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Building Where They Said It Couldn't Be Done!

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Summary

Construction of tall buildings in the centers of the world's large cities almost invariably involves working within severe site constraints. The constraints can involve all aspects of architectural and engineering design. As illustrated with examples drawn from the author's practice, many different structural engineering concepts are available for overcoming limitations imposed by site conditions. Creating opportunities for development of "impossible" sites through innovative design represents a unique — and uniquely rewarding — challenge to the structural engineer.

1. Introduction

Innovations and refinements in the structural analysis and design of tall buildings can make the building structure more efficient by providing the required strength and serviceability at less cost. But important as they are, these improvements in analysis and design (which may save the project owner a few dollars per square meter in construction cost) will rarely have a decisive effect on the economic feasibility of an urban development.

There are situations, however, where the structural engineer's contribution to the success of a project can be decisive. Most often, these situations involve the use of innovative structural engineering to overcome or circumvent constraints imposed by site conditions.

It is the rare tall building these days that can be placed on a "green field" location. Typically, the new urban building project has to conform to constraints imposed by existing conditions at the site. Site conditions can require that a building have a structurally-inefficient shape (e.g., unsymmetric or very slender). And site conditions can create a situation where there is no clear and direct path along which to transmit structural loads into the ground from floors located where they are functionally most desirable. It is the latter situation that is the primary subject of this paper.

Some of the main classes of solutions to the problem of transferring structural loads to the ground along indirect paths will be outlined. This will be followed by a discussion of a few unusual load-transfer challenges and solutions from the author's practice.

2. Types of Structural Transfers

At the most basic level, structural load transfer systems can be classified according to the type of load that is to be transferred — vertical force, horizontal force, or overturning moment. Transfer systems for vertical load and those for horizontal force and overturning moment will be discussed separately.

2.1 Transfer of Vertical Load

When the direct downward transfer of vertical load to the ground is prevented by an obstruction, the solutions include spanning across the obstruction or cantilevering out over the obstruction, as illustrated in Figure 1. The transfer trusses or girders (trusses shown) used for the span or cantilever could be located near the bottom of the building or at the top (or anywhere in between).

Locating the transfer trusses or girders at the bottom will usually result in lower construction cost. When the transfer elements are at the top, floor loads have to be carried up to the top through hangers and then down to the ground through the support columns. The extra distance through which the loads have to be transmitted will be reflected in increased column and hanger material and cost. Also, the construction sequence can be awkward. Yet another difficulty with the hung-from-above design is proper control of floor elevation, since floor loading simultaneously stretches the hangers and compresses the support columns.

Despite these drawbacks, transfer trusses or girders are sometimes placed at the top, either within the building envelope or exposed above the roof. This is done when transfer components at the lower floors would have an unacceptable effect on the functional or architectural design of the project.

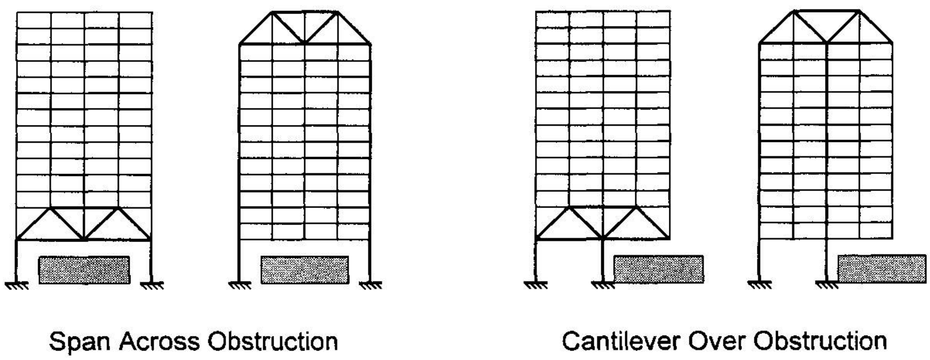
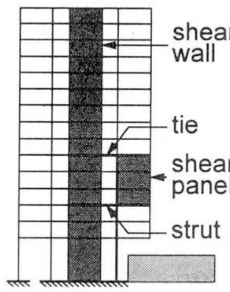


Fig. 1. Structural transfer concepts for vertical load

A possible alternative to the transfer cantilever shown in Fig. 1 is the "tied-back shear panel" transfer system shown in Fig. 2. In this design, vertical load is shifted laterally by means of a vertical wall panel (or diagonally-braced truss panel) loaded in essentially pure shear. The corresponding moment is restrained by a tension tie at the top of the panel and a compression strut at the bottom, both connected to the building's main lateral load-resisting system.



