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Steel and the Skyscraper City: A Study on the Influence of Steel on the Design of Tall Buildings

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At the turn of the century, building design began to evolve. Improvements included indoor plumbing, the advent of escalators, and creation of the "Chicago window." Perhaps the most notable change was the development of the skyscraper. Innovations in steel production were integral to the era of the skyscraper. In 1897, Henry Grey revamped the rolling process to include wide-flange sections, enabling designers to create taller, more efficient structures. Improvements continue to influence the skyscraper city and its revival. From Bay Adelaide in Toronto; to 150 North Riverside in Chicago; to 1WTC and 225 West 57th Street in New York, many projects have been designed and constructed quickly and efficiently thanks to processes that have doubled the yield strength of wide-flange beams. Over the history of steel in tall buildings, innovations in its production have brought increased efficiency and sustainability to projects around the world.

At the turn of the 20th century, horse-drawn carriages filled the streets, only 39 percent of the U.S. population lived in cities, and the Wright Brothers were just taking flight. Buildings were built much as they had been for centuries, but that was about to change.

The Industrial Revolution Leads to the Mass Production of Steel

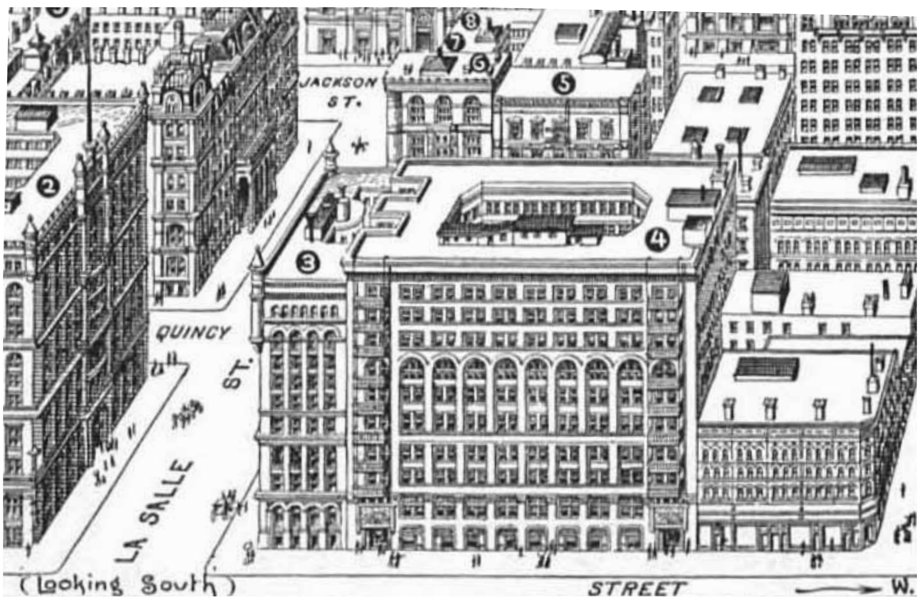
It is important to note that before the 1800s, steel was expensive and challenging to produce, making it a material that was used in limited applications – most notably for the blades of swords, knives, razors, and surgical instruments. It was not until the 1800s that two important changes to the processing of iron ore set the stage for producers to start the mass production of iron, and eventually steel.

