OPTIMAL DESIGN: AN ENABLING TOOLKIT FOR THE VIABILITY OF SUPER TALL TOWERS

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Abstract

Construction of super tall buildings across the globe has become more and more challenging. In some cases, code prescribed high lateral load considerations for wind and seismic make it prohibitive to conceive tall buildings and in some other case empirical results of geotechnical conditions recommend foundation system that are un-constructible. This paper addresses the various aspects of Optimal Design that make super tall buildings, more viable around the globe. Of particular interest, the Performance Based Design (PBD) is discussed and examples projects are provided to illustrate the benefits of using PBD. These advantages include various perspectives of super tall building design and construction, including the wind, seismic, foundation, structural node, and constructability.

***Keywords:** Performance Based Design, Optimal Design, Supertall*

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1. INTORODUCTION

With more than 50% of the human population living in cities, the demand for space has been increasing exponentially. Building vertical and avoiding large sprawling cities provides one of the most sustainable solutions to rapid urbanization. Compact cities improve the standard of living by reducing travel times and increasing efficiency of public transportation. This trend is resulting in taller buildings in cities worldwide. Cities where building tall was unimaginable a few years back are now ground for constructions that aim for the sky.

However, to make construction of Super Tall Buildings across the globe a reality one has to recognize the challenges associated with it. International building codes are typically sufficient for the design of 99% of buildings constructed but Super Tall Buildings almost always fall in that last 1% where literal application of many of code provisions results in uneconomical and unbuildable designs. Building sites with relatively high seismicity, sometimes combined with undesirable soil conditions require innovative design solutions and design processes. Cities with high wind require a detailed wind tunnel analysis to predict realistic estimates of wind loads and creative solutions through modification of building geometry that result in reduced wind load demands. Super Tall buildings inherently demand a more sophisticated Performance Based Design approach as their design transcends prescriptive standards for the determination of lateral loads and response under a range of limit states from habitability to survivability. Performance Based Design is one of the tools of Optimal Design that enables more transparent and risk-informed collaborative decision making between owners and designers to achieve life safety and include more holistic design objectives.

Very often large transportation infrastructure hubs occupy large tracts of land in the heart of urban centers which otherwise would be very desirable for development. Building departments of cities worldwide are allowing construction using the air-rights above transportation infrastructure to maximize appropriate use of valuable real estate. This results in the design of complex structures with unique and challenging interface with foundation systems.

In Addition, extreme fast track building construction schedules has resulted in a compressed time from project conception to the completion of construction. Similarly, latest 3D digital modelling tools allow designers to conceive complex buildings with unique geometries. The desire to build big but at the same time build economical structures has led to the need for the development of optimal design procedures that achieve constructability and affordability.

2. PERFORMANCE BASED DESIGN (PBD)

2.1PBD for Wind

For any super tall building, the effects of wind always control the design of the structural lateral system. Wind induced vortex shedding or crosswind building movements can cause intolerable building accelerations that can give people motion sickness. Major strategies have to be employed early on in the design process to address the effects of wind. In the design process of Burj Khallifa (see Figure 1), SOM's proprietary software and PBD based design technology allowed the designers to increase the height of building height while reducing base forces and building motions. Figure 2 shows the wind tunnel test of different Burj Khallifa models and the evaluation of the tower shape with PBD is shown in Figure 3.

Another example is the 555m Lotte Super Tower (Figure 13). Several early configurations were tested in a scaled wind tunnel model and Wind tunnel loads were found to be approximately 60% of those calculated by the wind specified in the KBC. This permited the design of the building to proceed using 80% of the wind load specified by code, thus creating significant value for both the designers and the client.

Figure 1. Burj Khallifa.

