Belt Trusses and Basements as "Virtual" Outriggers for Tall Buildings

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INTRODUCTION

The outrigger concept is in widespread use today in the design of tall buildings. In this concept, "outrigger" trusses (or, occasionally, girders) extend from a lateral load-resisting core to columns at the exterior of the building. The core may consist of either shear walls or braced frames.

Outrigger systems can lead to very efficient use of structural materials by mobilizing the axial strength and stiffness of exterior columns to resist part of the overturning moment produced by lateral loading. There are, however, some important space-planning limitations and certain structural complications associated with the use of outriggers in tall buildings.

A variation on the outrigger theme is the "offset" outrigger concept proposed by Brian Stafford Smith.[1] Offset outriggers can overcome or circumvent many of the problems associated with conventional outriggers. A further, more specialized, development of the offset outrigger concept is the use of belt trusses and basements as "virtual" outriggers for tall buildings, as proposed in the present paper. A belt wall is used in this way in a tall building now under construction in Malaysia.[2]

CONVENTIONAL OUTRIGGER CONCEPT

In the conventional outrigger concept, the outrigger trusses or girders are connected directly to shear walls or braced frames at the core and to columns located outboard of the core. Typically (but not necessarily), the columns are at the outer edges of the building. Figure 1 is an idealized section through a tall building with two sets of outrigger trusses, including one at the top.

The outrigger trusses in Figure 1 are shown three stories tall, with double diagonals in an "X" configuration. Shallower and deeper trusses have been used, with diagonals of various configurations. The number of outriggers over the height of the building (two in Figure 1) can vary from one to three or more.

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The way in which the outboard columns resist part of the overturning moment produced by wind or other lateral loads on the building is illustrated in Figure 2. The outrigger trusses, which are connected to the core and to columns outboard of the core, restrain rotation of the core and convert part of the moment in the core into a vertical couple at the columns. Shortening and elongation of the columns and deformation of the trusses will permit some rotation of the core at the outrig-

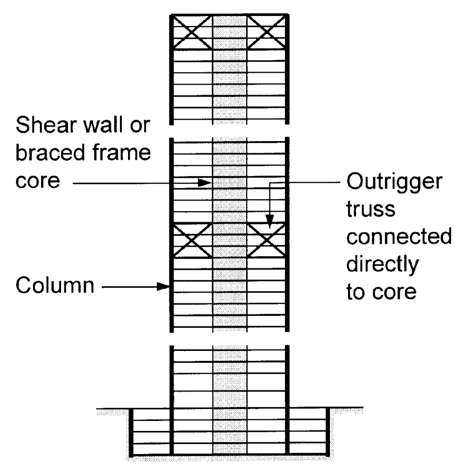

Fig. 1. Tall building with conventional outriggers.

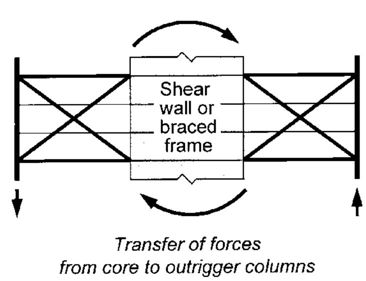

Fig. 2. Force transfer in conventional outrigger system.

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ger. In most designs, the rotation is small enough that the core undergoes reverse curvature below the outrigger.

Problems with Outriggers

There are several problems associated with the use of outriggers, problems that limit the applicability of the concept in the real world:

1. The space occupied by the outrigger trusses (especially the diagonals) places constraints on the use of the floors at which the outriggers are located. Even in mechanical-equipment floors, the presence of outrigger truss members can be a major problem.
2. Architectural and functional constraints may prevent placement of large outrigger columns where they could most conveniently be engaged by outrigger trusses extending out from the core.
3. The connections of the outrigger trusses to the core can be very complicated, especially when a concrete shear-wall core is used.
4. In most instances, the core and the outrigger columns will not shorten equally under gravity load. The outrigger trusses, which need to be very stiff to be effective as outriggers, can be severely stressed as they try to restrain the differential shortening between the core and the outrigger columns. Elaborate and expensive means, such as delaying the completion of certain truss connections until after the building has been topped out, have been employed to alleviate the problems caused by differential shortening.

"VIRTUAL" OUTRIGGERS

In the conventional outrigger concept, outrigger trusses connected directly to the core and to outboard columns convert moment in the core into a vertical couple in the columns. In the "virtual" outrigger concept, the same transfer of overturning moment from the core to elements outboard of the core is achieved, but without a direct connection between the outrigger trusses and the core. The elimination of a direct connection between the trusses and the core avoids many of the problems associated with the use of outriggers.

The basic idea behind the virtual outrigger concept is to use floor diaphragms, which are typically very stiff and strong in their own plane, to transfer moment in the form of a horizontal couple from the core to trusses or walls that are not connected directly to the core. The trusses or walls then convert the horizontal couples into vertical couples in columns or other structural elements outboard of the core. Belt trusses and basement walls are well suited to use as virtual outriggers.

Belt Trusses as Virtual Outriggers

Figure 3 is an elevation of a building similar to the structure in Figure 1 except that it has belt trusses at the exterior, instead of conventional outrigger trusses between the core and the exterior.

The way in which overturning moment in the core is converted into a vertical couple at the exterior columns is shown in Figure 4. Rotation of the core is resisted by the floor diaphragms at the top and bottom of the belt trusses; thus, part of the moment in the core is converted into a horizontal couple in the floors (Figure 4a). The horizontal couple, transferred through the two floors to the truss chords, is converted by the truss into vertical forces at the exterior columns (Figure 4b).

The forces and moments in all components can be determined by three-dimensional elastic analysis of the lateral load-resisting system, which includes the core, the trusses, the exterior columns, and the floors that connect the core to the trusses. The in-plane stiffnesses of the floors at the top and bottom of each outrigger should be represented accurately in

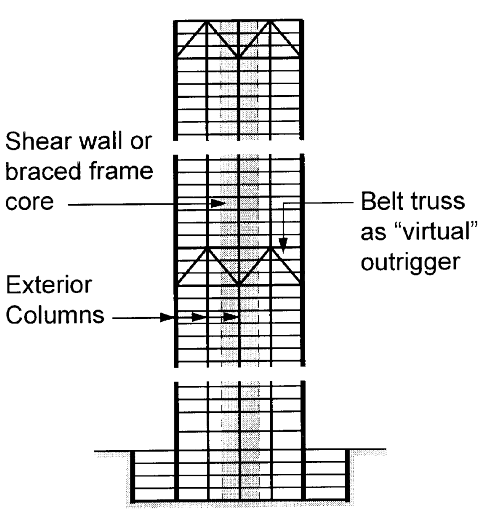

Fig. 3. Tall building with belt trusses as "virtual" outriggers.

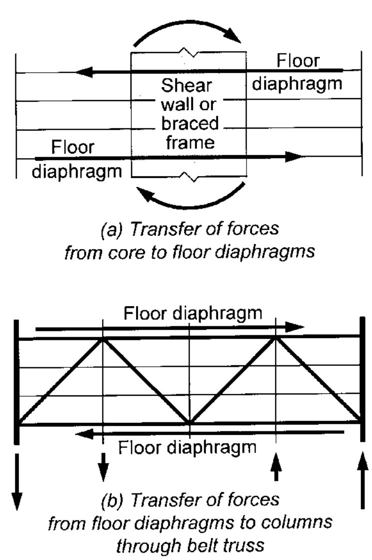

Fig. 4. Force transfer using belt truss as virtual outrigger.

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the analysis (such as through the use of planar finite elements). These floors should not be regarded as infinitely stiff diaphragms.

When the core is a steel braced frame, the transfer of horizontal forces between the core and the floors can be achieved through shear studs on the horizontal frame members. When the core is a concrete shear wall, forces may be transferred through the concrete-to-concrete connection, with reinforcing steel extending through the connection. The transfer of horizontal forces between the floor diaphragms and the chords of the belt trusses can be achieved through shear studs on the chords.

The floor slabs that transfer horizontal forces from the core to the belt trusses will be subjected to in-plane shear (in addition to the usual vertical dead and live load effects) and should be proportioned and reinforced appropriately. In many applications, it will be necessary to use thicker-than-normal slabs.

The use of belt trusses as virtual outriggers avoids many of the problems associated with the use of conventional outriggers, including all four of the items listed previously under "Problems with Outriggers":

1. There are no truss diagonals extending from the core to the exterior of the building.
2. The need to locate outrigger columns where they can be conveniently engaged by trusses extending from the core is eliminated.
3. The complicated truss-to-core connection is eliminated.
4. Differential shortening or settlement between the core and the outboard columns does not affect the virtual outrigger system since the floor diaphragms, though stiff in their own plane, are very flexible in the vertical, out-of-plane direction.

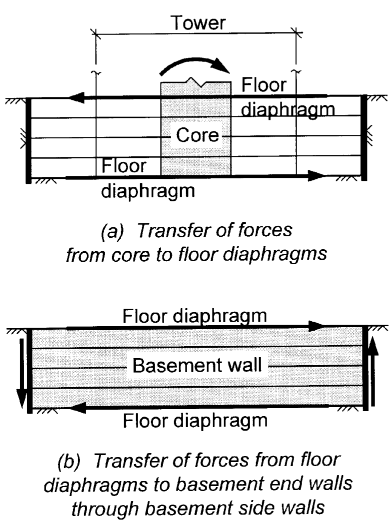

Fig. 5. Force transfer using basement as virtual outrigger.

Basements as Virtual Outriggers

The basement of a tall building can serve as a virtual outrigger, to create a base with a greater effective width for resisting overturning. This can reduce lateral load-induced forces in foundation elements and eliminate uplift. Since basement walls are typically of ample strength and stiffness to be effective as outriggers, there may be little additional cost involved in applying this concept.

The principle is the same as when belt trusses are used as virtual outriggers. Some fraction of the moment in the core is converted into a horizontal couple in the floors at the top and the bottom of the basement. This horizontal couple is transmitted through the floor diaphragms to the side walls of the basement, which convert the horizontal couple into a vertical couple at the ends.

For the building shown in elevation in Figure 3, the transfer of forces when the basement is used as a virtual outrigger is illustrated in Figure 5. The final vertical reactions at the ends of the basement (see Figure 5b) can be supplied by friction or adhesion of soil against the wall surfaces or by conventional foundation elements under the walls.

The effectiveness of the basement as an outrigger is likely to be greatest when the core has a "soft" support, such as footings on soil or long caissons subject to elastic length changes. A "hard" support, such as footings directly on rock, may result in most of the moment in the core going down directly into the core foundation, not into the outrigger system.

The forces and moments in the various components can be determined by three-dimensional analysis. It is important that the stiffness of the core foundation be modeled with reasonable accuracy (not as rigid supports). The in-plane stiffnesses of the floors that connect the core to the basement walls should also be modeled accurately; the floors should not be idealized as perfectly rigid diaphragms.

Note on Modeling of Base Restraints for Tall Buildings

The concept of using a basement as a virtual outrigger brings up a related issue: There is no single, generally-accepted way

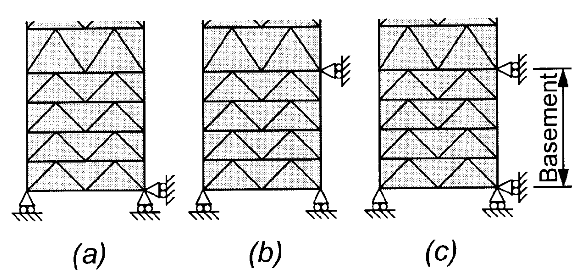

Fig. 6. Alternative support idealizations for building with basement.

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Table 1. Results of Analysis of 75-Story Building Example 1	
Type of Outrigger	**Lateral Displacement at Top Due to Wind (inches)**
No outrigger	108.5
Conventional outrigger	25.3
Belt truss as virtual outrigger	37.1
Belt truss as virtual outrigger 10-fold increase in floor diaphragm stiffness	31.0
Belt truss as virtual outrigger 10-fold increase in floor diaphragm stiffness 10-fold increase in belt truss stiffness	26.0

of modeling the horizontal restraints at the base of a building that has a basement, even when there is no deliberate attempt to use the basement as a virtual outrigger.

Three alternative simplified models for the support of a building's lateral load-resisting system are illustrated in Figure 6. In idealization (a), horizontal restraint is applied at the bottom of the basement. In (b) it is applied at the top of the basement. In (c) it is applied at the top and the bottom. (As a variation on (c), restraints could be applied at all floors that engage the basement walls, i.e., at the ground floor and all basement floors.) The foundation is represented by vertically non-movable supports in Figure 6; springs could have been shown instead.

There is little published information on the horizontal restraint conditions assumed in the design of the world's tall buildings. Anecdotal evidence suggests that idealizations (a) and (b) have been used in most designs. However, unless the building's lateral load-resisting system is isolated from the basement walls by special detailing, horizontal restraint will be present at all basement floors; this approaches condition (c), except that the restraints will be of less than infinite stiffness.

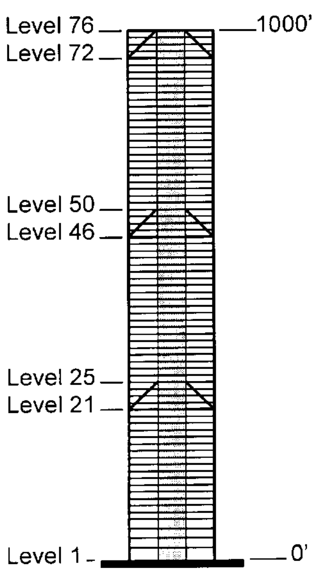

Fig. 7. Elevation of building studied in Example 1.

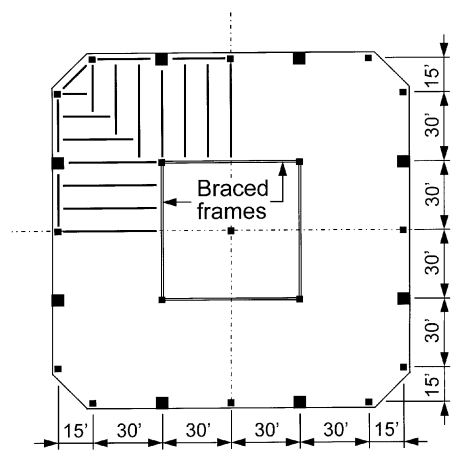

Fig. 8. Idealized typical floor plan of building in Example 1.

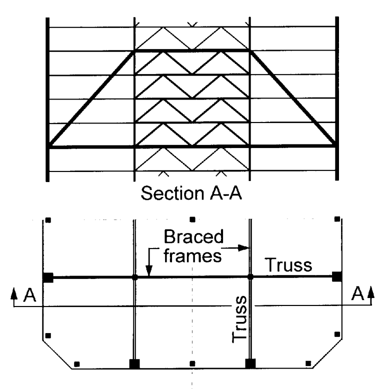

Fig. 9. Conventional outrigger system in Example 1.

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The concept of using a basement as a virtual outrigger is, in essence, simply a matter of realistic three-dimensional modeling of the restraints at the base of the building, together with careful proportioning, design and detailing of all components to maximize the outrigger effect and to resist all the resulting forces and stresses.

EXAMPLES — BELT TRUSSES AS VIRTUAL OUTRIGGERS

Plaza Rakyat Tower

The 77-story Plaza Rakyat office tower in Kuala Lumpur, Malaysia, uses a concrete shear core, a concrete perimeter frame, exterior concrete belt walls at two levels, and a conventional outrigger system at the roof as the building's lateral load-resisting system. Details of the design can be found in Reference 2. The belt walls, which are analogous to the belt trusses discussed in the present work, were found to be very effective in increasing the building's lateral stiffness.

Example 1. A 75-Story Building

A 75-story steel-framed office tower will be used to investigate the effectiveness of belt trusses as virtual outriggers. This building does not represent a particular real structure that has been built or proposed. However, the dimensions, general layout, and other characteristics have been selected to be representative of a building for which the use of outriggers would be a plausible solution. Designs with conventional outriggers and virtual outriggers will be compared.

An elevation of the building is shown in Figure 7. The floor-to-floor height is 13 ft., except that the lowest four stories are taller; the total height is 1000 ft. The building has three sets of 4-story deep outriggers: between Levels 72 and 76 (at the top); between Levels 46 and 50; and between Levels 21 and 25.

A simplified floor plan of the building is shown in Figure 8. The floor is nominally 150 ft. square (to column grid lines) and has a 60-ft. square core. The corners of the floor are chamfered 15 ft. The span from the core to the exterior columns is 45 ft. The lateral load-resisting system consists of bracing at the walls of the 60-ft. square core and the three sets of outriggers indicated in Figure 7.

Columns along the exterior edges of the tower are at 30-ft. centers. The 60-ft. square core has columns at the corners and at the center, to create 30-ft. spans for the floor framing within the core. There is no column at the center of each 60-ft. side of the core, since the braced frame that constitutes the side of the core can easily support dead and live loads across a 60-ft. span. (This arrangement places more than 90 percent of the core column steel and 90 percent of the core gravity load at the corners of the core, where the steel area and gravity load are most useful for resisting lateral loading on the tower.)

Typical floor framing outside the core is indicated in Figure 8. All connections are simple shear connections; there are no moment connections. Typical floor slabs consist of 3¼-in. of lightweight concrete over 2-in. composite metal deck.

The layout of the conventional outrigger system is shown in Figure 9. The outriggers engage large "supercolumns" at the edges of the floor. (Composite construction would be considered for the supercolumns in a real project; however, steel is used in this example to simplify the analysis by avoiding the complications caused by non-elastic behavior of concrete.) The layout of the belt truss used as a virtual outrigger is shown in Figure 10. The outrigger locations along the height of the tower are indicated in Figure 7.

The core bracing is the same in both designs and is indicated in Figure 9. With work points for the core bracing diagonals set at the top of the horizontal members, there is adequate clearance under each inverted "V" of diagonal bracing for access to the elevator lobbies in the core.

Design Loads

Design loads are in accordance with the City of Chicago Building Code. The design wind load, applied on the projected elevation of the building, varies from 20 psf at ground level to 42 psf at the top.

Member Sizes

Members were proportioned with enough accuracy to provide a reasonable indication of the behavior of the structure and the effectiveness of the outriggers. The general approach was to size members for the structure with conventional outriggers, and then to retain the same sizes for the design with virtual outriggers. This allows direct comparison of the two outrigger systems. Stresses were checked at a few locations in the design with conventional outriggers, but there was no exhaustive code-checking of members.

The eight "supercolumns" (the columns engaged by the conventional outriggers) have a cross sectional area of 1155 $in.^2$ at the base of the building. Other exterior columns have a maximum area of 269 $in.^2$ The columns at the four corners

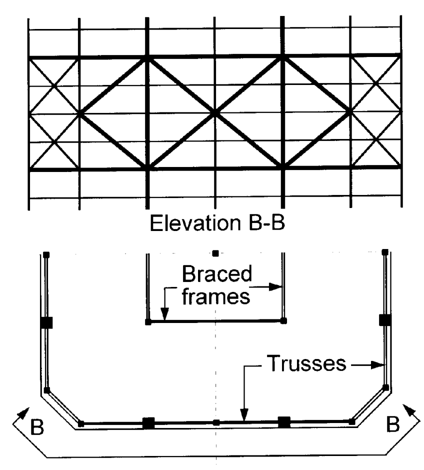

Fig. 10. Virtual outrigger system in Example 1.

