Title: **Steel and Skyscrapers: A Productive History and a Sustainable Future**

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Steel and Skyscrapers: A Productive History and a Sustainable Future

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Nicoleta Popa has managed, coordinated and advised on research projects featuring partners and subcontractors from across Europe, the United States, and China. Each project aims to increase steel's sustainability contribution to the construction of tall buildings, with deliverables including new products and solutions; modifications to standards, codes, and regulations; and development of new technical agreements, design aids, promotional materials, and campaigns. Popa's expertise includes sustainability, cost optimization, composite construction, fire design, and building physics.

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Abstract

This research aims to demonstrate recent developments in the partnership between steel and skyscrapers. It highlights steel's sustainability characteristics and explores the impact that the material and its supply chain have on the complete life cycle analysis of a building. The study summarizes climate-action initiatives in the steel production industry, recognizing how responsible producers are striving to reduce the carbon impact of this reliable structural material. It explores the material's influence on design and construction efficiencies, alerting designers to a selection of the latest innovations in specifications, design methods, and evaluation ideologies. The overarching goal of this research is to unlock creativity in the design community by presenting experts with a summary of new ideas on how to create sustainable, cost-effective, optimized buildings for the future.

Keywords: Steel, Sustainability, Skyscrapers, History

Introduction

Steel and the skyscraper have a partnership that spans more than a century (see Figure 1). In combination with various advances in building technologies, steel enabled the 1930s surge in high-rise construction and high-strength steel led to its 1970s renaissance. As the tall building revolutionized the urban landscape—facilitating the reorganization of societies and their priorities—steel, due to its affordability and durability, has always been the material of choice for the design and construction of building's primary structural systems. Today, however, society's burgeoning concern for sustainable development and conflicting messages on the affordability, safety and environmental impact of steel have resulted in confusion about its place in high-rise construction. Steel has, in fact, benefited from recent technological advancements that improve its sustainability profile. Its role in complete life cycle assessment of a building provides insights on climate-action initiatives that steel producers are implementing to address global warming concerns. Summarized herein is a selection of the latest innovations in specifications, with a focus on very high-strength steels, which can help reduce the amount of steel used in buildings. Also covered are design methods, emphasizing ways to simplify fabrication and erection, which can help to reduce the amount of energy used in construction of a building; and evaluation ideologies, aimed at standardizing floor area measurements, which can help increase the operational efficiencies of buildings, and therefore positively influence their environmental impact.

Sustainability of Steel

According to the United Nations and International Energy Agency (UN, IEA 2017) the built environment is responsible for 39% of global energy-related CO_2 emissions and more than 35% of global final energy use. Therefore, to meet the global ambition of limiting the worldwide temperature change to 2°C above pre-industrial levels, it is imperative that all members of the development, design and construction communities take responsibility to achieve this goal. In particular, members must be educated on the wholesale environmental impact of buildings; they must understand the mechanisms that positively and negatively affect sustainable outcomes; and they must base their design choices on the true characteristics of a material—ranging from product details to the sustainability initiatives implemented by producers.

Life Cycle Assessment of Tall Building Structural Systems

Striving to inform the community on the true environmental impact of the building industry, CTBUH endeavored on a two-year-long research project to analyze the whole life cycle of a tall building's structural system. Supported by ArcelorMittal, the project studied the extraction and production of the structural system's building materials, transportation of said materials to site, construction operations, final demolition of the building, and the end-of-life of the materials" (Trabucco, et al. 2014, 2015, 2016). As the first complete life cycle assessment (LCA) to be performed on tall building structural systems, the project faced a myriad of decisions to isolate variables and determine the best course forward in evaluating impacts. Ultimately, it was determined that the project would focus on global warming potential (GWP) to evaluate the amount of carbon that is released throughout the life cycle of a structure; and on embodied energy (EE) to serve as an indicator of the consumption rate of electricity, fossil fuels and natural gas during a building's lifetime.

