Title: **CTBUH Research Project: A Whole LCA of the Sustainable Aspects of Structural Systems in Tall Buildings**

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Subjects: Structural Engineering
Sustainability/Green/Energy

Keywords: Composite
Concrete
Embodied Energy
Life Cycle Analysis
Steel
Structure

Publication Date: 2014

Original Publication: CTBUH 2014 Shanghai Conference Proceedings

Paper Type:
1. Book chapter/Part chapter
2. Journal paper
3. **Conference proceeding**
4. Unpublished conference paper
5. Magazine article
6. Unpublished

CTBUH Research Project: A Whole LCA of the Sustainable Aspects of Structural Systems in Tall Buildings – Interim Report

CTBUH研究项目: 高层建筑结构体系全寿命可持续性评估 ——中期报告

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Abstract

This paper illustrates the tasks completed so far and the initial findings of the first part of a 24-month long, US $300k research project on the Life-Cycle Assessment of tall building structures. The research is aimed at investigating the energy / sustainability differentials of steel, concrete and composite structural systems in tall buildings, when considering the whole life cycle from cradle to demolition / recycling.

The research considers the use of different structural systems and materials for the erection of 250 and 500 meter tall towers. The LCA impact due to the erection of the building's structural system is studied in its full detail and an accurate inventory of materials is being calculated for all construction and demolition phases.

Keywords: Life-Cycle Analysis, Embodied Energy, Tall Building Structures, Steel Structures, Concrete Structures, Composite Structures

摘要

本文阐述了一项历时24个月之久并耗资30万美金的高层建筑结构体系全寿命可持续性评估研究项目的目前进展和第一阶段初期成果。此研究旨在探究建筑的全寿命周期内——从初建到拆毁/回收阶段，高层建筑钢结构、混凝土结构及混合结构体系的耗能及可持续性的差异。

本研究审视了高度在250m至500m范围内的高层建筑不同结构体系和材料的使用。建筑结构体系下的全寿命周期影响此得到了详细的分析，并且准确计算出一份为建设和拆毁阶段使用的详细材料清单。

关键词: 全寿命周期分析，内含能量，高层建筑结构，钢结构，混凝土结构，混合结构

Introduction and Background

The Council on Tall Buildings and Urban Habitat commenced in January 2013 on a major research project to determine the role of tall building structural systems in the assessment of its life cycle impacts.

The results of the 24 month long research, sponsored by ArcelorMittal, will reveal the environmental impact of structural materials (such as steel, concrete and composite construction) and structural systems (such as core and outrigger or diagrid) through the entire life of the building. A few prior smaller-scale research projects have attempted to assess the environmental impact of tall buildings (Suzuki & Oka, 1998; Treloar et al, 2001) but they did not benefit from an approach on the wider typology of tall buildings, or on the effects of height and of different structural systems. Additionally, the results from these studies are not published in their full detail, therefore it is difficult to make a comparison base for the correct evaluation of the impact from different structural types.

引言和背景介绍

世界高层建筑与都市人居学会于2013年1月启动了一个探究在建筑全寿命周期内高层建筑结构体系的影响重要研究项目。

此项目由阿塞洛米塔尔钢铁集团赞助，历时两年之久，研究将在建筑整个生命周期内研究并揭示其结构材料 (如钢材、混凝土和混合结构) 和结构体系 (如核心筒、外伸支架和胁肋构架) 的环境影响。在此之前，一些小规模的研究尝试探索高层建筑的环境影响 (Suzuki & Oka, 1998; Treloar et al, 2001)， 但未从高层建筑更广阔意义的层面上入手或探索建筑高度的影响和不同结构体系的应用。此外，这些研究成果并未公布其详细内容，因此难以建立对不同结构类型影响的合理评价方法以及比较基础。

此外，已有的研究中采用的个案研究涵盖范围仅仅局限于建筑的"建设"和"使用"阶段，而并未考虑建筑末期性能和结构材料的回收情况。这篇论文展示了项目的初步成果，此项目现在已完成了60%。

Additionally, the case studies presented in the literature are limited to the "construction" and "use" phases of the building, without considering the buildings' end of life and recyclability of the structural materials. This paper presents the initial findings of the project, which is now approximately 60% complete.

Research Methodology

The methodology of a research is a process-based method in compliance with the ISO norms 14040 on life-cycle assessment. The scope of the research is to determine the structural system with least environmental impact for buildings of 250 and 500 meters height. The system boundaries are defined so as to include all materials and parts that create the building's structure (including foundations) throughout their entire life-cycle, from material extraction and production to their disposal or recycling.

Research Phases

The research considers the life cycle of a building in three main phases; Construction phase, Life phase, and End of life phase, as described below:

1. Construction Phase

In the first part of the study, the life cycle of the tall building structures are assessed up to the completion of construction phase. This phase includes the production of different structural materials and components, transportation of different materials to the job site and construction procedures of the building structures on site.