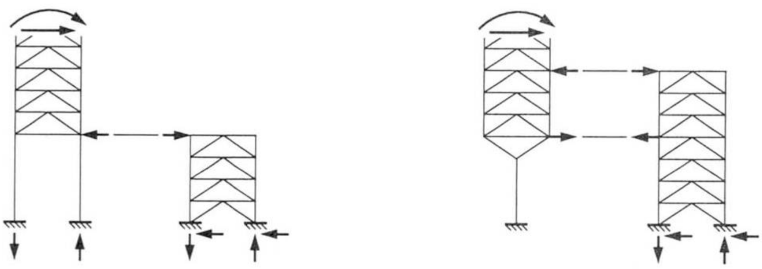
Tied-Back Shear Panel

Fig. 2. Tied-back shear panel transfer concept for vertical load

In many situations the shear panel will be less disruptive of the use of the building than conventional cantilever trusses or girders. The drawback is that the moment imposed on the building's lateral load-resisting system can be substantial. (Of course, balanced panels on both sides of the building would avoid this problem.)

2.2 Transfer of Horizontal Shear and Overturning Moment

Structural design concepts for transfer of horizontal shear and overturning moment from one part of a building structure to another are illustrated in Fig. 3. In the picture on the left, shear alone is transferred, while the moment continues down to the ground. In the picture on the right, both horizontal shear and overturning moment are transferred. (The building's lateral load-resisting system is shown as a truss or braced frame in the illustration; it could be a shear wall or rigid frame instead.)



Transfer of Shear Alone   Transfer of Shear and Moment

Fig. 3. Structural transfer concepts for horizontal shear and overturning moment

Transfer of horizontal shear in a building structure (left side of Fig. 3) is usually a simple matter. Building floors are typically very stiff and strong in their own plane, and can be designed to transmit large in-plane forces at little additional cost.

Overturning moment can be transferred from one part of the building to another as a horizontal couple, using floors to transmit horizontal force in one direction at one floor and the opposite direction at another floor (right side of Fig. 3).

3. Examples

The use of innovative structural transfer systems will be illustrated with four examples drawn from the author's consulting engineering practice. One of the projects was not actually built; it succumbed to changes in market conditions late in the design process. The other three examples are buildings that have been completed.

In the following discussion of the four projects, there will be some simplification and idealization of actual conditions, for purposes of clarity. Additional information on the three completed buildings can be found in the database of the Council on Tall Buildings and Urban Habitat. (The database is accessible to Council members through the Internet.)

3.1 Morton International Building

The Morton International Building (Reference 1), at 100 North Riverside in Chicago, is a 36-story, 101,000 m^2 office building. The lower 12 floors, of 4,300 m^2 each, hold lobbies, parking space for 435 cars, and a 26,000 m^2 computer center for the local telephone company. The upper floors hold rental office space.

The entire project is above an active rail yard, which had defeated all previous attempts at developing the site, though it is at a prime location on the Chicago River. As shown in the schematic site plan in Fig. 4, the rail tracks cover almost the entire site. The streets in the area are about 10 m above the tracks.