Among many conclusions, the results of the LCA study reconfirmed one issue that is already understood: obtaining an accurate LCA is not yet an exact science. Its challenges lie in the selection of appropriate boundary conditions, establishment of assumptions, and in the sensitivity of its outcomes to even the smallest decisions of a project. Therefore, it is important that project stakeholders (designers, consultants, and materials suppliers) work together early in the design process to ensure that structural systems are highly optimized and use innovative

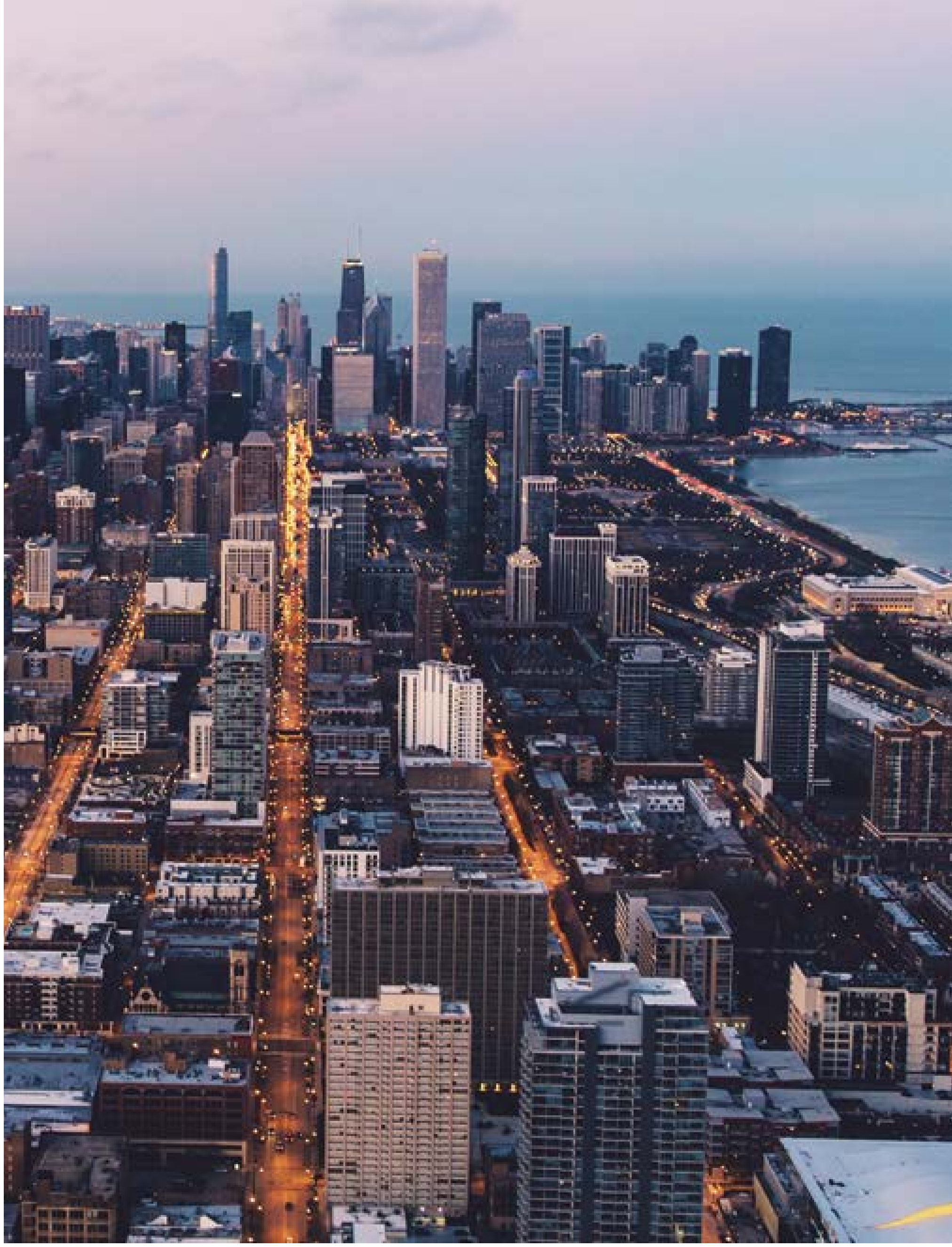

Figure 1. Steel enabled the 1930s surge in high-rise construction, and high-strength steel led to its 1970s renaissance. © Austin Neill (cc by-sa)

