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Economical & Efficient Structural Solutions
经济高效的结构解决方案

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With the completion of the Ping An Finance Center (PAFC) in 2016, one of the tallest towers in China and the world will be unveiled. As more and more tall buildings exceeding 500 meters are designed, we are entering a new age of megatall buildings and embracing a new level of design challenges. This era presents the question of whether traditional structural systems and design approaches are still applicable, or whether new design tools can improve the performance and sustainability of these structures. This chapter will touch on building shape optimization and how a refined and comprehensive structural analysis leads to a more sustainable building.

平安国际金融中心 (PAFC) 在2015年建成后，将成为中国乃至世界最高塔楼之一。在这个超过500米高层建筑不断涌现的年代，我们进入了超高层建筑发展的新时代，同时也面临着新一轮设计上的挑战: 我们所熟知的传统的结构体系和设计方法是否仍然适用，还是需要开发新的设计工具去保证结构的性能和可持续性? 这篇文章将涉及到建筑形态优化，并探讨如何通过精细全面的结构分析从而设计出更有可持续发展性的建筑。

Structural System

PAFC's structural system consists of a reinforced composite concrete core with steel outriggers connecting to eight composite super-columns at four levels.

The exterior frame is composed of seven double-layer belt trusses located at the mechanical and refuge floors as shown in Figure 3.1 , Figure 3.2, and Figure 3.3. The exterior belt trusses are connected to a super-diagonal at each exterior face of the building (Figure 3.2).

Core wall thicknesses range from 1500 mm at the base to 400 mm at the top. Supercolumn plan dimensions range from 6.0 meters by 3.2 meters at the base to 2.9 meters by 1.4 meters at the top. The main lateral-force resisting system is designed for a 100-year return period wind (strength limit state) and 50-year return period wind (serviceability limit state) based on wind loads determined by wind tunnel testing.

The Importance of Wind Optimization for the PAFC

Shenzhen is located close to the South China Sea; a building of 660 meters will be exposed to typhoon wind speeds of up to 60m/s or more. This emphasizes how important it is to refine the massing to reduce the wind impact on the structure. With the support of RWDI's wind tunnel, studies were conducted to investigate various exterior shapes of the tower. Small adjustments such as chamfered corners and recesses in the façade contributed to a reduction in the wind load. These alterations to the exterior façade positively reduced the effect of cross winds relating to the horizontal movement perceived by humans.

A final comparison of the various exterior tower studies was not made, however, a 32% reduction in overturning moment and 35% reduction in wind load compared to China code were achieved due to the optimization of the tower shape.

A building enhanced for wind usually exhibits improved seismic behavior as well since core walls and column sizes can be smaller, and the number of outriggers and their size are smaller. All of these points contribute favorably to a reduced overall mass of the structure which

结构体系

所选结构体系包括钢混组合核心筒和从四层竖起的八根组合巨柱，并用钢伸臂桁架把二者联系起来。

如图3.1，图3.2，图3.3所示， 外部框架由位于机电层和避难层的七个双层带状桁架组成。外围的带状桁架在建筑的每个外表面由大型斜杆相连 (见图3.2) 。

核心筒墙的厚度从底部1500毫米递减到顶部400毫米。巨柱的平面尺寸从底部的6米X 3.2米递减到顶部的2.9米x1.4米。主要抗侧力系统的设计依据的是由风洞实验得到的100年一遇的风荷载 (强度极限状态) 和50年一遇的风荷载 (正常使用极限状态) 。

PAFC风优化的重要性

深圳靠近中国南海，660米的建筑将暴露在风速超过60米每秒的台风下，这更突显出优化结构从而降低风对其影响的重要性。在RWDI风洞实验室的帮助下，不同的建筑外形方案被研究。一些小的调整例如改变建筑拐角处的倒角和幕墙上的凹陷等都有助于减少风荷载。这些幕墙系统的方案大大减小了横风造成的能被人感知的结构横向位移。

