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Parametric Analysis and Design Engine for Tall Building Structures

高层建筑结构的参数化分析和设计工具

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Abstract

With the rise in CPU power and the generalization of computers, engineering practice has also changed from hand calculations to 3D computer models, from elastic linear analysis to 3D nonlinear static and transient dynamic. With holistic design approaches and current trends in freeform and contemporary architecture, BIMis no longer a dream but also a reality. BIM is not only providing a medium for better coordination but also shortens the round-the-clock time in updating models. With parametric modeling tools, structural information is also linked with BIM systems and quickly produces analysis and design results from checking to fabrication. This paper presents a new framework which links the BIM system by parametric means, but also creates and produces the connection FE model and fabrication drawings, etc. This framework will aid structural engineers in producing well coordinated, optimized and safe structures.

Keywords: BIM, Parametric Modeling, Structural Analysis, Finite Element

摘要

随着CPU功能的提高以及计算机的推广，工程计算也由手算发展到三维计算机模型，从线弹性分析发展到三维非线性静力分析和瞬态动力分析。结合传统设计方法以及当前自由形式和当代建筑的发展趋势，BIM概念不再是一个梦想，而是现实。BIM不仅为更好的协调提供了媒介支持，而且在更新模型方面缩短了循环时间。基于参数化建模工具，结构信息也与BIM系统结合，并迅速通过检查结果产生分析和设计。本文展现了一个新的框架，不仅通过参数化方式结合BIM系统，而且创造并产生有限元模型和制作图纸等的连接。该框架可以帮助结构工程师更好地进行协调，优化并保证结构安全。

关键词： BIM、参数化模型、结构分析、有限元

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Introduction

It is interesting to know that the A5 CPU used in a hand phone (such as iPhone 4S) or tablet is more powerful than a Cray 2 computer which cost US$17million[1] in 1985. Following the first Z1 computer in 1935, the size of computers reduced while increasing in speed. In 1965, Gordon Moore presented his Moore's Law that the components in integrated circuit double every ten years. In the early '80s, the availability of minicomputers allowed software applications to be shifted from military or aerospace industries to domestic use. One of the most well known is the release of the Unigraphics system by McDonnell Douglas. Unigraphics converted the Automated Drafting and Machining (ADAM) coding into the current systems of Computer Aided Design (CAD), Computer Aided Manufacturing (CAM) and Computer Aided Engineering (CAE) applications. Although Unigraphics was already in 3D, but the cost of minicomputers was still too expensive for some small firms.

Following the very early Personal Computer (Apple I) assembled by two youngsters in the mid-80s, the cost of computers became more affordable for building industry practices. The work for draftsmen changed from hand

简介

有趣的是，我们知道在手机（例如iPhone 4S）或平板电脑中使用的A5 CPU比1985年价值1700万美元[1]的Cray 2计算机还要强大。继1935年的第一台Z1计算机，计算机的尺寸在变小，而速度却在加快。1965年Gordon Moore提出了他的摩尔定律，即集成电路组件每十年增加一倍。在80年代初期，微型计算机的普及化使得软件的应用从军事或航空航天工业覆盖到家用。众所周知Unigraphics系统就是由麦道公司开发的。Unigraphics将自动制图和加工（ADAM）转化为现名为计算机辅助设计（CAD），计算机辅助制造（CAM）以及计算机辅助工程（CAE）的应用。虽然Unigraphics 已经是3D了，但是对于那时候建筑行业的一些小公司来说，微型计算机 (mini computer) 的成本仍然过于昂贵。

随着80年代中期由2个年轻人组装的个人电脑（Apple I）的出现，建筑行业越来越负担得起计算机的成本了。绘图员的工作也由手工绘图转变为2D CAD制图和90年代的3D制图。 在3D的环境中，建筑、工程和施工（AEC）的真实交流语言不单是1860年代Carl Culmann提出的“图纸”了。原因是结构越来越复杂，而且很难用2D绘图的方式来定义了。现在图纸的定义可能意味着“3D对象”。

drawings to 2D CAD drawings and in the '90s in 3D drawings. With a 3D environment, the true communication language of Architecture, Engineering and Construction (AEC) industry is no longer "drawings" as emphasized by Carl Culmann in the 1860's. It is because structures are getting more complicated and cannot be defined by means of 2D drawings. The definition of drawings nowadays may mean – "3D objects".