products that positively affect the sustainability bottom line (e.g., through energy-saving production methods, by reducing the weight of material in the final structural system, etc.). Narrowing the discussion to conclusions of interest for this study, the LCA study revealed that:

1. On average, design solutions based on steel typically demonstrate better environmental performance when compared to concrete systems. More specifically, in terms of GWP, steel systems always outperform concrete with lower GWP values. For EE values, steel systems outperform concrete when considering the life cycle through "Module D", which accounts for the benefits of end-of-life recycling of steel; however, as an optional module for assessment, it is at the evaluator's discretion whether or not this is taken into account, and results can differ if Module D is ignored.

2. The recyclability of steel benefits all tall building scenarios at the end of their life cycle, as even concrete buildings feature recyclable steel reinforcing bars. Though disparate opinions exist on whether this benefit should be realized, the LCA study concluded that the high recycling potential is an intrinsic value of steel and this 'credit' should be

communicated as part of the additional information necessary to make an informed decision on the environmental properties of a structural system (Trabucco, et al. 2015, 2016).

3. Transportation of construction materials and demolition waste does not significantly impact a building's LCA. Therefore, if a material with better environmental performance can be sourced from a supplier that is distant from the project, its influence on the sustainability of the overall structure should be taken seriously. This suggests that if, for example, steel is being considered for a project in China, and said project would see the sustainability benefit (e.g., less material demand, simplified fabrication, reduction in labor hours, etc.) by using a product from Europe, then the distance it must travel is not expected to outweigh the environmental benefit that the product brings to the LCA.

4. Horizontal systems (beams, floor slabs, etc.), which represent anywhere from 30% to 80% of the weight of a building (50% to 80% in shorter scenarios and 30% to 60% in taller scenarios) can have a considerable effect on the environmental impact of a building.

5. Significant environmental benefits can be realized by choosing the optimal material provider. Therefore, it is important for designers to be aware of the sustainability practices of material producers and be aware that using specialty materials (i.e., very high-strength steels) from responsible suppliers can bring significant sustainability benefit to projects, in the form of reduced carbon impact from the production site, to the construction site.

Responsible Sourcing

According to the UN World Commission on Environment and Development's *Our Common Future*, sustainable design is an effort to meet the requirements of the present without compromising the needs of future generations (WCED 1987; Ali, Armstrong, 2009). In that vein, the tall-building design and construction community—which is composed not only of the developers, architects, engineers and contractors who design and build them, but also a wide range of material suppliers, software developers, and building systems manufacturers, who support them—must engage in a highly coordinated effort to ensure that sustainability goals are achieved.

Putting the lens on material producers, it is particularly important for design teams to be aware of the sustainability initiatives in which their producers engage. From recycling, repurposing, and reducing waste produced during their industrial processes, to addressing climate challenges in a holistic manner, responsible producers understand the importance of discovering new methods of furthering economic and social development, while also minimizing environmental impact.

> "Most tall-building steel originates from scrap-based electric-arc furnace processing, but end-of-life steel scrap is expected to meet less than 50% of steel needs by 2050."

As a model example, steelmaking methods and processes have continuously evolved and improved. Today, close to optimal energy efficiency levels have been achieved with almost all end-of-life scrap and byproducts being both recycled and reused. The next transition—to very-low-emissions steelmaking—is not only possible, but also achievable, based on technologies that enable the reduction or elimination of carbon emissions.

