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Belt Truss Stiffness Analysis and Optimization
环带桁架刚度性能分析与优化

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Megastructures have come into widespread use in supertall buildings in recent decades, due to their high efficiency in satisfying diversified building performance requirements. Belt trusses are one of the key structural members of megastructures. Belt trusses have two functions in megastructures. One function is to act as the transferring members for all the secondary floor systems, and the other function is to engage all the perimeter columns in resistance to lateral loads. The performance of the belt truss depends greatly on its stiffness. Thus the belt truss stiffness has to be carefully calibrated for better megastructural performance.

There are four belt-truss types in engineering practice, namely, ordinary single truss, L-type single truss, U-type single truss and double truss. The stiffness analysis and design criteria of the belt trusses are discussed first, then discussed in the case of the Suzhou Zhongnan Center to illustrate the stiffness analysis and optimization of the belt truss in a real project. Bending stiffness analysis, torsion stiffness analysis, internal force analysis and eccentricity analysis were conducted, and the optimization suggestions were obtained for the analysis and design of the four kinds of belt trusses.

近几十年来，巨型结构由于对满足结构各方面性能要求十分高效，在超高层结构中已得到了广泛的应用。而环带桁架是巨型结构的关键结构构件之一，在巨型结构中，环带桁架主要有两种功能，一是作为楼板体系的转换构件，二是连接所有的巨柱形成抗侧力体系共同抵抗外荷载。环带桁架的性能很大程度上取决于其提供的刚度大小，因此，环带桁架的刚度设计需要深入的研究以在巨型结构中获得更好的性能表现。在工程实际中常用的四种环带桁架类型为: 单层环带桁架、L形环带桁架、U形环带桁架及双层环带桁架。本节首先对环带桁架的刚度分析及设计准则进行了讨论。以729m高的苏州中南中心为案例，文章具体阐述了环带桁架的刚度分析和优化的过程。针对案例进行了抗弯刚度分析、扭转刚度分析、环带桁架上下弦杆内力分布均匀性分析及环带桁架布置偏心分析的全面考虑，从而得出了关于四种环带桁架类型分析和设计的优化建议。

Introduction

Megastructures originated with the development of the girder transfer floor in the late 1960s. Megasystems consist of megacolumns, belt trusses and outrigger trusses. The megasystem has great advantages over the ordinary system because: 1) The megastructure meets the functional requirements of the architecture much better; 2) The megasystem has large overall stiffness, which is evenly distributed along the height. It's an ideal lateral load resisting system with a clear load path for gravity and lateral loads; 3) The system is flexible enough to satisfy seismic design requirements, allowing different materials and systems to be applied to the main and sub-structure. 4) The construction period is reduced due to the fact that the main structure is constructed in advance and the substructures are constructed simultaneously in different platforms; 5) The structure is cost-effective, with better overall stability. All of these advantages make the megastructure an efficient structural system for satisfying diversified building performance requirements (Shen, 2001).

Belt trusses are one of the key structural members of megastructures. Belt trusses have two functions in megastructures. One function is to act as the transferring members for all the secondary floor systems, and the other function is to engage all the perimeter columns in the resistance to lateral loads. There are four belt truss types in engineering practice, namely ordinary single truss, L-type single truss, U-type single truss and double truss. The belt trusses and the mechanical structures work together with megacolumns and outrigger trusses to form a megaframe structural system. The belt trusses support all the gravity columns and transfer the load in the floor from the belt trusses to the megacolumns, and thus decrease the pulling forces in the megacolumn due to wind loads or earthquakes. The outrigger trusses reduce the bending deformation of the core wall and mobilize the mega columns efficiently to decrease the overall deflection and the story drifts. However, the introduction of megasystems also has some disadvantages, such as huge steel consumption and large member dimensions. Thus structural optimization is desirable for megasystems.