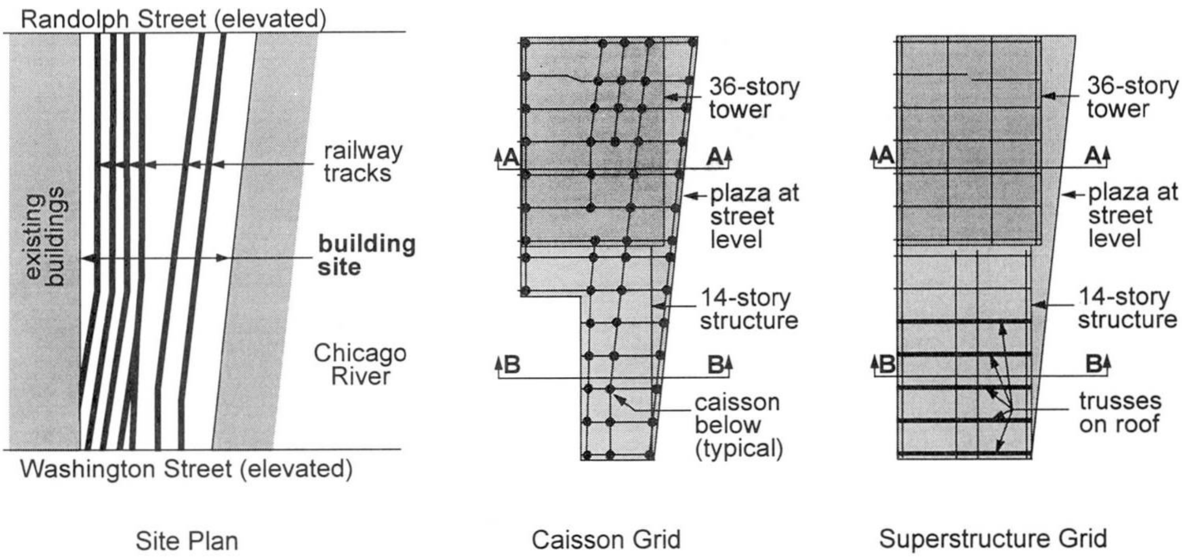


Fig. 4. Schematic layout of Morton International Building

Development of the Morton International site was made possible by a comprehensive transfer system. Foundation caissons (drilled piers) and track-level columns were located where track clearances were adequate, as shown in the caisson grid in Fig. 4. The caisson locations did not coincide with column locations in the building above (see superstructure grid in Fig. 4).

A complete grid of concrete transfer girders, about 2.5 m deep and between 1.0 and 2.5 m wide, transfers load from the building columns above to the track-level columns and caissons below. The top of the girder grid is at street level. The columns below the girders are of reinforced concrete (and are, in effect, extensions of the caissons). The building above the girders is framed in steel. Schematic Section A-A in Fig. 5 shows the relationship between building columns, transfer girders and caissons.

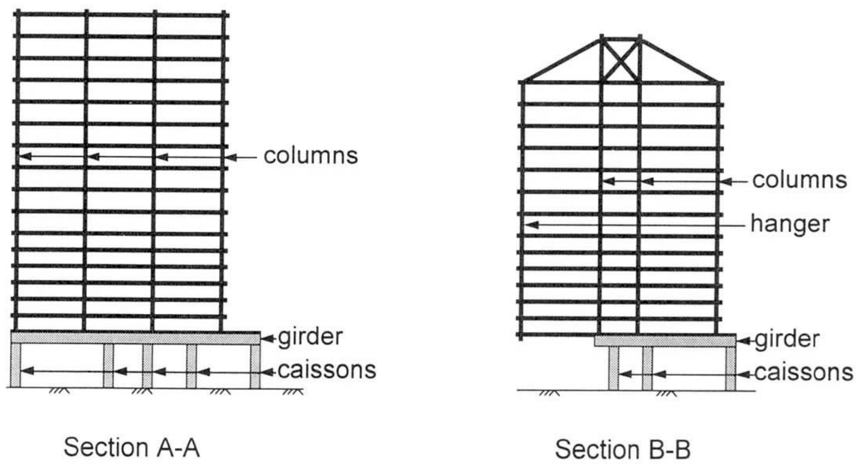


Fig. 5. Schematic sections through Morton International Building (see Fig. 4 for location of sections)