For example, ArcelorMittal has committed to significantly reducing its carbon footprint by 2050 (ArcelorMittal 2019a). The company has lowered its carbon footprint by 21% since 2007 (ArcelorMittal 2019b)—an achievement resulting from improvements in the technical carbon efficiency of its steel plants. It has identified three main technological pathways, which it is actively engaging to continue toward its goal: (1) the use of waste sources of carbon in place of coal, in combination with carbon capture utilization (CCU); (2) electrolysis or hydrogen-based steelmaking, powered by large volumes of renewable energy; and (3) carbon capture and storage alongside the continued use of fossil fuels.

The company's clean power initiatives include the use of bio-coal in place of fossil fuels, to reduce the demand for coal and coke in blast furnace operations; engagement of carbon capture and storage (CCS) technologies in conjunction with carbon capture and utilization (CCU) technologies, which enables the production of up to 80 million liters of ethanol per year. This is equivalent to saving CO_2 at a rate of 600 trans-Atlantic Boeing 747 flights annually. Hydrogen-based and direct-electrolysis ironmaking is already being employed in Hamburg, Germany, and should enable the organization to be first steel producer in the world to operate a zero-carbon emissions mill.

Though these efforts are primarily related to production of steel via blast furnace, basic oxygen furnace and direct-reduction iron routes, it is important for readers to recognize that most tall-building steel originates from

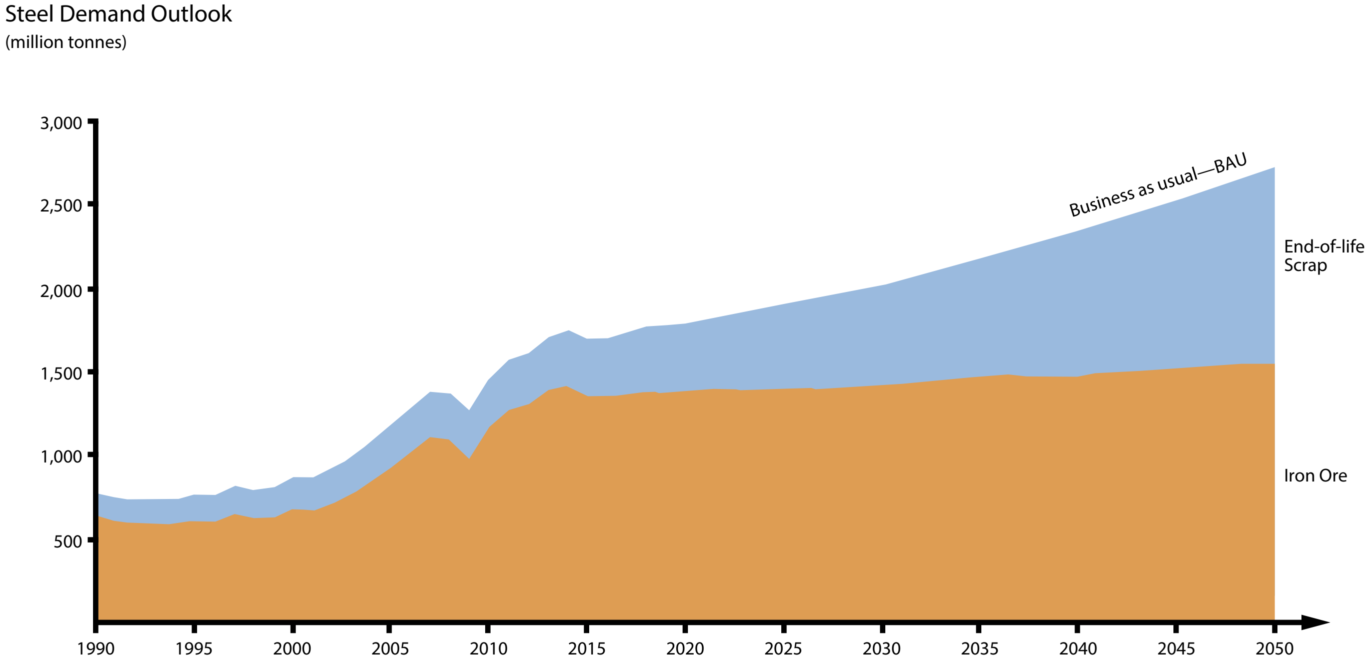

Figure 2. The steel demand outlook is robust, and increasingly, supply will come from recycled scrap. © ArcelorMittal

