THE RUSSIA TOWER, MOSCOW

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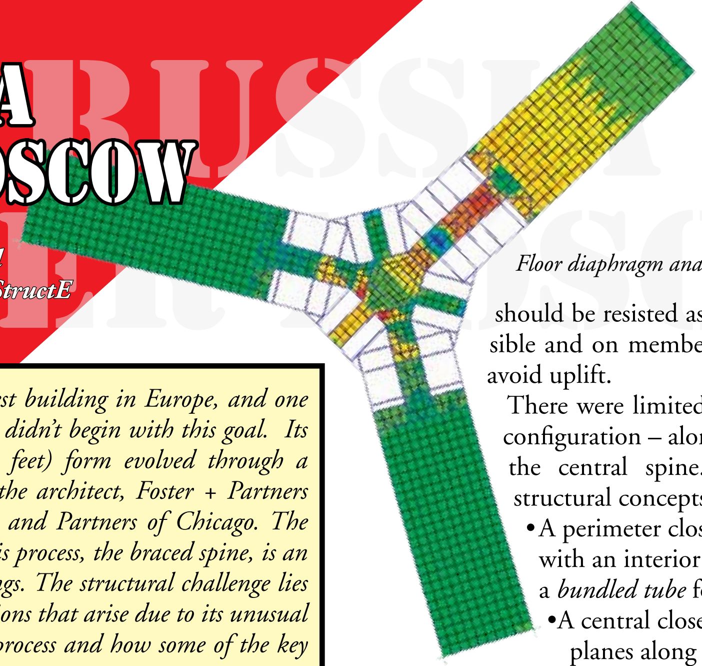
Russia Tower will be the tallest building in Europe, and one of the world's highest; but it didn't begin with this goal. Its striking 600 meters (1968 feet) form evolved through a collaborative design process between the architect, Foster + Partners of London, and engineer, Halvorson and Partners of Chicago. The new structural system developed in this process, the braced spine, is an efficient concept for super-tall buildings. The structural challenge lies in addressing the nonstandard conditions that arise due to its unusual form. This article shares the design process and how some of the key structural issues have been addressed.



Floor diaphragm analysis.

Three Towers to One-of-a-Kind

When the developer first approached Foster + Partners of London, he envisioned three 30-60 story towers on the triangular site: office, residential and hotel. Foster began exploring numerous massing options for the three separate towers. But on the triangular site, each leg at 300 meters (984 feet), it was apparent that three towers would be very tight.

Foster favored a layout of rectangular towers arranged radially at 120 degrees, to maximize outward views. This resulted in slender towers, structurally possible but inefficient. Possibilities for linking these were discussed, and Halvorson suggested three structural options:

- Rigidly: the towers share loads and work together like a frame.
- Diaphragm: the towers share loads, but with pinned connections between.
- Flexible: the towers remain structurally independent with the connection accommodating differential movements.

The entire team favored this idea of joining the towers as it also offered added efficiency for other building systems, such as elevators, and (perhaps more importantly) allowed the chance to create something greater than the sum of it's parts.

The powerful (and taller) form was born as the three slender towers were pulled together and linked at their inner tips, tapering the elevations and extending them vertically to maintain the same floor area. The separate towers became wings radiating from a central spine. Structurally, they were now rigidly linked, working together as a single structure – with any one wing stabilized by the other two.

Keeping with the client's desire for three separate buildings, Foster showed that each wing might house a separate use. But, they recommended stacking the program types vertically for efficiency. Excited by the striking form and the benefits of stacking, the owner agreed to this scheme. The leap had been made – from three 'typical' buildings to a single one-of-a-kind tower. The challenge became making it work!

