

Structural Design Innovation: Russia Tower and Other Tall Collaborations

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Abstract

A number of tall buildings created through the collaboration of the practices of Lord Foster, Foster and Partners, and the author and his firm are presented. The designs are placed in context with the fundamental principles of efficient design of tall building structures.

Keywords: Foster, Halvorson, innovation, collaboration, tall buildings

Introduction

This is the story of collaboration over a period of about a decade that led to a number of unique and innovative ideas about tall building structures. It began in 1999 and goes on today. Through a mutual acquaintance, the author met Sir Norman Foster, now Lord Foster, in connection with a project in Chicago, the author's home base. Since then, the two Principals and their firms have collaborated on a number of projects – each one unique in form and in structural detail, but each fitting into the fundamental pattern of efficient tall building structural design. The collaboration has culminated in the design of the Russia Tower, a 118 story tall mixed-use building in Moscow. Before addressing several selected building concepts resulting from this collaboration briefly, and the Russia Tower in more detail, some background on the recent history of tall buildings will allow the building designs to be placed in the context of the broader evolution of efficient tall building systems.

Efficiency in Structural Design

Tall buildings are extremely complicated animals – no one person can absorb and apply all aspects of the technology relevant to their design. Similarly, the temperament, personality and interests of people attracted to the different aspects of the development, design and construction are markedly different. So, collaboration of individuals with different skills and different interests is necessary to put the pieces of tall buildings together. To the extent these pieces fit together well in a pleasing fashion and each of the pieces represents the best that technology has to offer, and together they all meet the needs of the client, then the collaboration has been successful.

For structural engineers this means, at a minimum, that the structural system employs systems and materials appropriate to the building's height and configuration, that the system performs well, and that the system can be constructed efficiently. But on a higher level, the structure can also inform the architectural design and vice versa - the structure and architecture can be one. Think back through your personal list of great buildings of all time. Don't the structural forms relate to the

architectural forms of the buildings? Maybe you're thinking of the Pantheon? Notre-Dame Cathedral? The Chrysler building? Lever House? The buildings that come to mind are all probably true to the structure. Their organization, appearance, transparency and solidity are probably all related to their structure. (Even if you are thinking of somewhat "arbitrary" building forms – the successful ones probably employ structural systems appropriate to their "arbitrariness".)

What does make an efficient tall building structure? The primary influences on the structure are gravity and lateral wind or seismic loads. The structural engineer, unfortunately, has no ability to affect gravity loads – he or she can select lighter materials to minimize the loads to be resisted, and can make the elements carrying gravity loads of newer, stronger materials, but these are a matter of degree and there is very little revolutionary that can be achieved. It is in the area of resisting lateral loads and deformations that the collaboration between architect and engineer has the greatest effect.

The principles of efficient tall building structural design were presented in a paper presented by the author in 1988 (Halvorson, 1988), and are quite simple:

- Resist the overturning forces due to wind (or lateral loads in general) on vertical elements placed as far apart as possible.
- Channel gravity loads to those vertical elements resisting wind overturning forces.
- Link these vertical elements together with structural elements forming rigid planes.
- To the extent possible, resist lateral forces with members axially loaded in compression rather than loaded in tension or bending.

These principles are so significant in taller buildings that they may entirely outweigh what passes as "conventional wisdom" for low-rise buildings. As one classic example, the Sears Tower employs steel floor trusses spanning 23 m for the sole purpose of delivering gravity loads from the floor framing directly to the columns resisting wind overturning forces. No one would suggest that 23 m floor spans are the most

efficient approach in a low-rise building, but in the Sears Tower, the overall benefits make that span attractive. We will examine how these principles have been employed in the buildings resulting from this collaboration later in the paper.

Structural systems to resist lateral loads in tall buildings – all endeavoring to follow these principles - have undergone major shifts over the last century. Skipping over the bearing wall structures of the early 20th Century and the transition to cast iron frame systems, the structural systems employed by the profession as of 1984 are shown in Figure 1. This figure is taken from a review done by the author that year, surveying the types of systems employed in tall buildings. The conclusions of that paper were that tall buildings generally employed “tube” systems and the tallest of the tall buildings were of structural steel.

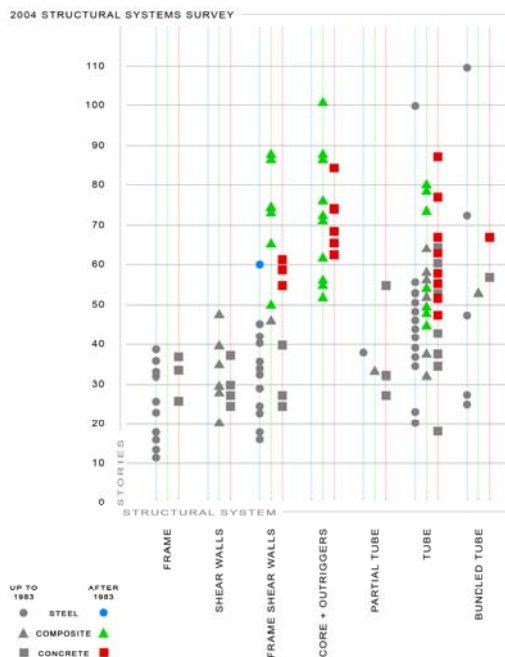


Figure 1. Survey of Structural Systems in Tall Buildings

“Tube” structures are characterized by closely spaced, wide columns organized in small bays around the perimeter of the building. The columns are moment-connected together with deep spandrel beams. The behavior of the system is like that of a hollow tube formed by the perimeter of the building, thus the name. This system follows the principles outlined above closely in that the lateral load resisting system is on the perimeter of the building and thus provides the broadest possible base for the structure. A large portion of the gravity loads are carried on the tube frame, in the same elements that resist wind overturning forces. Further, the tube frame is a very rigid link, with a stiffness almost equivalent to that of a solid wall, between the windward

and leeward faces of the building. Variations on a simple perimeter tube were developed for particular cases: a “tube-in-tube” system to take advantage of some resistance available from an inner structure around the central core, and, a “bundled tube” system (e.g., Sears Tower, Chicago) which employed additional tube frames through the interior of the building to link across the building plan. Another variant, a “braced tube”, employed diagonal bracing to provide the rigid planes linking opposite faces of a building together (e.g., the John Hancock Tower, Chicago).

So, in 1984 the future seemed clear – tall buildings were going to use tube systems of structural steel. Perhaps only politicians can read their old statements and not blush at how wrong they could have been. In hindsight, though, these tube systems had significant drawbacks. They occupied the most valuable perimeter real estate in towers and resulted in 40 to 50% of the perimeter being opaque. The detailing and fabrication of the many moment-resisting connections required to form the tube frame were expensive.

The situation in 2004 looked markedly different as is also shown in Figure 1 from information presented to the AIA National Conference (Halvorson, 2004). In the intervening 20 years, there were essentially no tall buildings constructed entirely of structural steel. Structures were being designed and built either entirely of reinforced concrete or of a mixture of structural steel and concrete, i.e., composite construction. In the 2004 survey, there continued to be framed tube systems, but only of reinforced concrete wherein the moment connections between columns and beams were less costly due to the inherent continuity of reinforced concrete. These concrete tube buildings also were generally found in countries where a structural steel industry had not yet developed. Also, the braced tube continued to be a popular system since it does meet all the principles outlined above without expensive moment connections.

However a “new” structural concept proved to be very popular: a core and outrigger system that utilizes a stiff central spine, usually around a central core, with large beams, walls or trusses extending from the core to perimeter columns at several levels to help stabilize the slender core structure. The advantages of this system are several:

- Gravity loads are carried by reinforced concrete which is perhaps one-seventh the cost of structural steel in carrying a given compression load;
- Floor framing is of structural steel and deck which allows the longer floor spans preferred in office and mixed-use buildings, is easier to coordinate with horizontal mechanical distribution reduces the gravity loads that must be carried down to the foundations, and provides flexibility for future modifications;

- The only structural elements located at the perimeter of the building are effectively gravity load columns which can be organized in large bays creating significantly more transparency; and,
- The costly moment connections in the tube frames are eliminated.

Against that backdrop of these developments in tall building structures, let us now look at the efforts of the collaboration between the firms of Foster and Partners and Halvorson and Partners. All of these efforts involved months of studying and refining alternatives – both in form and structure, but there is space here to comment only on the final solutions.

Corporate Office Building, Chicago



Figure 2. Corporate Office, Chicago (Foster + Partners, 2001)

For this first collaboration in 1999 between Foster and Halvorson, an office development was proposed for an urban site in Chicago, surrounded by tallish buildings with very little open space in the general area. Foster envisioned a long, linear core along the North side of the site with a large, unobstructed rectangular block of office space adjacent to the core (Figures 2 and 3). This left a large open space to the South of the building for a public park. The building height was approximately 46 stories above grade, or 210 m.

This massing resulted in a core with a slenderness ratio that approached 9 to 1, so it was necessary to utilize the entire North-South building dimension to resist lateral loads. A “diagrid” system was developed with sloped columns that both carried all the gravity loads on the building as well as resisted all lateral loads. Steel floor trusses, as used in the Sears Tower, were employed to clear span the office block and deliver floor loads directly to the diagrid columns. The diagrid columns were conceived as composite elements wherein a steel box section could be erected as for any conventional steel building, and then filled with high-strength concrete to provide the final strength required.

The concept used the entire base dimension of the building to resist lateral loads and gravity loads were carried by the same elements that resisted wind overturning forces. Members resisted loads as axial forces rather than in bending, and largely utilized inexpensive concrete to carry compression loads. So in all respects, the concept closely followed the principles for efficient tall building design outlined above.

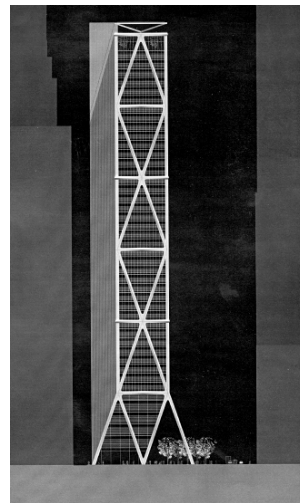


Figure 3. Elevation (Foster + Partners, 2001)

Competition Entry, Milan

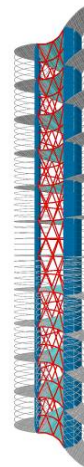


Figure 4. Milan Structure Diagram (Halvorson and Partners, 2004)

The building concept for this competition entry was to create “petals” of floor space in the sky, each of which would form an individual living space.

There were three petals per level organized as shown in Figures 4 and 5 around a central volume which would enclose the vertical circulation and provide communal gardens every three stories. Unobstructed views from the units and transparency of the central space were primary goals in the design.

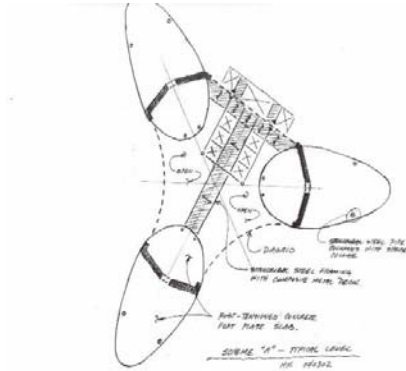


Figure 5. Plan (Halvorson and Partners, 2004)

The structural solution provided large concrete wall elements hidden in between rooms of the petals to support all gravity loads on the tower. Additional gravity columns necessary for support of the floor framing were envisioned to transfer periodically to these wall elements, so that all gravity loads of the tower would be carried by the three elements, one set of walls per petal. Diagonal steel bracing linked these wall elements together and provided lateral support for the glass wall enclosing the central sky gardens. It was envisioned that the floor framing in the units would be a flat plate concrete system to maximize ceiling heights, and structural steel in the central space to allow large clear spans with the heavy planting loads.

The solution provided great transparency in both the units and the central spaces. It also closely followed the principles for efficient design in these ways:

- All gravity loads were carried by concrete elements that also resisted wind overturning forces;
- These concrete elements were located at nearly the greatest possible plan dimension from one another; and,
- The links between the vertical elements were rigid diagonal bracing – all elements resisted overturning forces with their axial, rather than bending, strength and stiffness.

Caja Madrid (formerly Torre Repsol), Madrid

This 250m tall office tower was originally designed as the headquarters for Repsol YPF, the Spanish oil company, before being sold to the Spanish bank Caja Madrid. Its distinct form, two external cores bracketing a central office floor plate, evolved in an iterative design process – in an effort to provide valuable, unobstructed views and a dramatic, column-free ground floor lobby.



Figure 6. Caja Madrid Under Construction (Halvorson and Partners, 2007)

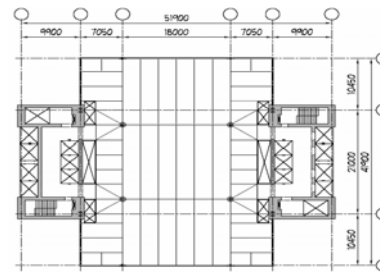


Figure 7. Plan (Halvorson and Partners, 2005)

The structural solution was, given the slenderness of the cores, to carry the entire gravity weight of the tower on the two cores in order to avoid uplift on the cores. Therefore, the center office floor plates had to be transferred to the cores. To achieve the large clear floor spans desired and the unobstructed views, structural steel was selected for the floor framing and gravity columns in the office areas. (See Figure 7.) The natural way to transfer these loads to the cores was by means of a steel truss spanning between the cores. However, since the steel gravity columns and the concrete cores would shorten differently under load and over time, it was decided to provide several transfer trusses over the height of the building to minimize the accumulation of the differences in shortening. Therefore it became possible to utilize the trusses not only to transfer gravity loads, but also to act as large “beams” linking the two cores together to resist wind loads in that direction. Therefore, the cores needed to be of a substantial dimension in one direction to resist wind loads as a cantilever on their own, but could be more slender in their other dimension since in that direction they participated as “columns” in a wind frame.

The final solution is, in a sense, a core and outrigger scheme in that each of the cores has an outrigger – not to columns, but rather to the other core. The scheme also utilizes concrete to carry all the gravity loads of the tower, and the steel trusses have members resisting lateral forces as axial loads.

Index Building, Dubai



Figure 8. Index Building Rendering (Foster + Partners, 2001)



Figure 9. Index Building under Construction (Foster + Partners, 2007)

The Index Building, an 80 story, 330 m tall mixed use building, is another example resulting from the collaboration to develop and express a logical structural system. The tower incorporates office functions in the lower third of the tower with residential functions in the upper two thirds as apparent in Figure 8. Here the entire depth of the plan was developed to resist lateral loads in the short direction of the building by means of four thru-thickness, reinforced concrete walls. In fact, since the walls extend beyond the plan of the building, the effective base of the building is substantially wider than the plan dimension of the building. In the long direction of the building, which had significantly lower loads, lateral resistance was provided with the two cores at the ends of the building acting as columns in a large one-bay, two story mega-frame.

The office floor framing is of steel floor trusses designed to clear span the 27 m bays in between the walls, thus delivering the floor loads directly to the thru-thickness walls carrying lateral loads. Above, in the residential building, it was found more economical to

utilize a conventional flat plate floor framing system that transfers to the larger grid below by means of the large beam at mid-height of the tower forming part of the mega-frame.

The system follows the principles outlined above in that the lateral loads are resisted by axial loads in the wall elements, the length of which is as great as possible; gravity loads are carried by the same elements carrying lateral overturning forces; and, the gravity elements are of reinforced concrete.

Residential Concept Tower, New York



Figure 10. Residential Tower Structure (Halvorson and Partners, 2006)

This residential tower concept was conceived as a sensitive addition to a landmark building that would provide the economics necessary to renovate the landmark to its original form and detail. The scheme created a new vertical pathway in one bay of the existing building to accommodate lifts, stairs and MEP risers, from which the larger tower form emerged above the existing building (see Figure 10). This approach minimized disruption to the existing floor plan and created a distinct separation between the existing landmark building and the new tower above.

By the nature of the scheme, all gravity loads had to be transferred to the central core which was conceived in reinforced concrete. The tremendous weight of the entire tower “held down” the core so that it alone could easily resist the overturning forces due to wind without uplift. Over the height of the tower a post-tensioned flat plate concrete floor system would be transferred to the core by means of a structural steel transfer system balanced about the center core.

While not a super-tall building, the concept does follow the principles outlined above – the primary system is of reinforced concrete, it is axially loaded and resists the entire gravity load as well as the wind overturning forces. The core does not, of course, develop the entire plan dimension of the building in resisting lateral forces, but this is acceptable nevertheless given the relatively short height of the building.

Central Market, Abu Dhabi



Figure 11. Central Market Rendering (Foster + Partners, 2006)

The Central Market development in Abu Dhabi is a 650,000 square meter mixed-use project incorporating office, hotel, residential and retail components. It has three towers, the tallest being 88 stories as shown in Figures 11 and 12. The architectural concept emphasized transparency, openness and views in the towers, while using high-performance glass and energy savings devices to minimize energy use.



Figure 12. Residential Tower Frame (Halvorson and Partners, 2006)

The three towers utilize similar structural systems and are of reinforced concrete, reflecting the local construction economies. The towers are provided with reinforced concrete core walls surrounding the central lifts, stairs and MEP shafts. While the cores are very stiff elements, the central cores have only a small percentage of the total lateral stiffness required for the towers. The cores are stabilized by adding outriggers – large, story-deep reinforced concrete beams located at plant floors – extending from the core to the perimeter columns. These perimeter columns are in turn linked to all the remaining perimeter columns with perimeter “belt” walls. Thus, the entire building plan dimensions, and the entire building weights, are used to resist wind

overturning forces. Nevertheless, on a typical residential floor only about 10% of the exterior elevation is opaque structure, allowing the transparency that is central to the architectural concept.

Russia Tower, Moscow



Figure 134. Russia Tower Rendering (Halvorson and Partners, 2006)

The new Russia Tower will be Europe’s tallest building at 612 m (2000 ft) in height. (See Figure 13) Its structural system, which became a primary architectural expression for the tower, evolved through an intensely collaborative process. The innovative ‘braced spine’ structural system developed in this process is an extremely efficient concept for super-tall structures and was a direct response to the design challenges and opportunities presented by this project. The Client initially envisioned three towers to separately house office, residential, and hotel spaces. Of the numerous massing options considered for three separate towers on the site, a radial arrangement of three thin towers at 120° to each other (Figure 14) to maximize outward views and exposure to sunlight was preferred.

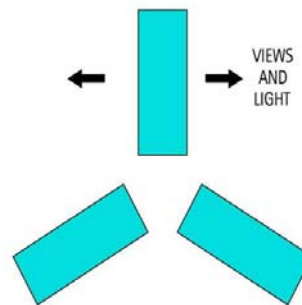


Figure 14. Three separate towers (Halvorson and Partners, 2005)

However, this resulted in very slender forms: the extreme being the 70+ story hotel and residential tower with an aspect ratio of over 10:1. The design team felt that schemes for linking or integrating the towers into one structure could be far more efficient.

Structurally, the three towers that were originally independent were thus rigidly linked, working together as a single structure – any one wing stabilized by the other two. Each wing was tapered in elevation (see Figure 15), providing a large base dimension for stability, and reducing or eliminating wind vortex shedding as a concern.

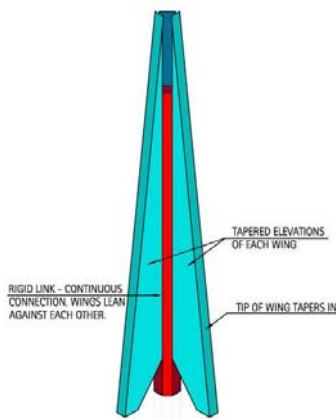


Figure 15. Three in one Tower (Halvorson and Partners, 2007)

There were limited locations to place structure in this configuration – along the wing faces and tips, and around the central zone were the obvious places. Numerous alternative structural concepts were discussed – including core with outriggers, a diagrid exoskeleton and stepped core bracing. However, one structural concept that related to the form of the building was particularly intriguing to the design team. The concept located a series of sloping, parallel columns along the faces of each wing which would serve both to carry the gravity loads of the floors, and to laterally brace a central core (Figure 16).

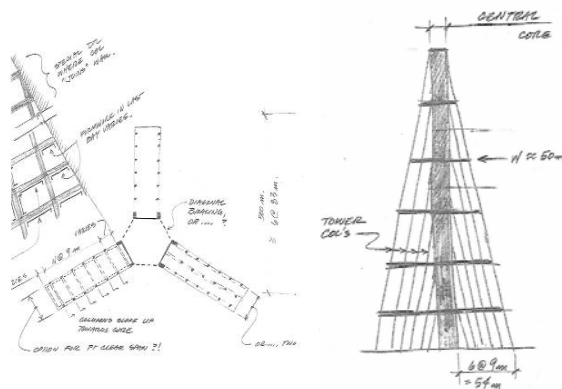


Figure 16. Sloped parallel columns (Halvorson and Partners, 2005)

This arrangement maintained consistent bays that offered repetition in the horizontal framing, but after study it was decided to originate all the sloped columns at one point at the base of each wing (see Figure 17). This adjustment reduced the repetition in the scheme, but did allow all overturning forces to be resolved at the furthest point from the building center – and, it was a stunning, unique form.

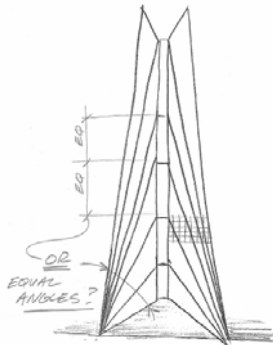


Figure 17. Columns to one point (Halvorson and Partners, 2005)

At this point, the design had come full circle to a very familiar structural form – that of a cable stayed mast. Instead of tension cables, however, the tower has sloped columns acting in compression (which became known as ‘fan columns’) to prop the center core (or “spine”) against lateral loads. The concept closely follows the fundamental principles of efficient tall building organization in that the fan columns carry both gravity load and wind overturning forces as direct axial loads, eliminating even the bending that occurs in outriggers.

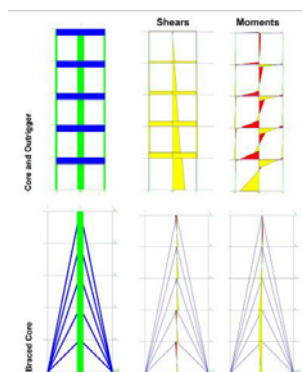


Figure 18. Braced spine vs. Core and outriggers (Halvorson and Partners, 2005)

As indicated in Figure 18, the shear and moment forces in the core are substantially reduced from that found in a core and outrigger system. The braced spine system resulted in the ultimate efficiency for a tall building in that the core elements and the fan column sizes were established by the strength required for compression under gravity load combinations, and were found to work for resisting lateral forces with only minor adjustments.

In order to stiffen the building in a torsional sense, it was found necessary to create closed forms around the center spine and each of the wings. This was accomplished by creating what came to be known as “reverse fan” columns along the faces of the wings, and linking around the tips of the wings with chevron bracing. (see Figure 19)



Figure 19. Add reverse Fan columns (Foster + Partners, 2005)

In the final design, seven fan columns radiate from the base abutments toward the central spine, where they then “bounce off” the spine to create the reverse fan columns (see Figure 20). Relatively light steel erection columns, which are designed only for temporary construction loads, are first erected at each fan column location just like a conventional steel building. These erection columns are later encased by reinforced concrete which provides the final fan column strength for permanent loads. Floor framing loads are delivered to the steel erection columns, which then shed their loads into the concrete columns via shear studs.

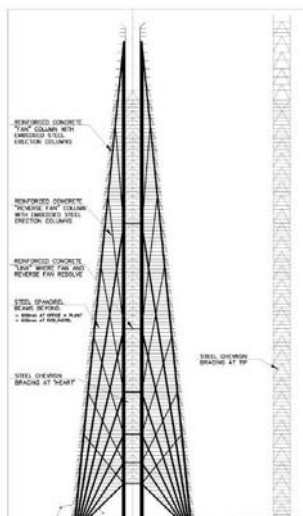


Figure 20. Elevation (Halvorson and Partners, 2007)

The central spine is formed by reinforced concrete walls hidden in core elements in each wing, which are linked together across the open space in the central “heart” by two-story steel chevron bracing. Where the fan columns intersect the spine, substantial horizontal

reinforced concrete beams are provided to resist the thrusts of the fan columns. Like the fan columns, the core walls utilize steel erection columns.