At the same time, structural engineers also changed their practice from hand calculations to now very complex 3D nonlinear transient dynamic analysis. Without computers and software, a lot of ideas would still be on a piece of paper. For example, the Water Cube for the Beijing Olympics was firstly created by scripts instead of sketches and drawings. The National Stadium geometry was first created by CATIA; box sections were "intruded" following the external surface (not centreline) and twisted to ensure the external envelope follows the "Bow" shape. With the popularity of 3D modeling techniques, the industry is moving forward to Building Information Modeling (BIM).

According to Ghang Lee[2], "BIM is the "process" of generating and managing building information in an interoperable and reusable way. A BIM system is a system or a set of systems that "enables" users to integrate and reuse building information and domain knowledge through the lifecycle of a building". In the early stage of BIM, structural engineers use it to produce the global model of the building structure and BIM is only a tool to produce computer models. Figure 1 shows an architectural image of a building project, the Revit 3D and GSA (a general structural analysis software developed by OASYS) model. Through BIM tools, engineers can produce the floor plan in seconds as in Figure 2.

We can treat BIM as the second generation of the CAD system. It grows from 2D to 3D plus includes an additional database to collect the information for points, lines, surfaces and solids as entities. Some BIM systems can even store the information for structural models such as loads, node and member numbers etc. However, the authors are unable to find the appropriate BIM software with parametric capability that can handle complex geometry and at the same time a complex structural model including connection details. For a complex connection, a minor update in geometry may induce several days to update the Finite Element analysis model. To increase the productivity and accelerate the work cycle time for complex and tall buildings, a

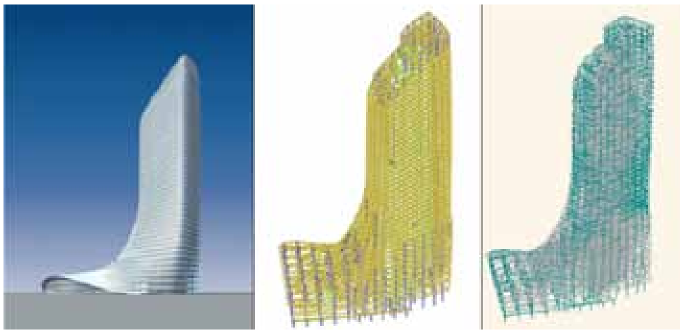

Figure 1. Architect Image (With courtesy of Studio PeiZhu) Vs Revit Model Vs GSA Structural Model
图1. 建筑图片(朱锫建筑事务), Revit 模型及GSA结构模型对比

同时，结构工程师们也将手工计算转变为现在非常复杂的3D非线性瞬态动力分析。如果没有计算机和软件，许多想法只能是空谈。例如，北京奥运会水立方是采用脚本完成绘图，再通过计算机分析完成。国家体育场的几何图形最早是由CATIA软件创建的；箱形截面沿外表面（不是中心线）侵入，并扭曲以保证外壳可以形成“弓”形。随着3D模型技术的普及，我们所处的行业将会在本世纪20年代向建筑信息建模（BIM）方面向前推进。

根据Ghang Lee[2]先生解释，“BIM是以一个可互操作且可重复利用的方式生成和管理建筑信息的‘过程’。BIM系统是使用户可在建筑物的整个生命周期内对建筑信息和领域进行集成和重复使用的一个或一组系统。”在BIM的早期阶段，结构工程师利用BIM来生成建筑物结构的整体模型，而BIM仅仅是一种生成计算机模型的方法。图1显示了一个建筑项目的建筑图片，Revit 3D模型和GSA（OASYS开发的一种结构分析软件）模型。通过BIM模型，工程师可以提取平面图并快速生成楼层平面，如图2所示。

我们可以将BIM视为第二代CAD系统。他由2D发展到3D，再加上额外的数据库用以收集点、线、面和实体信息。有些BIM系统甚至可以存储结构模型信息，例如荷载，节点和单元号码等信息。但是，本文的作者无法找到适当而具有参数化能力的BIM软件，同时处理复杂的几何图形以及同时处理复杂的结构模型，包括结点细节等。对于一个复杂的连接结点来说，几何中一个细小的更新都会导致有限元分析模型的更新。为了提高工作效率，缩短复杂高层建筑的工作周期，一款“连接”软件架起了BIM和分析软件的桥梁。这种“连接”将进一步发展为一个枢纽，连接BIM，通用建筑分析软件，有限元分析，非线性分析。笔者利用与IFC[3]标准相近的基于XML数据库，开发了一种名为分析与设计引擎

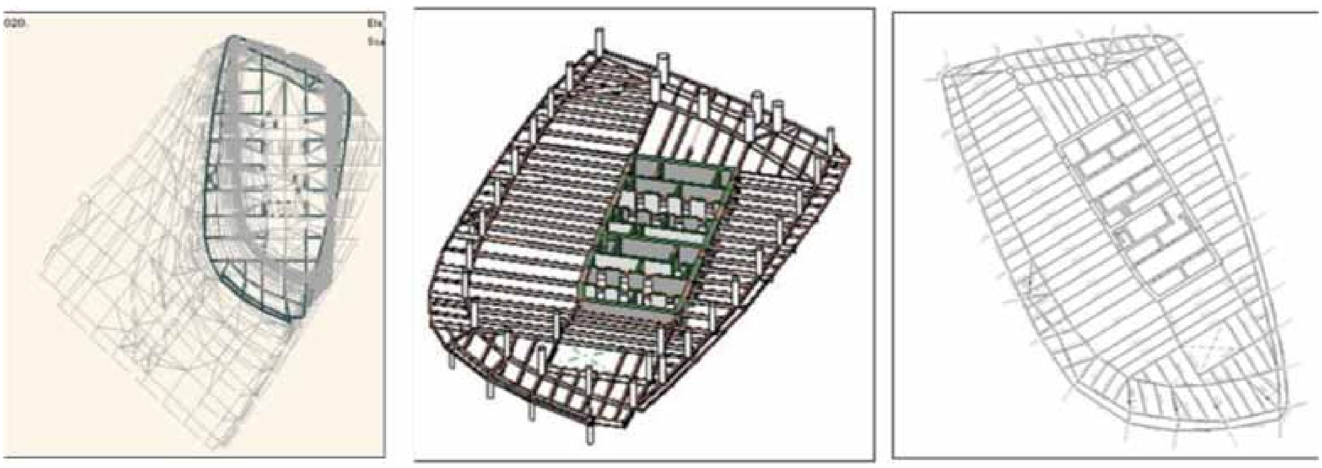

Figure 2. Extract of 2D and 3D floor plan from 3D BIM model.
图2. 从3D BIM模型中提取2D和3D楼层平面

[1] http://www.blogintech.com/ipad-2-as-strong-as-super-computer-1985.html
[2] Ghang Lee, Rafael Sacks, Charles M. Eastman, "Specifying parametric building object behavior (BOB) for a building information modeling system", Journal of Automation in Construction, Vol 15, 2006, pp 758 – 776.
[3] http://en.wikipedia.org/wiki/Industry_Foundation_Classes

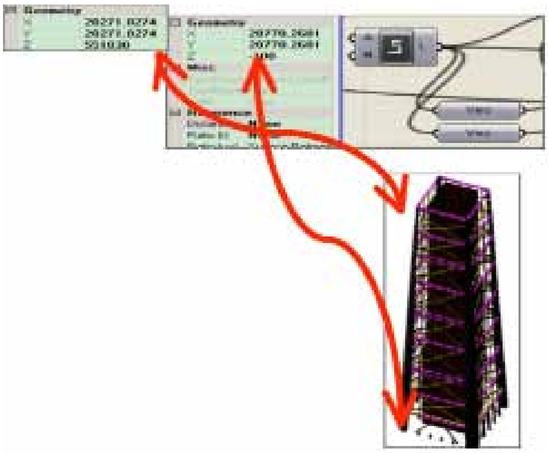

Figure 3. Geometry object defined by parameters and component
图3. 由参数和组件定义的几何对象

"link" software bridging between BIM and analysis software is needed. This "link" was further developed to be a hub core that connects BIM, software for general building analysis, Finite Element Analysis, Nonlinear Analysis. Using an XML database similar to the IFC[3] Standard, a framework named Analysis and Design Engine (ADE) is developed. Through this database hub, users can select his favourite software for parametric modeling, BIM, analysis software and even software to produce steelwork shop drawings (see Figure 3).

Parametric Modeling

Because of the trends in free form surfaces and increasing heights, the automation of generating the global structural model is not good enough to meet the speed and complexity requirements. The use of object oriented concepts, genetic algorithm and parametric modeling techniques are now applied to structural analysis and design and even construction and fabrication drawings.

With parametric modeling, the design (model) dimensions can be adjusted at any time in the design process while the associated dimensions, which described the design, will change in according with the pre-defined relationship.

This is extremely useful in tall building design especially when the building envelope is not a constant. In the case, the structure is straight in the external surface that the variables are only the square at the top and bottom; the designer can easily define the relationship of each four vertical corner edges by means of its relative and /or functions.

Besides the exterior, the designer can also define other structural components such as core, columns, bracing, and outriggers (see Figures 4 and 5).

Once the parameters for the components are defined, engineers can update and modify a particular or several dimensions to produce the design that he/she is looking for. Figure 6 shows the change of the bracing pattern.

The word parametric means the geometric definitions of the design, such as dimensions and topology, can be varied at any time in the design process. Parametric modeling is accomplished by identifying and creating the key features of the design with the aid of computer software. The design variables, described in the sketches, are described as parametric relations and can then be used to quickly modify/update the design.

Depending on the tool chosen by the engineer, some tools require and/or allow the user to use scripting to drive the input and output.

（ADE）的框架。通过该数据库枢纽，用户可以自行选择他所中意的软件，用来进行参数化建模，BIM，分析软件，甚至生产钢结构施工图的软件(见图3）。

参数化建模

由于自由曲面的发展趋势，当代建筑的需要以及建筑物日趋高大，生成整体结构模型的自动化功能已经不能满足速度性要求和复杂性要求。目标导向概念的应用，遗传算法以及参数化建模技术现已应用于结构分析，设计，甚至施工和制造图纸中。

通过参数化建模，设计（模型）的尺寸在设计过程中可以随时调整，而用于描述设计的相关尺寸都将随着预先定义关系而发生变化。

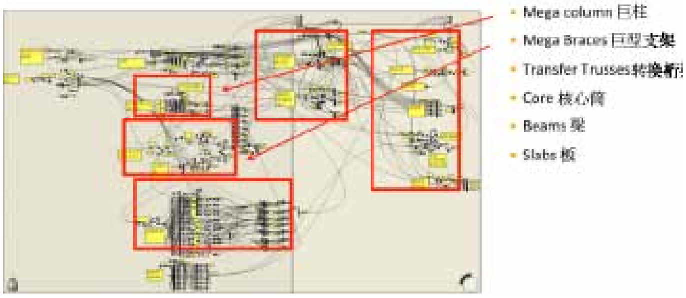

Figure 4. Structural element objects
图4. 结构单元对象

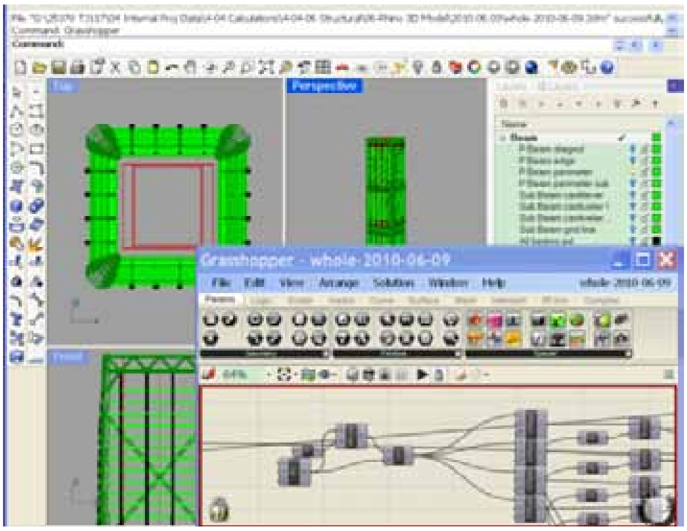

Figure 5. Building object
图5. 建筑对象

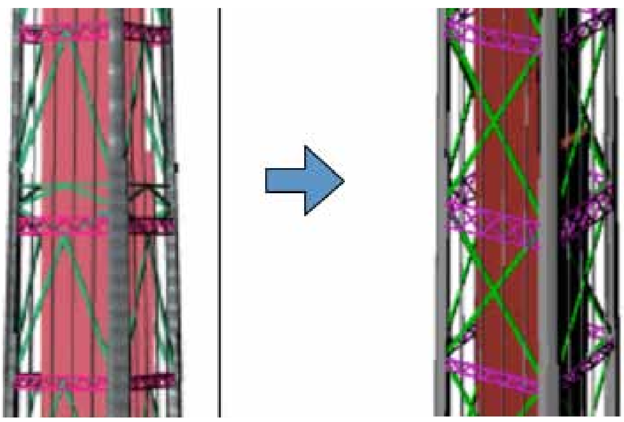

Figure 6. Bracing pattern can be changed by just updating some of the key parameters
图6. 支撑布局可以通过更新一些关键参数而改变

Parametric Modeling and Computer Design Optimization (CDO)

The development of parametric modeling technique extends the application of CDO from member section optimization to topology and structure system optimization. In the early design stage we need to consider different types of schemes and make a choice by comparison such as concrete or steel; column spacing; braced or not; with or without outriggers etc. The comparison will give us the direction to find a most effective structure and give information to the client to make the decision. Parametric modeling is the base of this kind of optimization study and makes it possible to generate different structural schemes automatically (see Figures 7 to 9).

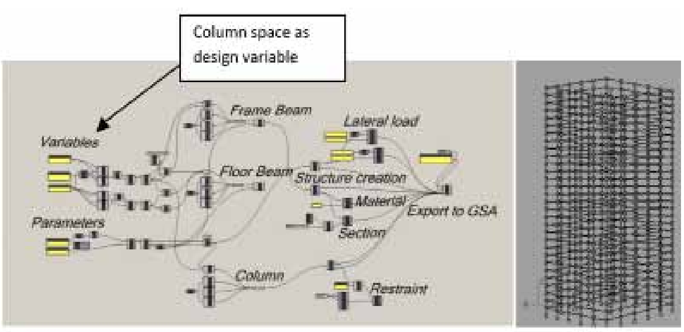

Figure 7. Parametric modeling to generate different structure systems
图7. 参数化建模以生成不同的结构体系

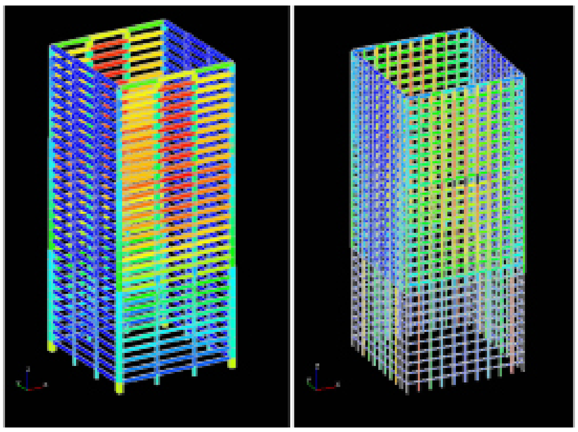

Figure 8. Virtual work analysis results for different schemes
图8. 不同方案的虚功分析结果

这是高层建筑设计中非常有用的，尤其当建筑外壳不确定的时候。在这种情况下，结构直接位于外壳内，而变量仅仅是顶部和底部的尺寸；设计师可以通过其关系和功能，简便地定义四个垂直边角的关系。