The first step in the study of the construction phase was the creation of an Expert Panel of structural engineers from the CTBUH membership network that gathered in a meeting for the identification of the most suitable examples to be studied (see end of paper for details of the Expert Panel).

A real building, located in downtown Chicago, was selected as the most suitable base case study, based on which multiple design scenarios were developed. The example building was chosen mainly for its recent completion (it was completed in 2009), its floor plan (that could represent class A High-Rise office buildings), and its structural system (with a central concrete core and gravity resisting steel frame). From the 60 story tall schematic structure obtained from the example building, the panel of experts suggested to design 8 different structural variations listed in Table 1. Additionally, it was decided to extend the research boundaries so as to include the design of a supertall building structure with the same variations. The schematic design was thus "extrapolated" to deliver a building with the height of 490 meters. This enlarging process was conducted in a way that the resulting building has comparable characteristics but, at the same time, reasonable proportions. The core to window span was therefore maintained at 13.5m (as it was in the real case study, which also reflects the average lease span in Class A office buildings in Chicago), the floor to floor height was kept at 4m, and the core dimensions were sized so as to reflect the average net rentable-to-gross floor area ratio of similarly tall office buildings. The same 8 structural scenarios adopted for the shorter building were also used in the taller tower (see Figure 1).

The next phase of the research consisted of structurally engineering so as to create an inventory of materials for the 16 different designs identified for the analysis. This is an important step of every LCA analysis, also required by the ISO 14040 norm.

Scenario No. (方案编号)	Scenario Description 方案描述
Scenario(方案) 1a & 4a	Concrete core with steel frame (Steel grade 345 MPa) 混凝土核心筒与钢框架 (钢等级345 MPa)
Scenario (方案) 1b & 4b	Concrete core with steel frame (Steel grade 450 MPa) 混凝土核心筒与钢框架 (钢等级450 MPa)
Scenario (方案) 1c & 4c	Concrete core and composite frame 混凝土核心筒与复合框架
Scenario (方案) 2a & 5a	All concrete structure with wide and shallow beams 全混凝土结构与宽扁梁
Scenario (方案) 2b & 5b	All concrete structure with narrow and deep beams 全混凝土结构与窄厚梁
Scenario (方案) 3a & 6a	Diagrid (Steel grade 345 MPa) 斜肋构架 (钢等级345 MPa)
Scenario (方案) 3b & 6b	Diagrid (Steel grade 450 MPa) 斜肋构架 (钢等级450 MPa)
Scenario (方案) 3c & 6c	Composite diagrid 复合斜肋构架

Table 1. Description of various structural scenarios (to be read in conjunction with Figure 1)
表格1各种结构方案的描述 (请结合图1阅读)