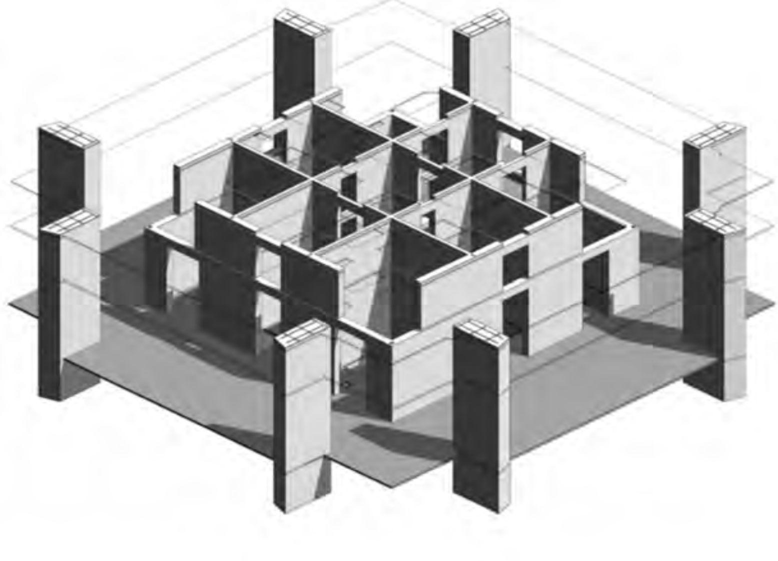


Figure 3.1. 3D view of a floor.
Figure 3.1. 楼板3D视图

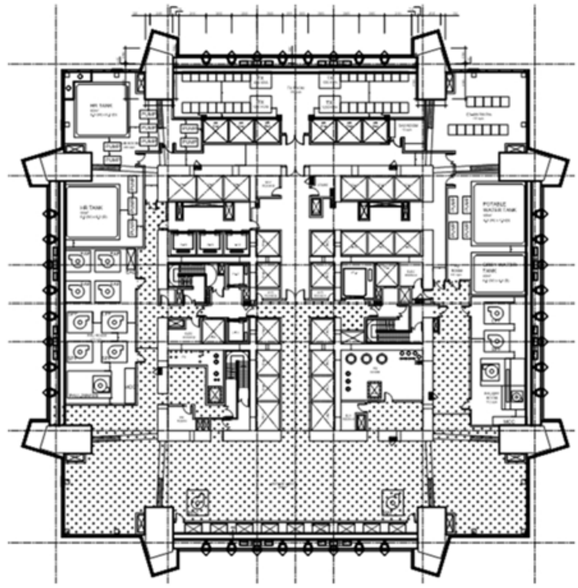


Figure 3.2. Plan view of a mechanical floor. (Source: KPF)
Figure 3.2. 机电层平面图 (KPF提供)

determines, in combination with the ground acceleration, the seismic load.

Shenzhen is located in a medium seismic zone, with a return period of 50 years and 10% probability the peak ground motion of 0.1g falls into the design category 7 per China seismic code classification. The numbers in Table 3.1 show that wind and seismic parameters were controlling the building design for different design requirements.

The Importance of Lateral Structural Optimization for PAFC

Various structural solutions were developed by Thornton Tomasetti. Examples include a Vierendeel truss scheme, to express the architectural vertical rising façade lines, as well as various hybrid solutions. Each scheme was evaluated by comparing it to material sustainability and availability, construction budget, and construction schedule.

The final lateral load resisting system chosen was a composite concrete, which is connected to the supercolumns by two-story outriggers located on Levels 25, 48, 79 and 95. Seven double belt trusses were added to serve a double role. The first

最终的结构外形方案还没有决定。但是相比于中国规范，现阶段结构形状优化已经实现了32%倾覆力矩和35%风荷载的缩减。

结构抗风性能提升通常也会带来结构抗震性能的提升，这是因为核心筒墙壁和柱子尺寸都会减小，伸臂桁架的尺寸和数量也会减少。这些变化都有助于减少结构的总质量，进而减少由重力加速度共同决定的地震荷载。

依据中国地震规范分级，深圳位于中型地震区，回归期是50年，并且在0.1g的加速度下有10%的概率,地表运动峰值会落到7级抗震设防烈度内。表3.1中的数据显示风和地震荷载控制建筑的不同设计需求。

PAFC侧向结构优化的重要性

Thornton Tomasetti提供了不同的结构设计方案。比如用来表达建筑方面竖直上升的幕墙线条的空腹桁架方案，以及其他几种混合方案。每种方案都通过比较材料的可持续性和实用性、施工预算和施工进度进而作出评估。

最终的抗侧力体系选择的是组合混凝土结构，并且用双层伸臂桁架在25，48，79，95层与巨柱相连。增加七个双层带状桁架来主要提供两个主要功能，第一个功能是模拟伸臂桁架来提供侧向刚度，第二个功能是通过传递每个区的重力荷载来保证巨柱处于受压状态。为缩小核心筒的墙厚，宽翼缘钢柱被嵌入墙内最高应力的边界区域，这些柱子有以下两个作用，一是加固核心筒，二是为伸臂桁架的荷载传递到墙内提供清晰传力路径。由于核心筒墙是主要承载重力荷载和抵抗侧向荷载构件，为了防止其在高剪切应力和轴向应力共同作用下出现脆性剪切破坏，核心筒墙从基础到12层加入内埋钢板， 来提升结构延性并进一步减小墙的厚度。

为了减小外侧墙的重量，第六区域以上的核心筒从9个32mX32m的单元格中去除外围4个单元格的面积，减小到5个单元格 (见图3.3) 。这样可以增加塔楼上层区域更有价值的外围办公区域的面积。这是当下超高层建筑设计方案的普遍做法。