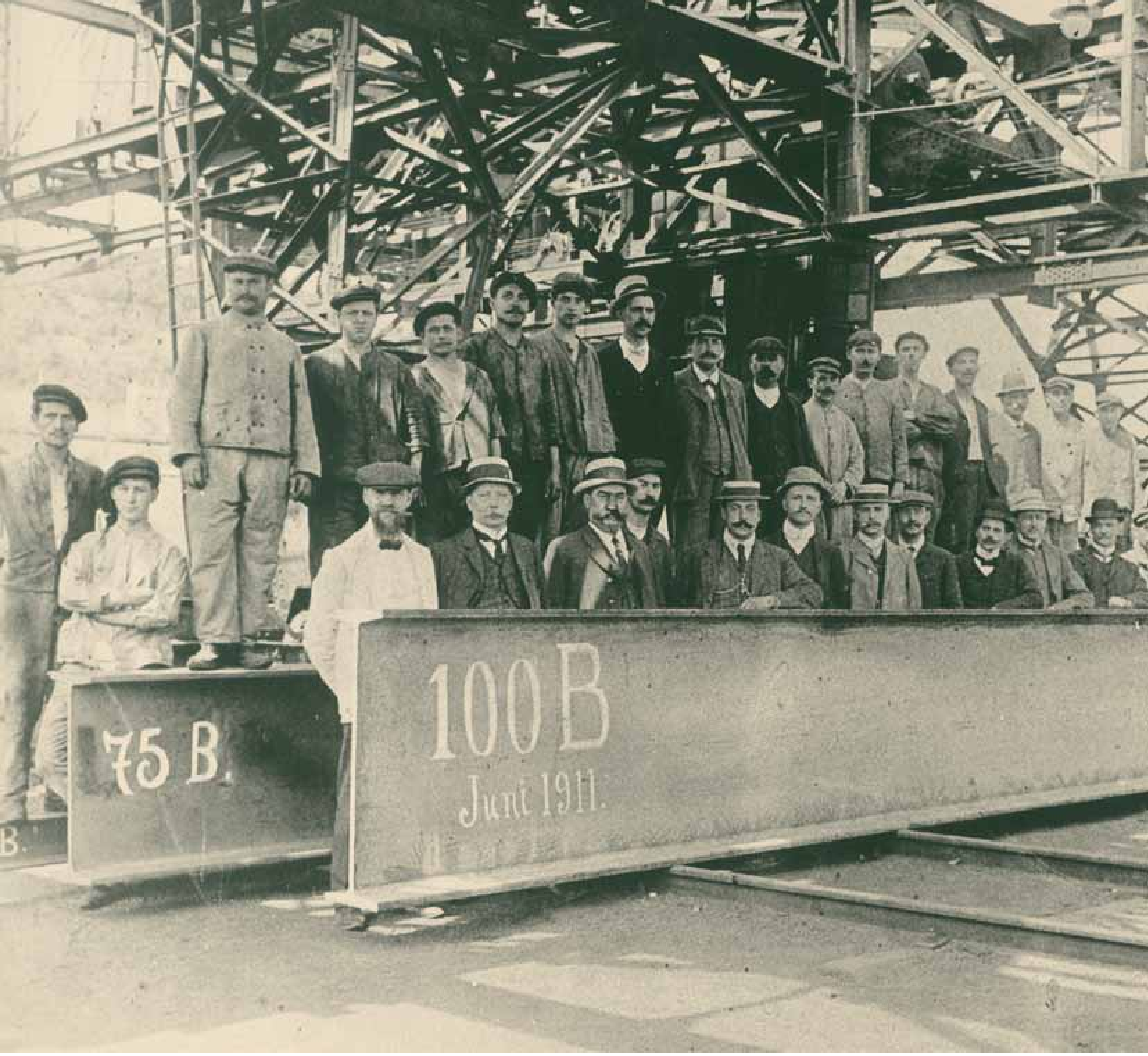
The first development of note came from the Scottish ironworks industry in 1828. While working on a blast furnace at his facility, engineer James Beaumont Neilson recognized that the furnace could run more efficiently if hot rather than cold air was forced through the system. A blast furnace operates as follows: iron ore and limestone are heated to temperatures exceeding 2,000 degrees Fahrenheit (1,090 degrees Celsius), thereby forming a molten liquid composed of iron and slag. Similar to using a bellows to strengthen the fire in one's hearth, forced air helps facilitate heating of the system by burning the fuel source. Typical fuel sources of the time were coal – a natural resource readily available throughout the world – and coke – a man-made derivative of coal with a high carbon content. Prior to the invention of the hot blast, coke was the preferred source of blast furnace fuel, due to its low ignition point and, therefore, its compatibility with the cold blast. Preferences shifted, however, when Neilson introduced the hot blast. The preheated air enabled efficient burning of coal, thereby leading to not only lower costs for fuel but also a reduction (up to 33 percent!) in the amount necessary to run the furnace.