除了外观，设计师还可以定义其它结构组件，例如核心筒，柱，支撑和伸臂。（图4，5）

一旦定义了组件的参数，工程师可以更新和修改特定的或者几个尺寸，以生成他/她所期待的设计。图6显示了支撑布局的变化。

文中“参数”的含义是指设计中的几何定义，例如尺寸和拓扑结构，可以在设计过程中随时改变。参数化建模是通过电脑软件辅助设计识别和创建关键特征。草图中所示的设计变量被描述为参数关系，可用于快速修改/更新设计。

由于工程师所用工具的不同，一些工具需要，且允许使用者使用脚本控制输入和输出。

参数化建模和计算机优化设计（CDO）

参数化建模技术的发展将CDO的应用由构件截面优化延伸到拓扑结构和结构系统优化。在设计前期，我们需要考虑不同类型的方案，并通过比较作出选择，例如混凝土结构或钢结构；柱距；带支撑或不带支撑；有无伸臂桁架等等。对比将会给我们一个方向，找到一个最有效的结构，并将信息传递给业主，帮助他们作出决定。参数化建模是这种优化研究的基础，并可以自动生成不同的结构方案。(图 7 到图 9)

分析及设计引擎（ADE）

如前所述，除了整体的几何形状，信息可以轻松调整并生成整体结构模型。对于简单结构来说，Revit等程序或可以利用其设计模型很容易地将BIM模型转换为结构分析程序。然而，由于高层建筑中的组件通常需要特殊处理和考虑，所以对于高层建筑来说，这个过程并不是直接的。对结构工程师来说，BIM的传统使用就是协调和生成整体分析模型。然而，对于复杂结构，一根梁上的小小的改变都会造成相应几天甚至几周的额外工作以完成结点加工图。作为一种尝试，为将BIM延伸到结构设计中，本文作者引入一种名为分析与设计引擎（ADE）的框架，使工程师能更容易掌控及管理模型。BIM成为了一种与其他单位如建筑师和机电工程师交流的电子媒介。结构信息由自主研发以XML为基础的

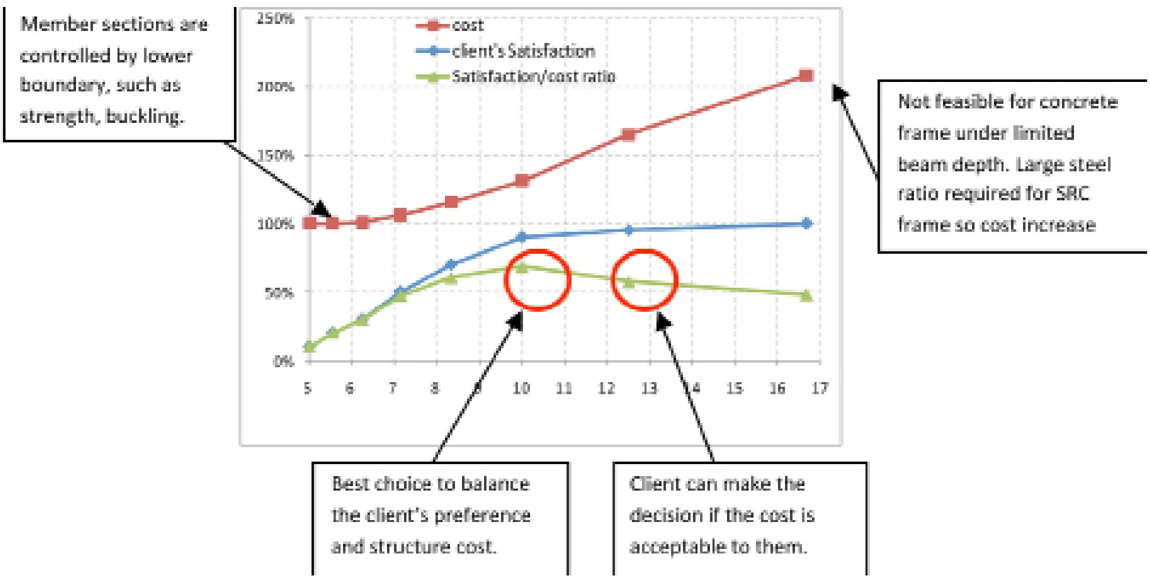

Figure 9. Results comparison and evaluation
图9. 结果对比及评估

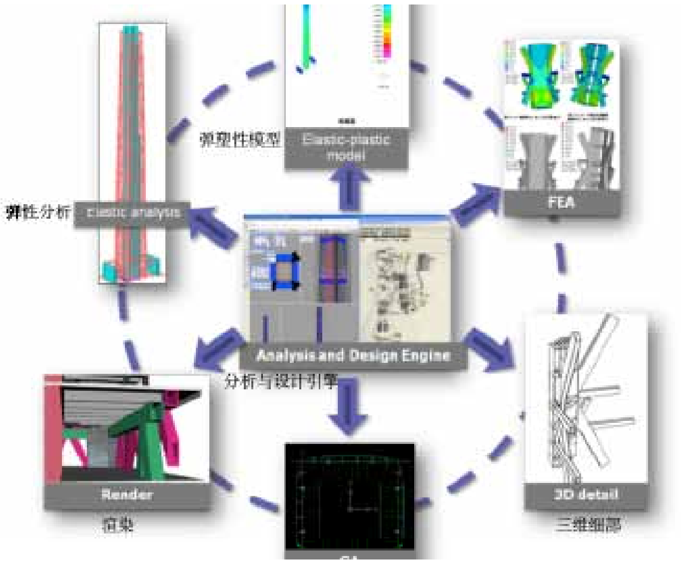

Figure10. Frameworks for Analysis and Design Engine (ADE)
图10. 分析与设计引擎（ADE）的框架

Analysis and Design Engine (ADE)

As mentioned before, besides the global geometry information can be frolic, adjust, and generate the global structural model. For simple structures, programs such as Revit can easily convert the BIM model to structural analysis programs with its design modules. However, for tall buildings this process is not that straight forward because the components in tall buildings usually require special handling and care. The conventional use of BIM for structural engineers is on the coordination and the generating of the global analysis model. However, with complex structures, a minor change in a beam may introduce days or weeks of adoptive work in preparing the connection shop drawings. As an attempt to extend BIM into structural designs, the authors introduce a framework named Analysis and Design Engine (ADE), which revokes the full control and managment by the engineer. BIM becomes a communication media with other parties such as architects and service engineers. The structural information is hosted by a self-developed XML database with a data structure similar to the IFC Standard. ADE is an object-based framework, which allows future expansion and ease of maintenance. With ADE, the engineer can obtain the following information within seconds:

- General layout drawings for plan and elevation;
- Linear model for code-based design with graphical analysis results for visualization and presentation;
- Nonlinear keyword file for LS-Dyna analysis to ensure the structures will not collapse in a severe earthquake (i.e. performance check);
- Connection geometry in IGES for Finite Element Processing including Pre-processing in generating meshing, analysis and post-processing.
- 3D connection shop drawings in X-Steel format for fabrication.
- Detailed section definition.

The diagrammatic drawing of the Analysis and Design Engine (ADE) is shown by Figure 10.

As shown in Figure 11, the column section sizes and steel ratio can be determined by analysis. Nevertheless, the detailed section design is still complex including cavity partition, exact plate position, steel plate thickness etc. Parametric modeling was used to generate a set

数据库控制，数据结构类似于IFC标准。ADE是一种以目标为基础的框架，它具有可扩展性和维护的简便性。利用ADE，工程师可以在很短的时间内获得以下信息：

- 平面和立面总体布置图纸；
- 基于规范设计的线性模型并生成可用于演示的可视化分析结果；
- 用于LS-DYNA分析的非线性密码文件，以确保结构不会在严重地震中倒塌（即性能检查）；
- 用于有限元分析过程IGES中结点的几何模型，包括网格生成前后过程、分析过程等。
- X-Steel格式的3D 结点加工图用于结点制造
- 详细的截面定义

分析与设计引擎（ADE）的简图如图10所示。

如图11所示，通过分析可以得出柱截面尺寸和配筋率。然而，详细的截面设计仍然是复杂的，包括腔体分区，钢板的准确位置，钢板厚度等。参数化建模在设置一些逻辑规则和制约因素后，自动生成详细的截面，例如两块连接板之间最大厚度差，最大宽厚比等。当截面尺寸和配筋率发生变化，详细截面定义也要相应地调整。

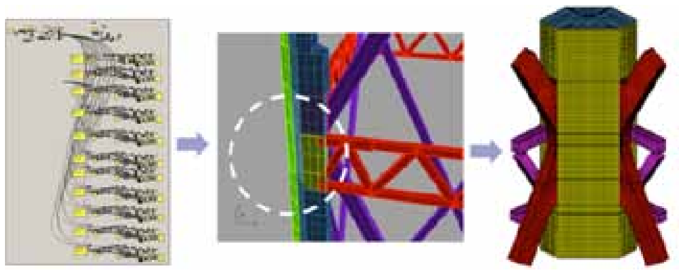

Figure 11. Finite Element Model generated by ADE
图11. ADE生成的有限元模型

结论

本文简要回顾了计算机软件由2D时代到3D参数化BIM系统的发展历程。然而，商业适用的BIM和结构分析软件的联系相对较弱，可能无法处理复杂的几何形状和超高层建筑。本文回顾了软件和结构分析软件的开发，并提出了用于提高参数化建模技术在高层建筑中应用的框架。分析与设计引擎（ADE）的引入不仅将几何信息转换为整体计算机分析模型，还可以将其它特定软件如用于非线性瞬态分析的LS-DYNA，以及有限元分析中的有限元预处理和后处理联系起来。有了ADE，自动更新将不只局限于BIM和整体结构分析模型；它还可以生成更新施工图，包括结点细节。最后，ADE模块已在中国天津597米高的高银117大厦中成功试用（图12）。在不久的将来，这个框架将会扩展到4D（包括时间）和5D（包括时间和资源/成本）应用中。

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of detailed sections automatically after setting some logic rules and constraints, such as the maximum thickness difference between two connecting plates, maximum free width/thickness ratio. When section sizes and steel ratio change, the detailed section definition can be adjusted accordingly.

Conclusion

This paper briefly reviews the history of computer software development from the 2D era to 3D parametric BIM systems. However, the link between commercially available BIM and structural analysis software is relatively weak and may not be able to handle complex geometry and supertall buildings. This paper reviews the software and development of structural analysis software and presents a framework for an advanced application of parametric modeling techniques in tall building modeling. The Analysis and Design Engine (ADE) is introduced in not just converting the geometry information into a global computer analysis model but also linking to other specialist software such as LS-Dyna for Nonlinear transient analysis, Finite Element pre- and post processor for FE analysis. With ADE, the automatic update is not just focueds on BIM and global structural analysis models; it can also generate the updated construction drawings including connection details. Finally, this ADE module was successfully tested in the 597 meter tall Goldin Finance 117 project in Tianjin, China (see Figure 12). The framework could further be extended to 4D (with time) and 5D (time and resources/cost) in the future.

Figure 12. Image of 597m tall Goldin Finance 117 Building (Source: P&T)
图12. 597米高的天津高银117大厦（出自：P&T）

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