然而，所形成的独特的内缩角为在带状桁架中的两个角柱间引入V型撑系统提供了很好的机会，从而很可观的提升了外围框架的刚度。这样Thornton Tomasetti可以大大地减少伸臂桁架和带状桁架上的钢材，并且简化这些构件与核心筒墙和巨柱间的连接。

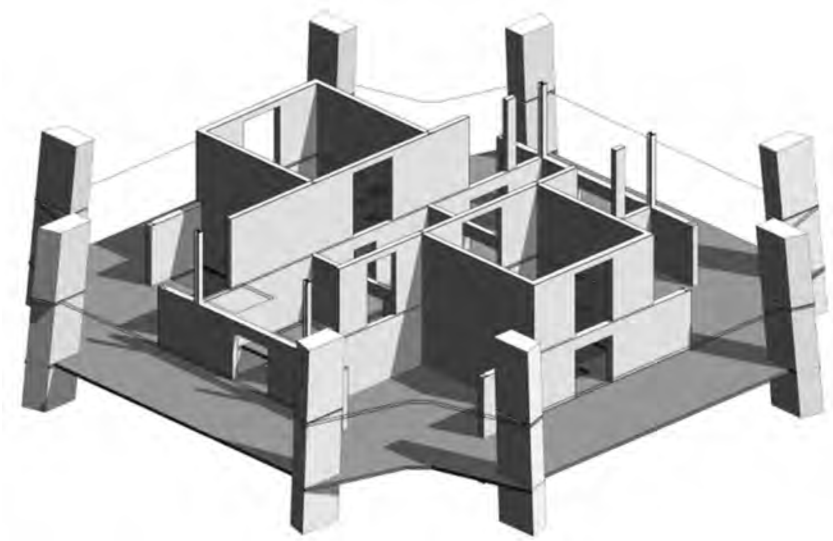


Figure 3.3. 3D View of floor above Zone 6.
Figure 3.3. 6区以上3D视图

function is to act as "virtual outriggers," contributing to the lateral stiffness of the structure. The second is to ensure that the supercolumns stay under compression by transferring the gravity load at each zone. To keep the core wall thickness to a minimum, wide flange steel column shapes were embedded within the boundary zones, which are the most highly stressed areas of the walls. These columns serve two purposes. They strengthen the core and they provide a cleaner load path for the outrigger forces into the wall. Due to the fact that core walls play a critical role in resisting most of the gravity load and lateral load, and to eliminate any concern about brittle shear failure when subject to a combination of high shear stress and axial stress, embedded steel plates were used to reinforce the walls from foundation to level 12. These plates both enhance ductility and permit a reduced wall thickness.

In addition to reducing the weight of the exterior walls, the nine-cell, 32 meter by 32 meter square core was reduced to a five-cell core above zone six by eliminating the exterior four corner cells (Figure 3.3). This wall reduction increased the valuable office floor space at the upper zones. This is a common solution in the design of megatall buildings today.

However, distinctive cut-back corners provided a unique opportunity to introduce a chevron brace system, which connects the two corner columns between the belt trusses, increasing the exterior frame stiffness of the tower perceptibly. As a result, the engineers were able to deplete the steel material on the outriggers and belt trusses considerably and was able to simplify connections to the core wall and supercolumns.

新的抗震设计规范在2010年被引入，相应的设计也应当作出调整。其中一条是: 外围框架不仅要如国际规范中规定的那样承载20%总的地震力，并且每层按刚度也要抵抗至少6%的底部剪力。提供第二个内层带状桁架 (双层带状桁架) 和一个链接各个内层带状桁架的外部大型斜撑可以很有效的实现这些要求。这些改变可以平滑无缝的利用到建筑和结构设计中，从而提高外围框架的容错冗余量和刚度。

典型的楼板骨架是传统的组合钢梁再加上浇注于金属板上的125毫米厚混凝土板。只有在机电层和避难层是特殊的水平钢隔板将伸臂桁架和带状桁架连接到核心筒，防止混凝土隔板在剧烈的地震作用下开裂。

考虑到这座建筑的重要性和体量，更加复杂的分析方法被采用来理解结构的抗震性能。在中高地震区域内，基于性能的设计

Base Reaction of PAFC 平安国际金融中心 基座反应				
Load direction 荷载方向			X	Y
Seismic 地震	Frequent 频繁	Base Shear(kN) 基座剪力	68,919	70,213
		Base Moment(kN-m) 基座弯矩	19,862,018	19,844,231
	Medium 中度	Base Shear(kN) 基座剪力	189,451	192,914
		Base Moment(kN-m) 基座弯矩	55,499,627	55,447,930
	Rare 罕见	Base Shear(kN) 基座剪力	348,928	351,195
		Base Moment(kN-m) 基座弯矩	104,134,022	104,070,056
100 year design wind 100年 设计风强		Base Shear(kN) 基座剪力	98,641	98,957
		Base Moment(kN-m) 基座弯矩	36,978,739	36,797,355

Table 3.1. Link beam performance.
表3.1.耗能梁段的性能

New seismic design requirements were introduced in 2010 and needed to be incorporated into the design. One of them was that the exterior frame must not only be designed to take 20% of the total seismic load, as usually required by international standards, but it had to resist 6% of the total base shear at every floor based on its stiffness as well. A very efficient way to do that was to provide a second inner layer of belt truss (double belt truss) and an exterior superdiagonal that was connected with all belt trusses. These changes were seamlessly incorporated into the architectural and structural design to achieve additional redundancy and a higher stiffness contribution of the exterior frame system.

The typical floor framing is a traditional composite steel beam design with a 125 mm-thick concrete slab on metal deck. Only at the mechanical and refuge floors was a special horizontal steel diaphragm introduced to tie the outrigger and belt trusses back to the core, in case the concrete slab diaphragm experienced cracks under severe earthquake conditions.

Considering the importance and scale of this building, more sophisticated analysis approach was performed to understand the seismic behavior. Performance based design (PBD) becomes more and more important and common in the design of supertall buildings in medium and high seismic zones. It gives the designer a better understanding of how the building behaves non-linearly during unique seismic events. The results are then compared to different performance levels (immediate occupancy (IO), life safety (LS) and collapse prevention (CP), which are based on the ASCE 41-06.

The PAFC was evaluated for a rare earthquake, defined as a quake that occurs every 2,475 years, by using two synthetic (man-made) and five recorded ground motions. These time-history curves were then applied to a very complex 3D computer simulation, which took into consideration the non-linearity performance of material.

Figure 3.4 shows how the performance of important structural elements was evaluated for the PAFC on the basis of the link beam. As can be seen, only 2% of link beams exceed the life-safety performance level for one of the sets of ground motions (US787), while all other link beams perform within the life safety performance level or better.

PBD成为越来越重要和普遍的超高层设计分析方法，它使设计者更好的理解结构在特殊地震作用下的非线性响应，PBD的结果之后再根据ASCE 41-06与不同的性能水平 (直接占用 (IO)，生命安全 (LS)，防倒塌 (CP)) 相比较.

PAFC还需对在2475年一遇的地震下的结构反应作出评估，使用的是两条人工合成的和五条现实记录的地震波。这些时程曲线之后被应用于一种考虑材料非线性性能的复杂3D计算机模型中。

图3.4以耗能梁段为基础，展示了重要结构部件的性能是如何被评估的。只有2%的耗能梁段在一组地震波 (US787) 下超过了生命安全性能水平，其他耗能梁段均在生命安全性能水平以内或者更好。

PBD的分析结果给设计团队提供了非常有用的结构性能信息，从而可以保证在达到需要的安全等级的同时保持建筑设计的经济性。

获得的信息之后可以被用来设计很多复杂的钢结构连接件。国际规范和中国规范对常遇地震下的结构强度设计都有着硬性的要求。但是对于中震和罕遇地震，还需要用有限元模型来进行连接设计。