scrap-based electric-arc furnace processing. And, because forecasts show that end-of-life steel scrap is only expected to meet less than 50% of steel needs by 2050 (see Figure 2), what is achievable in upstream iron-ore-based production will continue to play an important role in meeting the world's demands for sustainable steel well beyond 2050.

Steel and Skyscrapers: A Partnership Through Time

Steel's contribution to the development of affordable, durable, and—most important—sustainable structures has made it a preferred tall building construction material for more than a century (see Figure 3). Enabled by advances during the Industrial Revolution—from the development of high-volume steel production techniques by Neilson and Bessemer, to the invention of the wide-flange rolling process by Henry Grey—the design of a steel-framed structure was revolutionary (Finnigan, et al. 2015). The system replaced bulky load-bearing walls with comparably petite structural elements, which allowed design teams to not only

Figure 3. Steel's contribution to the development of affordable, durable, and—most important—sustainable structures has made it a preferred tall building construction material for more than a century.

From left to right: Flatiron Building, New York City, 1902 © Detroit Publishing Company via CTBUH; Sears Tower, Chicago, 1974 © Steveboerger (cc by-sa); River Point, Chicago, 2017 © ArcelorMittal

100 Tallest Buildings by Region

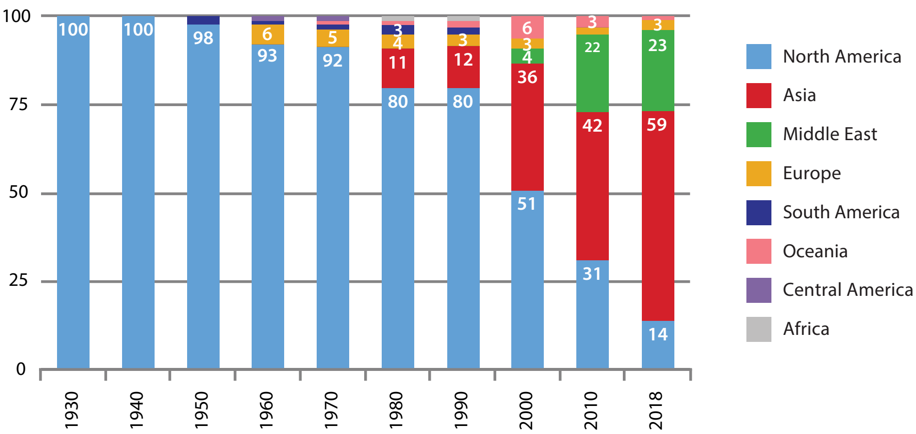

Figure 4. Asia dominates the globe as host to tall buildings, with 59 of the world's top 100 existing within its borders. © CTBUH

"reach for the sky," but also create buildings with plentiful floor space to accommodate their everyday functions.

Today, the steel industry upholds its commitment to the skyscraper, with material producers engaging in continuous improvements that have led to innovations in specifications, design methods, and evaluation ideologies—all of which are helping to create the cost-effective, optimized buildings of today and the future. Though a myriad of advancements could be listed across the steel industry, the focus of this section will be the headway in hot-rolled structural shapes, their specifications, and design methods and evaluation ideologies to which they directly relate.

Specifications: Pioneering High-Strength Steels to Limit Environmental Impact

One of the most traditional methods of employing steel to achieve sustainable tall-building construction solutions is derived from very high-strength versions of the material to reduce the weight of the primary structural system. The beneficial consequence of this practice is a more favorable environmental impact, due to reduction in embodied energy value for the elements and reduction in carbon emissions during construction—up to a 30% reduction can be realized. Setting the stage for designers to employ this strategy requires years of product development and testing followed by modification of design standards—across the globe—to remove any obstacles that may arise when a building's permitting process is underway. Recent developments in this context include introduction of 80-ksi [550-MPa] structural shapes to ASTM, which is included in the ASTM A913/A913M specification (2019); publication of the Chinese Standard GB/T 33968-2017 (2017), which enables designers to use rolled shapes with yield strength up to 500 MPa; and initialization of discussions on expanding composite design standards (AISC 2016) to enable the use of steel rolled shapes with yield strengths of up to 80 ksi (550 MPa).

Composite Megacolumns: Optimization of Sourcing, Construction and Erection

Asia dominates the globe as host to tall buildings, with 59 of the world's top 100 existing within its borders (CTBUH 2019) (see Figure 4). The shortest building in this category stands at 315 meters (70 stories). Based on Ali & Moon's new classification of tall building structural systems (2018), which advanced Fazlur Khan's original charts, buildings of this height and above lend themselves to design featuring core-outrigger systems for interior structures or a wide range of options for exterior structures. Ali & Moon also confirm that core-outrigger structures are frequently given preferential application due to their structural and architectural efficiency, a belief which is evidently correct, based on the frequency with which said system is employed in the Asian market.

Elaborating further on the utilization of core-outrigger structures in Asia, it is common practice to pair these with megacolumns of composite construction, with a preference for using complex concrete-filled tubes (CFTs). Though these robust elements are well-equipped to handle in-situ loading demands, they are arguably inefficient to construct, for the following reasons, among others:

As built-up sections, by nature, CFTs require significant shop welding; they are typically limited to one-story "lifts", due to their substantial unit weight; and their welded splice connections are difficult to detail and execute, due to their maze-like plan configurations. In addition, field-splicing at every floor results in an increased potential for quality-control issues, as well as increased susceptibility to field-safety issues, with iron workers forced to perform welding at increasingly extreme heights. Nonetheless, as a dominant form of construction, in a market that is frequently constructing tall buildings, it is imperative that efficiencies be found, not only for the design of these systems, but also their construction.

To address this challenge, CTBUH published *Composite Megacolumns: Testing Multiple, Concrete-Encased, Hot-Rolled Steel Sections* (2016), which suggests design methodologies that serve as best practices in using multiple, discrete hot-rolled steel sections encased in concrete (henceforth referred to as "composite columns") in place of complex CFTs for composite megacolumns (Trabucco et al. 2016). The goal of this publication was to encourage use of this alternate construction typology to simplify erection. Based on Chinese, European and US codes, the simplified calculations have been tested using 10 scale models (six of which were subjected to static loading, and four were subjected to quasi-static loading), which were further validated using finite element models developed by China Academy of Building Research (CABR) and ArcelorMittal (see Figure 5).

Industry-Accepted Criteria for Measuring Tall Building Floor Area

Floor-area definitions are critical to a variety of decisions in the development of tall buildings: they are used by architects, engineers and builders to enable the design and construction of buildings and their associated systems; they serve as the basis on which developers estimate real estate values; they factor into property managers' determinations of operational efficiency; and they affect the ability of tenants to evaluate whether a particular space is adequate for meeting their usage needs. It is imperative to the economic sustainability of multinational corporations that clearer understanding of this number is gained—no matter the market. To support this objective, CTBUH recently engaged in a sponsored research project focused on establishing industry-accepted criteria for measuring tall building floor area.

Composed of more than 80 professional and non-profit organizations from around the world, International Property Measurement Standards Coalition (IPMSC) was established by the World Bank in 2013 with the sole mission of developing and implementing international standards for measuring floor area of property. As part of its study, CTBUH was invited to join IPMSC to contribute considerations on the unique aspects of tall buildings and their impact on the development of an internationally-accepted standard. CTBUH based its arguments for appropriate evaluation methods on cross-examination of numerous international floor-area measurement standards—including those published by Royal Institute of Chartered Surveyors (RICS) in the United Kingdom; Building Owners and Managers Association (BOMA) in the United States; the Hong Kong Buildings Department; Property Council of Australia (PCA); and the Urban Redevelopment Authority (URA) in Singapore (Miranda, Trabucco 2019).