The second development of note was by Sir Henry Bessemer in 1856. During the Crimean War (October 1853 – February 1856), Bessemer – a self-made English inventor – became fixated on improving the process used to make steel for military ordnance. As a result, he invented the Bessemer converter and so-called Bessemer process, from which molten iron could be transformed into high-quality steel quickly and in large quantities.

Prior to Bessemer's invention, the most reliable steel production method was the crucible process, a technique in which wrought iron, combined with charcoal, is melted in a clay and graphite pot, or crucible. Tedious and expensive, it could take hours to heat the crucible and subsequently liquefy the base materials. In addition, one crucible, with its full load, would need to be small enough to be manually lifted out of the furnace. As expected, these limitations left it nearly impossible to create vast quantities of the metal.

In the Bessemer process, on the other hand, more than 15 tons of molten iron could be fed directly into the converter. Air would then be forced through the material, and oxygen would combine with impurities in the iron, thereby pulling them out and leaving behind liquid steel. Based on the size of the converter and the efficiency of the process – a batch of steel could be created in





less than 20 minutes – Bessemer's invention set the stage for steel to transform from a niche product to one of the most readily available materials in the world.

Invention of the Wide-Flange Section Leads to the Birth of the Skyscraper City

The first uses of mass-produced steel were limited primarily to the railroad industry. It was not until 1889 – 30 years after the invention of the Bessemer process – that the world saw its first all-steel framed building. The Rand McNally Building (1889–1911) was a 10-story facility designed by architects Burnham and Root, with support from the structural engineers Wade and Purdy and Theodore Starrett. Constructed in Chicago, the building was home to Rand, McNally & Co., a printing and publishing company.

The revolutionary building featured more than 3,700 tons of steel (Chicagology 2013). The material was used in the form of beams, channels, rails, angles and the newly introduced Z-bar steel columns, which were fabricated by riveting four Z-shaped sections to a central plate, thus creating an I-shaped member with upturned tips at each flange toe. The Rand McNally Building represented a new era of efficiency in building systems. The use of steel meant that as the height of the building increased, the proportional increase in support structure at the building's base would be much lower than that required for masonry walls. As a result, the encroachment of the structure on usable interior space was significantly reduced.

Opposite: Artist's rendering of the original Rand McNally Building, Chicago. (cc-by-sa) Rand McNally (1893)

Top: First production of 40-inch-deep Grey beam. Source: ArcelorMittal

While an engineering marvel of its time, the Rand McNally Building likely served as an example to developers of the expense involved in reaching these new heights. After all, the built-up column sections necessitated drilling, riveting and thoughtful detailing of the plate that composed the member. The labor hours associated with the extra fabrication of these pieces no-doubt drove up the overall costs of construction and left the door open for simpler members composed of a single piece.

A promising replacement to built-up sections started to take shape in the late 1840s. At Forges de la Providence, a Belgian steel company, Alphonse Halbou developed a method to produce I-shaped members from a single ingot. By the 1880s, the I-shaped section was created by sending a rectangular piece of hot steel through horizontal rollers (axis parallel to the ground) and compressing the web of the section. The flanges were formed when the steel, soft from being heated to elevated temperatures for rolling, moved to fill voids at the edges of the rollers. From an engineering perspective, the I-shaped member had obvious benefits, including the ability to resist shear forces with its web, bending moments with its flanges, and provide more rigidity to the building due more efficient distribution of the area. However, because the flanges were formed in a somewhat passive manner, there were often irregularities in this portion of the section. As a result, early generation I-shaped columns were only reliable for supporting buildings of up to 20 stories.

In the late 1890s, Henry Grey, an English engineer working for the steel industry in the United States, developed a rolling process that would take the I-shaped member to the next level. The process he created used both horizontal and vertical rollers (axis perpendicular to the ground) to create the I-shaped profiles. By applying forces simultaneously to the web and flanges, and subsequently to the tips of the flanges, Grey controlled the distribution of steel throughout the section. Grey's innovation made the rolling process more reliable and helped to alleviate the oft-encountered problems of flange cracks and high internal stresses in I-shaped profiles.

In addition to devising this new rolling process, Grey had an integral role in creating the wide-flange section used today. Grey's rolling stands were built in a way that the rollers themselves could be moved inward or outward to adjust not only the thicknesses of the flange and web but also the width of the flange. With his technology, Grey enabled the production of sections up to 44 inches (1,100 millimeters) deep and those with flanges in excess of 20 inches (500 millimeters) wide (Follweiler 2010). Though Grey's technology was developed and initially tested in the United States, the first mill to be constructed with his rolling stands was located in Differdange, Luxembourg.

Completed in 1901, the Differdange mill rolled its first of the new generation wide-flange members in September of that year and the first successful 40-inch- (1,000-millimeter-) deep section in June 1911. The linear weight of this profile was more than 200 pounds per foot [lb/ft] (300 kilograms per meter [kg/m]). Upon completion and opening of the first Grey mills, the second of which was built in Bethlehem, Pennsylvania, the era of the skyscraper began. Numerous steel-framed buildings constructed between 1901 and 1929 became the world's tallest, but it was not until 1930, with the completed Chrysler Building in New York City reaching 1,046 feet (319 meters), that steel buildings eclipsed the world's tallest structure, the iron-framed Eiffel Tower.

Constructed with more than 20,000 tons of steel that had a yield strength of approximately 30 kips per square inch [ksi] (200 megapascals [MPa]), the race to the top for the Chrysler Building was accompanied with plenty of drama. Originally designed to stand 808 feet (246 meters) (Assad 2010), the ultimate building height rose when automotive mogul Walter Chrysler started competing with banker George Ohrstrom to construct the tallest building in the world. Ohrstrom was funding the Bank of Manhattan building and pushed for the development of a building that would be 945 feet (288 meters) tall. Upon discovering this, the team behind the Chrysler Building reached higher – designing and constructing the 1,046-foot- (319-meter-) tall building, a feat made possible through the use of wide-flange structural steel shapes. After completion of the Chrysler Building, it held the title of world's tallest building for just 11 months before it was surpassed by the Empire State Building, also located in New York City.

Mills Evolve, Leading to the Production of Sustainable Steel

From the early 1900s, through the late 1960s, the use of blast furnace technology was the standard for production of steel shapes. The steps necessary to turn out sections from a blast furnace, however, were time and energy intensive, and as a result the more efficient electric arc furnace technology was employed in mills starting in 1969.

To understand how blast furnace, as well as electric arc furnace, technology is used to make a structural shape, it is important to note the three basic steps:

1. Production of molten steel that meets a desired chemistry.
2. Conversion of molten steel into a beam blank, billet or bloom.
3. Deformation of the semi-finished product into the final desired shape.

To produce a section using blast furnace technology, step 1 is broken down as follows:

- Coal is converted to coke by heating it to temperatures exceeding 2,400 degrees Fahrenheit (1,315 degrees Celsius).

Bottom: Chrysler Building, New York. Source: Wikipedia

"Numerous steel-framed buildings constructed between 1901 and 1929 became the world's tallest, but it was not until 1930, with the completed Chrysler Building in New York City reaching 1,046 feet (319 meters), that steel buildings eclipsed the world's tallest structure, the iron-framed Eiffel Tower."

- Coke, iron ore and lime are sent to feed the blast furnace. The materials are fed from the top of the furnace and are exposed to a hot blast. The warm air helps ignite the coke and raises the temperature of the iron ore and lime to their melting point.
- The molten mixture collects at the base of the furnace.
- In the liquid material, derivatives of the lime combine with waste material from the iron ore to create slag. The byproduct floats to the top of the liquid and is easily separated from the remainder of the material. Every few hours, the heavier component of the molten mixture, known as pig iron, is tapped through the bottom of the furnace and used to feed a basic oxygen furnace (BOF), which can be considered as an advanced Bessemer converter.
- In the BOF, oxygen is forced through the pig iron, removing impurities and converting it to steel.
- At a ladle furnace, the chemistry of the liquid steel is tested and adjusted to meet the relevant specifications.