下图是用来展示巨柱，伸臂桁架，双层带状桁架 (一个在内一个在外)，和两个巨型

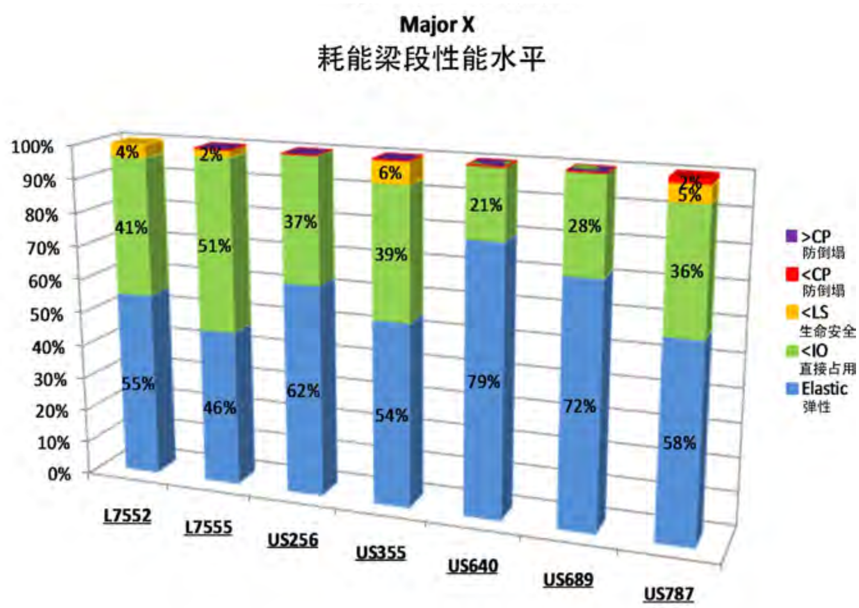


Figure 3.4. Link beam performance level
Figure 3.4. 耗能梁段性能水平

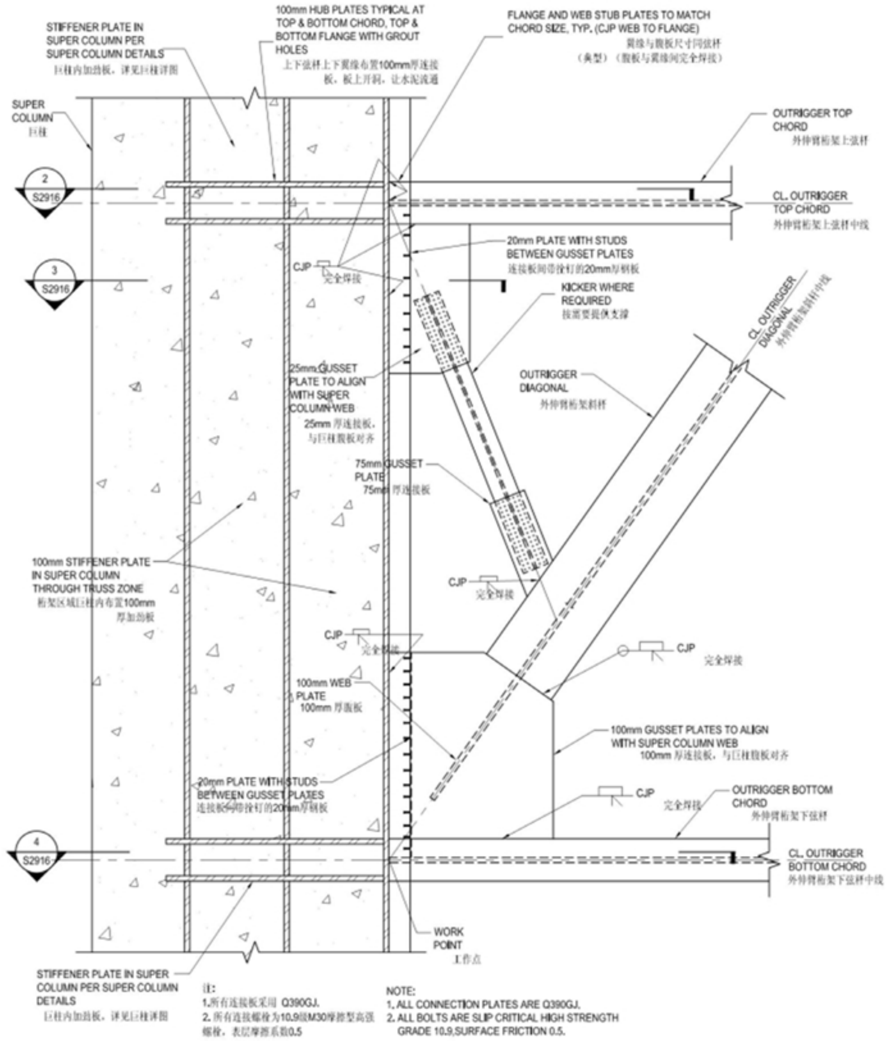


Figure 3.5. Connection of super column and outrigger
Figure 3.5. 巨柱和伸臂桁架的连接

The analytical results of the PBD provided the design team with very useful information on building performance ensuring the desired level of safety while maintaining an economical building design.

The information obtained was then used to design many of the complicated steel connections. International and China building codes have rigid requirements related to strength design for the frequent seismic level. However, to evaluate medium or rare seismic events, a finite element analysis (FEA) was used to perform the connection design.

The following is an example of how a connection of a super-composite column (SC), an outrigger truss (RT), a double-belt truss (DBT) (one interior truss and one exterior truss), and two diagonal megabraces (MB) were modeled and analyzed. Design details of the connection are shown in Figure 3.5 & Figure 3.6.

In addition to the detailing information shown in Figure 3.6, it was assumed that welds and bolts would not fail before connection elements, so they were not specifically modeled. This assumption is consistent with the traditional design philosophy where welds and bolts have capacities at least equal to the capacities of the members connected. The corresponding finite element model (FEM) is shown in Figure 3.7 and Figure 3.8. The model also conservatively ignores any contribution of typical reinforcing bars, since many of them are potentially subject to being interrupted at the joint by steel connection plates. All load combinations gravity, wind and

斜撑间的连接构件是如何建模和分析的。连接设计详图如图3.5、图3.6所示。

除了在图3.6中的详细信息以外，焊接和螺栓被假定为不会在连接件破坏前被破坏，所以它们没有被特别建模出来。这样的假定与传统设计理论 (焊接和螺栓的承载力至少与连接构件相同) 相符。相应的有限元模型 (FEM) 如图3.7，3.8所示。 这个模型也保守的忽略所有钢筋的影响，因为这些钢筋大多数在节点处被连接钢板打断。包括重力，风荷载，地震荷载的所有荷载组合都在分析中被考虑。连接模型之间的内力则从基于时程分析和中国规范反应谱分析的塔楼模型中提取出来。

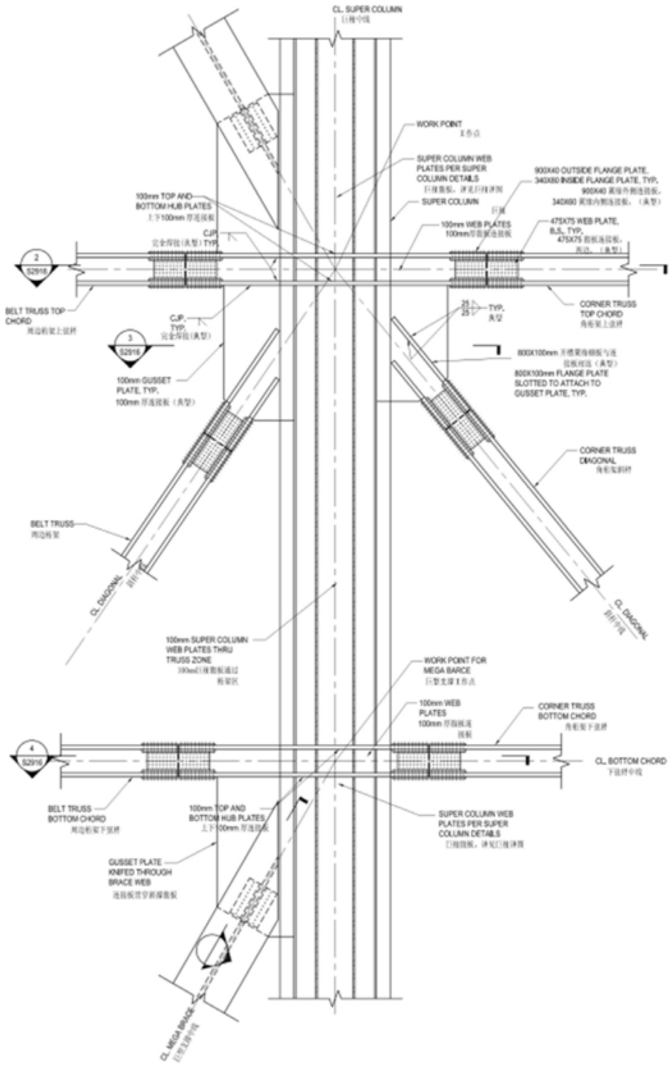


Figure 3.6. Connection of super column, belt truss and super diagonal
Figure 3.6. 巨柱，带状桁架和大型斜撑的连接

seismic loads are considered in the analyses. Member forces applied to the connection model were extracted from the tower study based on both time-history analyses and China code spectrum analyses.

The Importance of Sustainability

Usually the construction, structure, and the envelope of a building consume more than 50% of the overall Embodied Energy (EE) Figure 3.9. EE played an important role in the tower design, and is defined as the total primary energy consumed from direct and indirect processes associated with a product or service and with the boundaries of cradle-to-grave.

The very comprehensive structural analysis and optimization of the PAFC led to a substantial increase in efficiency of the structure, which is again reflected in the reduction of the EE.

On the material side of energy savings, the following items were implemented in the structural design, allowing for significant savings in steel and concrete.

1. A reduction in wind load led to smaller structural sizes, which in turn reduced the seismic forces.
2. The use of an outrigger system to engage the entire footprint of the building (to increase lateral stiffness by creating a larger lever arm to resist the overturning moment) reduced the concrete core wall sizes.

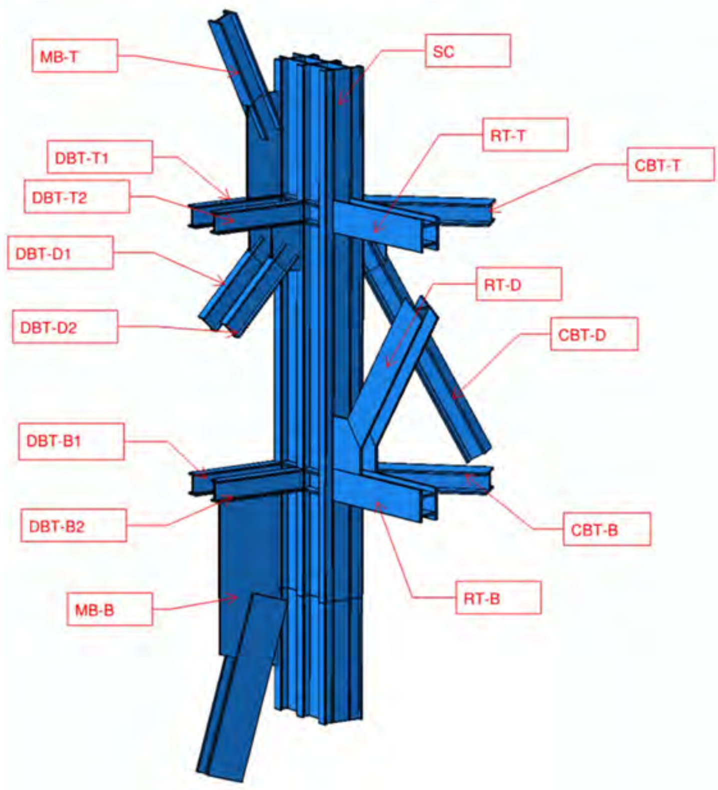
PAFC可持续性的重要性

通常而言，施工，结构，以及建筑围护结构占用了超过50%的建筑固化能耗 (Embodied Energy) ,如图3.9所示。固化能耗 在Thornton Tomasetti的设计中占据了重要的地位，其被定义为产品或服务全生命周期内所有间接和直接的流程所消耗的一次能源总量。

PAFC上全面的结构分析和优化可以大大改进结构的使用效率，从而也在建筑固化能耗 (EE) 的减少上反映了出来。

从材料的角度来说，为了节省能源，以下几条被应用于结构设计中，从而显著地减少了钢材和混凝土的用量:

1. 风荷载的减少使得结构体量减小，从而也减小了地震荷载
2. 整个建筑的设计都融入了伸臂桁



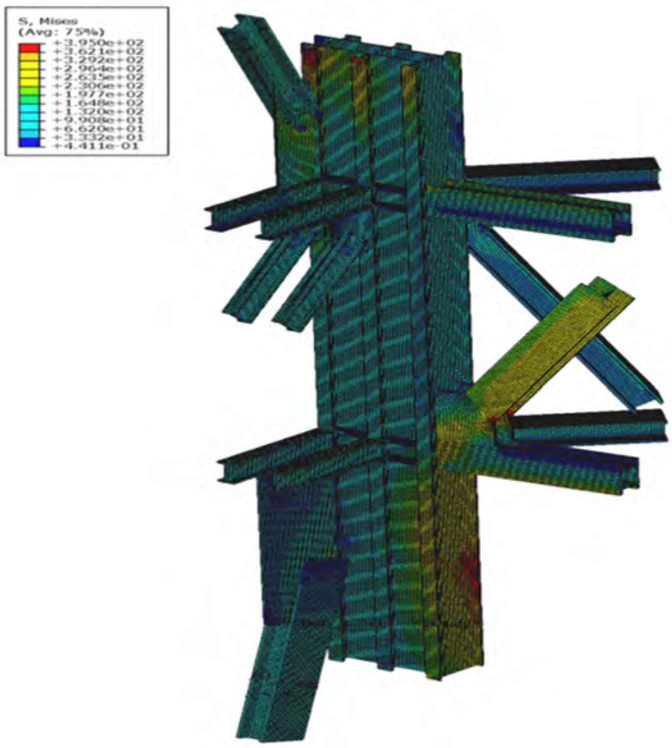


Figure 3.7. Finite element model of connection
Figure 3.7. 连接构件的有限元模型

Figure 3.8. Right: Stress contour of connection under severe seismic
Figure 3.8. 右侧: 连接构件在大震下应力图

3. The use of recycled material, such as concrete and steel, was specified in the project documents.
4. Cement substitutes such as fly ash and granulated blast furnace slag was recommended.
5. Mainly local materials were used to reduce manufacturing and transportation energy costs.

In addition to the construction items mentioned above, the long-term sustainability of the building was taken into consideration as well.

1. A center-core option was chosen to maximize the daylight exposure, and main structural components have been located on levels with low occupancy.
2. The use of a recycled-water cooling tower bleeds off grey water, which reduces potable water use by 30%, but required the structural design to provide additional openings in floors and structural walls, which needed to be coordinated closely within the design team from the beginning of the design.
3. To achieve natural ventilation by taking in cooler, drier air from a higher altitude, special attention needed to be paid to the design of the supercolumns.
4. The use of an Ice storage system in the basement levels provided a savings of 4% of the total annual energy consumption. The structural design was adjusted to provide support for multiple heavy ice tanks in these areas.
5. The structural integration of mechanical openings and shafts for lighting control in areas that cannot use natural daylight saves about 4% of the annual energy consumption.
6. The roofs of the podium have been structurally designed to incorporate special rainwater collectors to reduce the consumption and operation of the green roofs. That led to 100% water savings during the summer irrigation needs.

The items listed above will contribute to PAFC's pending LEED certification.

架的设计理念 (通过构建大的杠杆臂来抵抗倾覆力矩，从而增加侧向刚度)，这样就减小了混凝土核心筒墙的尺寸。

3. 例如混凝土和钢材等可回收材料的使用都在项目文件里详细规定
4. 建议使用如粉煤灰和粒化高炉矿渣等水泥替代品
5. 主要采用当地的建筑材料，从而减少制造和运输上的能量损耗

除了上面提到的施工方面的条款，建筑的长期可持续性也被列入考虑范围。

1. 采用核心筒的结构形式来使得日照最大化，并且主要的结构组件位于占用率低的楼层
2. 使用循环冷却塔来放水可以减少30%的用水量，但这需要结构设计在楼板和承重墙上提供额外的预留孔，并且需要和整个设计团队在设计初期就紧密合作。
3. 为了能从高处吸入干冷空气从而实现自然通风，在设计巨柱时需要特别注意。
4. 在地下室的冰蓄冷系统可以使全年能耗减少4%。结构设计也相应地调整使得这些楼层可以承载多个重型蓄冰池。

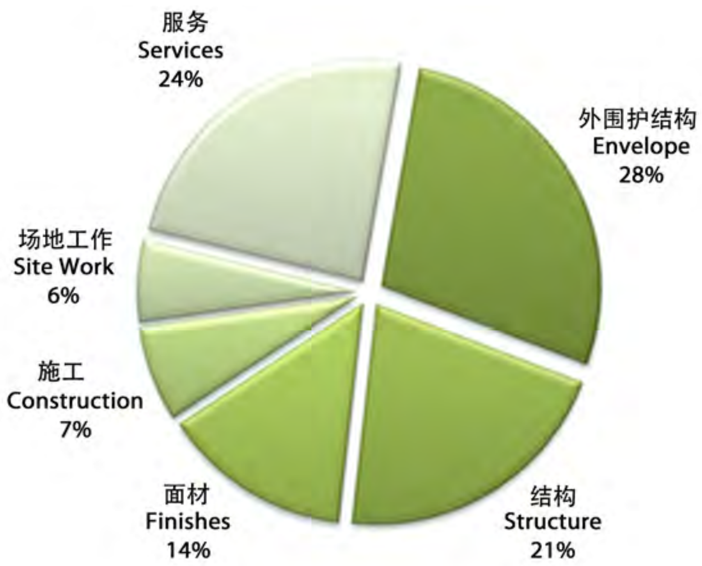


Figure 3.9. Embodied Energy Chart of a typical high-rise by Cole & Kernan 1996
Figure 3.9. 固化能耗 (EE) 图 (Cole & Kernan 1996)

5. 对于不能利用天然日光的区域，把机电开口和照明控制井洞进行合理的结构整合，从而节省大约4%的全年能耗。
6. 裙房屋顶的结构设计与特殊的雨水收集器相协调，从而减少绿色屋顶的能耗和运营。这样也节省了100%的夏季灌溉用水。

以上列出的条款都有助于PAFC的LEED 认证。

Conclusion

In the relentless pursuit to improve architectural form and structure, the design team used new, advanced analysis tools, enabling them to improve and achieve a new level of precision in design.

By enhancing the form and aerodynamic properties of the PAFC tower, the engineers were able to achieve a more efficient structural system, which reduced the overall material without comprising the structural integrity of the edifice. These efforts made a big contribution towards a smaller carbon footprint for a greener world.

Therefore it can be noted that:

- By architecturally adjusting the massing of the building with the support of wind tunnel tests, structural loading can be reduced considerably when compared to code design loads.
- With the help of more advanced analysis tools, structural elements can be further optimized to reduce weight and material.
- Repetition, cleaner forms and reduction in complexity, in combination with using less material and designing shorter construction times, will lead to less embodied energy consumption.

结论

为了严格地追求建筑形式和结构的改进提升，设计团队使用了先进的分析工具，从而使设计精度达到了一个新的高度。

通过提升PAFC塔楼的结构形式和空气动力特性， Thornton Tomasetti 在不牺牲大楼结构完整性的情况下使用更少材料的设计出了更高效的结构体系。这些努力，为实现低炭的绿色世界作出了巨大的贡献。

因此要点总结如下:

- 在风洞实验室的帮助下，通过调整建筑体量可以大大减少建筑荷载。
- 通过使用更先进的分析工具，结构组建可以进一步优化以减少其重量和材料用量。
- 结构的复杂性被降低，取而代之的是更简洁的且可被重复使用的结构形式。同时，建筑材料的用量减少，施工时间也会缩短。这些都会使结构的固化能耗进一步降低 (EE) 。

References (参考书目):

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