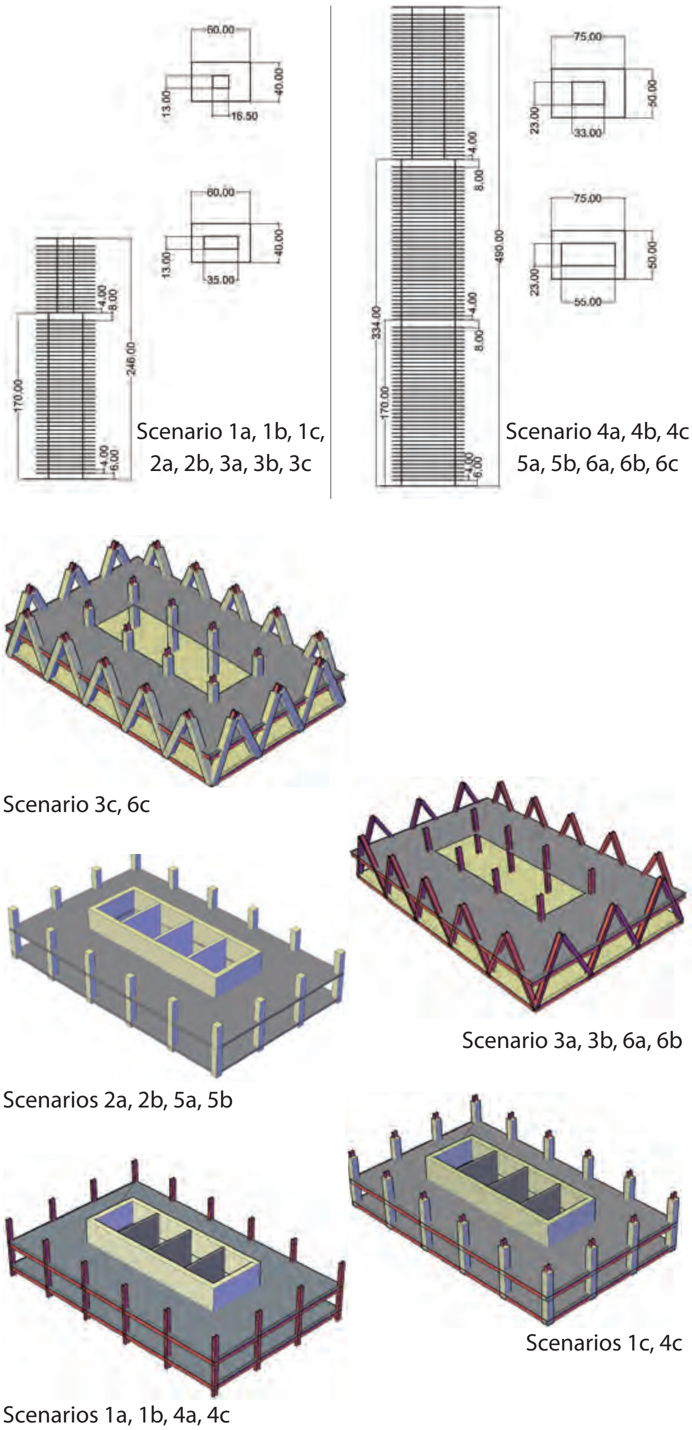

Figure 1. Schematic representation of the 16 scenarios used for the research (Source: CTBUH)
图1研究中的16个方案图示 (资料来源: CTBUH)

In order to accomplish this fundamental task, twelve leading structural engineering firms were asked to provide information on the structural quantities for the scenarios. The structural experts have contributed to the research by providing the overall quantities of structural steel, concrete, rebar, etc. required for each of the building structures described above. This step not only provided the most reliable data backed-up by the experience and knowledge of industry leaders, but also helped to increase the awareness on the project.

2. Life Phase of the Buildings
Another major phase of the research was to assess the environmental impacts of different structural systems and materials during the life phase of the building.

Among all building systems and materials, the structural components are considered the most durable parts of the building, built to last as long as the building exists. A few cases of significant structural modifications do exist in the tall building world, for example the "Tour First" in Paris, which underwent a major extension / transformation between 2007 and 2011. Thanks to additional structural reinforcements, the building height was increased from the original 159 to 231 meters.

Typically speaking however, the structural system of a tall building does not change during the life phase of the building, and the research project has found that the choice of steel vs. concrete vs. composite does not massively impact the operating energy consumption of the building during the life phase (in comparison to the construction or end of life phases). There are some implications of course, for example concrete offers more thermal mass to reduce heat loss during cold seasons but comfort is ensured even in steel buildings by the presence of high-mass floor systems made of composite (steel-concrete) construction. But, typically speaking, the choice of structural system and material does not significantly impact the consumption of energy during the life phase of the building. Conversely, concrete columns take up more floor area than steel meaning there might need to be more floor surface (ie: an extra floor) to achieve the same overall usable area.

One part of the research project is now assessing what building structural material/system offers the most flexibility, and allows (as a consequence) for greater building adaptability to alterations based on future market needs. This study will accommodate an extreme case (for example, as outlined above in the Tour First project) as well as other smaller-scale changes which might be needed to update a building, based on the new requirements of the tenants, so as to extend its service life. Such alterations may include: addition/removal of portions of the building or entire floors (for the creation of a double height space or the insertion of additional lifts or stairs), addition/removal of internal walls (for instance when an office building is transformed into a residential or hotel tower), or even strengthening the existent structures to accommodate heavy equipment (machineries, air handling units or pools) or meet newer building codes and criteria (for instance to match new seismic regulations).

3. End-of-Life
The end of life of buildings is the third major phase of a building's life being investigated in the research. Data was first collected on precedent of the demolition of tall buildings, as well as consulting experts for the future demolition plans for existing buildings.

Even considering the shorter, 60 story tall scenario (approximately 250m in height), the demolition of such a building would represent by far the tallest demolition job ever accomplished. In fact, the

研究方法

本研究采用基于流程的方法，并符合ISO 14040标准中的"生命周期评估"规范。研究的范围是探究250m和500m高层建筑其环境影响最小的结构体系。其中定义了结构体系的界限，包括全寿命周期中结构 (包括地基) 的所有材料和部件，涵盖材料提取、生产到其处置或回收各个阶段。

研究阶段

本研究将建筑全寿命周期分为以下三个主要阶段: 建设阶段; 使用阶段; 终期阶段。

建设阶段
在本研究的第一部分，高层建筑结构全寿命周期评估涵盖到施工阶段完成阶段。此阶段包括了不同结构材料和部件的生产、将不同的材料运输到工地以及建筑结构的施工步骤。