The result of this research is a proposal, currently being discussed within the IPMSC Standard Setting Committee, to add one more measurement standard that would somehow reflect what is usually called "carpet area": the floor area of a building that is actually available for the intended functions of the building's design (see Figures 6 and 7). This measurement number is of the utmost importance, not only for real-estate transactions and comparisons, but because it would become the ultimate parameter used by numerous professionals to evaluate the building and to design most of its services. With an actual, agreed

Figure 5. Composite megacolumns were tested for a CTBUH research project at the China Academy of Building Research. © CABR

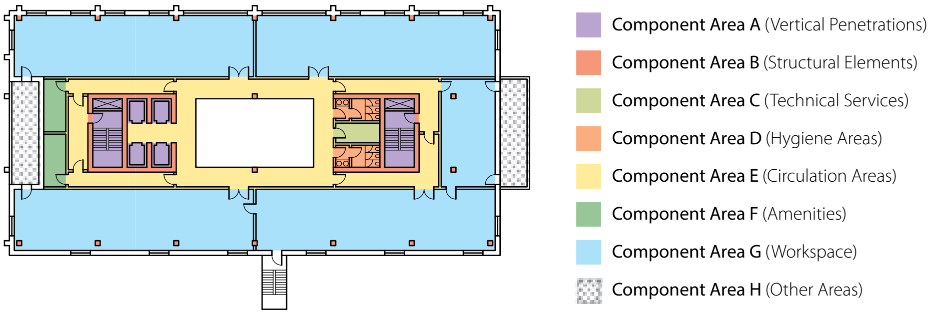

Figure 6. An example of IPMS-2 for office buildings, separated by the IMPS Component Areas. © CTBUH, IPMS

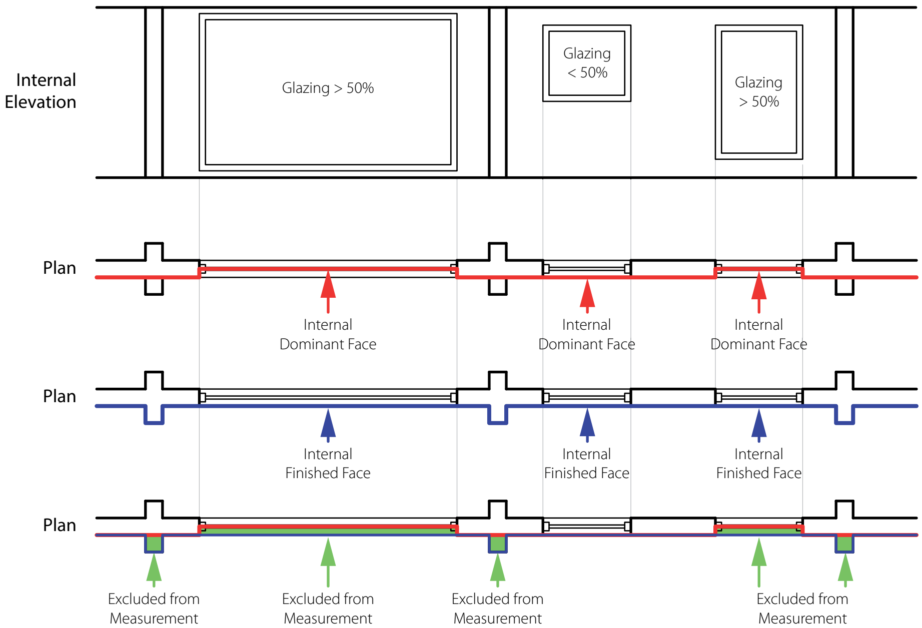

Figure 7. Comparison of Internal Dominant Face (used in IPMS-2 definition) with Internal Finished Face (to be used in the new IPMS-4 standard, currently being drafted). © CTBUH, IPMS

> “Using ASTM A913 Grade 65 (450) steel enabled a 17% (215-ton) reduction in the weight of the gravity columns in the Northwestern Mutual Tower and Commons project.”

