Structural Innovations: Past / Present / Future

Abstract

The towers of 50 years ago utilized simple and strong constructions, built upon bold, but easily comprehensible, structural techniques that were developed collaboratively by the architect and the structural engineer in order to create optimal forms that were calculated simply with a slide rule. But while the early pioneers of the urban built environment used many of the same materials and systemic approaches used to create today’s modern city, the ability to conceive, rationalize and optimize a design is free from many of their prior constraints due to new techniques, technologies and materials. By appreciating the legacy of the people who developed designs of the past that allowed the proliferation of innovation 50 years ago, an appreciation for how the fields of architecture and engineering have evolved will guide the prudent investment of resources and creative talent for the next 50 years.

Keywords: Artificial Intelligence, History, Innovation, Leadership, Performance-Based Design

Introduction

The built environment is humankind’s lasting creation and a reflection of culture and the people who influenced its making. Looking at the structural innovations in tall buildings, both history and lessons in human decision making is made evident, yielding a robust platform to consider the future of what can, and should come next.

Tall buildings came about as an outgrowth of material breakthroughs, most notably with rolled steel shapes and their use in building construction. The required manufacturing was initiated by other industries, namely railroads, bridges, and ship building. But the use of more readily available steel, and new construction techniques, led to an explosion of increasing building heights from the 1890s through the 1930s, starting with the rebuilding of Chicago after the Great Fire (Bellis 2018). This, coupled with the elevator inventions of Elisha Otis, made the underpinnings of the first skyscrapers (The First Safety Elevator 2019). While there were many notable towers and innovations at the start of tall building construction with steel, perhaps two of the crowning signature towers are New York City’s Chrysler building, and the 102-story Empire State Building (see Figure 1).

War and economic uncertainties put a damper on tall-building construction for several decades after these earlier towers, but the fascination with “tall” exploded again during the 1960s with the re-birth of the world’s tallest building competition (Glanz & Lipton 2003). The creation of the Council on Tall Buildings and Urban Habitat (CTBUH) came about when cities began to rise higher and the density of urban living started exponentially increasing. The Council met a need: gathering the foremost experts to discuss topics of where and how buildings are planned and constructed, as well as where ideas could be debated, opinions exchanged and collaborations started. It became the forum where next generation building strategies could be envisioned and compared (CTBUH 2009).

Establishing a “Height Committee” to set the rules by which the world’s tallest structures would be evaluated against (see Figure 2) is still an integral part of CTBUH today, but CTBUH’s creation served a much more fundamental need. It brought together a range of multidisciplinary experts in this field.
Tall Building Visionaries

The structural engineering leaders at CTBUH’s start, Fazlur R. Kahn, William LeMessurier, John Skilling, and Leslie Robertson, among others, are the visionaries whose contributions defined the re-birth of the skyscraper. Looking beyond the buildings and their innovations, it is fascinating to understand what motivated these practitioners to fundamentally change the status quo. They were artists, explorers, and risk takers. They were also dedicated to improving the built environment and CTBUH was a platform to do just that.

To quote Lynn Beedle on the founding of CTBUH: “It stemmed from… the exploding urban population; creating an increased demand for tall buildings; the need for economy in construction; the frequent neglect of human factors at the expense of livability and the quality of life; the need for new research required in the field… It is not an advocate for tall buildings per se; but in those situations in which they are viable, it seeks to encourage the use of the latest knowledge in their implementation” (Beedle 1992). Indeed, it was the people, their interactions, and interconnections, that propelled CTBUH forward. This is one of the key reasons that CTBUH has been a success; it connects the people of the tall building industry together.

Innovations in Structural Engineering

Framed by a backdrop of rapid change and development in the year of the Council's inception 1969, the constraints of the past were challenged in every industry, including architecture and engineering. For structural design, this period fostered big ideas. Composite construction, tubular frames and megaframes, outriggers, castellated beams, post-tensioned slabs, damping systems—these were all ideas from the time of CTBUH’s founding.

There was a simple, but strong elegance in many of the towers of this time. The interior forest of columns of earlier towers were eliminated and long-span floor systems of 40 or more feet (12 or more meters) became the norm. For tower lateral systems, the more direct the load path, the more effective. This approach also often parallels the most materially efficient solutions, and hyper-rational approaches were indeed a focus of the day.

Towers at the start of the 1970s included early two-dimensional frame computer models, but the engineering teams still significantly relied on their hand calculations and slide rules for most of the work. This led to engineers that intuitively...
understood their building designs, and it showed within their clean load path solutions.