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of the core have an area of 860 in.^{2} at the base. Column sizes decrease over the height of the building to about a quarter of the maximum near the top. All column sizes and core bracing member sizes are the same with both outrigger types.

The outrigger truss members are about the same size in the conventional and virtual outrigger designs (except that the diagonals in the chamfered corners of the belt trusses are smaller). Typical truss members are very large W14 sections (W14×730 maximum) in the lowest set of trusses; the other trusses are somewhat lighter.

Specially strengthened floor diaphragms are required at the top and bottom of each virtual outrigger, to transfer horizontal force from the core to the chords of the belt truss. The slab is 10-in. thick, including the metal deck, at the lowest truss (at Levels 21 and 25), 8-in. thick at the second truss (at Levels 46 and 50), and 6-in. thick at the upper truss (at Levels 72 and 76). Regular-weight concrete is used in these slabs.

Method of Analysis

The building was analyzed as a three-dimensional elastic structure, using the GTSTRUDL computer program. In the modeling of the floors at the top and bottom of each outrigger, beams were represented by line members and the slab by planar finite elements. Foundation deformation was neglected in the analysis; columns were assumed to be mounted on non-movable supports at the base.

Results and Evaluation

The lateral displacement at the top of the building due to wind loading was found to be 25.3 in. for the design with conventional outriggers and 37.1 in. for the design with belt trusses as virtual outriggers.

The structure was also analyzed with no outriggers at all (and no change in core member sizes). The displacement increased to 108.5 in.

The structure with virtual outriggers was analyzed with a ten-fold increase in the in-plane stiffnesses of the floor slabs at the top and bottom of each belt truss. The displacement decreased to 31.0 in. When, in addition, the belt truss member sizes were increased ten-fold, the displacement decreased further to 26.0 in.

It is clear from this example (results summarized in Table 1) that belt trusses used as virtual outriggers are effective at coupling exterior columns to the core of a tall building. However, they are significantly less effective than conventional outriggers connected directly to the core. Note that the virtual outriggers engage all exterior columns while the conventional outriggers engage only some of the exterior columns. If both systems were equally effective, the virtual outriggers would result in a stiffer building, not the more flexible building indicated by this analysis.

One of the factors reducing the effectiveness of belt trusses as virtual outriggers is the in-plane deformation of the floors at the top and bottom of the trusses. Clearly, these floors cannot reasonably be idealized as rigid diaphragms. Deformation of the belt trusses also contributes to the reduced effectiveness of the virtual outrigger system, as compared to conventional direct outriggers.

SUMMARY AND CONCLUSIONS

Techniques for using belt trusses and basements as "virtual" outriggers in tall buildings have been proposed. Belt trusses used as virtual outriggers offer many of the benefits of the outrigger concept, while avoiding most of the problems associated with conventional outriggers. Basements used as virtual outriggers can create a wider effective base for resisting overturning.

The application and effectiveness of belt trusses as virtual outriggers has been demonstrated through an example. It is clear from the example that the virtual outrigger concept works as intended. However, with the same outrigger column sizes and locations, virtual outriggers will be less effective than conventional direct outriggers because of the reduced stiffness of the indirect force transfer mechanism.

In many applications, the reduced effectiveness or efficiency of the virtual outrigger system (compared to conventional direct outriggers) will be more than compensated for by the following benefits offered by the proposed concept:

1. There are no trusses in the space between the core and the building exterior.
2. There are fewer constraints on the location of exterior columns. The need to locate large exterior columns where they can be directly engaged by outrigger trusses extending from the core is eliminated.
3. All exterior columns (not just certain designated outrigger columns) participate in resisting overturning moment.
4. The difficult connection of the outrigger trusses to the core is eliminated.
5. Complications caused by differential shortening of the core and the outrigger columns are avoided.

In the lateral load analysis of a building with the proposed virtual outrigger system (or any other type of indirect or offset outrigger system), the in-plane stiffness of the floors that transfer horizontal forces from the core to the outriggers should be modeled accurately. These floors cannot reasonably be idealized as rigid diaphragms.

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