Fig. 6. Morton International Building

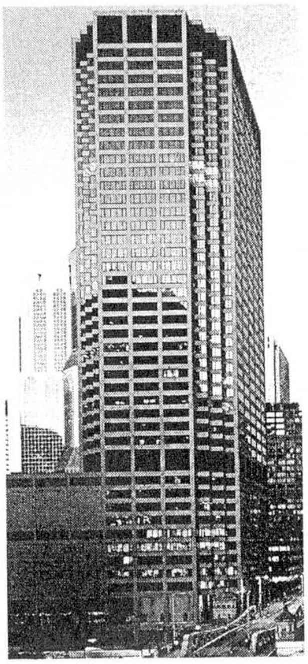
There was no room for caissons or columns among the tracks in a 20 m x 46 m area at the southwest corner of the site (see caisson grid in Fig. 4). In early planning concepts, this area was left unbuilt. However, it proved to be very important that there be floors above this foundation-less area. The telephone company demanded full 4,300 m^2 floors; efficiency of the parking layout also required full floors, without a cut-out in the corner. The solution was to provide a cantilever transfer system to support the part of the building below which there could be no caissons. Cantilever trusses at the bottom, just above the tracks, would have been most economical but would have disrupted the parking layout. So the trusses were placed on the roof, where they became part of the architectural expression of the building, as indicated in Section B-B in Fig. 5 and the photograph in Fig. 6.

The Morton International Building is a good example of the use of an innovative structural transfer system to create an opportunity for development of a site that had previously been judged to be undevelopable. The entire building superstructure, both the 36-story tower and the low-rise portion, is supported on the grid of concrete girders above the railway tracks. The cost of the girder system, distributed over the floor area that it supports, was fairly modest.

The cantilever trusses support only a small fraction of the total floor area in the project. The additional floor area made possible by the cantilevers came at a very high price, if expressed in dollars per square meter of additional space. But this $\$/m^2$ figure does not tell the whole story. The cantilever system played an important role in the success of the entire project by creating the floor size demanded by a major tenant and by allowing an efficient parking layout.

3.2 Chicago Mercantile Exchange Center

The Chicago Mercantile Exchange Center (Reference 2), at 10 and 30 South Wacker Drive in Chicago, includes two 40-story, 116,000 m^2 office towers and two stacked column-free trading halls, of about 4,000 m^2 and 3,000 m^2 respectively. Parking is provided on four floors below street level. The photograph in Fig. 7 shows one of the two towers and part of the structure enclosing the trading halls.



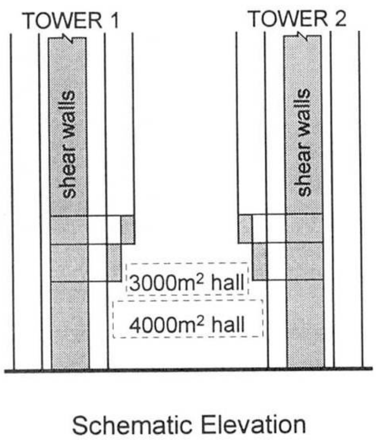


Fig. 7. Chicago Mercantile Exchange Center

Typical floors in the office towers are of just under 3,000 m^2, a size considered optimum in the local office leasing market. The challenge to the structural engineer on this project was to accommodate two 3,000 m^2 office towers and a 4,000 m^2 column-free trading hall on a site with a total area of under 8,000 m^2. The solution was to cantilever each tower about 10 m over the trading hall, as shown in the schematic elevation in Fig. 7.

The building is constructed of reinforced concrete, except that steel framing is used for the long-span floor above the lower trading hall and the roof above the upper trading hall. The lateral load-resisting system is a shear wall core in each tower. The project was completed in two phases: Phase I consisted of one tower and the trading halls; Phase II was the second tower.

Since the office towers overhang the trading halls by 10 m, it was necessary to transfer load out of one row of exterior columns in each tower. Transfer girders or trusses spanning across the halls would have been very expensive because of the long spans involved, and would have been further complicated by the phased construction of the project. Cantilever girders or trusses supported on the first row of interior columns and extending back into the building was another possibility. But this would have resulted in a large amount of wasted space. The cantilevers would have had to extend back into the elevator cores, which would have required a larger back-to-back spacing of elevators and wasted area on all floors in the towers.

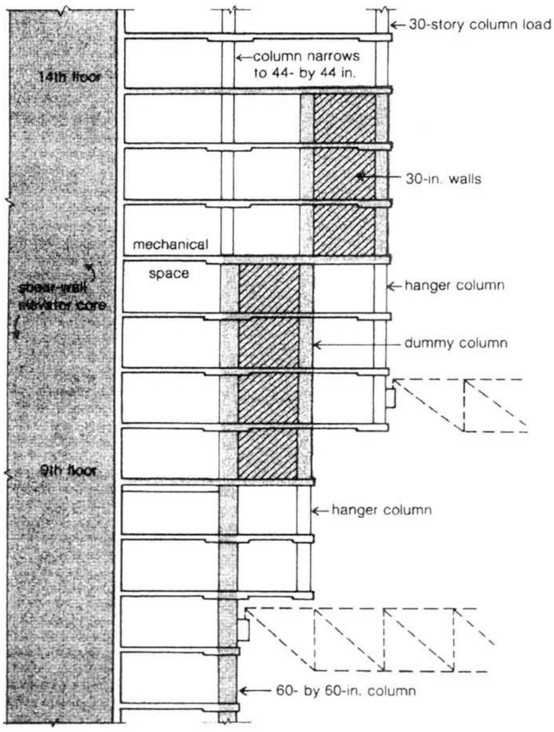


Fig. 8. Shear panel transfer system at Chicago Mercantile Exchange Center

The solution adopted was the tied-back shear panel concept explained in Section 2.1 and shown schematically in Fig. 2. The application of the concept to this project is shown in Fig. 8. The 10-m horizontal transfer is achieved in two steps over seven stories (with a total height of 25 m). The shear panels are reinforced concrete walls 760 mm thick. The tension tie at the top and the compression strut at the bottom transfer overturning moment in the form of a horizontal couple to the shear wall core.

One of the interesting structural engineering details in the Chicago Mercantile Exchange Center project is that the overturning moments imposed by the transfer system cause lateral deformation of the shear cores. The towers were erected out-of-plumb by up to 100 mm to compensate for this. Subsequent lateral displacements, including long-term effects, brought the towers to a plumb condition.

3.3 Unbuilt Mixed-Use Project

This example will deal with a very large mixed-use project that involved extensive transferring of both vertical and lateral load. The project was not built, but the engineering concepts were fully developed (and tested for cost) before work was stopped.

The general layout of the project, simplified and idealized for clarity, is indicated in Fig. 9. It includes a 70-story office tower, two 40-story office towers and a 20-story hotel, with a common 6-story base or podium holding retail space. Parking is accommodated in several below-ground basement levels. The total floor area in the project is about 500,000 m^2. The project was to be constructed in two phases. The first phase, of about 250,000 m^2, included the entire basement and podium (including the lower floors of all the office towers), one 40-story office tower and the hotel.

Architectural and engineering design had been completed to the point of receiving a construction manager's Guaranteed Maximum Price for Phase I when the project was stopped because of changes in market conditions.

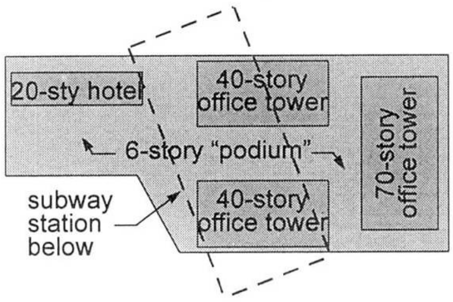


Fig. 9. Overall layout of unbuilt mixed-use project

The most obvious site-related engineering challenge on this project was the presence of a subway station running diagonally across the middle of the property (see Fig. 9). This had discouraged all previous attempts at developing the site, even though it was at a prime location. The top of the concrete roof slab of the subway station structure is about 2 m below the surrounding ground surface.

The solution to the problem posed by the subway was a grid of cast-in-place concrete transfer girders just above the station roof slab. The girders were supported on the station walls, some existing columns within the station where additional capacity was available, and new columns inserted where possible within the station. The concept is similar to that adopted for the Morton International Building (see Section A-A in Fig. 5), but without the cantilevers and hangers.