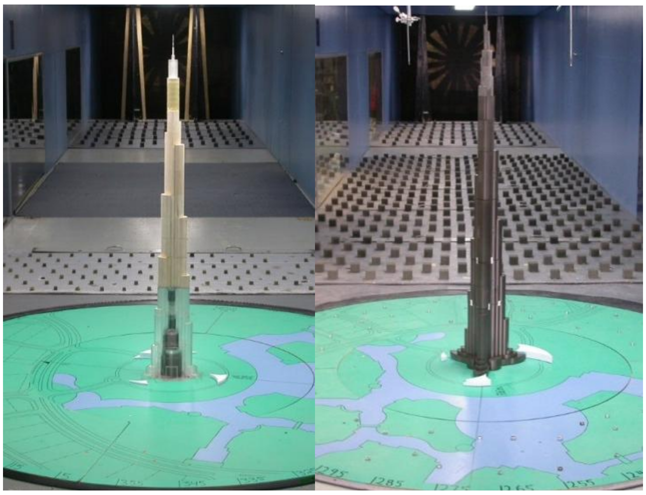


Figure 2. Burj Khallifa wind tunnel studies.

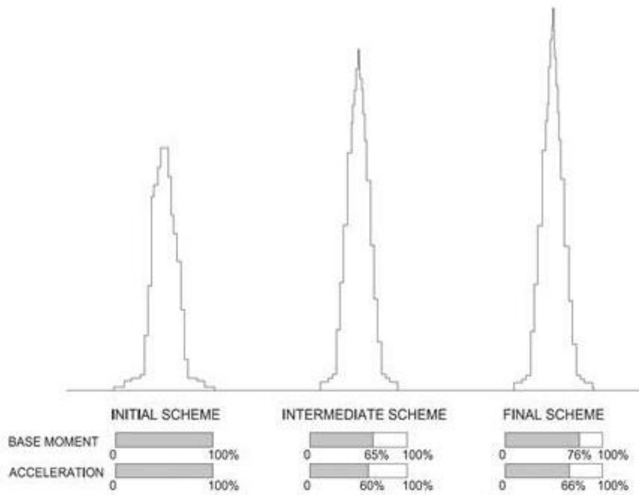


Figure 3. Burj Khallifa tower scheme evolution.

2.2 PBD for Seismic

PBD applies not only to the wind design but also can be used for theseismic analysis and design. By employing PBD, the seismic base shear can be greatly reduced. Taking Pertamina Energy Tower as an example (see Figure 4), the base shear under seismic load can be reduced to less than 40% of the value calculated by code (see Figure 5) [1]. The significant reduction of the base shear would not only gives flexibility to the designs, but also generates significant savings for the construction.

Figure 4. Pertamina Energy Tower.

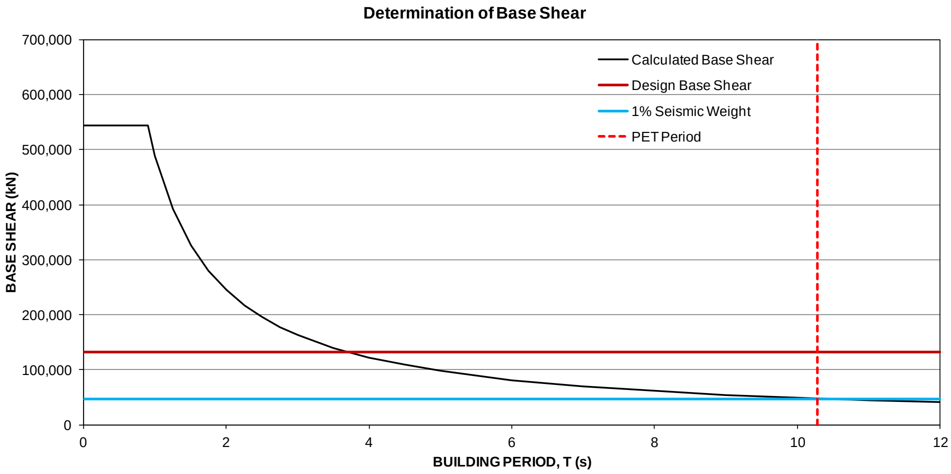


Figure 5. Pertamina Tower response spectrum.