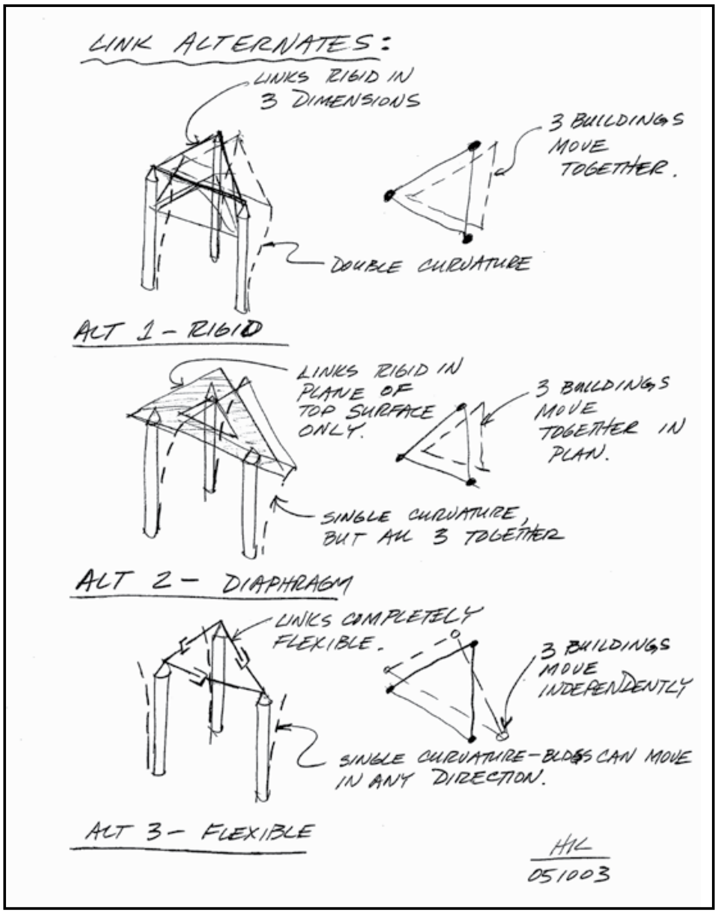
Structuring the Form – the Braced Spine

Halvorson had discussed with Foster that the key for designing tall buildings is resisting lateral loads – specifically wind. The system is most efficient if it resists wind load and gravity loads on the same structural elements. Also, overturning forces due to wind should be resisted as far from the building center as possible and on members carrying sufficient gravity load to avoid uplift.

There were limited areas to locate the structure in this configuration – along the wing faces and tip and around the central spine. Halvorson suggested two initial structural concepts.

- A perimeter closed tube around each wing, with an interior triangle tube at their link – a *bundled tube* form.
- A central closed hexagonal tube with stiff planes along each wing to brace the central tube, potentially avoiding tip bracing.

Foster was excited by the design opportunities in the second suggestion. Numerous versions were discussed – core with outriggers, a mega-diagrid exoskeleton, stepped core bracing, etc. It began to take its current form when Halvorson suggested a series of parallel sloping columns at regular spacing to brace the core. Foster countered that these sloping columns might all come to one point at the base of each wing. It was an aha moment. Although the regularity of Halvorson's version was lost, it allowed all overturning forces to be resolved at the furthest point from the building center – a structural principle given earlier. And, it was stunning.

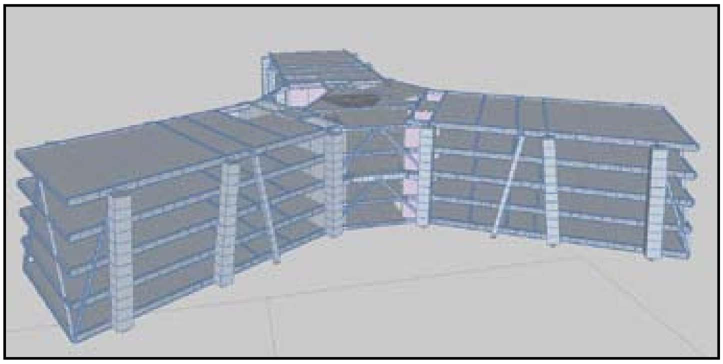


Structural options for linking three separate towers.

At this point, the design had essentially arrived at an already well known structural form – a cable stayed mast. Instead of tension cables, the tower has sloped columns in compression (which became known as *fan column*) to prop the spine against wind loads and carry gravity loads. A parametric study illustrates its structural efficiency. The *braced spine* system resists lateral loads by inducing axial forces in the fan columns and the *spine* must only span laterally between these brace points. The resulting shears and moments for the spine are much lower than those in the often used core and outrigger system. The form was also very stiff laterally, with a stout 5:1 aspect ratio for overturning. Lateral acceleration limits, which usually govern the design for tall structures, were safely met without requiring any additional damping.