施工阶段研究的第一步是在CTBUH会员网络中选出数位结构工程师可组成专家小组，进行会议并讨论确定最适合的研究案例 (请见文末有关专家小组的详细信息) 。

基于多种设计方案，位于芝加哥市中心的一座建筑被认为是最适合作为分析研究的基础性案例。该建筑入选主要原因是其在近期完成施工 (建筑本身于2009年竣工) 、其平面图 (可代表高级高层写字楼) 和它的结构体系 (中央有混凝土核心筒和重力耐热钢架) 。从建筑案例中提取的60层高楼的结构原型出发，专家小组设计出8种不同的结构变化 (如表1所示) 。此外，研究的边界也得到拓展，其中包括一幢具有相同设计结构的超高层建筑。由此方案推演出一座490m高的超高层建筑。在放大的过程中的大楼具有一定的可比性，但在同时也具有合理的比例。因此，核心窗口跨度维持在13.5m (因为它是实际项目，这也同样体现在芝加哥A类写字楼的平均跨度上)，层高维持在4m，核心筒大小反映类似高度办公楼的平均可出租面积的比例。在较低的建筑物中所采用的8个结构设计也被用在较高的建筑中 (见图1) 。

研究的下一阶段建立了的16种不同设计的材料目录以用于分析。这是每一个全寿命周期分析中的重要步骤，同时是ISO14040标准的要求。

为了完成这一基础性工作，十二个业内领先的著名结构工程公司提供不同情况的结构工程量信息。结构专家们为上述每一个建筑结构的研究提供了所需的钢材、混凝土、钢筋等材料。这一步骤不仅因行业领导者的经验和知识得到了最可靠的数据支撑，同时也提高了项目的认知。

建筑生命阶段
研究的另一个主要阶段是评估不同结构体系和结构在建筑不同生命周期中对环境的影响。

在所有建筑系统和材料中，结构部件被认为是建筑中最耐用的组成部分，在建筑存在期间经久耐用。世界上高层建筑中确实有一些重要的结构改动案例，如位于巴黎的"Tour First"，分别在2007年和2011年间经历了两次重大扩建和改造转型。由于进行了额外的结构加固，建筑高度从原来的159m增加到231m。

但是在通常情况下，一座高大建筑的结构体系并不会在建筑寿命周期中发生改变，而研究也发现，钢材与混凝土或者复合材料的选择不会大规模影响建筑物在全寿命周期的运行能耗 (相比于建设阶段或寿命末期) 。当然也会存在一些影响，例如混凝土在寒冷季节能提供更多热量以减少热损失，但是钢结构建筑中由复合

tallest building ever demolished voluntarily is the 186 meter tall Singer Building dismantled in New York in 1968.[1]

To acquire LCA information on the demolition procedure for the structures considered in this study, a double strategy was adopted: 1) the study of published information about the recent demolitions of real tall buildings, and 2) a survey on the demolition methods by industry leaders in this field. Regarding the first branch of analysis, very useful information has been found on the website of the "Lower Manhattan Development Corporation " (LMDC, 2014) regarding the dismantling of the 157 meter tall Deutsche Bank building (one of the buildings damaged during the collapse of the World Trade Center during the 2001 terrorist attacks in New York). The building was demolished between 2007–2011 in two separate phases (the deconstruction works were halted for several months after a fire 2007 that killed two firefighters). A further tier of the study assisted with identifying the suitable options that could be used to demolish a building with the size of the 250m scenarios used for this research (Mizutani & Yoshikai, 2011; Kayashima et al., 2012). This resulted in the exclusion of all methods that cause a sudden collapse of the entire building structure in such a dense urban scenario (thus controlled implosion with explosives and controlled structural failure), for a number of reasons that include: the catastrophic consequences of demolition errors, the insurance cost to protect the contractor from the damages occurred to adjacent buildings, infrastructure, etc., and the low compatibility of such methods within dense urban environments (dust, noise, vibrations and interference with other structures are the most limiting factors). Alternative dismantling techniques were consequently identified, and the key companies employing these technologies were contacted.

The second branch of the end of life study of tall buildings was made possible thanks to the support of three leading experts in demolishing large and complex projects: Brandenburg, Despe and Taisei. The three companies were provided with the following information needed to develop a demolition project for the 60 story scenario used for the research: schematic drawings of the building, load capacities of the structures and the inventory of structural materials obtained from the structural contributor. Four of the eight shorter scenarios were chosen for this study (see Table 2).

The results provided by the demolition experts include new, comprehensive information on the duration of the demolition works, the logistic arrangements, the equipment used by each contractor , and the amount of structural waste and debris produced as a result of the demolition process of each scenario, as well as the expected cost of the demolition job. The information obtained through this survey is currently being compared and integrated with the results of the literature study, to create an "inventory of materials and proccesses" for the end-of-life phase of the buildings. This phase of the study has not been completed yet and the results will be presented in the final report.