Early designs for the project included expansion joints through the 6-story "podium" structure to separate it into four segments, one at each tower, as indicated in Fig. 10. This permitted the four towers to act independently in resisting lateral load, in conformance with conventional practice. But the joints gave rise to certain problems. The most obvious difficulty was that relative movement at the joints could be as much as 200 mm as the towers oscillated out of phase with one another during the design wind event. This was especially problematic in that some of the joints went right through ballrooms and other finished spaces.

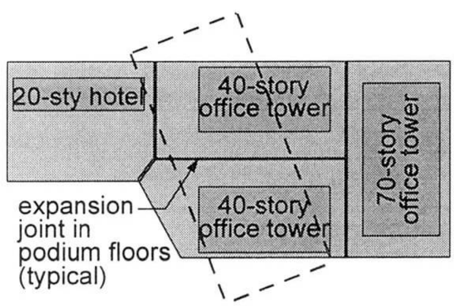
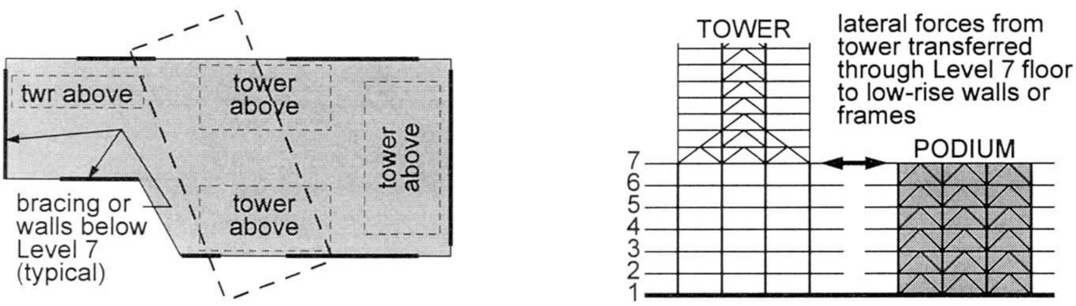


Fig. 10. Conventional expansion joint configuration

The office towers used braced-frame cores with outriggers to "supercolumns" as their lateral load-resisting systems. The initial structural design, again following conventional practice, carried the lateral forces from the towers straight down through the podium floors to the foundation. The problem here was that the diagonal bracing could not be carried down through the lower six stories since the retail space below the tower cores needed to be open. So instead of braced frames, massive steel rigid frames were proposed in the podium floors below the tower cores.

The problems posed by the large movement at expansion joints and the massive (and expensive) rigid frames below the tower cores were eliminated by a redesign that eliminated the expansion joints, causing the entire four-tower project to act as a single structure.



Shear Walls and Bracing in Podium Lateral Force Transfer Concept

Fig. 11. Design concept with no expansion joints

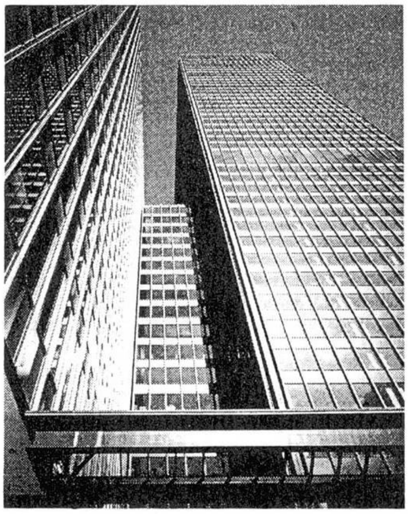
With expansion joints eliminated, a separate bracing system was not needed below each tower in the podium floors. Bracing and walls were provided wherever they would fit conveniently, scattered throughout the project, below Level 7 (at the top of the podium), as shown on the left side of Fig. 11. The Level 7 slab was designed to transfer horizontal shear forces from the tower bracing systems to the podium bracing as shown on the right side of Fig. 11.

The redesign to eliminate the expansion joints and transfer lateral loads as indicated in Fig. 11, together with a few other structural engineering refinements, reduced the estimated cost of this project by \$60 million.