The gravity load path was also clear – loads are carried as axial force in core walls and sloped fan columns. Transferring vertical gravity load into a sloping column induces a horizontal force component in the perimeter beams that is balanced between the three wings – essentially in 3-dimensional arching action.

The remaining challenge was torsion. The core itself was not sufficiently stiff; the entire perimeter needed to become a *closed section*. After much head scratching, Halvorson suggested that where the fan columns hit the central core, a *reverse fan* column might deflect at the same relative angle to the core and extend upward. Foster and the team liked it! With these, the faces of the wings were now triangulated. The rigid wing faces were linked by four-story steel chevron bracing at the tip of each wing to provide the *closed section* needed. The torsional period reduced from 12 to 5 seconds.



Four story portion of tower.

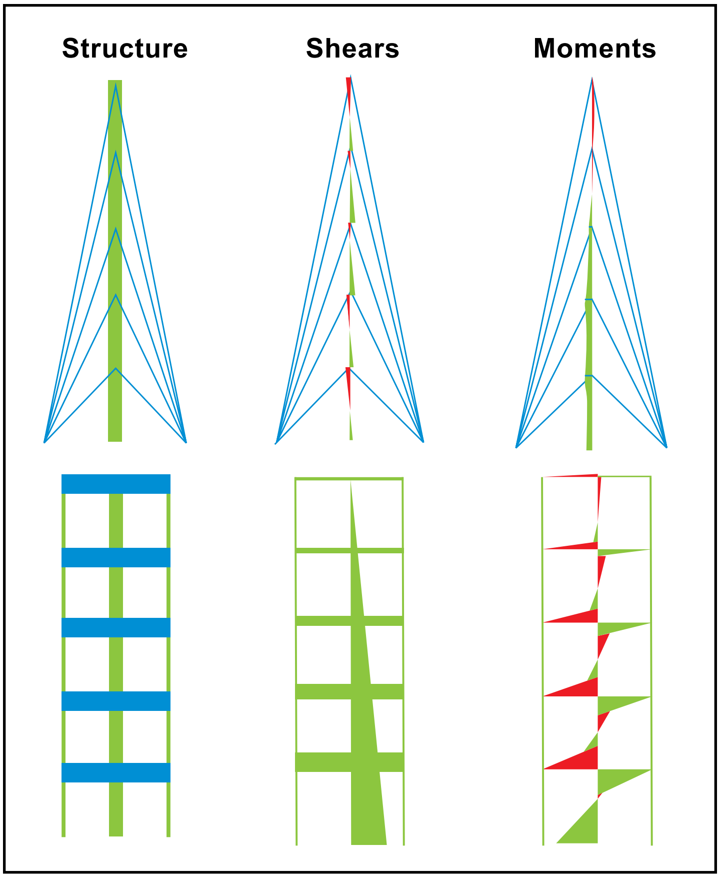
Making the Braced Spine Reality

As a concept, the *braced spine* structure is very efficient. But, ensuring this carries through in reality requires careful thought for structural material selection, constructability, and specific design challenges related to its unique form.

Structural Materials

Concrete is the structural material of choice in Moscow, and for carrying pure compression forces it is economical. In the Russia Tower, the fan columns, reverse columns and the core structure (or *spine*) carry primarily compression forces, with low shear and bending forces and no tensions (the wind axial tensions never exceed the gravity compression forces). Reinforced concrete seemed a logical choice for these elements.

However, the remainder of the structure needed to be steel. Perimeter spans vary due to the fan column layouts, reaching 18 meters (59 feet) in some bays. Post-tensioning was not a viable option in Moscow, making steel the only choice. At the office levels, built-up composite steel trusses span the 21 meters (69 foot) wide wings and frame into steel perimeter girders. At the hotel and residential floors, long perimeter spans also warranted steel framing. Interior steel columns were introduced for these levels to reduce interior spans and allow for shallower floor framing and higher ceilings. The loads from these columns transfer to the perimeter fan columns at mechanical levels (every 11-14 floors) via story high steel trusses. This transfer avoids differential shortening issues that can arise where gravity loads are shared by steel and concrete over many floors, and ensures gravity loads are directed to the primary members carrying wind loads.



Lateral Loads: Comparison of Braced Spine to Core with Outriggers.

Constructability

Erection of this complex, composite structure is a critical concern. Halvorson encouraged that the entire structure could be constructed as a steel building, using steel erection columns for the fan columns and core walls, with concrete encasement to follow some floors behind. This allows all erection tolerances and scheduling to be established by standards of steel construction, reducing the challenges of reconciling tolerances for concrete and steel construction that might occur if a stepped form concrete forming system was instead used.

Structural Challenges

Although it is a simple structural concept, the design of its members is less straight-forward. There were two issues on which considerable time has been spent:

1) Column design: what are the unbraced lengths or k-values for these columns? With 4-story bracing at tips, fan columns intersecting at varied heights, continuous walls and 2-story bracing around the spine between core walls – it was not obvious.
2) Diaphragm design: what stiffness and strength is sufficient to brace the columns and maintain Y-shaped form under wind loads? At the maximum, the wings extend 57 meters (187 feet) beyond the core.

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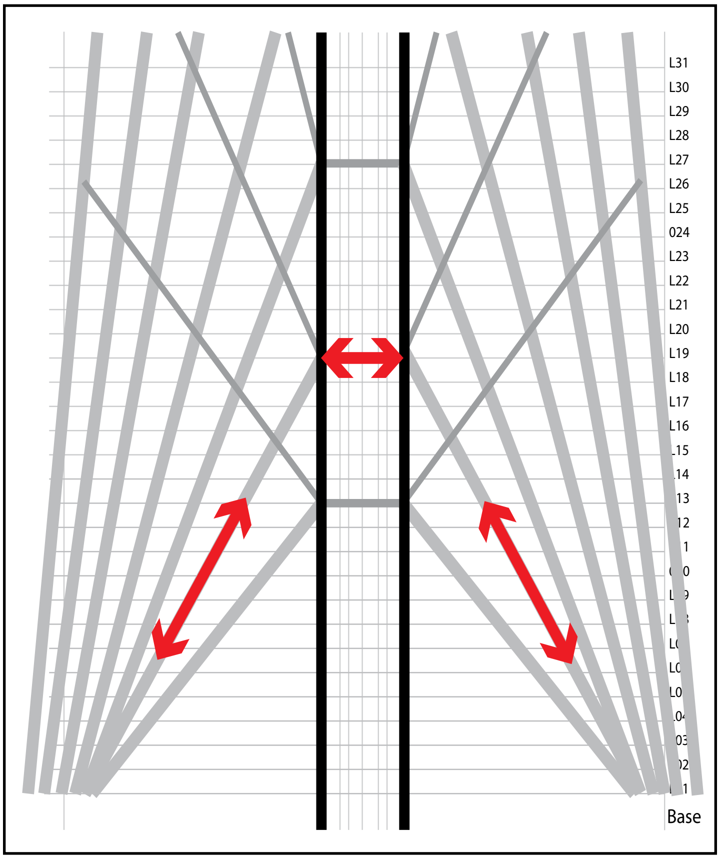
To address these related issues, Halvorson and Partners established a design methodology closely related to the *Direct Analysis Method* outlined by AISC, with special consultation by Dr. Jerome Hajjar of the University of Illinois. A full non-linear analysis was carried out, which considered material non-linearity (by modifying material properties) and geometric non-linearity (by applying notional loads to emulate initial out-of-plumbness and using p-delta analysis to capture all secondary forces).

This methodology captures all primary and secondary forces, allowing columns to be designed with k=1. Columns were designed using this method and also using the standard ACI methodology considering conservative estimates for bracing lengths. A model with even more conservative material reductions was also checked for buckling.