LCA Analysis

The information obtained on the multiple phases of the tall building structure has been used to create lifecycle plans with GaBi 6, an ISO-14040 compliant software widely accepted for doing LCA analyses. The software allows the insertion of individual processes to assess the entire production path of the product or system being analyzed (in this case the structure of a tall building). An important fact to be noted here is that LCA analysis is a relatively new discipline, compared to other centuries-old branches of science, used only occasionally for the analysis of products/

Scenario No. 方案编号	Scenario Studied for Demolition 方案描述
Scenario (方案) 1a	Concrete core with steel frame (Steel grade 345 MPa) 混凝土核心筒与钢框架 (钢等级345 MPa)
Scenario (方案) 1c	Concrete core and composite frame 混凝土核心筒与复合框架
Scenario (方案) 2a	All concrete structure with wide and shallow beams 全混凝土结构与宽扁梁
Scenario (方案) 3a	Diagrid (Steel grade 345 MPa) 斜肋构架 (钢等级345 MPa)

Table 2. The end-of-life of tall buildings being studied with the support of demolition experts
表2. 在爆破专家的支持下进行高层建筑寿命末期的研究

材料 (钢材和混凝土) 组成的高质量楼板也能确保舒适度。但是通常来讲，结构体系和材料的选择并没有显著影响建筑物寿命周期的能耗。相反，混凝土柱子比钢柱子占用更多的面积，而这意味着有可能需要更多的楼面积 (即: 一个额外楼层) 来实现相同的整体使用面积。

本研究项目中一个一个部分正在评估可以提供最大灵活性而能更好地适应未来市场需求变化的建筑材料和结构体系。本研究将收录一些非典型案例 (例如，如上所述的"Tour First"项目) 和一些根据住户要求或用来延长建筑使用寿命的一些小规模建筑更新或改动。这样的改变可能包括: 建筑物或整个楼层的添加/移除 (用于创建一个双倍高度的空间或加设电梯或楼梯)，增加或拆除内墙 (如当一个办公楼被改造为住宅或酒店大楼)，甚至是为了适应重型设备 (机械、空气处理机组或泳池) 而增强已有结构，或满足新的建筑规范和标准 (例如，符合新的抗震规范)。

建筑寿命末期

建筑寿命周期的末期是建筑物全寿命周期中的第三个主要阶段。首先收集以往高大建筑物的拆迁数据，并咨询专家现有建筑的未来拆迁计划。

即使建筑更低，60层楼高的建筑 (高度约250m) 的拆迁将是迄今为止完成的最高的建筑拆迁。事实上，历史上认为拆除的最高建筑是1968年拆除的纽约186m辛格大楼。[1]

为了获得结构拆卸过程的LCA信息，一项双重战略被采纳: 1) 对最近拆除的高层建筑的发布信息进行研究，2) 由行业领袖对拆卸方法进行调查。前者的研究得到了非常有用的信息，在"曼哈顿下城发展公司" (LMDC，2014年) 的网站上发现了关于157m的德意志银行大厦 (在纽约2001年恐怖袭击时世界贸易中心崩塌过程中损坏的建筑物之一) 的重要信息。该建筑在两个不同的阶段,2007-2011年间被拆除 (拆除工作在2007年两名消防队员牺牲的火灾之后的几个月进行)。在这些信息的基础上进行了高层建筑拆迁的另一些研究，包括确定拆除250m高建筑的方法，(水谷，吉开2011年;萱岛等，2012年)。这能够避免整个建筑结构由于多种原因在人口密集的城市条件下突然崩溃 (从而控制爆炸并防止结构损坏)，其中包括: 错误拆除的灾难性后果，防止相邻建筑物及基础设施损坏的保险费用，以及密集城市环境对这种方法的低容忍性 (粉尘，噪音，振动，与其他结构干扰是最重要的限制因素)。因此，确定了可替代的拆除技术，并建立了与采用此技术的重要企业的联系

该研究的第二个分支: 对高层建筑寿命末期阶段的研究，得到了大型复杂项目拆除领域三大主导专家的支持而进行。他们分别是: Brandenburg, Despe 和 Taisei公司。以下必要的信息提供给三家公司以进行一幢60层高楼的拆迁项目: 建筑示意图，结构承载能力以及结构材料清单。八个结构方案中高度较低的四个被选择用于本研究 (见表2)。

1: The World Trade Center Towers 1&2 in New York, cannot be considered within this list as their 2001 demolition was the consequence of a terrorist attack, rather than a controlled demolition.
1: 纽约世界贸易中心的塔1与塔2不应被归在这一类别中，因为它们的破坏是恐怖袭击所导致的结果，而不是一次可控的拆除。

assemblies as complex as buildings. For this reason some information is not readily available regarding specific materials/operations in the construction industry (such as welded wire fabric, metal decking sprayed-on fireproofing, etc.) and, especially, very little information on specific construction site tasks (such as crane lifting, formwork installation, spraying of fireproofing, etc.). Information on many "steps" of a construction work are simply not included in the standard inventories of processes and materials databases. Though it is believed that these operations represent, individually, a marginal fraction of the building construction's total environmental impact (which is largely represented by the embodied energy and emissions from the production of building materials), their cumulative impact may be more significant.

To fill these gaps, data is now being collected on multiple production/construction processes as part of this project, to both refine the information already available on the structural materials and develop new processes and plans on the specific materials and tasks that do not yet have standard procedures. This task is also made possible thanks to the involvement of product associations and individual manufacturers such as WorldSteel, ACME Refining and Bluff City Materials.

