Title:	**Innovative Solutions to Complex Geometric Forms in Tall Buildings**
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Subjects:	Architectural/Design IT/Computer Science/Software
Keyword:	Structure
Publication Date:	2012
Original Publication:	CTBUH 2012 9th World Congress, Shanghai
Paper Type:	1. Book chapter/Part chapter 2. Journal paper 3. **Conference proceeding** 4. Unpublished conference paper 5. Magazine article 6. Unpublished

Innovative Solutions to Complex Geometric Forms in Tall Buildings

高层建筑复杂几何形式的创新方案

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Abstract

There is an trend in tall buildings towards ever more complex geometric forms, as clients and architects look to distinguish their buildings. That such buildings are becoming the norm, as opposed to merely achievable, is testament to the advances in computing and the modeling and analysis software now commonly available. In dealing with the challenges posed by such buildings, it is becoming increasingly necessary for engineers to innovate and to step outside the boundaries of codified design. It is also important for engineers to revert to basic principles to ensure full understanding of the theory behind codified design limitations and the implications of stepping 'outside the box'. This paper examines the geometric complexities of one tower, and two innovative design solutions in particular that were necessary to achieve the desired geometry.

Keywords: Complex Geometry, Strut and Tie, Concrete Shear, Composite Link Beams

摘要

由于客户和建筑师希望突出自己的建筑，高层建筑的几何形式变得越来越复杂。与刚刚可实现这些形式恰好相反的是，这样的建筑越来越普遍，这证明了计算、模拟、分析软件的进步，已经可以应用在这些建筑上了。在处理这些建筑带来的挑战时，工程师已经越来越有必要做出创新，并走出拘泥于规范化设计的围栏。对工程师而言同样日趋重要的是还原到基本原理，完全理解程式化设计局限和“走出盒子”的含义。这篇文章研究了一幢塔楼的几何复杂性和可以实现所需要的几何形式的两种创新设计方案。

关键词：复杂几何形式；拉压杆；混凝土剪力；组合连梁

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Mark Lavery has worked on a portfolio of projects at the leading edge of tall building engineering over the last 10 years, leading and developing teams in a variety of roles on more than 35 tall building projects, principally as lead engineer but including roles as: multi-disciplinary project design manager, FIDIC Engineer and peer reviewer, as well as value engineering and specialist roles. His tall building experience includes seven "super-tall" buildings, and three "mega-tall" buildings, with the 1000m tall Nakheel and Harbour Tall Tower being the tallest designed tower.

Mark从事高层建筑的前沿设计已经超过10年，他带领团队参与了超过35个高层建筑项目。在这些项目中，他主要是作为团队的带头工程师，也会担任多领域项目设计经理、FIDIC工程师和项目评估者、工程评审专家等。他在高层建筑领域的经验包括7座“超高层”建筑，三座“超大型”高层建筑以及1000米高的世界最高Nakheel Harbour塔楼。。

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Spencer Robinson is a creative, design led engineer with experience across a range of sectors and building types. He has led multi-disciplinary teams on large, complex projects both in the UK and overseas. Spencer's other tall buildings experience includes leading structural teams on a number of commercial towers in London's city centre and he led the concept development for the 160m and 140m hotel and residential towers adjacent to the Millennium Dome.

Spencer Robinson是一个富有创造力的顶尖设计工程师，具有各种建筑类型的设计经验。他带领多领域团队在英国和海外参与了多项大型复杂的项目。Spencer的其他高层建筑经验包括带领结构团队参与了伦敦市中心的大量商业塔楼设计，他提出了临Millennium Dome的160m旅馆和140m高层住宅的设计理念。

Introduction

Following recent advancements in computer software and the increasing levels of competence of both architects and engineers in using such software, architects are becoming increasingly confident pushing the boundaries of geometric complexity. With geometric modeling software, such as Rhinoceros, complex geometry can be created through definition of curves and surfaces, thereafter broken down to create centerline stick geometry and area elements for structural analysis. Available software add-ins also enable this geometry to be defined parametrically, allowing quick modifications to form and onward manipulation of the analysis geometry. Thus form can quickly be tried, tested and refined at a conceptual level.