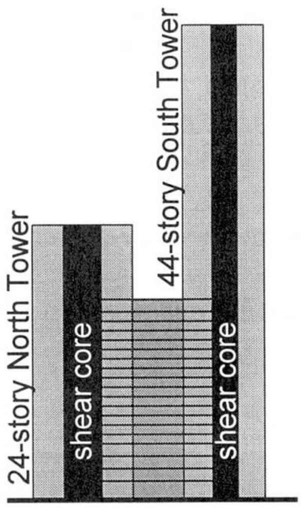
3.4 Boulevard Towers

The Boulevard Towers office development, at 205 and 225 North Michigan Avenue in Chicago, consists of a 44-story, 86,000 m^2 South Tower and a 24-story, 82,000 m^2 North Tower. Up to the 19th level, a 30 m wide infill structure spans the 12 m space between the two towers, resulting in floors of over 5,600 m^2 each. The structure is constructed of reinforced concrete, with shear wall cores as the lateral load-resisting system.

Both towers straddle an existing commuter train station, which had to remain open throughout the construction period. A comprehensive grid of concrete girders supports tower columns and shear walls and transfers load to columns between the tracks and on the station platforms. The main subject of this discussion, however, will be not the transfer over the railway station but the linkage between the two towers. (The linked design anticipated some of the concepts proposed for the unbuilt mixed-use project discussed in Section 3.3.)



Photograph



Schematic Elevation

Fig. 12. Boulevard Towers

The 19-story infill between the two towers (see Fig. 12) links the towers structurally. There are no expansion joints between the infill structure and either tower. A joint at the infill would have been subject to very large relative movements — of the order of 300 mm at the 19th floor —

which would have been difficult to accommodate in the architectural and functional design of the project. Moreover, use of the infill floors to link the two towers structurally offered important benefits.

The lower North Tower has much larger floors than the taller South Tower. (Typical floor areas are 3,200 m^2 in the North Tower and 2,100 m^2 in the South Tower.) Architectural and space-planning requirements made it possible to have a deep shear core in the stubby North Tower, but only a shallow core in the slender South Tower. If the two towers had been structurally independent, the lateral load-resisting system of the taller tower would have been extremely inefficient and expensive. Linking the towers (see schematic elevation in Fig. 12) allowed the deeper, stiffer core in the lower building to resist most of the combined lateral loading imposed on the two towers.

The link floors represent a transfer system for both shear and moment, as shown schematically on the right side of Fig. 3, except that not all the moment is transferred from the taller to the shorter tower. However, sufficient moment is transferred that the moment in the shear core of the South Tower is greater at the 20th floor (just above the link) than further down in the building. At the base, the two shear cores share overturning moment roughly in proportion to their stiffness, with the core of the lower building supporting significantly more than half the total.

The project was built in two phases. The shorter North Tower was built first; the taller South Tower was completed four years later. Compared to a design with the towers structurally separated by expansion joints, the linked design resulted in modest additional cost in the shorter tower and major savings in the cost of the taller tower.

4. Conclusions

Innovative structural transfer systems can create opportunities for development where they didn't exist before. This is illustrated by the Morton International Building and the unbuilt mixed-use project discussed in this paper. Existing conditions at the sites of both these projects had defeated all previous attempts at development. At the Chicago Mercantile Exchange Center, an unusual transfer system made it possible to place two office towers and a trading hall where it would otherwise have been economically possible to develop only one tower adjacent to the hall. In all these situations, the purpose of the transfer system was to carry to the ground, along indirect load paths, gravity loads from floors located where they were most useful.

Structural transfer systems can also be used to transfer horizontal shear and overturning moment from one part of a project to another. Transfers of this type can produce major reductions in the cost of the overall development, as illustrated by the unbuilt mixed-use project and the Boulevard Towers buildings. In both these cases, the transfer system integrated into a single structure towers that would, in a conventional design, have behaved as independent structural units.

As cities become ever more densely developed, structural engineers will have increasing opportunities to make decisive contributions to the economic feasibility of projects '.y conceiving innovative transfer systems.

5. References

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2. "Unique cantilevers carry 400,000 sq ft of tower," *Architectural Record*, November 1983, pp. 136-139.