Initial Findings

At the moment of writing this paper the research is still underway and the final conclusion cannot be made with currently available information. However, some general trends can be identified:

1 – The initial results of this study show that, if the boundaries of the LCA are limited to the construction phase and without taking into account recyclability, Concrete structures show a lower embodied energy than Steel structures but, on the other hand, Steel structures cause lower emission of greenhouse gasses than Concrete structures. Though it might be thought that embodied energy and CO_2 emission should be proportional, this is not the case as the chemical reactions happening during the production of cement release significant CO_2 in the atmosphere

2 –Steel structures have a lower environmental impact (both in terms of greenhouse gasses and embodied energy) than concrete structures if the boundaries of the analysis are extended to include the end-of-life phase. In fact, steel structures benefit from the high recyclability of steel, which can be recycled an infinite number of times without a loss of its structural properties. Concrete, on the contrary, can only be reused in a "down-cycling" process, meaning that the characteristics of the recycled concrete are lower than the original material and it can typically be used as ballast material, filler and other non-structural applications.

Even if building structures are generally designed to last for many decades, programming their end-of-life through a detailed dismantling plan can significantly improve the environmental impact of tall buildings. Standardized steel profiles can be designed to be reused "as they are", without the need to be remelted in a furnace, thus resulting in a recovery of the environmental burden caused by their production. However, in order to fully benefit from the environmental advantages offered by the use of standardized steel profiles, an adequate system of norms must be developed at an international or regional level, in order to give to all relevant parties involved certified information on the previous life of each structural element.

3 – High Strength Steel (F450MPa) can contribute positively to the sustainability of steel structures by reducing significantly the amount of

由爆破专家研究的成果包括整个拆卸工程的的综合性信息，包括统筹安排，承包商提供的设备，每个方案拆除产生的结构垃圾和碎片数量，以及拆拆迁的预期成本。通过本次调查所获得的信息，并与文献研究的结果结合起来进行比较，为报废的阶段的建筑建立"材料清单"。 这一阶段研究报告的尚未完成但其结果将在最终报告中提出。

建筑全周期评估分析

在高层建筑结构的多个阶段获得的信息已经被用于创建GaBi6，一款被广泛接受的ISO-14040标准生命周期分析软件。该软件允许单个进程的插入，以评估该产品或系统 (此处指的是高楼的结构体系) 的整个生产路径。值得要注意的是，相对于其他具有百年历史的学科，生命周期分析是一个相对较新的学科，只能偶尔对像建筑物一样复杂的对象进行分析。因此，一些在建筑行业和建材具体操作方面没有现成的信息 (如焊接钢丝网，金属饰面板喷上防火等)，特别现场的具体施工信息更少， (如起重吊装，模板安装，喷涂防火等) 。施工中许多"步骤"的信息根本不包括在工艺和材料数据库的标准清单中。虽然人们认为这些操作对环境的影响并不显著 (这在很大程度上体现建筑材料固有能量和生产过程的碳排放) ，但是其累积影响可能会非常严重。

为了填补这些研究的空白，现在正在收集多个生产/施工流程数据，作为该项目的一部分。既细化已经可用的结构材料的信息，并制定具体的材料标准、新的工作流程和标准程序。这个任务还可能由产品协会和个别制造商参与，如国际钢铁协会，ACME炼油公司，以及Bluff City Materials建材公司。

初步成果

在写这篇文章时，研究仍在进行中，而最终结论需要更多的信息才能得出。尽管如此，一些总体趋势仍然可以被确定:

一、本研究初步成果显示，如果生命周期的评估 (LCA) 仅局限于施工阶段，并在未考虑到循环利用的情况下，相较于钢结构混凝土结构展现出较低的建筑物化能; 另一方面，钢结构的温室气体排放比混凝土结构的要低。虽然耗能和二氧化碳排放量是成比例的，但这种情况并不是水泥的生产过程中的产生的化学反应向大气释放二氧化碳。

二、如果分析的范围延伸至建筑寿命周期的末期阶段，那么较混凝土结构而言 (在温室效应和建筑物化能两方面来说) ，钢结构对环境的影响较低。事实上，钢结构受益于钢材本身的高回收性，可以在不损失结构性质的基础上得到无限次再利用。反之，混凝土只能够在"改造利用"过程中得到再次使用，这就意味着被回收的混凝土的特性要低于原始材料，并且通常被用于压载材料填充物和非结构应用。

即使建筑结构设计时一般使用期限可以持续几十年来，但在建筑生命末期时通过详细的拆解计划可以显著提高高层建筑对环境的影响。标准化的钢型材不需要在熔炉中融化便可保持现状得到重复使用，从而完全弥补它们在生产时对环境造成的负担。然而，为了可以从通过使用标准化的钢材所提供的环境优势中充分受益，适当的规范系统必须在国际或地区范围内开发，从而向在回收前使用过每个结构元件的所有人提供认证信息。

三、高强度钢材 (F450MPa) 可以通过显著减少所需的垂直结构部件 (以及节省由结构所占据的地面空间，从而可能减少所需的楼层数) 的结构材料数量而在钢结构的可持续性方面做出积极贡献。初步研究结果显示较高级别的钢铁在生产时未产生显著的环境影响。因此高强度钢材的使用可以得到提倡，从而减小高层建筑施工对环境的影响。

structural material required for the vertical structural components (and also saving floor space occupied by structure, thus possibly reducing the number of floors required). The initial findings show that no significant additional environmental effects are involved in the production of steel with high grades above lower grades. Its use can thus be advocated when possible to reduce the environmental impacts connected with tall building construction.

