of wind and structural engineering to achieve sustainability in global form are defined. In fact the new configurations have the characteristics of a sound structural system and meantime they reduce wind load on global body of structure, are efficiently able to produce energy in creative ways by their innovative configuration. Configuration-based classification of tall buildings discussed in this paper helps the designer to find the right road toward sustainability in global forms which incorporate every common aspect involved in the design process. The configurations consist of single and clustered forms each one with three subdivides. Considering sustainability in super-tall buildings in terms of both structure and energy efficiency could absolutely open a new vision in aesthetics of high-rise buildings.

Keywords Super-tall Buildings, Interaction of Structure, Architecture and Energy, Configuration, Sustainability

1. Introduction

The need to create tall buildings in dense cities is obvious. With Feeling a great need to super-tall building, considering the whole aspects of tall building in order to achieve sustainability in the design process should be one priority. It has been demonstrated that super-tall buildings could benefit from its great height to achieve sustainability[11]. In that paper, the temperature, air pressure, wind, moisture and solar effects on super-tall buildings has been discussed, but how a super-tall building can be primarily designed to have the potential of sustainability. The term sustainability should be referred to structure, architecture and energy efficiency. In this era architects, structural engineer, developer and urban planners should cooperate together to reach the goal of real sustainable tall buildings[7]. In the age of increasing structure-based architecture and also energy efficient architecture, there is rarely an interaction between structural configuration and energy efficient strategies. In fact, architect and structural engineer cancollaborateand use structurally resistant forms for consideringsustainable design facts in addition to carrying gravity, earthquake and wind loads[7]. This approach needs a great understanding of different structural systems appropriate for super tall buildings, energy resources and its impact on the building and an “engineering-aimed creativity’’ to come up with an attractive architecture which has a great sustainable story behind!

The principles of efficient structural design of a tall building are as follow (Halvorson, 1988),[9]:

- Resisting the overturning forces due to lateral forces on vertical elements placed as far apart as possible.
- Channeling gravity loads to those vertical elements resisting overturning forces.
- To the extent possible, resisting lateral forces with members axially loaded in compression rather than tension or bending.

For every tall building design the primary structural performance objectives should be set as reducing overturning moments, shear lag effect and lateral story drift.

2. Architecture-Structure Interaction of Super-tall Building’s Systems

In this section the inherent interaction between structure and architecture of super-tall buildings’ systems which seems necessary to be given a great consideration to

* Corresponding author:
ktaghizad@ut.ac.ir (KatayoonTaghizadeh)
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achieve a conceptual design, are discussed.

2.1. Braced Bundled Tubes

A tubular system acts as a simple tube resisting more torsion and overturning moment. A framed tube could not be used for super tall buildings because beam and column designs are controlled by bending action, resulting in large size. In addition, the cantilever behavior of the structure is undermined and shear lag is increased in the columns (axial forces in the corner columns are greater than the middle ones and the distribution is nonlinear). Braced tube system can partially solve the problem by stiffening the widely spaced columns by diagonal braces to create wall-like characteristics. A bundled tube is a cluster of individual tubes connected together to act as singular tube greatly used for super-tall buildings (e.g. Sear Tower, Chicago). In order to increase the height of the tower structurally bundled with tubes and helping its cantilever action, diagonal members could be added thus obtaining the structural system the so called braced bundled tube.

The bundled tube system offers great freedom in the architectural planning by creating a variety of existing building forms. It means that a bundled tube system can have a plan including many singular tubes at its base and just one at its highest level. The numbers of bundled tubes could be reduced as the height increases without loss of structural integrity[1]. This concept has positive effect on the response of the tower against wind. In basic tubular system, the closely spaced columns lead architect to make a structural view facade but large windows could not be used. Braced tube system has the structural expression of facade in addition to advantages of using large windows and opening. In bundled tube system, the perimeter columns could be placed with wider space even when using moment resistant frames with rigid connections (basic tubes) and interior planning limitation is eliminated by relatively larger column to column space.

2.2. Core and Outriggers

The system consists of the outriggers connected to a structurally stiff core to avoid cantilever behavior of the core. Outriggers serve to reduce overturning moments in the core, total lateral displacement and story drifts of supper-tall buildings and also transfer the reduced overturning moments to the perimeter columns in the form of tension-compression forces. These forces are often distributed by belt trusses located at the level of outriggers to the perimeter columns. The system can benefit from using off-set outriggers to reduce core wall thickness in addition to making a wind resistance structure. Outriggers can also be supported by some mega columns at the perimeter of building which make this system appropriate for super-tall buildings.

In core and outrigger system, the exterior column spacing can easily meet aesthetic and the building's perimeter framing system may consist of simple beam-column framing without the need for rigid-frame-type connections. For super-tall buildings, connecting the outriggers with exterior mega columns opens up the facade system for flexible aesthetic and architectural articulation thereby overcoming a principal drawback of closed-form tubular systems[1].

2.3. Diagrid

The state-of-the-art term, diagrid, comes from diagonal grid which is appropriate for tall and super-tall buildings with complex form from both structural and architectural point of view.

Diagrid system is a development of tubular system which consists of diagonal members at the perimeter of the building. The difference between diagrid and conventional braced tube system is that vertical elements at the perimeter of the building system are almost eliminated in diagird system (vertical mega columns could be placed at the corners to achieve more stability) and both gravity and lateral forces are resisted by diagonal members[1]. This is possible due to their triangulated configuration in a distributive and uniform manner. In facts, diagonal members act as inclined columns so meeting one of the principles of efficient structural design, mentioned before.

2.3.1. Comparison of Diagrid with other Structural Systems

Diagrid structures are much more effective in minimizing shear deformation because they carry shear by axial action of the diagonal members, while conventional tubular structures carry shear by bending of the vertical columns and horizontal spandrels (Moon, 2005). Despite of core and outriggers, the diagrid structure provides bending, shear and also torsional rigidity but outriggers alone do not add shear rigidity to the core, so stiff core is an absolutely necessary component of buildings equipped with outriggers but diagrid structures do not need core with high shear rigidity because shear can be carried by the diagrids located on the perimeter, even though super-tall buildings with a diagrid system can be further strengthened and stiffened by engaging the core, generating a system similar to a tube-in-tube,[1]. In this case, the core could behave like a cantilever and diagrid resists shear action, but because of the interaction between the core and diagrid under lateral loads, shear transfer should be checked in the place of significant changes in lateral stiffness of each system.

Despite of the other systems for super-tall buildings, diagrid has a great potential of attractiveness in addition to structural efficiency. A diagonal member of the system can cover more than 3 or 4 stories. This condition without vertical columns makes an unobstructed view for the building. As the diagrid does not need a stiff core system in tall buildings, the interior spacing can be better done. For the complex forms of tall and super-tall buildings, the diagrid system may be the best alternative in both structural and cost effectiveness aspects,[3] and[1]. Diagrid members is often made by steel which clearly express their regular diagonals on the facades, but the state-of-the-art form of diagrid can be made of concrete creating new architectural aesthetic expressions. Due to properties of concrete, the structural facade could be more fluid and irregular.

2.4. Space Truss

Space truss structures are modified braced tubes with diagonal members connecting the exterior to interior,[4]. In a typical braced tube structure, all the diagonals, which connect the corner columns, are located on the plane parallel to the facades. However, in space trusses, some diagonals penetrate the interior of the building. The structure efficiently resists lateral shear by axial forces in the space truss members. But the system could inherently obstruct the view (e.g. Bank of China Tower in Honk Kong).

2.5. Super Frame

Super frames consist of mega columns usually located at the corners composed of braced frames to act as a whole like a column. The mega columns are linked together by multistory trusses at about every 15 to 20 stories. These links are designed to reduce lateral displacement, lateral story drift and enhancing total stability. The system can produce super-tall building with more than 150 stories, but the buildings forms depends on a great degree to structural system (e.g. the 168-story tall Chicago World Trade Center proposed by Fazlur Khan in 1982).

3. Moving toward Sustainability Using Wind-originated Concepts

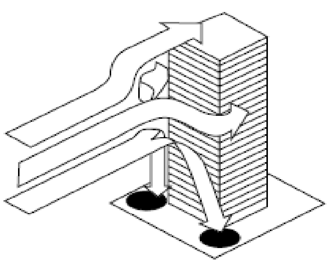

Figure 1. Effect of wind on tall buildings

With increasing the height of the building the effect of earthquake load generally reduces but needs precisely consideration in the analysis and design procedures. Vice versa, the wind power increases as the height increases, so considering the effects of wind power and coming up with the alternatives to not only eliminate the dangerous impact of wind loads but also gaining energy from wind power should be taken in to account from the first steps of the design as a decisive option to move toward sustainability. From dynamic effect point of view, both wind ward and cross-wind direction should be taken into account. Also cross wind direction is more critical in tall and super-tall buildings because of vortex shedding phenomenon[1],[10]. Figure 1 shows the effects of wind on tall buildings.

In general there are three ways to reduce these effects; stiffening the structure as the wind load increases, using auxiliary damping and applying shape strategies. Since the advent of high rise building, Different global shape were used and many in-detail researches show that some modification in the global shape can greatly reduce the effects of wind power on tall and super-tall building. These modifications include:

- Softening corners: chamfered or rounded corners greatly reduce base moment and vortex shedding (e.g. Taipie 101).
- Using setbacks and tapered forms: the loaded area gradually reduces as the height increases (e.g. Petronos tower).
- Using twisted forms: twisted forms are effective in reducing vortex shedding by disturbing wind loads (e.g. Turning torso residential tower).
- Using varied cross section: this alternative can lead the architect to create attractive forms (e.g. Burj Khalifa in Dubai; Burj Khalifi is also a good example of using softened corners and tapering and setbacks).
- Creating opening and porosity: by creating slots at the edge of the building, vortexshedding effect greatly reduces. Using large openings especially at vertical surface of the upper floors results in generating energy using turbines at the place of openings in addition to reducing wind load (e.g. 151 Incheon tower in Korea).
- Round top (e.g. Wuhan Greenland Center)

For today's world in which fuel resources in its end, it is crucial to consider energy efficiency during the design phases. To obtain energy efficiency or generally speaking, sustainability, so many rules and concepts should be applied to the building. In the case of wind (and also solar) power, a smart environmentally responsible designer of a high-rise building comes up with an idea to both reduces wind power on the global body of the structure and use it for energy generation. For this pure concept to be practically feasible, a great insight of structural principles and wind effects is needed for the architect to employ them during the form generation process in a creative manner,[3]. The concept and principles are the same but the results vary for different projects each with specific situation. In fact different strategies should be applied for different primary configurations to achieve sustainability in global form which integrates architectural form and structure1. In next part of the paper, two global configurations, one as a cluster and one as a single tower are described and discussed.

4. New Configurations and Original Concepts for Sustainability

Tall buildings can be classified from configuration point of view which include regular, regional and creative free

[1] Discussion about "reaching sustainability in architectural form of tall buildings for various configurations" is extensive and is under research by second author of the paper.

forms for single towers and completely separate, entirely connected through the height and partially connected for clustered towers,[4]. The classification aims at defining new procedure for sustainable design of high-rise building's form using structural and energy efficiency principles.

4.1. Single Towers

4.1.1. Regular Form

Traditional forms of tall buildings have been usually inspired by their conventional structural systems. These structural systems consist of framed tube, braced tube, bundled tube, tube in tube and outriggers and belt trusses which shown an exterior expression of architecture [2]. In these systems the major collaboration should have been between structural and façade system to achieve a structure-based architecture. There was always a problem that the structure which had good performance from structural point of view, had disadvantages of obstruction of view (E.g. braced tube) or interior planning limitations (E.g. bundled tubes). With the development of structural engineering and advent of state-of-the-art structural systems such as Diagrid, space truss, super frame and Exo-skeleton the architectural expression of high-rise buildings with more attractiveness was unfold, super tall buildings were feasible to design and construction, the problem of obstruction of view could have been partially solved and The architect was more free to generate hybrid and mixed-use tall building but construction cost and complicated joints were problem in addition to lack of innovation in energy efficient systems.