The ideas for iconic towers from this era were theories of structural design, executed on a scale never before attempted. The original World Trade Center Towers, with a perimeter-bearing wall and spandrel frame, where every vertical window mullion was a structural member; 875 North Michigan Avenue’s (formerly the John Hancock Center) exposed braced tube; and the Willis Tower and its bundled tube frame were each inspired innovations (Baker 2001). Wind-tunnel modeling and the start of human perception to motion criteria for tall building designs also came into being, with the University of Ontario and Dr. Davenport emerging as one of the foremost experts on the topic (see Figure 3).

In addition to the evolving structural designs, the world also was experiencing disruptive technological advances: from slide rules, to punch cards and mainframe computers, to the PC. As evolving analysis tools allowed for faster, more complex analysis, collective design abilities and willingness to complicate load paths with more indeterminate structural systems grew. However, this has not always been beneficial, as a lack of constraints sometimes has led to a lack of discipline within the design process. But with these newfound abilities it became easier to run parametric studies, and to evaluate new prototype ideas. Design optimization became of paramount importance, and finally the industry could create three dimensional models that represented the strength and stiffnesses of tower systems with increasingly detailed comprehension.

Columbia Center in Seattle, Washington, was an early megafame design that used the power of a mainframe computer for one of the first three-dimensional space frame analysis efforts. It was also an early use of enlarged composite steel and concrete columns, within a megaframe of a steel-braced core within a triangular tower footprint. Viscoelastic dampers distributed up the tower were also added for improved human comfort during building motion (see Figure 4).

While the modern skyscraper started as a US invention, its popularity as a construction typology came when it was deployed within Southeast Asia, China, and the United Arab Emirates. An elegant expression of a megafame similar to the Columbia Tower arrived with the Bank of China Tower in Hong Kong. It showcases engineer-architect collaboration to find both a structurally optimal design and a pure building expression. TAIPEI 101 was another step for supertall tower systems that built on these earlier ideas, but with a new geometry. It included a stiff core spine, with outriggers in a tic-tac-toe arrangement to exterior megafame composite columns, and a pendulum rooftop damper (see Figure 5). Jin Mao Tower in Shanghai represents the next generation of this idea. It also built on the “tic-tac-toe” structural layout, but Jin Mao Tower has an even
stiffer concrete core up the tower’s center, with outriggers to enlarged columns on the building perimeter. This system has since become a frequent starting point for many supertall towers within Asia, especially in China.

Burj Khalifa, with its buttressed central core and tripod base, re-invigorated structural systems and building dynamics for ever-higher towers. Anytime a tower is considered for a world’s tallest effort, the project scale is an opportunity to advance practices with new approaches and ideas. The idea to always be searching for further innovation was lost with some, but not all, of the repeat-formula, supertall towers that have followed Jin Mao. But for Burj Khalifa, Bill Baker went back to basics, re-considered the most fundamental ideas around tower engineering, and built upon materials and systems of the past, but in a refreshingly new supertall tower structural configuration (see Figure 6).

These are just a few of the innovations seen in evolving tower designs. Other notable advancements since CTBUH’s start have included the diagrid exoskeleton as a tower form. The United Steelworkers Building in Pittsburg from 1963 was one of the first diagrid-bearing wall systems (Hatch & Sprague 2016) (see Figure 7). But this idea as a more efficient expression for a tower was later championed by Foster + Partners, among others, on projects like the New York City Hearst Tower and 30 St Mary Axe (The Gherkin) in London. Using a bi-directional curving diagrid, the project was a study in the expanded use of prefabricated building components. Shanghai Tower’s double-skin exterior hanging façade, completed in 2015, was also notable for challenging how we think about building exterior forms and their support.

Also, more recently, at the prefabricated building component level, the dual-plate steel core of Rainier Square Tower in Seattle, is gaining attention. It is not the first dual-plate shear wall system ever used, but its focus on more simplified prefabricated modular construction, as well as the laboratory testing that went into rationalizing its high-seismic design characteristics to then justify its use on the west coast of the United States, is helping to move industry further along with new ideas and approaches for how construction is approached.

Figure 6. Left: Burj Khalifa (Dubai) is the world’s current tallest building. Right: Aerial drawing of Burj Khalifa, showing its three-petal footprint. © Donaldytong (cc by-sa)(left), Source: Skidmore Owings & Merrill LLP, redrawn by Magnusson Klemencic Associates (right)

Figure 7. The United Steelworkers Building (Pittsburgh) was one of the first diagrid-bearing wall systems. © Magnusson Klemencic Associates
Each of these innovations are memorable and, in some way, have been transformative. They exhibit an inspired engineering effort that advanced an idea. The most notable developments have occurred when structural design rejects the status quo by embracing a challenge to innovate and advance the built environment, refining and improving existing methodologies for future projects.