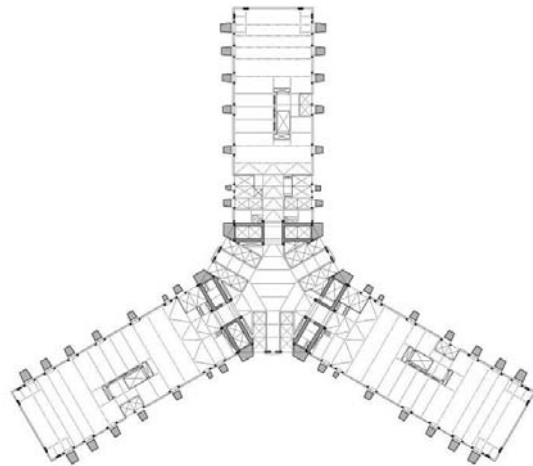


Figure 21. Plan (Halvorson and Partners, 2007)

Four-story steel chevron bracing at the wing tips serve to link the rigid faces formed by the fan and reverse fan columns, creating ‘closed sections’ in each wing for torsional stiffness. The bracing also props up the floor framing of the cantilevered wing tips, which extend 4 m beyond the outermost fan columns – allowing column free corners with relatively shallow spandrel..

An 11-story atrium is located in the space created below the sloping columns. Between the base and Level 11, each of the wings is an independent element, since it is not connected to or braced by the other wings. Stability for each of the wings is created by locating bracing on the underside of the wings and by interconnecting several of the fan columns along each face.

The vertical elements of the spine carry down to the foundations providing a direct load path for gravity loads, however, all the beams and bracing linking the elements together are removed to provide transparency in the atrium. Consequently, the independent structures of each wing also serve to stabilize the building as a whole.

In the lower third of the tower, composite steel floor trusses span the 21 m width of the wing to provide a column free office floors (see Figure 21). At the perimeter, steel spandrel beams support the interior floor framing and resist axial loads induced by sloping columns and other floor diaphragm forces. In the core areas where the wings intersect at the spine of the tower, there are numerous significant floor openings. Here, the typical slab thickness is increased, and in-plane floor diaphragm bracing is added to channel diaphragm forces around these openings.

In the hotel and residential levels higher in the tower, a pair of internal column lines along the centre of the wings reduces spans to allow shallow, conventional steel floor framing to maximize ceiling heights. The loads from the interior columns in the hotel and residential floors transfers to the perimeter structure at 'plant' levels approximately every 12 floors by means of a grid of story-high steel trusses. This transfer is necessary to avoid differential shortening issues between the steel interior columns and the concrete fan columns. The transfers also direct gravity loads to the fan columns, which are concrete and therefore more cost-effective in carrying the compression loads. Perhaps most significantly, the transfers direct sufficient gravity loads into the fan column that net tensions under wind load conditions are effectively eliminated.

Three independent masts formed from the wings extend 100 m above the roof level. They are structured by the extension of the outer most fan columns in each wing and the inner core wall around the spine.

The structural concept for the Russia Tower epitomizes the principles for efficient design of tall building structures in that it resists the overturning forces due to wind over a very broad base in relation to the massing of the building. The tower channels gravity loads to the same elements that resist wind overturning forces. The links from side-to-side of the building are formed with extremely rigid structural elements. Finally, the fan columns resist lateral forces as axially loaded reinforced concrete members in compression rather than being loaded in tension or bending.

Conclusion

Having examined briefly the building schemes resulting from the collaboration between Foster and Partners, and Halvorson and Partners, there is a consistent thread of innovative structural concepts which follow the fundamental principles for efficiency in tall building design:

- Resist the overturning forces due to wind (or lateral loads in general) on vertical elements placed as far apart as possible.
- Channel gravity loads to those vertical elements resisting wind overturning forces.
- Link these vertical elements together with structural elements forming rigid planes.
- To the extent possible, resist lateral forces with members axially loaded in compression rather than loaded in tension or bending.

The buildings result from the collaboration of two individuals and firms, neither of which could have developed the schemes on their own. Put side-by-side, there is no apparent similarity in the design of the buildings, other than that their structural concepts and their architectural concepts are one. The organization of the buildings, their appearance and their structure are all intimately related. Simply put, the buildings look like they work and work like they look.

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