Using an electric arc furnace, on the other hand, leads to the following breakdown of step 1:

- Ferrous scrap, in combination with lime, is placed in an electric arc furnace. Graphite electrodes are lowered into the furnace and charged. The arc between the

Bottom: Blast furnace. Source: ArcelorMittal

Opposite: Electric arc furnace. Source: ArcelorMittal

electrodes raises the temperature in the furnace to more than 3,500 degrees Fahrenheit (1925 degrees Celsius) – a temperature high enough to melt more than 160 tons of scrap into molten steel in as few as 40 minutes. Similar to a blast furnace mill, derivatives of the lime combine with waste material from the scrap to form a slag that floats to the top of the molten material. The heavier component of this molten mixture, however, is liquid steel.

- At the end of the charge, the steel is separated from its byproducts and moves along to a ladle furnace, where the chemistry of the liquid metal is tested and adjusted to meet the relevant specifications.

For both production processes, steps 2 and 3 are described in detail as follows:

2. From the ladle furnace, the molten steel moves to the continuous caster where a beam blank, billet or bloom is created. The continuous caster was another innovation in steel production. Introduced in the 1950s as a replacement to ingot casting, where molten steel cools in a large, rectangular stationary mold, continuous casting forms the steel into the beam blank shape while still at an elevated temperature. The transition from ingot casting to continuous casting led to many benefits in the production of structural steel shapes, including significant reduction in the possibility of material segregation, inclusions and lamellar tearing.
3. The beam blank, billet or bloom is then sent to the rolling mill where it is deformed into the final desired shape.

Modern builders know that it is not just the size and strength of the building that matters. The impact on the environment must be taken into account. A critical benefit of using scrap-fed electric arc furnaces to create a batch of steel is that it results in considerably lower need for natural resources and the use of significantly more recycled materials when compared to steel made using blast furnace technology. In fact, material produced using an electric arc furnace can have recycled

content values approaching 100 percent, thereby making steel sections a highly sustainable building material.

The recycled content of structural steel shapes is only one aspect of their production that is sustainable. It is a primary objective of most mills to refine the production process in order to reduce the quantity of waste material. Steel producers also look for opportunities to recycle by-products from the manufacture of steel. Some examples include collection of slag to be used for the base and top layers of pavement in roadways, steel dusts for zinc and zinc oxide production, and mill scale to be used in the manufacture of glass products and within the steel industry as an alternate to iron ore.

The innovations to date in structural steel production have not only improved the quality of the material and the efficiency with which it is produced, but also reduced its impact on the environment.

The Rolling Process Transforms, Leading to the Resurgence of the Skyscraper City

From their beginning through the 1950s, structural shapes – like all types of steel products – were formed using what is known as a hot rolling technique. In the hot rolling process, all deformation (or "working") of the steel blanks, or semi-formed shapes, occurs at temperatures above 1,800 degrees Fahrenheit (1,000 degrees Celsius). This type of rolling relies mainly on the chemical composition of the material – most specifically the carbon content – to provide strength, which during this period was typically 36 ksi (250 MPa).

A downside of hot rolling is that the material's high carbon content and fairly coarse grain structure can lead to low toughness, therefore making the final section subject to brittle fracture. As a result, it was common practice to perform heat treatments, such as normalization or quenching and tempering, after rolling to refine the grain structure of the material and subsequently improve its strength and toughness. While an effective solution to the issues associated with hot rolling, post-rolling heat treatments, such as normalization or quenching and tempering, could be time- and energy-intensive – after all, they typically required complete cooling of the rolled section, followed by use of an external source to reheat it, and upon completion of these steps, the section would again have to cool completely before it could be prepped for final delivery. Consequently, it became desirable to find other ways to arrive at these same results.

As a result, in the 1950s, producers considered research performed in 1925 – research that indicated how low-alloy steel with a fine grain structure could be achieved by working the steel at low temperatures. Accordingly, producers developed a new method to roll sections: the thermo-mechanical control process (TMCP). Steel products made from TMCP are worked at 1,800 degrees Fahrenheit (1,000 degrees Celsius), just as hot rolled steels. The rolling process, however, is briefly interrupted to allow for cooling of the semi-rolled section, and the section is deformed again at lower temperatures. The second phase of rolling typically occurs between 1,650 degrees Fahrenheit (900 degrees Celsius) and 1,470 degrees Fahrenheit (800 degrees Celsius), but the exact temperatures used are governed primarily by chemical composition, as well as the characteristics of the microstructure that the producer seeks to achieve.