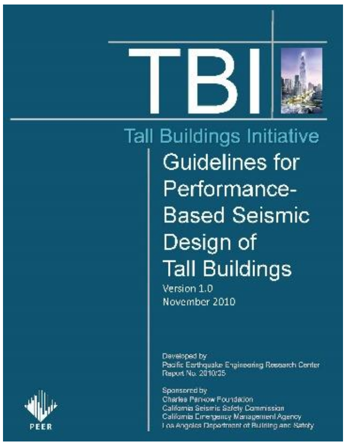


Figure 6. Guidelines for performance-based seismic design of tall buildings by Tall Building Initiative.

In the United states, the Tall Buildings Initiative (TBI) has developed the guidelines of Seismic PBD and recommended them as an alternative to the conventional seismic design procedures for tall buildings.

2.3 PBD for Foundations

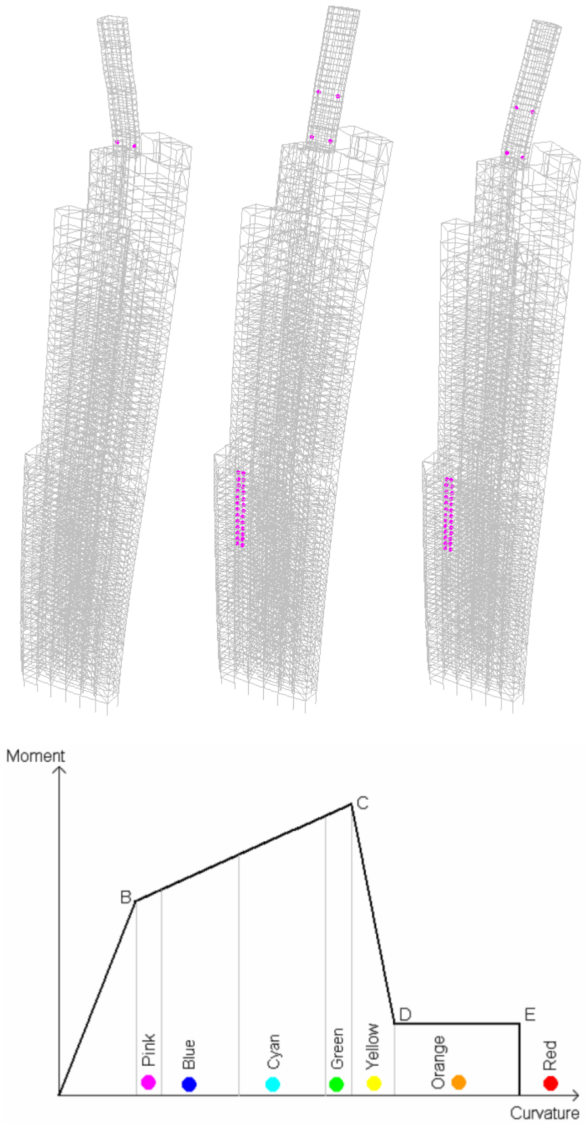
When constructed the Pertamina Energy Tower (PET) will be the tallest building in Indonesia. The tower is located in Jakarata, a city situated in a river delta, is founded on sand and clay deposits that were found to extend at least 300m below the surface. This challenging location, combined with a high seismic load required the implementation of a deep foundation composed of a thick concrete mat supported on bored reinforced concrete piles. In order to limit the extent of the foundation, the design team approached the challenge from two sides. First numerous efforts were undertaken to reduce the weight of the building, therefor reducing the seismic and gravity demand on the foundation. Secondly an extensive test pile program was implemented with the goal of obtaining the most realistic data on the characteristics and behavior of the subsurface conditions. Thanks to PBD, the pile length has been reduced from 130 m to 100 m after the pile load test. Conventional pile construction in Indonesia has a typical limit of 100m depth. Every meter of the pile after 100 m costs 4 times that in the first 100m. Thus using PBD can cut the pile construction cost by as much as a half.This significant reduction in the depth of the piles leads to a corresponding savings in cost and embodied energy of the foundation system.

Figure 7. Pile load test of Burj Khallifa.

2.4 PBD in Chinese Project

In China PBD is also broadly used in super tall buildings. The Nanjing State-Owned Assets & Greenland Financial Center's Main Tower (Zifeng Tower) is a 450-meter tall mixed-use tower (see Figure 8). In order to obtain seismic approval from the national panel of experts, several analyses and design approaches beyond the Chinese Code were required. These included elastic design of all members for a 500-year earthquake and elastic design of some key elements for a 2500-year earthquake. Finally the elasto-plastic analyses were performed to verify the structure's behavior under the 2500-year earthquake (see Figure 9). This cumulative seismic design effort has resulted in one of the tallest structures in the world to date and represents the state-of-the-art in performance-based evaluation [2]. Shenzhen Shum-Yip Upper Hills, a mixed use development located in Shenzhen, People's Republic of China (see Figures14-17), is another example using PBD to optimize a super tall tower's seismic performance.

Figure 8. Zifeng Tower.



B –Nominal Moment C –Ultimate Moment
D –Residual Moment E –Collapse

Figure 9. Frames for various stages of the non-linear time history analysis of Zifeng Tower.

2.5 Optimal Design

Very often large transportation infrastructure hubs occupy large tracts of land in the heart of urban centers which otherwise would be very desirable for development. Building departments of cities worldwide are allowing construction using the air-rights above transportation infrastructure to maximize appropriate use of valuable real estate. This results in the design of complex structures with unique and challenging interface with foundation systems. Manhattan West North Tower is such an example that represents innovative structural solution as a response to open environment (see Figures 10-11).

Optimal Design with economical solution and easy to build structural system becomes the most appropriate medium to bridge the gap between project aspirations and budgetary constraints. In an increasingly competitive market, developers worldwide have also initiated marketing that hinges on creating 'first of kind', 'tallest', 'grandest', 'superior spatial experience', 'column-free spans'. These promises translate into demand for heroic structures that push the boundary of conventional systems and in most cases without a premium to the project budget. Burj Khallifa's highest scheme is made possible due to the optimal use of concrete (see Figures 1-3); Cayan Tower's "first of kind" innovative twisting scheme is achieved by stepped column option with walking column to column (see Figures 11 and 12); Korea's Lotte Super Tower's geometry is used to create an optimal load path for structure with optimum angle (see Figures 13-14). Shenzhen Shum-Yip Upperhill Tower One has achieved superior spatial experience and column-free spans by using optimal ladder-core system (see Figures 15-18). In Shum-Yip Upperhill Tower One, the optimal use of concrete results in minimum tension in the mega columns (see Figure 16 for gravity load path) [3]. In Manhattan West North Tower, detailed analysis of steel structures with Strand7 optimizes materials only where they are needed (see Figure 19. (b)) [4]. In order to make design more constructible, TEKLA is used for material and process optimization (see Figures 20 and 21).