The performance of the belt truss depends greatly on its stiffness. Thus the belt truss stiffness has to be carefully calibrated for better megastructural performance. The stiffness analysis and

引言

巨型结构的概念起源于20世纪60年代末，由梁式转换层结构发展而形成。巨型结构体系包含巨柱、环带桁架及伸臂桁架，相对普通的结构体系来说，巨型结构体系有如下优点: 1) 能更好地满足建筑在功能上的要求; 2) 提供了更大且沿高度均匀分布的结构整体刚度，对重力荷载和水平荷载传力明确，因而是理想的抗侧力体系; 3) 体系灵活多样，更有利于抗震，在主次结构中可以分别利用不同的结构材料和体系; 4) 由于主结构可以超前施工，且次结构可以在不同的工作面上同时进行，结构施工工期将大为缩短; 5) 具有更好的整体稳定性和更高的效能。所有这些优点使得巨型结构形成对满足结构各方面性能要求十分高效的结构体系 (沈祖炎，2001) 。

环带桁架是巨型结构的关键构件之一。环带桁架主要有两种功能，一是作为楼板体系的转换构件，二是连接所有的巨柱形成抗侧力体系共同抵抗外荷载。在工程实际中常用的四种环带桁架类型为: 单层环带桁架、L形环带桁架、U形环带桁架及双层环带桁架。作为巨柱之间的有效抗弯连接，位于各加强层的环带桁架可与巨柱和伸臂桁架一起形成一个巨型框架结构体系。相邻加强层之间的楼层荷载由重力柱支承并通过环带桁架传至巨柱，从而减少

design criteria of the belt trusses will be discussed in this chapter. Bending stiffness analysis, torsion stiffness analysis, internal force analysis and eccentricity analysis will be conducted to obtain the optimization suggestions for the analysis and design of the belt trusses for the Suzhou Zhongnan Center.

Stiffness Analysis and Design

The overall stiffness of the structure, provided by specific material quantities, indicates the efficiency of the structural scheme. For megastructures, efficient structural design can be achieved by properly calibrating the stiffness relationship between belt trusses, megacolumns and outrigger trusses. Using ordinary moment frames of multiple-story buildings and tall buildings as reference, the stiffness relationship of megastructures can be quantitatively assessed. Essentially, the outrigger trusses and belt trusses can be treated as a lattice beam for bending and torsion stiffness analysis.

An ordinary multiple-story frame structure was first used to calculate the linear stiffness of the beam-to-column ratio. The beam (concrete grade C30) section is 250 x 500 mmwith a span of 6 meters and the

Figure 3.31. Elevation rendering for Zhongnan Center (Source: Gensler)
图3.31. 中南中心立面渲染效果图 (来源: Gensler)

巨柱由侧向风荷载或地震作用引起的上拔力。而伸臂桁架的使用能将巨柱与核心筒有效地联系起来，减小了结构整体变形中的弯曲变形和层间位移角。然而，巨型结构体系在实际应用中也存在着一些不足需要改进，比如说用钢量大、构件尺寸过大。因此，巨型结构的优化设计刻不容缓。

环带桁架的性能很大程度上取决于其提供的刚度大小，因此，环带桁架的刚度设计需要深入的研究以在巨型结构中获得更好的性能表现。本文首先对环带桁架的刚度分析及设计准则进行了讨论。以苏州中南中心为案例，本节具体阐述了环带桁架的刚度分析和优化的过程。针对案例进行了抗弯刚度分析、扭转刚度分析、环带桁架上下弦杆内力分布均匀性分析及环带桁架布置偏心分析的全面考虑，从而得出了关于四种环带桁架类型分析和设计的优化建议。

刚度分析及设计准则

结构材料用量一定的条件下，结构所能提供的结构整体刚度大小能表明结构方案效率的高低。对于巨型结构来说，通过对环带桁架、巨柱及伸臂桁架刚度的合理分配可以获得高效的结构设计。以多层简单框架和高层结构为参照，巨型结构构件之间的刚度关系可以定量地表示出来。实际上，在刚度分析的过程中，伸臂桁架和环带桁架可以简化为格构式梁来分析。