The implication to structural engineers is that, as a consequence of the increased ability to create and analyze such forms, pushing these boundaries often leads to challenges in design and constructability, and perhaps more importantly to the unwary engineer, the risk of not identifying key force paths. A typical outcome of complex geometry is the generation of out-of-plane gravity forces

介绍

随着最近计算机软件的不断进步和建筑师工程师使用这些软件的能力不断提高，建筑师们对于增加建筑几何外形的复杂性越来越游刃有余。通过使用几何建模软件，例如犀牛（Rhinoceros），复杂的几何形状可以由曲线和曲面定义出来，此后再进行分解，创建中心线几何形式和区域元素进行结构分析。一些软件的附加应用可以进行参数化设计，实现快速修改模型进行几何分析。因此在概念阶段可以快速修改和尝试不同的几何形式。

对于结构工程师的启示是，随着创建和分析这些形式的能力逐渐增强，追求新的突破经常会带来设计和施工上的挑战，对于马虎的工程师可能更加重要的是会承担没有正确确定关键的传力路径的风险。一个复杂几何模型的典型特征是由于重力系统竖向力刚度的改变而出现平面外重力，比如倾斜的围护结构的变化。这会导致在构件中局部平衡的力不与此种作用相关或是力没有在局部受力点处平衡，需要寻找其他的荷载路径以达到力的平衡。

粗心的工程师对他们创建的如此复杂的模型自我感觉良好，看似对于设计提供了大量的数据，而实际上并没有理解基本原理

due to changes in vertical alignment of gravity systems, such as at changes in orientation of inclined facades. This can lead to forces that are locally balanced through elements not typically associated with such actions, or forces that are not balanced locally and indeed need to find alternative load paths to a position where these forces can be cancelled out.

The unwary engineer can be artificially comforted by their ability to create such complex models that seemingly provide them with a wealth of data for design, however without understanding the basic fundamentals and anticipating the force paths, key elements to the stability could be overlooked.

Such non-standard structural solutions can also lead to issues with codified design approaches and it is important that engineers understand the basis of the codified approach when working outside its confines.

Tower 114, King Abdullah Financial District, KSA

Tower 114, located at the heart of the new King Abdullah Financial District in Riyadh, KSA, is one such example of a tower pushing the boundaries of geometric complexity. The 253m tall Gensler designed office building is characterized by a series of inclined facades and structural set-backs to the North and South facades resulting in an eye-catching sculptural form (see Figure 1).

The inclined facades to the North and the set-back to the South result in several levels of unbalanced, out-of-plane, gravity-induced forces as identified in Figure 2, which have both direct and indirect structural design implications. The direct, and most obvious of the structural implications, is the need to restrain the out-of plane forces created by the "kink" to the gravity columns. The loading involved, the building height, and the nature of the geometry of the "valley" of the facades, which requires the "valley" column to collect transfer columns along its height, results in some enormous out-of-plane forces of up to 25MN. The nature of the geometry also means that direct force paths are not available and that the out-of-plane forces are only partially resolved at the level at which they originate. The resulting structural design needs to both resolve the forces that can be balanced immediately and to transfer the residual force to the lateral load resisting structural system (LLRSS) to a point where they can be finally resolved and equilibrium restored.

The second, and more indirect of the implications, is the huge shear forces in the core wall link beams that result from the increased gradient of the global overturning moment. This is amplified by the large floor to floor height and subsequent large stiffness of the core link beams at the adjacent plant floor level, which results in the forces at this level being amplified to a level of shear that exceeds the maximum allowable by a factor of more than 2, leading to a requirement for a bespoke composite solution.

Restraining the "Kick"

The lateral gravity "kick", caused by the instantaneous change in inclination of the facades, and accompanying change in inclination of columns, occurs at three levels: ground, Level 6 and Level 14. The most complex, and the one involving the largest forces and hence biggest challenges, occurs at Level 14; Figure 2 shows the orientation of these forces.