Figure 8. Northwestern Mutual Tower and Commons, Milwaukee, employed high-strength ASTM A913 Grade 65 (450) steel to reduce the amount of material required to meet the loading demand on the steel gravity frame. © ArcelorMittal (Rob Caroti)

measurement of the floor area available, one can gain a better understanding of the possible occupancy of the building, and from this, appropriately design means of egress, air-conditioning and elevator systems, etc.

IPMS has already been adopted, in various forms, across the globe: the Dubai Land Department uses IPMS as the official standard in property measurement; the Royal Institute of Chartered Surveyors (RICS) (United Kingdom) mandates the use of IPMS measurement standards, or in cases where an alternate standard is requested by a developer, dual reporting is required. The Australian Property Institute (Australia) recommends dual reporting based on IPMS and PCA standards; while BOMA (USA) fully incorporates IPMS guidelines in its BOMA 2017 publication. Increasing acceptance of this criteria suggests that buildings will move toward more sustainable structural systems, especially as these standards encourage the use of structural elements with efficient footprints to therefore maximize usable floor area measurements.

Bringing It All Together: The Economics of Using Steel For Sustainable Tall Buildings

To exemplify the mutually beneficial relationship among tall buildings, steel and sustainability, this study looks at the Northwestern Mutual Tower and Commons (see Figure 8) located in Milwaukee, Wisconsin. An office complex composed of two primary structures—a 32-story tower and five-story building at its base. The $450 million project not only features spaces to meet the operational needs of Northwestern Mutual, but it also contains a selection of concourses, exhibit spaces and dining areas that welcome the general public into this iconic building.

Constructed with a steel gravity frame and concrete core, the office tower employs Ali & Moon’s interior structure-based system, which suggests that structural efficiency was at the forefront of the project team’s considerations in designing the building.

Taking these efficiencies a step further, the team also employed high-strength ASTM A913 Grade 65 (450) steel to reduce the amount of material required to meet the loading demand on the steel gravity frame. The benefit of using this product was multifaceted, as it not only enabled a 17% (215-ton) reduction in the weight of the gravity columns in the building, compared to Grade 50 (345) steel. It also allowed for additional fabrication and erection benefits, including reduction in the amount of material and labor hours required for: reinforcement of elements (namely, elimination of 15 flange-plated columns, and elimination of reinforcing web and stiffener plates at some column connections), elimination or reduction of energy input (in the form of pre-heat and complex temperature control) for heavily-welded column splices, and implementation of smaller welds at column splices.

The overarching benefits of this project, while not explicitly evaluated for LCA outcomes, have implicit sustainability benefits, by way of reducing the amount of material (and related production waste) in the steel system; engaging labor more efficiently during fabrication and erection of the building (saving 35% in associated costs per column); and increasing the economic efficiency of the structure—saving the developer more than $800,000 in the overall fabrication and erection costs for the building (AISC 2017).

Conclusion

"Sustainable development is not a fixed state of harmony, but rather a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are made consistent with future as well as present needs" (WCED 1987). With the understanding we have today of the unintended consequences of using fossil fuels, it is increasingly important for the world to find a new way of doing things that enables further economic and social development, while minimizing environmental damage. Therefore, just as the tall building revolutionized society's relationship with the urban environment, steel is transforming its own relationship with tall buildings and sustainable development. Now, it is up to the project owners, developers, designers and builders to heed the recommendations of experts who have spent years studying the problems associated with environmentally conscious design, embrace innovative solutions, and utilize highly sustainable building products in ways that will continue to reduce our carbon footprint and enhance our future. ■

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