Left: Willis (then Sears) Tower, Chicago, under construction circa 1973. (cc-by-sa) Steveboerger

Opposite: Quenching and self tempering of wide-flange section at Differdange (Grey) Mill. Source: ArcelorMittal

Microstructure refinements achieved through TMCP not only improved toughness characteristics but also yield strength. As a result, it became possible in the 1950s for steel to meet yield strengths of up to 50 ksi (345 MPa). Initial use of this high-strength TMCP steel was in the manufacturing of ships, but in 1966, high-strength, low-alloy structural shapes came into production meeting the ASTM A572 specification. Further refinement of chemical composition of ASTM A572 steel led to creation of the ASTM A992 specification for structural shapes in the late 1990s.

With yield strengths up to 65 percent greater than those used to construct the Chrysler Building, these higher strength steels contributed to a revival of the skyscraper in the 1970s. This decade saw construction of Willis Tower and John Hancock Center in Chicago, as well as the original World Trade Center towers in New York. Willis Tower, with its bundled tube structural steel framing system that includes 42 ksi (290 MPa) steel, stands at 1,729 feet (527 meters) in height, and was declared the world's tallest building in 1974 – a title it held for 24 years. The John Hancock Center, which was completed in 1969, features up to 46 ksi (315 MPa) steel and reaches 1,128 feet (344 meters) in height.

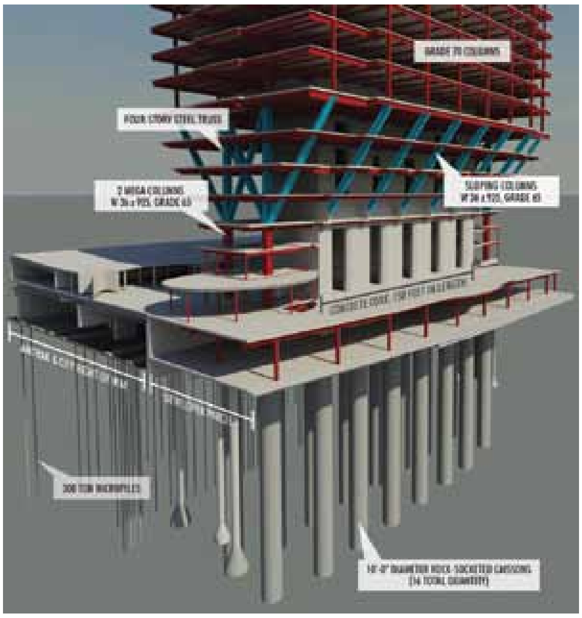
As steel with a yield strength of 50 ksi (345 MPa) was becoming the industry norm, a team composed of members of the research and development group from the Differdange mill (the world's first Grey mill) in conjunction with the Centre de Recherches Métallurgiques (CRM) in Belgium, was studying a process that could bring further advancements to TMCP steels. The research team surmised that it would be possible to use an in-line heat treatment process to, once again, raise the strength of steel, while also maintaining, and in some cases improving, toughness and weldability characteristics. As a result of its research, the team developed the quenching and self-tempering (QST) process.

QST is an in-line, rapid cooling and controlled reheating method designed for structural shapes. The QST is applied after the section has been rolled to its final dimensions and before it has reached the cooling bed. To receive QST treatment, the shape passes through a QST bank, where water is used to cool the outer layers of the section. The core, however, retains enough energy to enable the section to "reheat" itself from the inside out, thus leading to a self temper when it has reached a uniform temperature above 1,100 degrees Fahrenheit (600 degrees Celsius).

QST is similar to other heat treatments – normalizing and quench and tempering – described previously in that it can refine the microstructure of steel, thereby improving its strength and toughness. It differs from these processes, however, in its efficiency. Being an in-line process, QST does not require moving a large and heavy piece of steel from the rolling mill to a reheat furnace in another part of the mill – by avoiding this handling process, QST provides a savings in time and labor costs. QST also relies on the encapsulated energy, or retained heat, to reheat the section. Counting on the self-contained heat, rather than an external heat source, means far less energy is required for the reheat to occur and the pace at which the reheat occurs is more controlled.

The section resulting from QST has a grain structure even finer than TMCP steel and can exhibit yield strengths up to 70 ksi (485 MPa). In addition, the toughness characteristics of the material demonstrate good performance in even the most taxing of environmental conditions, and its low alloy content allows for favorable welding characteristics, in most cases requiring no preheat prior to performing welding procedures. High-strength, low-alloy steel shapes that are produced using QST meet the requirements of the ASTM A913 specification, which was introduced in 1993.

The reliable and economic production of steel shapes meeting the A913 specification has positively impacted the current phase of the skyscraper city, especially in North America, where the skyscraper was born. The iconic, 1,776-foot- (541-meter-) tall One World Trade Center in New York, used high-strength steel to not only bolster its perimeter steel moment frame but also to



save weight in the 45,000-ton structure. Also in New York, the soon-to-be constructed 217 W 57th Street project will be the city's first building to employ 70 ksi (485 MPa) structural steel shapes in its design. These members will boost the elevation of this primarily concrete building with efficiency (its use of high-strength steel led to approximately a 30 percent savings in weight of the steel mega-columns) and will make it possible for the building's residents to take in breathtaking views of their surrounding city.

Two other notable projects take advantage of 70 ksi (485 MPa) structural steel profiles: Bay Adelaide Centre, East Tower in Toronto and 150 North Riverside in Chicago. The first building in the world to use structural steel shapes of this yield strength, the 45-story Bay Adelaide Centre, East Tower realized an overall weight savings of more than nine percent when the high-strength steel was used in columns and short span transfer girders.

The design of 150 North Riverside, with perimeter columns vanishing into its concrete core, benefits from both 70 ksi (485 MPa) QST steel – the first building in the United States using structural steel shapes with this yield

Opposite Top Left: Construction progress of 150 N. Riverside, Chicago as of July 2015. Source: Marshall Gerometta

Opposite Top Right: Diagram of framing system for 150 N. Riverside, Chicago. Source: Magnusson Klemencic Associates

Opposite Bottom: One World Trade Center, New York City, under construction circa April 2011. Source: Antony Wood

"The design of 150 North Riverside, with perimeter columns vanishing into its concrete core, benefits from both 70 ksi (485 MPa) QST steel – the first building in the United States using structural steel shapes with this yield strength – and 65 ksi (450 MPa) QST steel."

strength – and 65 ksi (450 MPa) QST steel. Taking advantage of the higher yield strength resulted in a weight savings of six percent of the total steel tonnage for the project. In addition to the weight savings, fabrication and erection was simplified when the structural engineer followed in the footsteps of Alphonse Halbou and was able to substitute rolled W36x925 (W920x1377) sections for built-up box sections at the mega-columns as well as the built-up, concrete-filled sloping columns that transfer perimeter framing back to the concrete core. The production of sections with a linear weight up to 925 pounds per foot (1,377 kilograms per meter) is possible at Grey's original mill in Differdange.

The era of the skyscraper spans more than a century, and as demonstrated through this study, the influence that structural steel has had on both its birth and resurgence is indisputable. Of course there are other factors that enabled designers to construct useful buildings higher than six stories – the invention of the elevator; improvements in mechanical, electrical, and plumbing systems; and a market demand, resulting from limited real estate in city centers, to expand upward instead of outward – but no factor outside of advances in building materials, and in particular the production of structural steel, made it possible for a building to be higher than those that came before it.

Steel's Positive Influence: Design, Efficiency, and Sustainability

Building design is undergoing another transformation, as computer-based design and fabrication allow designers to move beyond right-angles and visualize buildings in three dimensions before they leave the studio. The structural materials used to support these fantastic designs must keep up with the dreams of the architects and engineers commissioned to prepare them. The advancements in structural steel begun by Neilsen, Bessemer, and Grey are ongoing and have resulted in the high-strength, easily weldable, efficiently produced material available today. Designers should take advantage of the capabilities of structural steel and can be confident they will meet and exceed the desires of their clients with an ecologically friendly recycled material.

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