The difference in magnitude of the column forces and the inclination of the elements, coupled with the irregular orientation of the columns, means that the forces cannot be cancelled immediately for

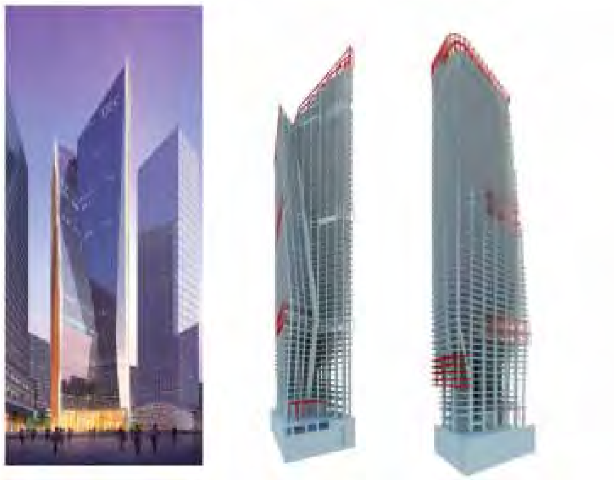

Figure 1. Overall rendering and structural system
图1. 全景渲染图和结构体系

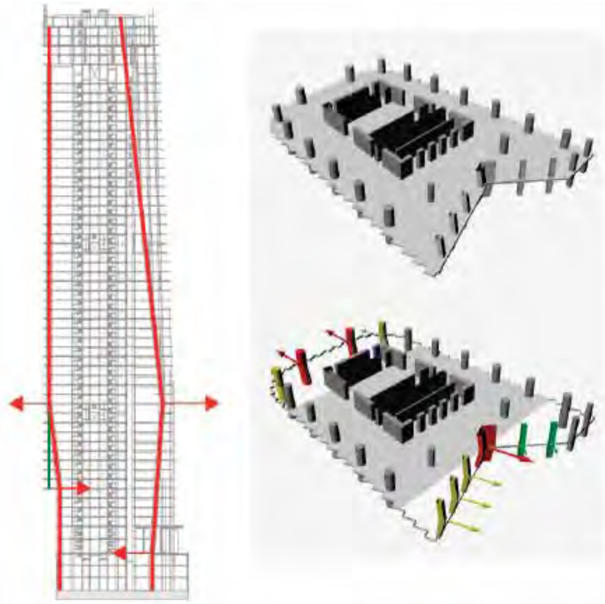

Figure 2. Diagram of unbalanced forces on structural system.
图2. 结构体系不平衡力示意图

和传力途径，从而忽略了对于结构稳定性至关重要的构件。

这些非常规性的结构方案也能导致系统化设计问题。当涉及到非常规的结构设计时，工程师理解系统化方法的基本原理是很重要的。

塔114，阿卜杜拉国王金融区，沙特阿拉伯

塔114，位于沙特阿拉伯首都利雅得的新建的阿卜杜拉国王金融区的中心，就是几何形式复杂性创新的一个例子。这栋办公建筑253m高由Gensler设计，特点是由一系列倾斜表面构成，北立面和南立面上的结构凹处形成了很引人注目的雕塑形式（见图1）。

倾斜的北立面和南面的凹处产生了有效层高度上不平衡的、在平面外的、由重力引起的受力，如图2所示，对于直接和间接的结构设计都有一定的影响。最明显和直接的结构影响是要限制由结点（kink）产生向柱平面外的力。所受荷载、建筑高度和“凹进”的立面需要“凹进”柱子在它的高度方向进行转换，导致一些地方平面外的受力高达25MN。这种几何形式的特性也意味着仅有直接的受力路径是不可行的，平面外的力只能有一部分被平衡。结构设计不仅需要直接的受力平衡，同时还要把剩余的力转换到抗侧力结构系统（LLRSS）上，以达到最终平衡。

equilibrium, and the net force is necessarily transferred to the LLRSS to be balanced partially at Level 6 and finally resolved at ground floor level. This means that two force transfer mechanisms are required: firstly to cancel the balanced portion of the forces and secondly to transfer the net out-of-balance forces to the LLRSS.

In order to balance the forces at the diaphragm level, a strut and tie arrangement was the obvious choice and elastic FEM analyses were carried out to identify the principal elastic stress paths and help guide the selection of the most appropriate strut and tie arrangement (see Figure 3).

Several options were considered for dealing with these forces at the Level 14 diaphragm: an external structural steel truss solution; a post tensioned strut and tie solution; and a standard reinforced concrete strut and tie solution. The options were each considered in light of: contractor preference; integration with gravity design; constructability; fire protection and robustness.

Due to the oblique arrangement of the strut and tie model, the steel solution would have led to congested detailing; crane lifting logistics and weight restrictions, lead time for procurement and difficulties with integration of the steelwork with the gravity design of the slab were all reasons contributing to the decision to rule out this option.

The post-tensioned options were ruled out due to a combination of the difficulty of detailing the anchorage zones for the large forces, the difficulty in moulding the tendon layout to the most appropriate strut and tie arrangement suggested by the elastic principal stress paths, the contractors preference to avoid the sequential stressing required to make the system work and the lack of achievable redundancy in the system.

The selected system was one consisting of a standard RC strut and tie solution, incorporating large diameter, high strength bars with steel thrust/anchorage blocks to mobilize the compression struts and act as an anchorage for the steel ties at changes in orientation. More material was required for this option than the others, but the ability to mould the solution to match the determined optimal strut and tie arrangement, and the contractor's preference for the simpler detailing and construction were all positive factors contributing to the selection of the system. Strain was carefully controlled to limit the column movement and serviceability cracking, and careful detailing was required to restrain the columns and prevent congestion with the vertical column reinforcement. Limiting the strain also ensured that the principal stress paths were not distorted from the assumed elastic distribution through cracking. Strut and tie was also used locally adjacent to the core walls to transfer the net force to the LLRSS with ties provided using standard reinforcement anchored into the walls (see Figure 4).

Mega Link Beams

The indirect implication of the large lateral "kicks" is the increase in the gradient of the bending moment diagram for the core, leading to a significant spike in the shear forces across the core link beams at the levels adjacent to the lateral thrusts. The increased shear force is felt most keenly at the immediately adjacent plant floor level, where the large floor to floor height and the correspondingly deep, and hence stiff, link beams attract very high shear forces, the magnitude of which were such that a conventional RC solution was not achievable.

Several options were considered, including localized thickening of the link beams, introduction of additional shear force paths between the core flanges, and the embedment of steel elements.

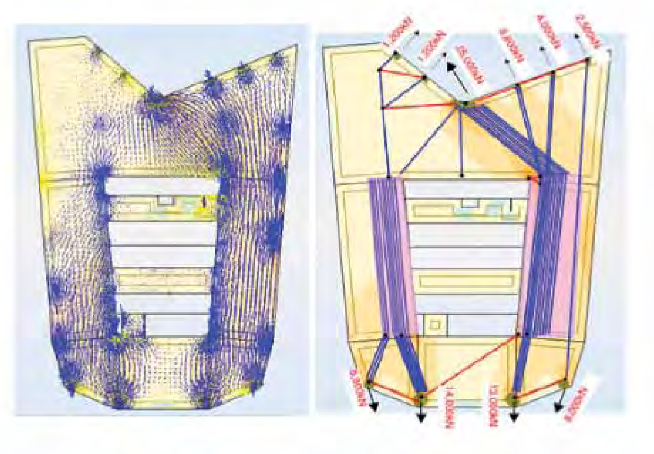

Figure 3. FEM analysis diagrams
图3. FEM分析示意图

第二点也是较间接的影响，是在核心筒连梁处有巨大的剪力，这是由逐渐增加的整体倾覆力矩所造成的。这些剪力由于层高较大和相邻层处的刚度很大的核心筒连梁所放大，这导致了该层剪力超过所允许的最大剪力的两倍，因此需要特别的综合解决方案。

限制“弯折力”

侧向的重力“弯折力”是由倾斜表面的突变引起的，并伴有倾斜柱子的变化，这种情况发生在三个楼层：地面层，6层和14层。其中最复杂的、受力最大的，也最有挑战的一层是在14层；图2表示出这些力的方向。

柱子上的力和倾斜构件上的力存在差异，由于柱子的不规则布置，意味着力不能马上被平衡掉，余下来的力有必要被转换到抗侧力结构系统，在6层平衡一部分，在地面层最终被完全平衡。这意味着需要两个力的转换机制：一是可以被直接平衡的力的部分，二是将剩余的非平衡的力转换到抗侧力结构系统中。

为了在刚性楼板层达到受力平衡，选择拉压杆装置是显而易见的方案，弹性有限元分析用来确立主要的弹性状态下的变力路径，帮助选择最合适的拉压杆装置（见图3）。

为了处理14层隔板的这些力，有以下几种方案：外部的钢结构桁架解决方案；后张预应力拉压杆方案；普通钢筋混凝土拉压杆的方案。在每个方案中都要重点考虑：承包商的意见，与重力设计的结合，可建设性，防火和坚固性。

由于拉压杆模型的倾斜安排，钢结构的解决方案将会导致拥挤的细部构造；起重机的起吊逻辑顺序和重量限制、 采购和交货时间、将钢结构与楼板设计相结合的困难性，都造成了放弃这个选择的原因。

后张预应力方案也被排除掉是综合了以下几种问题：由于受力较大导致锚固区细部构造的困难，预应力钢筋浇筑比最适合的按弹性应力路径布置的拉压杆更困难，承包商倾向于避免建造时持续的压应力和缺少结构冗余度的情况。

所选择的系统是由一个普通钢筋混凝土拉压杆方案，同时由大直径高强度的钢筋组成的。这些钢筋固定在钢块上形成斜压杆，为朝向变化的钢筋提供固定点。这种方案比其他的方案需要更多的材料，但是浇筑钢筋以实现最佳的拉压杆构造，承包商更希望简单的细部结构和建设过程都是选择这种系统的有利因素。应变被很仔细的控制，用来限制柱子的位移和开裂；需要仔细进行细部设计来约束柱子，以及避免柱钢筋出现拥挤。限制应变同样也确保了主要应力迹线不被开裂分布所干扰。拉压杆同样也应用在核心筒墙体局部，通过由在墙体内普通钢筋锚固所形成的连接，将力转移到水平抗侧力系统(图4)。

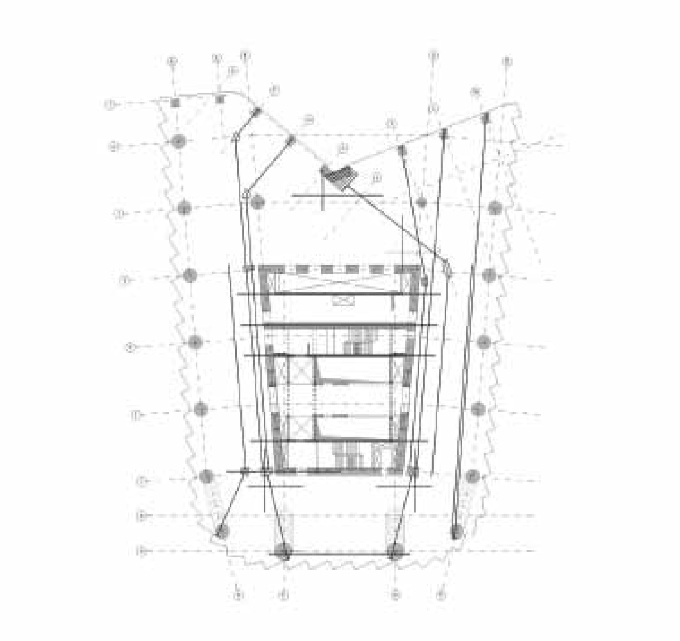

Figure 4. Final strut and tie arrangement
图4. 最终选择的拉压杆装置

Some success was achieved through provision of additional shear force paths through the core, but this could not eliminate the issue, and thickening of the core beam was impractical due to construction constraints, thus leading to the requirement of an embedded steel solution. The use of an embedded flanged beam section, often successfully used in RC core link beams with excessive shear forces, was not practical due to the depth of the beam, the magnitude of the forces and the restrictions over crane lifting capacities as well as the difficulties in embedding such an element and the associated stress transfers.

In order to overcome the issues and limitations, it was necessary to break the problem down to its basic component parts and to understand the force flow to determine the optimal solution. A strut and tie solution was adopted and elastic stress plots were used to help guide the selected strut and tie pattern, with the wall forces at the boundary of the discontinuity region, as well as the link beam forces themselves, studied to gain full understanding of the flow of forces through the beam and re-establishment of the wall forces (see Figure 5).

The strut and tie forces were reflective of the high shear, with very large loads in the diagonal compressive strut and the restoring tension ties, while the vertical struts adjacent to the opening were within codified limits for an RC solution, whilst very highly stressed.

The depth of the beam is such that a single diagonal strut spanning the opening was achievable at a reasonably optimum angle, and the elastic stress plots demonstrated the anticipated bottle strut , and clearly showed the lateral tensions.

Having determined that a standard RC solution could carry most of the forces with the exception of the main diagonal strut and the restoring tension ties, a solution began to take shape. As a significant portion of the shear was directly cause by a lateral gravity component, it meant that the shear flow was significantly higher in one direction that the other when combined with wind actions. Further simplification of the problem was therefore achieve by the fact that for the direction reverse to the gravity component, the beam acts comfortably within capacity as a standard RC beam, and that strengthening of the diagonal strut was required only in one direction.

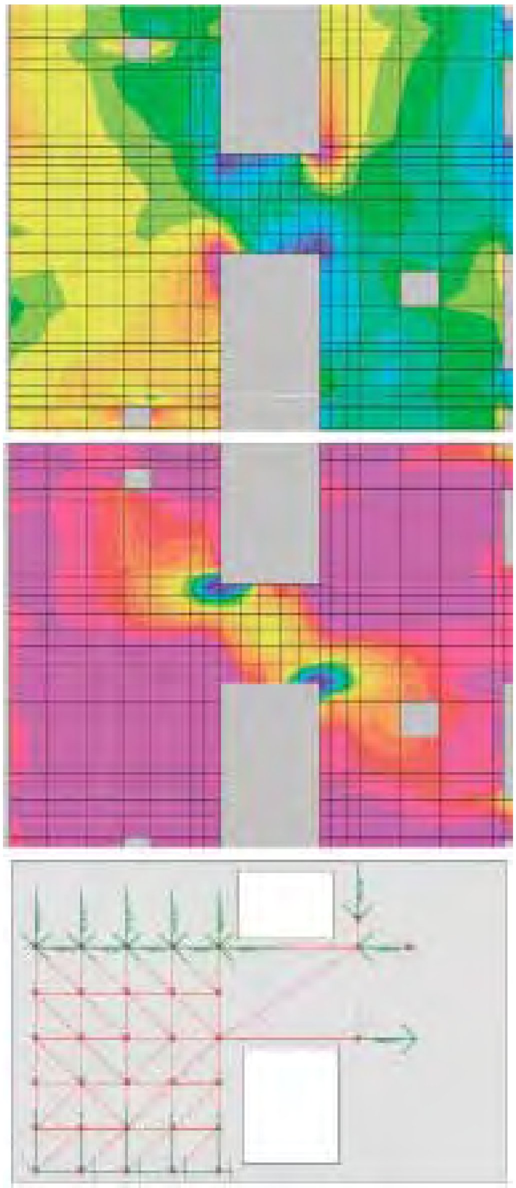

Figure 5. Stress contours adjacent to the opening and the selected strut and tie arrangement
图5. 为临近开洞处的等压力线和选择的拉压杆装置

巨型连梁

大的水平“弯折力”意味着增加核心筒的弯矩图的梯度，在相邻层核心筒连梁处产生很大的剪力。这个增加了的剪力在相邻层是非常敏感的，在这些地方高的楼层处，高且刚度大的连梁吸引了非常大的剪力，这样大的数量级对于传统的钢筋混凝土结构是不可实现的。

有一些选择可供考虑，包括局部加厚连梁，在核心筒翼缘之间引入设置额外的剪力路径，以及嵌入钢梁。

一些方式是可以成功实现的，比如在核心筒引入额外的剪力路径，但这种方法并没有解决问题；同样，由于施工上的限制，增厚连梁这个方案也是不可行的；因此只能转向采用嵌入钢梁的方案。使用嵌入的工字梁在处理钢筋混凝土核心筒连梁过大剪力的案例中是成功的，但在这个案例中却不太实际，原因有梁高问题，受力很大，起重机起重的限制，还有嵌入钢梁的困难性，和所引起的应力转换问题。

为了克服这个问题和其局限性，有必要把问题分解成基本的组成部分，通过理解受力流来确定最佳的解决方案。拉压杆方案被采纳，弹性应力图被用来帮助指导所选择的拉压杆形式，图中还表示了非连续区域的墙受力，以及连梁自身的受力，通过受力图可

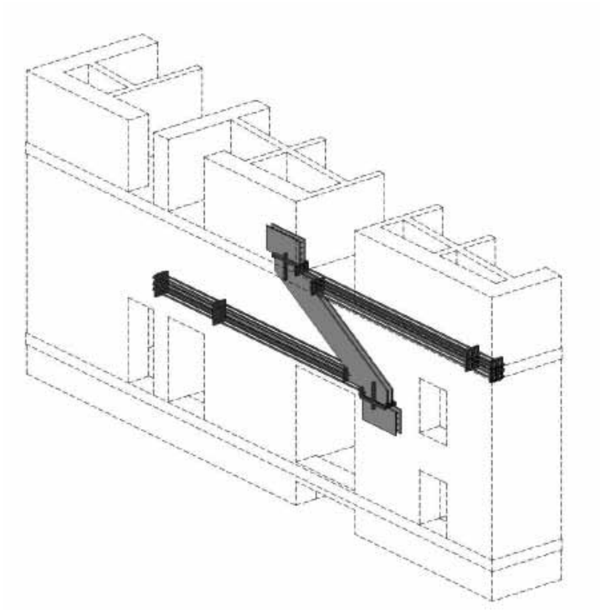

Figure 6. Axonometric view of mega link beam
图6. 巨型连梁轴测图

Considering all the factors, a bespoke composite mega link beam solution took shape consisting of embedded plate diagonally oriented and anchored with large diameter, high strength bars forming a 'Z' shape (see Figure 6) to both strengthen the diagonal strut and directly transfer the relevant portion of the restoring tension force into the bars. The embedded plates were sized to limit the stress, and hence strain, in the concrete section and ensure that the components of stress and strain sustained by the concrete were within codified limits.

The key to the success of the solution was twofold: firstly, the careful consideration of stress transfer from the concrete wall on one side of the beam to the embedded steel plate and subsequent transfer back to the wall on the opposite side of the opening, and secondly careful control of strain to ensure that cracking was controlled.

For stress transfer, the nodes were carefully detailed to ensure that the interactions of the concrete-only component, steel-only component and the combined system were all considered and a system of bearing plates adopted for the stress transfer; redundancy was also achieved through the use of shear studs at key nodes. For serviceability, it was ensured that sufficient reinforcement was provided at all tension areas to limit strains and cracking, particularly for the main tension ties for which a horizontal cage of standard reinforcement close to the concrete surface was provided. Limiting the degree of cracking also ensured that the assumed elastic distribution of stress remained valid. The use of the large diameter bars also ensured that congestion in the wall was minimized, with anchor plates used to anchor the tension and establish compression struts in the walls. In addition, the strut was analyzed as a composite section to check for buckling.

To aid constructability, openings in the horizontal bearing plates were provided to assist the flow of concrete and the elements were split into components (see Figure 7) to fit within the crane lifting capacity limit of 6 tons with connections kept as simple as possible and away from the most heavily loaded zones.

Conclusion

The increasing trend for complex geometry buildings has been fuelled largely by developments in the sophistication and capabilities of available 3D modeling and structural analysis tools. Such buildings are

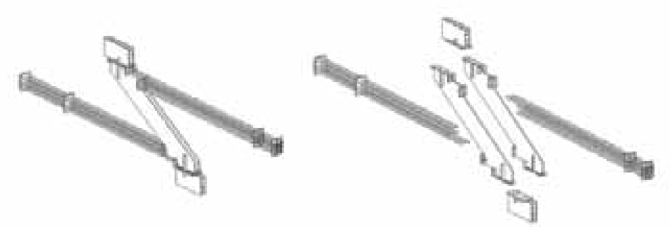

Figure 7. Exploded view of mega link beam showing individual components.
图7. 显示每个单独部件的巨型连梁分解图

以全面理解沿梁的受力流和墙受力的实际情况（见图5）。

拉压杆力反应了高剪力，在斜压杆和拉杆处都有非常大的荷载，而开洞两边的竖向杆的应力虽然很大，却仍可满足钢筋混凝土方案。

梁高设计成单独斜杆在一个最佳角度跨越洞口，弹性应力图表明了预期的杆件内力，清楚的显示出水平张力。

既然已经看到了钢筋混凝土可以承载除主要对角杆和拉杆之外的大部分的力，一个解决方案就要开始成型了。由于剪力的一个重要组成部分是直接由水平的重力分量引起的，也就意味着在风作用下一个方向上的剪力会远远大于另一个方向。再次简化这个问题得到如下的事实，就是在重力分力的反方向上，钢筋混凝土梁是完全可以承受的，因此只需要在一个方向上采用对角杆。