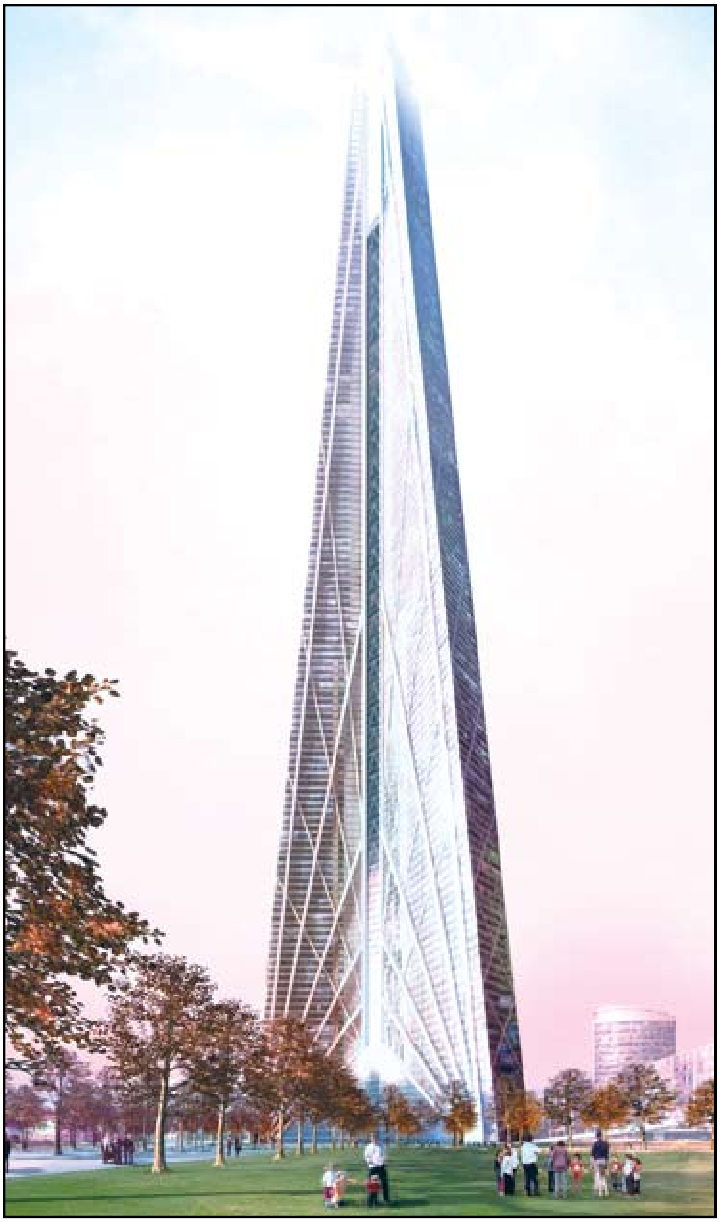
Related to the second issue above, the diaphragms in the full model were represented accurately, rather than simply assumed as *rigid*. This ensured column and wall designs captured any secondary effects due to diaphragm deformations and axial forces in the perimeter framing induced by 3-dimensional arching action. The diaphragms themselves were also analyzed for the additional in-plane strength requirements: considering wind loads along each wing (RWDI provided this information) and horizontal forces induced by out-of-plumb columns. Reinforcing steel was added as required. And, where high forces channelled around the many elevator and mechanical floor openings near the core, steel diaphragm bracing was added just below the slab.

The Result

The structural scheme is the architectural expression for the Russia Tower. Such a bold gesture and innovative design was achieved through collaboration and expertise of both the architect and structural engineer.▪



Gravity loads: 3-dimensional arching action under gravity loads.



The Russia Tower architectural rendering.

Robert A. Halvorson, S.E., P.E., FIStructE, has over 30 years of experience in significant structural engineering projects worldwide, including most recently the 250 meter Torre Repsol in Madrid, the 85 story Dubai International Financial Center and Chicago's first post-9/11 office tower, the Hyatt Center. Prior to forming Halvorson and Partners in 1996, he served as the Partner in charge of Civil/Structural Engineering for Skidmore Owings & Merrill. Robert can be reached at ***hp@halvorsonandpartners.com.***

Carrie Warner, S.E., P.E., Senior Project Engineer, has been instrumental in many of Halvorson and Partners' state-of-the-art projects over the past eight years. Developing professionally in parallel with the growing firm, her work includes the renovation of the Auditorium Theater and the 40-story One South Dearborn office tower, both in Chicago. In 2006, Carrie was selected for Crain's Chicago Business 40 Under 40. Currently she is serving as an adjunct professor at the University of Illinois at Chicago. Carrie can also be reached at ***hp@halvorsonandpartners.com.***