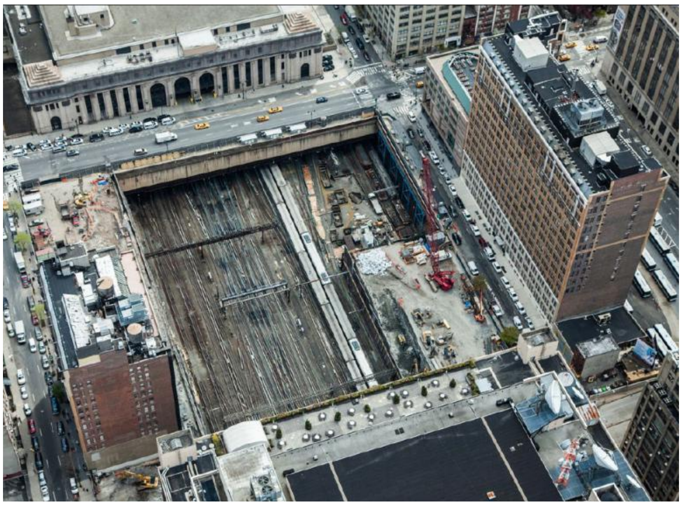


Figure 10. Site of the Manhattan West project over the 100 year old train tracks leading to Penn Station in Midtown Manhattan.

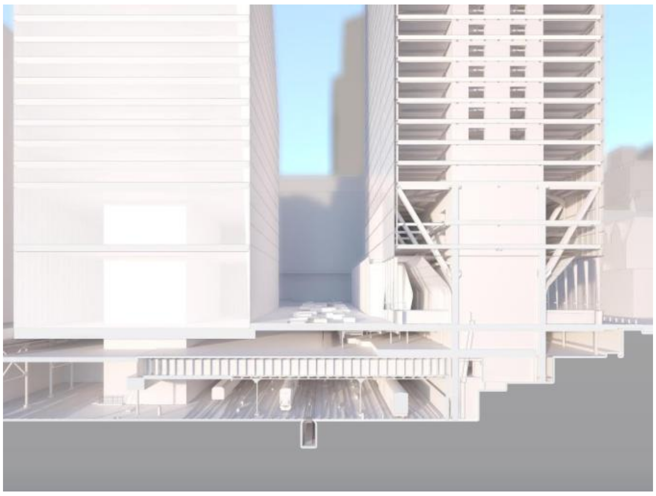


Figure 11. Section showing to Manhattan West towers situated over busy train infrastructure.

Figure 12. Walking column detail of Cayan Tower.

Figure 11. Construction photo of Cayan Tower.

Figure 13. Rendering of 555m Lotte Super Tower.

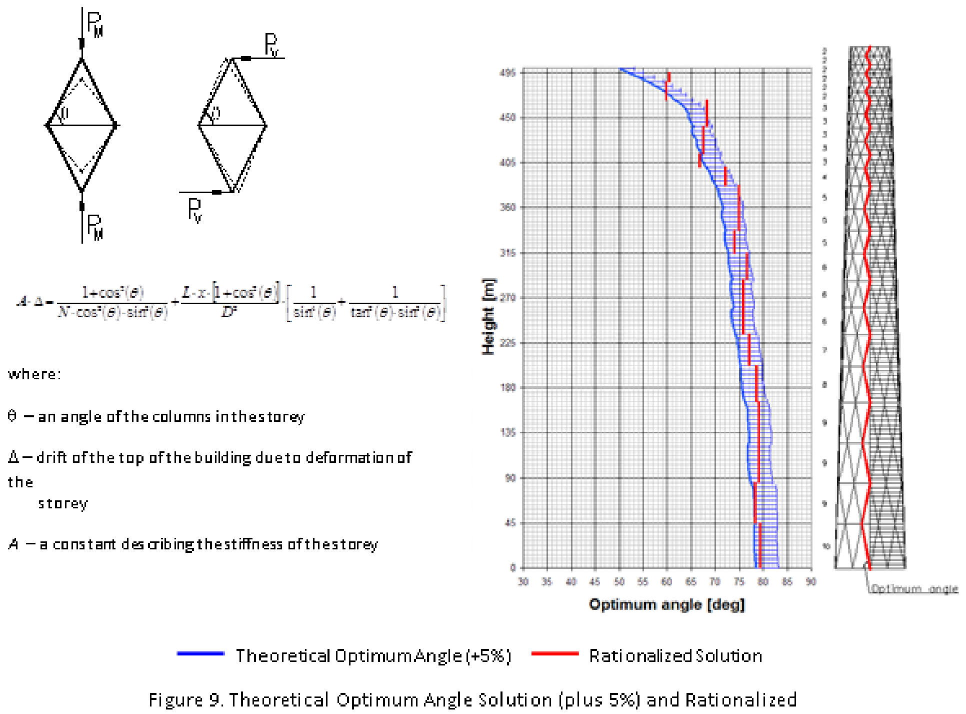


Figure 14. Optimum angle study of Lotte Super Tower.

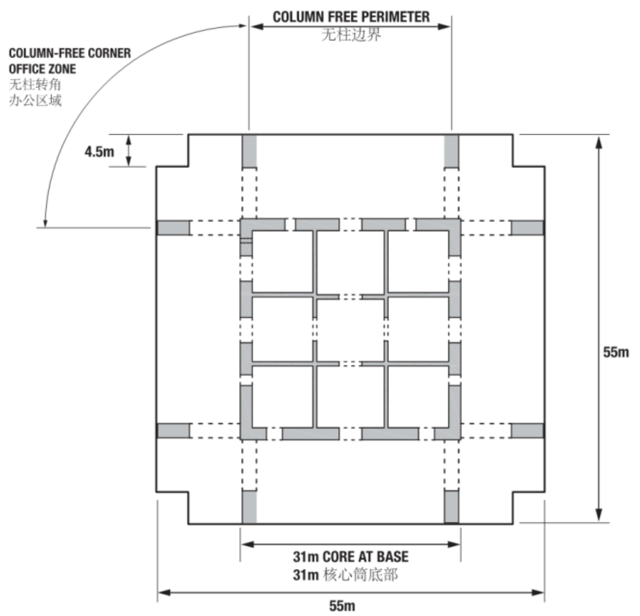


Figure 15. Shum-Yip Upper Hill mega column and core layout

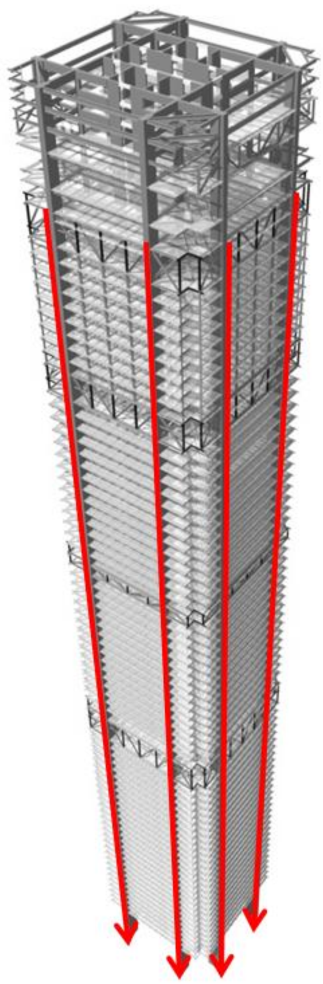
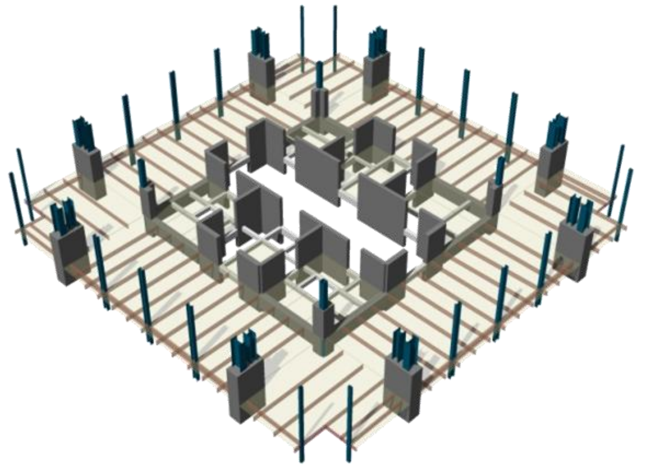
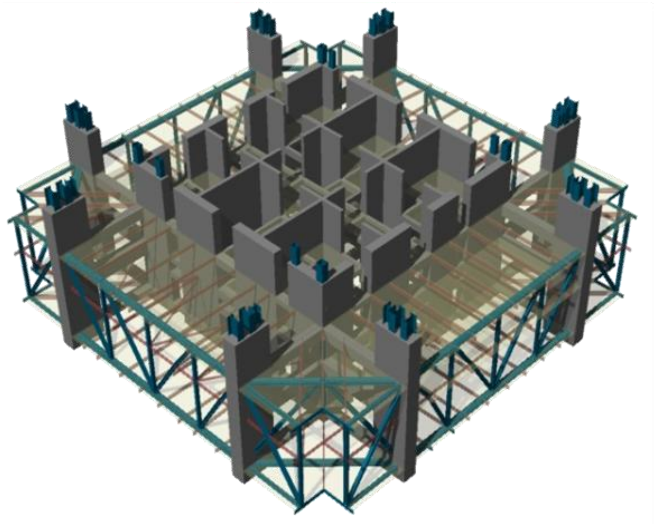


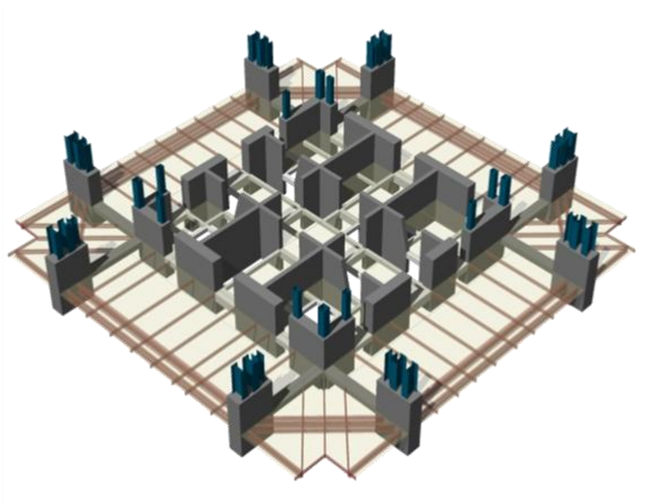
Figure 16. Shum-Yip Upper Hill Tower One gravity load path



(a)



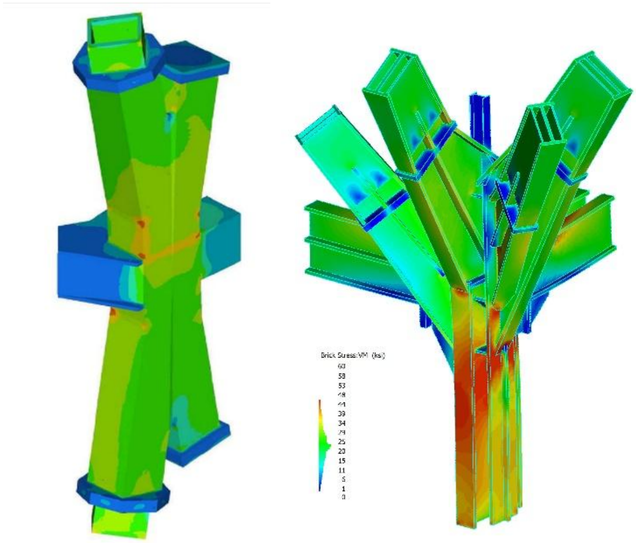
(b)



(c)

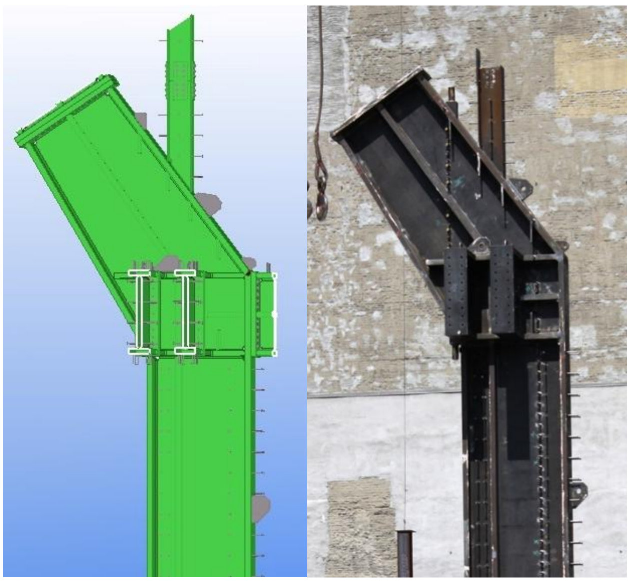
Figure 17. Three-Dimensional view of Shum-Yip Upper Hill typical floors: (a)hotel guest level (b) mechanical level (c) Office level.

Figure 18. Shum-Yip Upper Hill Construction Photo

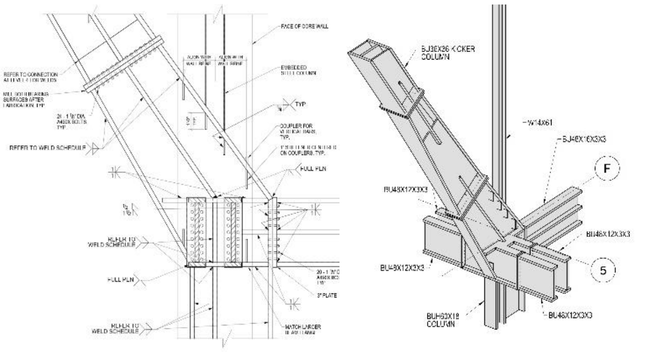


(a) (b)

Figure 19. Three-Dimensional Analysis of Structural Steel Node.



(a) (b)



(c)

Figure 20. Digital Modeling: (a) Complex steel node in Tekla, (b) Node erected on Site, (c) Node documentation in drawings.

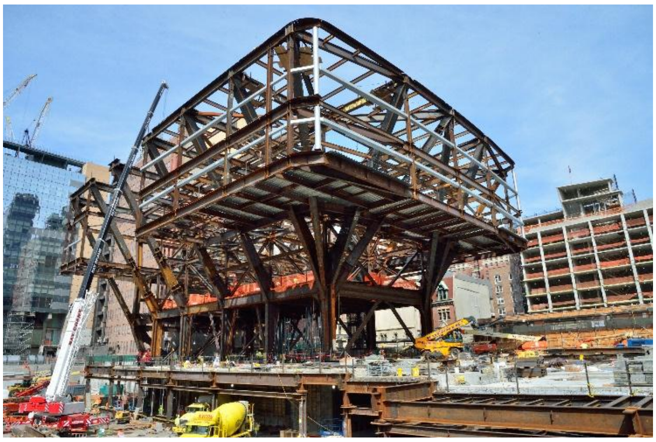


Figure 21. Manhattan West North Tower Construction Photo

3. CONCLUSIONS

Performance Based Design is broadly used for seismic design, wind design and foundation designs of super tall buildings around the world. Besides the tangible economic benefits, the design and construction profession today actively pursues the creation of optimal structures with efficient use of materials and a reduction of carbon footprint as an ethical standard for construction in the 21st century. Hence optimal design should not only be a toolkit applied in an optimal design, but also more of toolkit that should be mandatory for design of super tall buildings.

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IMAGE SOURCE

Figure 6. Pacific Earthquake Engineering Research Center
Figure 11. http://www.architectmagazine.com/

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