Advancing Technology

The evolution and use of computers, and the ability to process data faster than the human brain has often been called the Third Industrial Revolution, or the Digital Revolution (Menuez 2014). Indeed, this tool has profoundly changed how we design and build. Today, for any form a designer can envision, it is now possible to rationalize its stresses and strains, and then optimize it. Parametric studies can assist in considering a design within a virtual space, before it becomes a reality.

The Two Union Square (Seattle) project in 1989, with asymmetrical built-up beams, composite-filled pipe columns with 18,000 Psi (124.1 MPa) concrete, and viscoelastic dampened outriggers, still represents construction pushed to its optimization limits for the time.

Innovation was also on Frank Gehry’s mind when the Experience Music Project’s (MoPoP) design began in 1997. While not a tall tower, it was another major step forward in computer design capabilities and the early use of Building Information Modeling (BIM). The client, Paul Allen, challenged the team to use technology in a way it had never been used before within the building industry, and to make it “swoopy.” With no single-rulled surface and no drawings, a computer model became the description of the design, through to construction.

The team had a head start using the program Catia, borrowed from the aviation industry. Within the one program, the designers were able to visualize and describe the building geometry in three dimensions, analyze for building stresses and strains, cut sections, and create stiffening ribs, which could then be structurally proportioned. The model was also used to help create shop drawings that went to the contractor for erection sequencing and fabrication. All was done within the one model (Magnusson Klemencic Associates 2019).

BIM and the power that comes with it, to organize design information, is astounding. But while the software has become much easier to program and communicate with, its full potential has not yet been realized. Interoperability between different software platforms and liability challenges between owners, builders, and designers still leaves room for growth and certainly some of the elegance that first happened with the MoPoP design process has been clouded. But with time, we will overcome these hurdles.

But what has come from these advancements? For one, it is the ability to conceive, rationalize, and then describe to others sloping, twisting, and cantilever structures. CCTV Headquarters in Beijing, Marina Bay Sands in Singapore, Turning Torso in Malmö, or the Cayan Tower in Dubai are all examples.

Ultra-slim residential towers are another example of the transformed tall building typology. These towers started first in places like Hong Kong, with projects like Hang Lung (The Summit) and Highcliff (see Figure 8). More recent examples of even taller, slender towers can be seen in New York City, with projects like 432 Park Avenue, Central Park Tower, and 220 Central Park South. Projects like these are only responsibly possible through the use of both computer and physical wind-tunnel testing, ever-more efficient damping systems, and higher strength materials.

But these newfound abilities have launched us from the questions of whether innovative designs are possible, to a more reflective question of when and what to create. Beauty is important and indeed architecture is an art form expressed on the grandest of scales, which we all embrace. For the technical abilities we now possess, though, what problems we choose to solve with those abilities might say more about our values, than the structures we can create if there is enough money to make it so.

Performance-Based Design

With the expansion of technical abilities, building codes have also greatly expanded in an attempt to prescriptively manage how and what is built. But as design capabilities continue to outpace the code writing process, the most significant structures often end up being outside of the prescriptive building code system assumptions. This has led to a growth of performance-based design (PBD) approaches,
which target meeting the intent of the building code, but are justified through alternative means and usually a peer review panel approval process of some form. By going back to basic principles and designing to the intent of the building codes, PBD is again unlocking the engineer’s creativity and intellect.

Performance-based engineering requires careful consideration and action taken from a place of knowledge; it is not akin to a recipe with exact ingredients that will yield the same result each time. But it also takes full advantage of what the computer’s capabilities are: to allow for custom design and innovation. Importantly, it requires the engineers involved to possess a deep understanding of the variables and limitations of the software tools being used. Within the structural space, scenario and predictive modeling, it is now possible to account for both finite elements and time-historically-predicted stresses and strains regularly, which was previously not feasible. Considering more than one building hazard, such as the 50-year hazard with little to no damage, and then the 1,700- or 2,500-year hazard for collapse prevention, this is where more resources are being spent (Pacific Earthquake Engineering Center 2017). This started within the renovation and seismic design spaces, but it is now moving into performance-based wind and performance-based fire engineering with greater frequency.

Salesforce Tower in San Francisco, 2019’s Best Tall Building Worldwide, represents the state-of-the-art possibilities with performance-based seismic design (PBSD) within tall buildings. Ron Klemencic is the inspired engineer that has brought this forward, but it is only through the collaborative efforts of others, including people like Professor Jack Moehle, Ron Hamburger, and many others, that PBSD has become as innovative and robust as it currently is. The most significant advancements today, as seen in Salesforce Tower, come from collective input and sharing of intellectual resources, from the interactions of smart people working together to solve a building challenge (see Figure 9).