首先对一个常规多层框架的梁柱线刚度比进行了计算。常规框架梁截面取 250 x 500 mm，跨度6m，材料采用C30。柱截面取 500 x 500 mm，层高4.5m，材料采用C60。从而，梁柱的抗弯线刚度分别为$i_b = 1.30 \times 10^{10}\ N \times mm$及$i_c = 4.17 \times 10^{10}\ N \times mm$，梁柱抗弯线刚度比为0.31。同理，梁的扭转刚度与柱的抗弯线刚度比值可计算为1/6。

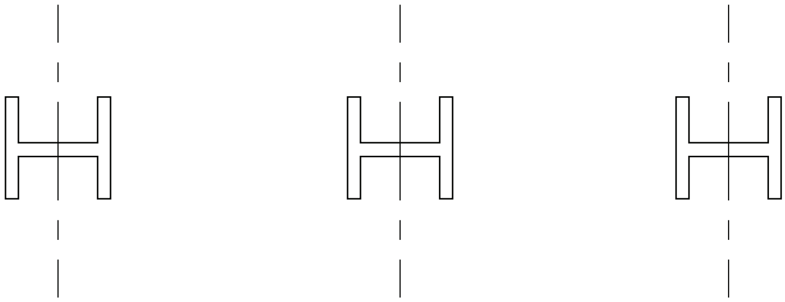

Figure 3.32. Simplified model of belt truss (Source: Guangjing Sha)
图3.32. 等效梁简化模型 (来源: 沙广璟)

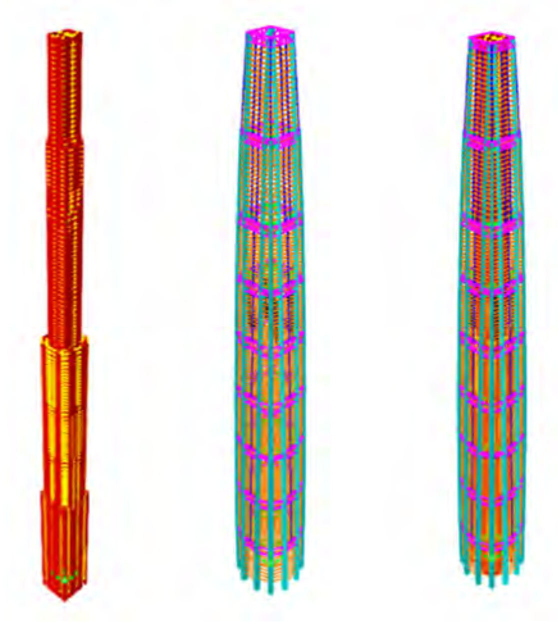

Figure 3.33. Structural lateral system of Zhongnan Center (Source: Guangjing Sha)
图3.33. 结构抗侧力体系 (来源: 沙广璟)

column (concrete grade C60) section is 500 x 500 mm with a height of 4.5 meters. The beam and column linear bending stiffness are $i_b = 1.30 \times 10^{10}\ N \times mm$ and $i_c = 4.17 \times 10^{10}\ N \times mm$ respectively and the ratio of the beam to column linear stiffness is 0.31. The ratio of the beam torsion stiffness to the megacolumn linear stiffness can also be obtained as 1/6.

A practical way of engineering ordinary tall-building structures was also employed to calculate the linear stiffness of the beam-to-column ratio. The beam (concrete grade C30) section is 300 x 700 mm with a span of 10 meters, while the column (concrete grade C60) section is 1,000 x 1,000 mm with the story height of 4.2 meters. The ratio of the beam torsion stiffness to the megacolumn linear stiffness can be obtained as 1/56.

For the stiffness calculation of the lattice members like the outrigger truss and the belt truss, a simplified method is to treat the truss as the equivalent of a beam. Figure 3.32 shows the simplified lattice member model of the belt truss and the outrigger truss. The stiffness can then be calculated as:

$$EI = E(I_u + A_u y_u^2 + I_l + A_l y_l^2 + I_m)$$

where I_u, I_l and I_m, and are the inertia moment of the upper, lower and middle chords of the truss. and are the areas of the upper and lower chords respectively. A_u and A_l are the distances between the upper chord and the middle chord, and between the lower chord and the middle chord.

From the analysis above, the ratio of the beam to column linear stiffness in ordinary frames is about 0.3 and the ratio of the beam torsion stiffness to the megacolumn's linear stiffness in ordinary frames is about 1/60~1/6. These parameters will be used as indices in the belt truss optimization.

Belt Truss Types

Traditionally, belt trusses can be divided into single– and double– belt truss systems. Belt trusses with additional horizontal bracings are proposed in this chapter to investigate their performances. Types of belt trusses studied here include single– and double– belt truss, L-type single truss and U-type single truss. Each type has its own advantages and disadvantages. For example, the single-belt truss needs less steel tonnage at the expense of reducing the safety redundancy of the structure. An L-type belt truss would hardly get the most out of the structural materials due to the significant difference between the internal forces of the upper and lower chords. A comparative study on different types of belt trusses will be found in the following section.

接着对一个高层结构的梁柱线刚度比进行了计算。梁的截面取 300 x 700 mm，跨度10m，材料采用C30。柱截面取 1,000 x 1,000 mm，层高4.2m，材料采用C60。从而，梁的扭转刚度与柱的抗弯线刚度比值可计算为1/56。

对于类似伸臂桁架和环带桁架之类的格构式梁的刚度计算，提供了一种简化的等效梁计算方法，简化模型见图3.32。图3.32显示了环带桁架和伸臂桁架的框架简化模型，其刚度可按式 (1) 计算:

$$EI = E(I_u + A_u y_u^2 + I_l + A_l y_l^2 + I_m)$$

式中，I_u, I_l and I_m， 及 分别是桁架上弦杆、下弦杆及中间杆件的惯性矩。A_u 及 A_l 分别是上下弦杆的截面面积。 及 分别是上下弦杆与中间杆件的距离。

从上述刚度分析可知，常规框架中，梁柱的抗弯线刚度比在0.3左右，而梁的扭转刚度与柱的抗弯线刚度比值在1/60~1/6左右。这些定量的参数将会在环带优化中作为参考指标。

环带桁架类型

传统意义上来说，环带桁架可分为两种类型: 单层环带桁架及双层环带桁架。本文提出了在单层环带桁架的上下弦杆额外增加侧向水平支撑的环带方案 (L形环带方案及U形环带方案)，并对其性能做了深入的讨论。列出了文中讨论的四种环带桁架类型的示意图。各方案都有优缺点，比如说单层环带方案用钢量小但是结构的安全储备量不够，L形的环带桁架上下弦杆内力相差较大而不能充分利用结构材料。在案例分析一节将会对不同环带方案的性能进行对比分析。

X direction stiffness of the mega column (N.m²)	Y direction stiffness of the mega column (N.m²)	X direction linear stiffness of the mega column(N.m)	Y direction linear stiffness of the mega column (N.m)
1.64×10^{12}	1.60×10^{12}	4.33×10^{10}	4.23×10^{10}

Table 3.11. Calculated results of bending stiffness (Source: Guangjing Sha)
表3.11.巨柱刚度、线刚度计算结果 (来源: 沙广璟)

Length of the chord/m	Section of upper chord/mm	Section of lower chord/mm	Section of diagonal member/mm
21.6	H1000 x 1000 x 800 x 80	H1000 x 1500 x 100 x 100	H1000 x 1500 x 100 x 100

Table 3.12. Section of the outrigger trusses (Source: Guangjing Sha)
表3.12. 伸臂桁架截面尺寸 (来源: 沙广璟)

Length of the chord/m	Section of chord/mm	Section of diagonal member/mm
19.5	H1000 x 1000 x 100 x 100	H1000 x 1000 x 100 x 100

Table 3.13. Section of the belt trusses (Source: Guangjing Sha)
表3.13. 环带桁架截面尺寸 (来源: 沙广璟)

Case Study

The Suzhou Zhongnan Center has nine zones along the building height, with two-story-high belt trusses installed in the mechanical floor of each zone. Outriggers are installed in zone 1 (two directions), 3(two directions), 4 (east-west direction), 6 (two directions), 7 (two directions), 8 (south-north direction), yielding five outriggers in each direction. The structural lateral load-resisting system is shown in Figure 3.33.

Bending Stiffness Analysis

Take zone 1 as an example to calculate the bending stiffness of the megacolumn, in this case a steel-reinforced concrete column. The section of the megacolumn in zone 1 is a 4.55 m x 4.55 m square section with embedded steel section of $h \times b\ t_w \times t_f = 3{,}300\ mm \times 1{,}000\ mm \times 70\ mm \times 70\ mm$. The calculated results of the stiffness and linear stiffness of the megacolumn are listed in Table 3.11. The section of the outrigger trusses and the belt trusses are listed in Table 3.12 and Table 3.13.

The bending stiffness of the outrigger trusses and single-belt truss can be obtained based on the equivalent beam model. The calculated results are as follows: the bending stiffness of the outrigger truss is $3.66 \times 10^2\ N \times m^2$ and its linear stiffness is $1.69 \times 10^{11}\ N \times m^2$, The bending stiffness of the belt truss is $2.54 \times 10^{12}\ N \times m^2$ and its linear stiffness is $1.30 \times 10^{11}\ N \times m^2$. The bending stiffness and linear stiffness ratio of the belt trusses, outrigger trusses and megacolumns are listed in Table 3.14.

From Table 3.14, one may find that the single-belt truss and the outrigger almost have the same linear stiffness, which is 3 to 4 times the linear stiffness of the mega column. That means the single belt truss can provide enough restraint to the megacolumn. Since the double-belt truss contributes less to the overall stiffness, it is less effective than the single-belt truss, though it will provide more restraint to the megacolumn.

Torsion Stiffness Analysis

Considering the weak torsional stiffness of the single-belt truss, the L-type single truss, U-type single truss and double-belt truss schemes can be applied to improve the torsional stiffness. The L-type belt truss has additional horizontal bracings in the upper chord of the single-belt truss and the U-type belt truss has additional horizontal bracings in both the upper and lower chords. The L-type single truss and U-type single truss are more attractive than the double truss due to their minimum interference with the useful space in mechanical floors.

The story height of the belt trusses are 5.5 meters and 5 meters respectively. The section of the upper and lower chords and the diagonals are all $h \times b \times t_w \times t_f = 1{,}000\ mm \times 1{,}000\ mm \times 100\ mm \times 100\ mm$ (where are h, b, t_w and t_f section height, width, web thickness and flange thickness respectively). The span of the belt truss is 19.5 meters.

案例分析

以苏州中南中心为案例阐述了环带桁架优化选型的具体运用。中南中心沿竖向共分9个区，每区在设备层设置一道两层高的环带桁架。伸臂桁架设置在1、3、4(东西方向)、6、7及8(南北方向)区，即在两个方向各设置了五道伸臂桁架。结构的抗侧力体系见图3.33。

抗弯刚度分析

以一区为例计算巨柱抗弯刚度，巨柱为刚混柱，一区巨型柱截面尺寸为4.55 m x 4.55 m，钢骨尺寸为 $h \times b\ t_w \times t_f = 3{,}300\ mm \times 1{,}000\ mm \times 70\ mm \times 70\ mm$，巨型柱刚度、线刚度计算结果见表3.11，伸臂桁架的主要截面尺寸如表3.12所示，单层环带桁架的主要截面尺寸如表3.13所示。

伸臂桁架的抗弯刚度及环带桁架可根据简化的格构式梁方法进行计算，得到伸臂桁架的抗弯刚度为 $3.66 \times 10^2\ N \times m^2$，其线刚度 $i = EI/l = 1.69 \times 10^{11}\ N \times m^2$。环带的抗弯刚度为 $i = EI/l = 2.54 \times 10^{12}\ N \times m^2$，其线刚度 $i = EI/l = 1.30 \times 10^{11}\ N \times m^2$。根据计算结果，将单层环带方案的环带、伸臂与巨柱的刚度比与线刚度比在表3.14中列出。

由表3.14可知，单层环带方案的环带、伸臂的线刚度较为接近且其线刚度是巨柱的3~4倍。由此可见，单层环带对巨柱的约束作用已经很大，考虑到双层环带尽管对巨柱约束作用更大，但对整体刚度贡献不大，却对建筑功能有较大的影响，另外还显著降低了结构经济性，没有单层环带方案经济。

扭转刚度分析

考虑到单层环带方案扭转刚度较小，可采用L形环带、U形环带及双层环带方案来增加扭转刚度。L形环带方案在上弦杆增加侧向支承，而U形环带方案在上下弦杆均增加侧向支承。由于L形及U形环带方案对建筑楼层使用空间干扰性较小，通常比双层环带更有吸引力。

环带所在两层的层高分别为5.5m及5m，环带长度19.5m，上、下弦及腹杆尺寸均为 $h \times b \times t_w \times t_f = 1{,}000\ mm \times 1{,}000\ mm \times 100\ mm \times 100\ mm$。

Member	Section of chord/mm		Linear stiffness (N.m)	
	Absolute value	Relative value	Absolute value	Relative value
X direction of the mega column	1.64×10^{12}	1	4.33×10^{10}	1
Y direction of the mega column	1.60×10^{12}	0.98	4.23×10^{10}	0.98
Outrigger trusses	3.66×10^{12}	2.23	1.69×10^{11}	3.9
Belt trusses	2.54×10^{12}	1.55	1.30×10^{11}	3

Table 3.14. Stiffness and linear stiffness results (Source: Guangjing Sha)
表3.14. 巨型构件刚度、线刚度计算值及相对关系 (来源: 沙广璟)

Schemes	Single layer	L type	U type	Double layers	Ordinary frame
Stiffness ratio	1/69	1/42	1/20	1/15	1/56~1/6

Table 3.15. Torsional stiffness comparison (Source: Guangjing Sha)
表3.15. 水平构件扭转刚度与竖向构件线刚度比 (来源: 沙广璟)

The calculation of the torsional stiffness of the outrigger trusses and the belt trusses is based on the equivalent-beam model. The analysis results of the outrigger trusses and belt trusses' torsional stiffness and the ratio of the beam torsional stiffness to the megacolumn linear stiffness in ordinary frames are summarized in Table 3.15.

The torsion stiffness of the single-belt truss is smaller than the linear stiffness (linear means the stiffness divided by the effective length) of the megacolumn in the same direction, while the L-type single truss and the U-type single truss schemes provide larger torsional stiffness. The torsional stiffness of the double-belt truss scheme is very close to the torsional stiffness of the U-type single truss.

The torsional stiffness and steel tonnage of the different schemes are listed in Table 3.16 for the analysis of the torsional efficiency. From Table 3.16, we can find that L-type and U-type belt trusses consume less steel tonnage than the single-belt truss scheme for the same torsional stiffness. On the other hand, the torsional stiffness of the double-belt truss provides the largest torsional stiffness but consumes the largest steel tonnage. Generally the U-type single belt truss provides the highest torsional stiffness efficiency per ton of steel.

Internal Forces Analysis
The bending moments of the principal axis of the belt truss' upper and lower chords in different schemes are listed in Table 3.17. A force couple is imposed on the midpoint in the upper and lower chords for the internal force analysis.

From Table 3.17, the bending moment in the principal axis of the upper and lower chords in the L-type belt trusses differ significantly, and the lower chord will yield early under the loads. In fact, the L-type belt-truss scheme is not economical. On the contrary, bending moments in the principal axis of the belt truss' upper and lower chords in the U-type belt truss are close to each other and smaller than other schemes, except the double-belt truss system, which makes the U-type scheme an ideal choice.

Eccentricity Analysis
The effective width of the beam-column core district varies greatly in different schemes due to the eccentric layout of the belt truss, which will return different shear bearing capacities. The effective width of the beam-column core district is equal to the minimum of $b_b + 0.5h_c$, b_c and $0.5(b_b + b_c) + 0.25h_c - e_o$. The centerline of the beam and the column do not coincide and the eccentricity is smaller than ¼ the column section. Note that b_b, b_c and h_c are sections of the beam and column, and e_o represents the original eccentricity.

The average effective width in different stories can be defined as the index of the effective width of the beam-column core district to the whole belt truss. The effective width is listed in Table 3.18.

From Table 3.18, one can find that the effective width of the beam-column core district in the single-belt truss scheme is small, thus the shear bearing capacity becomes small due to its large eccentricity. The effective width improves when horizontal bracings are arranged in the other schemes. The effective width of the U-type belt truss scheme is close to the double-belt truss scheme.

伸臂桁架及环带桁架的扭转刚度采用简化为等效格构式梁的方式进行计算，环带构件扭转刚度与巨柱构件线刚度比，以及普通框架梁扭转刚度与框架柱线刚度比分析结果见表3.15。

单层环带的扭转刚度较巨柱在相同方向的线刚度 (线刚度指刚度除以有效长度) 稍弱，而采用L形和U形环带布置方案可以提高环带桁架的整体扭转刚度，其中U形环带方案结果和双层环带方案的结果较为接近。

将不同环带布置方案的扭转刚度及其用钢量结果列于表3.16，对不同方案抗扭效率进行分析。从表3.16可以看出，L形和U形环带的用钢量比单层环带略有增加，但是扭转刚度有较大提高，双层环带的扭转刚度虽然最大，但是其用钢量也最大，综合来看，U形环带的单位用钢量抗扭效率最高。

内力分析
计算得到各环带方案上、下弦的主轴弯矩值见表3.17。此处模型是分别在环带上下弦杆的中点施加力偶的计算结果。

由表3.17结果可以看出，L形环带方案的上、下弦杆构件应力相差较大，在荷载作用下，下弦桁架会过早地屈服，是不经济合理的方案。而U形环带的上下弦弯矩值较为接近且受力较小 (除双层环带桁架外最小)，因此是比较理想的布置形式。

偏心分析
由于环带的偏心布置，各环带布置方案的梁柱核心区截面有效宽度会不同，从而引起截面抗剪承载力的不同。当梁、柱的中线不重合且偏心距不大于柱宽的1/4时，核心区的截面有效宽度取 $b_b + 0.5h_c$、b_c、$0.5(b_b + b_c) + 0.25h_c - e_o$ 三者的最小值。其中，b_b、b_c 及 h_c 分别是梁柱的截面尺寸，e_o 是初始偏心距。

定义各层桁架截面有效宽度的平均值作为评价环带桁架整体等效有效宽度的指标。各方案截面有效宽度计算结果见表3.18。

由表3.18的结果可知，由于梁柱偏心较大，单层环带的梁柱节点核心区截面有效宽度较小，节点核心区抗剪承载力较小。设置楼面支撑不同的方案对截面有效宽度有不同程度的提高，其中U形方案的计算结果与双层环带较为接近。

Schemes	Single layer	L type	U type	Double layers
Torsion stiffness	6.12 x 10^5	1.018 x 10^6	2.09 x 10^6	2.874 x 10^6
Steel tonnage (t)	152.25	156.6	160.9	308.9
Torsion stiffness / steel tonnage (relative value)	4,020 (1.00)	6,501(1.61)	12989 (3.23)	9304 (2.31)

Table 3.16. Torsional stiffness and steel tonnage results (Source: Guangjing Sha)
表3.16. 环带扭转刚度与用钢量之比 (来源: 沙广璟)

Schemes	Moment of the midpoint in the upper chord (kN.m)	Moment of the midpoint in the lower chord (kN.m)
Single layer	2,078	2,041
L type	660	1818
U type	605	601
Double layers	433	444

Table 3.17. Belt truss bending moment (Source: Guangjing Sha)
表3.17. 各环带方案上、下弦桁架弯矩值 (来源: 沙广璟)

Schemes	Single layer	L type	U type	Double layers
Effective width (mm)	2,412.5	3,125	3,838	4,550
Effective width/ width of mega column	0.53	0.69	0.84	1

Table 3.18. Effective width of beam-column core district (Source: Guangjing Sha)
表3.18. 各方案截面有效宽度 (来源: 沙广璟)

Conclusions

Belt trusses are one of the key members of megastructures. The performance of the belt truss depends greatly on its stiffness. This chapter records the stiffness analysis of belt trusses for better megastructural performance. Four belt truss types were discussed, namely the ordinary single truss, the L-type single truss, the U-type single truss and the double truss. Actual components in the Suzhou Zhongnan Center were then analyzed for bending stiffness analysis, torsional stiffness analysis, internal force analysis and eccentricity analysis for the four kinds of belt trusses. The following conclusions can be obtained:

1. For providing lateral restraints to megacolumns in the belt-truss / megacolumn plane, a single-belt truss is the most efficient compared with the other belt truss types, because the single-belt truss can actually provide enough bending stiffness
2. For providing lateral restraints to the megacolumns perpendicular to the belt truss / megacolumn plane, the U-type single truss is the best choice, since it has the best torsional stiffness efficiency per ton of steel
3. According to the results of internal torsional force analysis, the L-type belt truss will yield early under the loads, while the U-type belt truss will perform well; second only to the double-belt-truss scheme. Considering the relatively small steel tonnage and minimal interference to the useful space on the mechanical floor, the U-type single truss is an ideal choice
4. The effective width of the beam-column core district in the single belt truss scheme is small, so that the shear bearing capacity becomes small due to its large eccentricity. The effective width improves when horizontal bracings are arranged in the other schemes. The effective width of the U-type belt truss scheme is close to the double-belt truss scheme.

小结

环带桁架是巨型结构的关键结构构件之一，环带桁架的性能很大程度上取决于其提供的刚度大小，本文对环带桁架进行了刚度分析以获得更优的巨型结构性能。常用的四种环带桁架: 单层环带桁架、L形环带桁架、U形环带桁架及双层环带桁架的性能在文中均做了讨论。以苏州中南中心为案例，文章具体阐述了环带桁架的刚度分析和优化的过程。针对案例进行了抗弯刚度分析、扭转刚度分析、环带桁架上下弦杆内力分布均匀性分析及环带桁架布置偏心分析的全面考虑，得出了以下结论:

1. 从环带桁架与巨柱平面内环带对巨柱的约束作用来看，单层环带桁架相对其他的环带桁架形式是最高效的，因为单层环带桁架已经为巨柱提供了足够的抗侧刚度
2. 从环带桁架与巨柱垂直平面环带对巨柱的约束作用来看，U形环带是最佳的方案，因为U形环带方案的单位用钢量的抗扭刚度效率是最高的
3. 根据扭转分析结果，L形环带方案在荷载作用下会过早地屈服，而U形环带桁架的上下弦弯矩值较为接近且受力较小，仅次于双层环带桁架方案。考虑到U形环带桁架方案用钢量较小且对建筑使用面积的影响较小，U形环带桁架方案是理想的方案
4. 由于梁柱偏心较大，单层环带的梁柱节点核心区截面有效宽度较小，节点核心区抗剪承载力较小。设置楼面支撑不同的方案对截面有效宽度有不同程度的提高，其中U形方案的计算结果与双层环带较为接近

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