考虑到所有的因素，一个特制的复合超大型联系梁方案已经形成，由嵌入对角分布的、形成"Z"形(图6)的大直径高强度钢筋所固定的平面组成，既增强了对角杆，又直接把相关部分的拉力转换到钢筋中。根据限制应力和混凝土部分的应变来确定嵌入平面的大小，确保应力分力和混凝土中的张力是在规范限制范围内的。

这个方案成功的关键有两方面：一方面是仔细的考虑应力从梁一边的混凝土墙转移到嵌入的钢板，接下来再转移回开洞的另一边的墙上；第二是仔细控制应变，确保开裂是可控的。

对于应力的传递，节点要被仔细细化确保全面考虑到纯混凝土构件、纯钢构件和混合结构的相互作用，确保支承板进行压力传递；通过在一些关键节点使用剪力钉，可以实现剪力传递。从可维护性来讲，要保证在所有的拉应力区域提供足够的钢筋来限制应变和开裂，特别主要的拉力杆处要在临近混凝土表面有足够的配筋。限制开裂的程度同样确保了预计的应力弹性分布是有效的。使用大直径钢筋确保了墙内繁琐的细部构造被最简化，使用锚板来固定墙中拉压杆。此外，受压杆件作为组合构件来进行屈曲分析。

为了增强可建设性，水平支承板内的开洞有助于混凝土浇筑，构件被分割为组件（见图7）以符合起重机6吨的起重限制，节点尽可能的简单并远离最大受力的区域。图8表示一个超大型连梁在安装中。

结论

3D建模和结构分析工具的逐渐成熟和分析能力的提高大大推动了复杂几何形式的建筑的发展。这些建筑变得更容易可视化和进行分析，但任何分析软件都有这样一个风险，就是所采用的建模技术可能不会清晰的指明完整的关键受力路径。例子包括使用刚性楼板假定，主要是用于简化分析过程，这可能会遮盖掉一些重要的受力路径，不能给工程师们提供保证。对于所有的项目，工程师需要对形式的含义有扎实的概念性的理解，并要预想到这些受

becoming easier to visualize and to analyze, but there is a risk with any analysis software that modeling techniques adopted may not clearly reveal the full extent of key force paths. Examples include the use of rigid diaphragms, typically used to simplify analysis, which may mask important force paths and provide unwarranted comfort to engineers. As for all projects, engineers need to have a sound conceptual understanding of the implications of the form and to anticipate these force paths, using software as a tool rather than being a slave to it.

This is not to say that analysis tools do not have an important role to play, indeed the use of analysis output such as elastic stress plots, when modeled properly and used in the right way, can be invaluable in determining the most appropriate design solution.

Providing that key elements are identified, the design components can be broken down into simple pieces and innovative, bespoke solutions can be developed on the back of sound engineering judgment and basic structural mechanics.

Software advances are clearly positive developments for the development of tall building design and it is as important as ever that the engineer understands the implications of the geometry in clear and simple terms, rather than be reliant on the software to demonstrate those implications.

Engineers need to control their software, rather than let the software control them.

Ackowledgements

Rayadah Investment Company
Saudi Bin Laden Group
Gensler Architects

Figure 8. Mega link beam during installation.
图8. 在安装中的巨型连梁

力路径，把软件当做一个工具而不是完全受其驾驭。

这并不是说分析工具起不到重要的作用，的确，如果恰当的建模和使用软件，分析结果比如弹性应力图对于决定最合适的设计方案来讲是非常有用处的。

当确定了关键元素后，构件设计就可以分解成简单的部分，然后工程师在扎实的工程判断和基本的结构机制下提出创新的、特制的解决方案。

软件创新很明确的带领了高层建筑设计蓬勃发展，而工程师能够将几何模型的含义以清晰简单的形式理解清楚同样是很重要的，而不是要依赖软件去揭示那些含义。

工程师需要支配他们的软件而不是让软件支配他们。

鸣谢

Rayadah Investment Company
Saudi Bin Laden Group
Gensler Architects