4 – Concrete components are responsible, even in what are considered entirely Steel structures, for about 65% of the total weight of the building, due to their use in floor slabs. This results in a heavy weight load on the whole structure. This number increases up to 80% if the foundations are considered. As a consequence, all measures that can reduce the environmental impacts of concrete (and in particular of cement, the component that is responsible for the largest portion of its negativities) can positively affect the sustainability of tall buildings, even of those that have steel as their main structural material.

The other important fact to be considered is that the reinforcement steel used in concrete structures or the concrete components of steel structures is responsible for a considerable impact on structures' environmental impact and embodied energy, especially when adding to this the more difficult recovery process and lower residual value of such elements.

5 – Height is, clearly, responsible for an increase in the embodied energy of the building. In other words, the taller the building is, the more materials (and thus energy) are required to build it. The effect of height on building structures has to do with the exponential effect of the horizontal loads on the building, and therefore a higher density of structural materials per unit area, as well as the higher amounts of energy used to hoist larger quantities of materials to a much higher altitude. However, vertical structures are responsible for a smaller share of the total materials in the supertall building scenarios than the horizontal floor elements, with up to 80% of steel and concrete used to build the horizontal elements such as the beams and floor system. Research on how to reduce the material content of the horizontal parts of a building will result in a significant reduction in material costs and environmental emissions – more significant proportionally than a reduction in the size of the vertical structure.

6 – The transportation of structural materials impacts typically 1–3%, though in some cases as high as 5%, of the total environmental burdens caused by the construction of tall buildings. The largest share of this is caused by the delivery of materials to the construction site, as materials are typically transported by truck. The upstream transport operations (transportation of raw materials to the production facility, intermediate steps during the production process, etc.) are, on the contrary, less impacting on the environment, because of the extensive use of more efficient means of transportation such as ships, barges and trains.

The transportation of demolition waste has a smaller impact, since this is typically deposited close to site than, for example, the transport of initial structural sections or façade elements to enable the building construction. (Marinkovic' et al, 2010).

7 – Fires can cause the structural failure of steel elements if they are not adequately protected with fireproofing materials such as intumescent paints, sprayed-on cement bases pastes or gypsum plasterboards (Goode, 2004). These three systems have variable environmental impacts, with gypsum plasterboards being the least impacting material. However, when cost comes into the equation, sprayed-on materials are the most common solution, especially for structural elements concealed behind suspensded ceilings. On the contrary, concrete is more resistant to the

四、由于在楼板中得到使用，混凝土构件占据了整个建筑约65%的重量 (即使建筑完全被认为是钢结构) 。这导致了整个结构较大的重量负荷。而这个数字在将地基算入的情况下将上升至80%。可得到的结果是，所有可以减少混凝土对环境的影响的措施 (特别是负面影响最大的成分水泥) 可以积极地影响高层建筑的可持续性，这其中也包括那些将钢材作为其主要结构材料的建筑。

需要考虑的另一个重要的情况是，在混凝土结构中使用的钢筋或是在钢结构中使用的混凝土构件都会对结构方面的环境影响和建筑内化能方面产生相当大的影响，尤其是在考虑到这些元素更困难的恢复过程和更低的剩余价值时。

五、很显然，高度是建筑内含能增加的重要因素。换言之，越高的建筑物需要更多的材料 (因此也需要更多能量) 来建设。建筑结构的高度受到建筑物水平载荷指数的影响。所以，每单位面积的结构材料密度增高，也需要更多的能量来支持工程量更大的材料从而到达一个更高的高度。然而，较水平楼面结构构件而言，垂直结构在超高层建筑的多种情况下仅仅占据总耗材的一小部分。其中具有高达80%的钢材和混凝土用来建设水平构件，如梁和地板系统。对于如何减少建筑物水平部件的建成材料的研究将会明显降低材料开销成本和环境排放量—— 相比减小竖直结构的尺寸大小要更加成比例。

六、通常情况下，运输结构材料的影响可达到高层建筑建设产生的环境负荷总量的1%—3%，在有些情况下可达5%。而最主要是因为材料通常由卡车运输到施工现场。相反，上游运输业务 (将原材料运输至生产工厂，在生产过程中参与运输) 对环境的影响较小，因其大量使用如一般的船舶、驳船和火车等更有效的运输方法。

工地废渣料的运输对环境影响相对较小，因为这些材料通常会被放置在建设基地附近，例如初始结构部分或用于建设的外墙支撑构件。 (Marinkovic' et al，2010)

七、若钢材结构未被适当的防火材料 (如膨胀型涂料、喷涂的水泥基底糊剂或石膏板 (Goode，2004)) 包裹保护，那么将极易在火势中受到破坏摧毁。这三种材料皆具有可变的环境影响，其中石膏板是最不易受影响的材料。然而，当涉及成本时，喷涂的材料则是最普遍的解决方案，尤其是对于藏在悬挂天花板后面的结构元件。相反，在火灾期间在建筑物内混凝土抵御高温的能力更强，可以开发出更耐腐蚀，并且耐火性相同的被嵌入在混凝土复合结构的钢型材。

目前研究总结

在高层建筑结构整个生命周期中多个部分、任务、步骤和环节中所有收集到的信息将被补充到专门的建筑生命周期计划中，以使研究达到最丰富的细节层次。生命周期评估 (LAC) 的结果将会被审查和讨论，并对每个阶段进行分析，从而提取出最相关的信息，正如在上述结果中得到的简要初步成果介绍。

本研究其余部分将在未来数月中完成，而最终成果会在2015年年初公布。

曾协助过结构工程方案的数位顾问也将参与最终报告的同业互查。本报告将通过CTBUH技术指南系列书籍中发布。

high temperatures that can develop during a fire in a building, and the same level of fire resistance is achievable in composite structures where steel profiles are embedded in concrete.

Towards the Conclusion of the Research

All the collected information on multiple parts, tasks, steps and procedures in the tall building structure's whole life cycle will be added to the specifically created life cycle plans so as to reach the highest level of detail achievable. The results from the LCA will be examined and discussed as a whole and the life-cycle of the tall building structures will also be analyzed in each phase, thus allowing the identification of the most relevant aspects, as it has been briefly presented in the initial results section above.

The remaining parts of the research are to be completed in the next few months and the final output is expected to be released in 2015.

A group of consultants who assisted with the creation of the structural engineering scenarios will assist with the peer review of the final report. This report will be published by CTBUH within its Technical Guide series.

Acknowledgements

This research project has been made possible thanks to a research grant from ArcelorMittal.

The authors would like to acknowledge the work and support of all other contributors to the research beyond those listed in the authorship of this paper: Payam Bahrami (CTBUH), Jean-Claude Gerardy (ArcelorMittal), Nicoleta Popa (ArcelorMittal) & Mattia Mercanzin, (Iuav),

In addition, the Council would like to recognize the following individuals and companies who have assisted in the structural engineering scenarios and who sit on the project Expert Review Panel:

- Arup – David Farnsworth
- Buro Happold – Erleen Hatfield
- Halvorson & Partners – John Viise
- McNamara/Salvia – Mark F. Aho
- Nishkian Menninger – Levon Nishkian
- Severud Associates – Edward M. DePaola
- SOM – Benton Johnson
- Thornton Tomasetti – Wolfgang Werner,
- Walter P More – Tim Santi
- Weidlinger Associates – Chukwuma Ekwueme
- WSP – Allen Thompson.

Other firms contributed to the different phases of the research, such as demolition contractors (Brandenburg, Taisei, Despe), Bluff City Materials, Clark Construction, Gerdau Ameristeel, ACME Refining, MBL Recycling.

Special thanks also to Don Davies (Magnusson-Klemencic Associates) who has contributed a high degree of time and energy to the project, beyond just the remit of the peer review panel.

致谢

本研究项目由阿塞洛尔•米塔尔集团提供赞助支持。

在此，作者想要对所有为此项研究做出贡献的人表示感谢，他们是: Payam Bahrami (CTBUH)，Jean-Claude Gerardy (ArcelorMittal)，Nicoleta Popa (ArcelorMittal)和Mattia Mercanzin, (Iuav)。

同时，CTBUH还要感谢以下在结构工程方面提供帮助和担任项目专家评审组成员的公司及个人:

- Arup – David Farnsworth
- Buro Happold – Erleen Hatfield
- Halvorson & Partners – John Viise
- McNamara/Salvia – Mark F. Aho
- Nishkian Menninger – Levon Nishkian
- Severud Associates – Edward M. DePaola
- SOM – Benton Johnson
- Thornton Tomasetti – Wolfgang Werner,
- Walter P More – Tim Santi
- Weidlinger Associates – Chukwuma Ekwueme
- WSP – Allen Thompson.

以及为研究的不同阶段做出贡献的其它公司，包括: 拆除工程承包商 (Brandenburg，Taisei，Despe)，Bluff City Materials，Clark Construction，Gerdau Ameristeel，ACME Refining和MBL Recycling。

特别感谢Don Davies (Magnusson-Klemencic Associates)，为项目投入了大量时间和精力，远远超过了同行审查组成员的责任范围。

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