4.1.2. Regional Form

Figure 2. Regional forms; Left: Burj al Arab, Dubai. Right: Taipei 101 Financial Center, Taiwan

Regional forms can be offered in both clustered and single tall buildings. The most significant trend of tall buildings constructed in various Asian countries is that they use their own regional architectural and cultural traditions as main design motives [2]. These forms range from basic cultural concepts to climatic condition The architectural initiative of regional forms range from culture to climatic condition (figure 2). If using climatic condition to express regional architecture, sustainability can be seen in global configuration. In addition to global form, exterior skin can have a great effect on expressing regional architecture and consequently energy efficiency. With development of façade technology, structural façade systems like Exo-skeleton can be used in multi-functional way.

4.1.3. Creative Free Form

Single towers (and also clustered ones) can be designed in a creative way using wind and solar power concepts. In fact solar and wind-originated concepts can lead the architect to come up with innovative structurally sound forms which both have the ability of reducing natural forces impacts on the building meantime energy conservation and generation of wind, solar and rain. To achieve this using tapering, twisting, porosities and aerodynamic shapes during the form generation procedure is recommended. It also opens new vision is aesthetics of tall buildings (figure 3 (a) and (b)). With following this strategy wind load will be greatly reduced but because of inherent complexity of free forms, appropriate structural alternative should be opted. The structural alternative for these types of free forms could consist of shear core, outrigger and belt truss and exterior diagrid with mega columns.

Figure 3(a). Creative free forms; left: Pearl River Tower; funnel effect and influence on the form, both accelerating wind flow and decreasing turbulence. right: Nordhavnen Residences Copenhagen

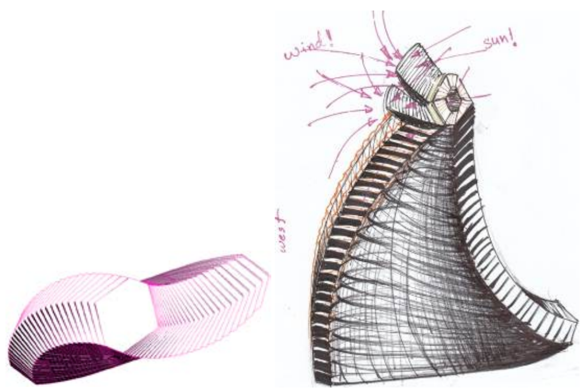

Figure 3(b). Bottom: 30-story conceptual tower (Seyedinnoor, 2011, [4])

4.2. Clustered Towers

A new trend in high-rise building design is clustering tower as one complex. The towers can be completely separate, entirely connected through the height or partially connected and detached in some areas. Designers have been designing many clustered tower but the question is that are they sustainable and how sustainability could be achieved in global form? All type of clustered towers can be designed with the same concepts of single forms but special issues in clustered forms deserve to be given attention as they can greatly help in achieving sustainability in global configuration.

4.2.1. Separate Form

Sustainable form design of separate clustered towers follows the aforementioned concepts for single towers. In addition pedestrian linkage can be used for quick evacuation and comfort of occupants. Also innovative forms with special direction can be used to harvest energy of wind power by funneling wind power to the special places equipped with turbines (figure 4).

Figure 4. Top: Tower 29, Dubai[9]; attractive, structurally sound and aerodynamic. Bottom: Bahrain World Train Center; wind turbine and its influence on the global form

Case study: Dubai tower 29

Dubai tower 29 by TVS – Atlanta, Georgia and Elnimeiri. M. represents sustainable design issues in terms of form and structure in addition to energy efficiency aspect. The tower benefits from incorporating twisting, tapering and tilting actions all in a single form. The structure of the building consists of exterior improved tube system, paired mega columns at the building corners, outriggers at two levels. The improved tube system proposed for this tower consists of continues slopped columns resembling the concept of diagrid system. Since outrigger system is appropriate choice for tilted forms while diagird is preferred for twisted ones (Seyedinnooor and Golabchi, 2013), the designer employed these systems to reach the sustainable-optimezed stuctural system. The form of the tower greatly reduces wind impacts while the crown (the spiral part at the top) houses wind turbine to produces electrical energy by harvesting wind which is abundant and steady at that height. Energy saving strategies also help the tower to reach a true sustainability. The façade is a multilayered curtain wall system featuring shading elements and sophisticated energy efficient glasspanels. Integratedfaçade system and well-located atrium (for balancing the light penetration) are some in case(Elnimeiri, 2008).

In general the tower addresses sustainability in three areas [8]:

- Energy saving strategies:

The proposed façade with the integrated elements offers significant reduction of the cooling load and hence of the cooling energy required. The well located multi story atriums offer deep penetration of day light while preserving a minimum surface to volume ratio.

- Form Contribution:

The plan- offsetting (morphing) will have a positive effect when the direction of the morphing causes the facade to tilt away from the sun.

- The Crown Contribution:

It is expected that significant amount of reliable and steady source of clean electrical energy will be produced from the wind turbine(s) housed there. That is because the turbines are located very high above the ground, where the air flow, most of the time, is abundant and steady.

4.2.2. Entirely Connected Clustered Form

Entirely connected clustered tall buildings can have their own central core or a condominium one which will be the intersection of tower. For the system with one condominium central core, the stabilization of each connected tower against lateral loads is ensured by the other towers and the system works as single structure if global plan of the system allows (E.g. a star with three wings, Figure 5). The system has the potential to greatly reduce the vortex shedding effect if in addition to global plan shape, tapering through elevation is considered. The system can be useful for super-tall buildings also in different ways by connecting a numbers of towers through their circumference resulting in a structural form the so called bundled tubes.

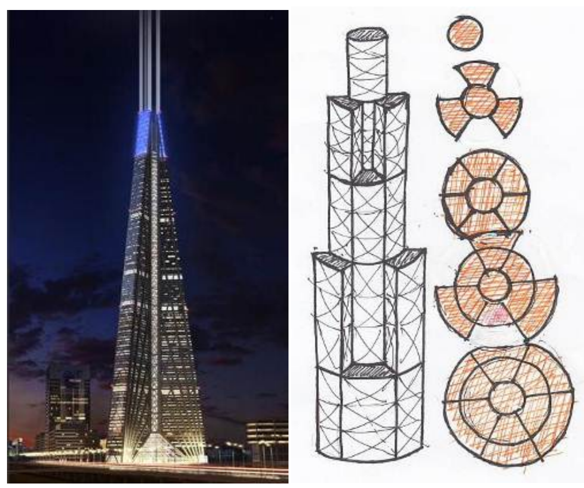

Figure 5. Left: Russia tower, (Halvorson and Partners, 2007). Right: combined structural system; Bundled tubes, external diagrid, internal core and outriggers, belt truss at the level of setbacks, perimeter mega columns, aerodynamic, funnel effect for harvesting wind power, ability of every single tube to has different height thus making attractiveness, great height potential

4.2.3. Connected and Partially Detached Form

In this system the towers are connected to each other but detached in some areas through their height. In opening areas, pedestrian linkage could be used. Through vertical opening areas, natural light could penetrate to the floors. Wind power is also reduced by creation of these opening[3]. The openings can also be used as a place to install wind turbines (if innovative forms are applied) in the way that overall form of the building direct the wind to the areas equipped with vertical or horizontal turbines so that the whole system can produce partial of its usage energy by its own while the effect of wind load on the structure is reduced because of the nature of innovative forms. The linked areas help to maintain overall stability of the whole cluster especially against wind load. Since the towers are structurally connected, the overall slenderness ratio is relatively low thus having higher height potential but with applying appropriate structural system. The tower itself can has a twisting and tapered form to ideally reduce wind power and the cluster of towers could be intertwined together to achieve higher levels of attractiveness in global form based on wind and structural principles[3]. The appropriate structural system for the proposed cluster could consist of an improved diagrid with core system because of natural complexity of the towers cluster (figure 6).

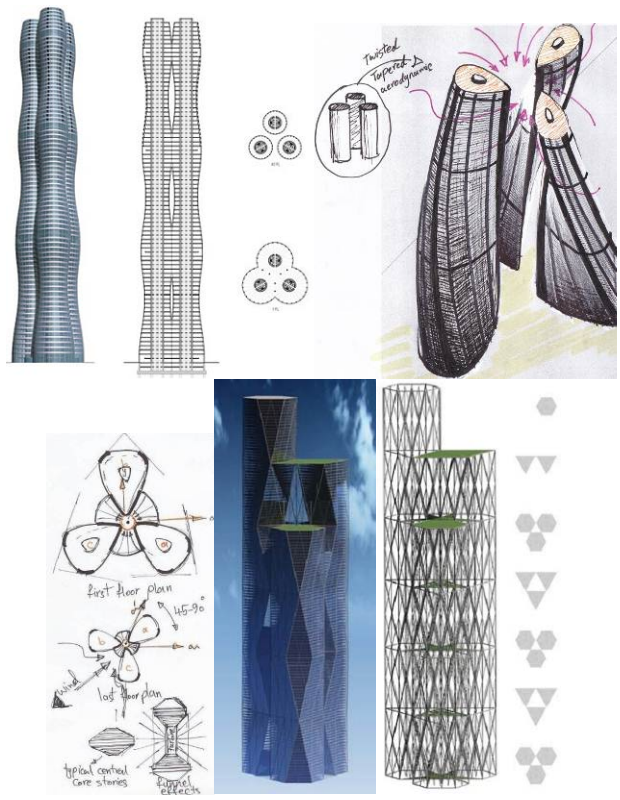

Figure 6. Left: Wave-form tower cluster (Land.P,[5]); Wind and light flows through openings thus reducing wind loading on tower clusters. Middle: Clustered towers for wind harvesting (Seyedinnoor, 2011, [4]); taper, twisted, curved corners, aerodynamic, funnel effect and wind turbines-equipped. Right: triangulated mega frame structure (Land. P,[5]); Clustering of the structure Pyramids allow a flexible articulation of the overall clustering form giving interior atria and through space

One point to be considered about clustered towers is that they could address the sub-categories of single towers if they act as single entity or the concept of single entity is considered as main design factor by the designer. The term entity is referred to all aspect of the design ranging from structure to social-cultural issues. For example, if buildings of a clustered tower together yield a cultural concept of the construction region, the whole system (clustered tower) addresses a regional form. The same story for completely and/or partially connected clustered tower could be of interesting issue. The whole system can act as structurally regular form consisting of single free-form towers. The efficiency of the system comes from clustering those geometrically irregular buildings completing each other and form structurally regular final configuration.

The term sustainability refers to all aspects and relates to all phases of the design which of the most important of them are: cultural and social issues, functions, energy efficiency (reduction in use and also generation energy), structure, construction technology, material recycle, cost etc. But for the current research the focus was on energy efficiency and structure and their impact on the global form and configuration.

5. Conclusions

New configurations for tall and super-tall buildings are inspired by the conceptsof sustainability. Present paper discusses the possibilities and challenges of using structural and energy efficiency concepts(especially related to wind and solar power) to create structurally sound forms which are energy efficient while architecturally attractive. While operatianl costs are a major area of reasearch for tall buildings, the paper discusses global form as it incoprporates, structuer, architecture and energy efficiency issues. A configuration-based classification is proposed focusing on structure, architectural form and energy efficiency principles which aims at defining new procedure for sustainable design of high-rise building's form. The classification includes regular, regional and creative free forms for single towers and completely separate, entirely connected through the height and partially connected for clustered towers. The new configurations reduces natural forces impacts on global body of structure by using shape modification strategies (like tapering, twisting, porosities, setbacks and using airfoil form for resisting against wind) meantime they are efficiently able to conserve and generate energy (especially from wind power) using their original concepts. To achieve a sustainable tall building's form, a great collaboration of the architect, structural engineer and wind expert from the first steps of the design and great insight in all aspects of sustainability from social issues to structure is needed.

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