Artificial Intelligence

Where will we go next? Some say we are entering the start of a Fourth Industrial Revolution, another era of rapid innovation, catalyzed by automation and Artificial Intelligence (AI), brought forward by our ever-more powerful computers, and their integration with robotics.

An important distinction, an algorithm of building code language that calculates the rebar requirements within a beam is not AI or Deep Machine Learning. AI can process huge data sets and can find patterns within a specific domain of that data. This allows for more detailed scenario and predictive modeling abilities and is a powerful analysis advancement. But while AI is moving us forward with more powerful data analysis and predictive findings within a singular domain space, AI is far from being able to make judgement calls between contradictory science findings or code provisions, or handle reasoning, common sense, or creativity.

Today, building codes are not yet cleanly programmable language. They often include contradictions that require judgment, as they are consensus documents written by professionals with varying opinions. A “code minimum” design is also not necessarily a wise design that meets an owner or societal objective, nor is it a guarantee to be a wise proportioning of materials. Caution and judiciousness should be exercised when considering the promise of a design software that does it all, (AI or other) without the expert’s thoughtful evaluation of the data that goes into and out of the computer-generated findings.

When used appropriately and from a place of knowledge and experience, AI is indeed going to transform engineering. Today, a modern tower’s non-linear time-history model (wind or earthquake) will generate terabytes of data, which is post-processed into statistical models that inform our value-based decisions on the design. AI has great potential here, but if we do not understand the input and output limitations with the data developed, there is the potential for it to be superfluous and counterproductive as well. What AI can and will soon do more of is further the ability to model scenarios of a building’s likely performance once a design is established. This leads to a more considered use of materials, but AI should
supplement and inform—not replace the engineer’s judgment, especially when life/safety implications are involved.

**Automation and Virtual or Augmented Reality**

Automation and virtual or augmented reality is making great strides in changing construction and necessary advancements. They are making construction safer, faster, and less wasteful. We are seeing the increased use of robotic assembly, and prefabricated building modules, for full rooms, core-wall components, flat-packed building partitions, or pre-assembled MEP systems. Seeing how these components can virtually come together, and troubleshooting issues in advance of construction’s start, is a great efficiency improvement (see Figure 10).

Increasingly, conventional critical construction path assumptions are changing. Recent critical paths for projects with large amounts of prefabrication have moved from what happens on the site, to the ability to deliver material to the site, and the transportation bottlenecks along the way. With this, processes from supply chain management and other manufacturing industries are finally making their way into the industry.

Automation’s current downfall, though, comes with the constraints it puts on customized, one-off building ideas and layouts. For more automation in design and construction to be embraced, the ability to economically allow for design flexibility, while still reducing waste and labor, is an area for growth. Taking a page from manufacturing, air shipping is also expensive. Flat-packing and more attention to how to ship kits of prefabricated parts, over entire room modules, holds perhaps the most promise.

**Environmental Implications**

Humanity is also entering an era where societal disruption and climate challenges are changing how we approach the built environment. Certainly, one of the greatest societal challenges over the next 50 years will be how the impacts of climate change are addressed. Like the explosion of ideas from 50 years ago, this current challenge is going to require creativity, innovation, and collaboration. Environmental considerations has already prompted a shift in how material selection is approached. Resilient design, adaptability, net-zero carbon and carbon sequestration—these are the topics that are now driving innovation (University of Washington College of Built Environments 2019). Our limited resources will require greater consideration and conservation of the materials used to build, and pressure for tracking and reporting on the carbon footprints of decisions in the built industry will only continue to grow (see Figure 11).

Carbon-negative concrete, timber, and steel have the potential to be building materials that absorb as much, or more, carbon than it takes to create them. These often seem like outlier ideas today, but these materials are already in existence. Some are not currently as economical as existing materials or have not yet been considered at scale, but this is within our 50-year future.

**Conclusion**

Our towers of 50 years ago, by necessity, required simple but strong ideas. They resulted in bold, yet easy to understand structures, with architects and structural engineers working hand-in-hand. Although the pioneers of these earlier towers used many of the same materials used today, we have an ability to conceive, rationalize, and optimize designs free from...
many of this prior generation’s analysis constraints. But with newfound freedoms, we must constantly ask ourselves: to what purpose? Indeed, financial, societal, and environmental impacts are the biggest drivers for where and what we chose to build today. Performance-based design, artificial intelligence, and automation in construction are all tools for the next 50 years. But even with these tools, it is the interconnectivity of people’s ideas, judgment and decisions, that will shape the future of the built environment.

To the next generation of thought leaders, think about your own place in this time and the challenges we currently face. It is a dynamic time and it will not be the same as the last 50 years. I encourage you to be a student of history and consider carefully the motivation, and aspirations of the leaders over the years of CTBUH.

References: