Modeling of Support Conditions at the Bases of Tall Buildings

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INTRODUCTION

Assumptions regarding the vertical and lateral support conditions at the base of a tall building can have a significant effect on the results of the analysis of the structure, and on the design based on that analysis. This is especially true when the building has a deep basement.

There is no generally accepted "standard" way of modeling the base restraints or supports. Several alternative idealizations are in use. These different ways of modeling supports for tall buildings will be discussed and evaluated in this paper. Through an example, some of the simple support models that appear to be in use will be compared with a complete three-dimensional analysis.

A technique for using a basement as a "virtual" outrigger to provide a wider base for resisting overturning effects, as proposed in a recent paper (Nair, 1998), will be investigated further in this work. This is shown to be a logical extension of the use of a complete three-dimensional model of the bottom of the building in the analysis of the structure.

SIMPLE SUPPORT IDEALIZATIONS

Three alternative simplified models for the support of a building's lateral load-resisting system are illustrated in Figure 1. The building shown has a four-story basement. 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 ground floor and all basement floors.

The foundation is represented by vertically non-movable supports in Figure 1. Elastic springs could be assumed instead, as indicated in Figure 2, to represent foundation elements that undergo vertical movement when subjected to load.

While 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.

None of these simple models represents the true three-dimensional nature of support conditions at the base of the building. The effects of these simplifying idealizations will be investigated in Example 1, by comparison with the results of a complete three-dimensional analysis.

"VIRTUAL" OUTRIGGERS

A recent paper (Nair, 1998) proposed the use of belt trusses and basements as "virtual" outriggers in tall buildings. This was suggested as a special application of the "offset" outrigger concept that had been proposed previously (Stafford-Smith, Cruvellier, Nollet, and Mahyari, 1996).

In the conventional outrigger concept, trusses or girders connected directly to the lateral load-resisting core of the building 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 basic idea behind the virtual outrigger concept is to use floor diaphragms, which are typically very stiff and strong in

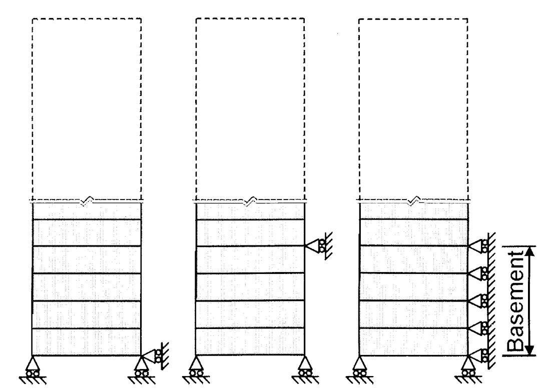

Fig. 1. Alternative support idealizations for lateral load-resisting system of building with basement, non-yielding foundation.

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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.

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 reduce or 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 use of the basement as a virtual outrigger is not limited to shear core type buildings. The concept is applicable even to framed tubes and other non-core designs.

The way in which a basement can function as a virtual outrigger is illustrated in Figure 3. Some fraction of the overturning moment from the tower above the basement is converted into a horizontal couple in the floors at the top and the bottom of the basement, as shown in Figure 3a. (Other basement floors also participate in the moment transfer, but they will be less effective.) 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 (Figure 3b).

The sharing of overturning moment between the tower structure and the outrigger basement, and the forces in the various components of the outrigger system, can be determined by three-dimensional analysis of the base of the building (as illustrated in Example 1). It is important that the stiffness of the foundation of the lateral load-resisting system be modeled with reasonable accuracy (not as rigid supports). The in-plane stiffnesses of the floors that connect the lateral load-resisting system to the basement walls should also be modeled accurately; these floors should not be idealized as perfectly rigid diaphragms.

The floors at the top and bottom of the basement 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 some applications, it may be necessary to use thicker-than-normal slabs.

The final vertical reactions at the ends of the basement (see Figure 3b) 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 shear core or other lateral load-resisting system of the tower 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 overturning moment from the tower going down directly into the core foundation, not into the outrigger system.

It may be noted that using a basement as a virtual outrigger does not involve any additional components in the building. Every basement under a tall building is a potential virtual outrigger, even if the designer does not use it as such. Using a basement as a virtual outrigger is, in essence, simply a matter of realistic three-dimensional modeling of the re-

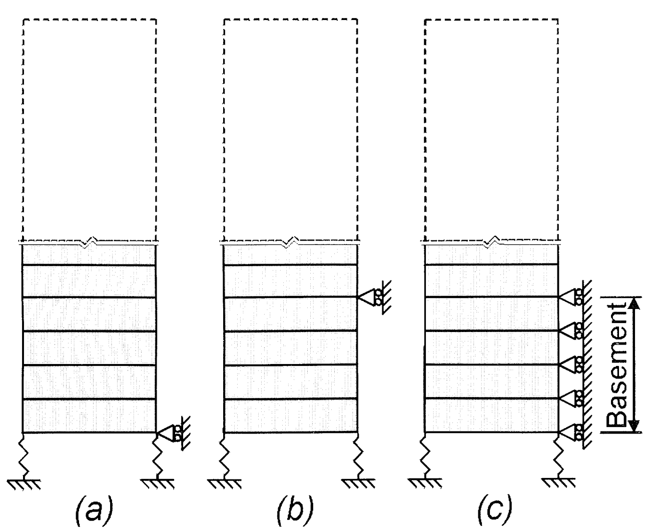

Fig. 2. Alternative support idealizations for lateral load-resisting system of building with basement, elastic foundation.

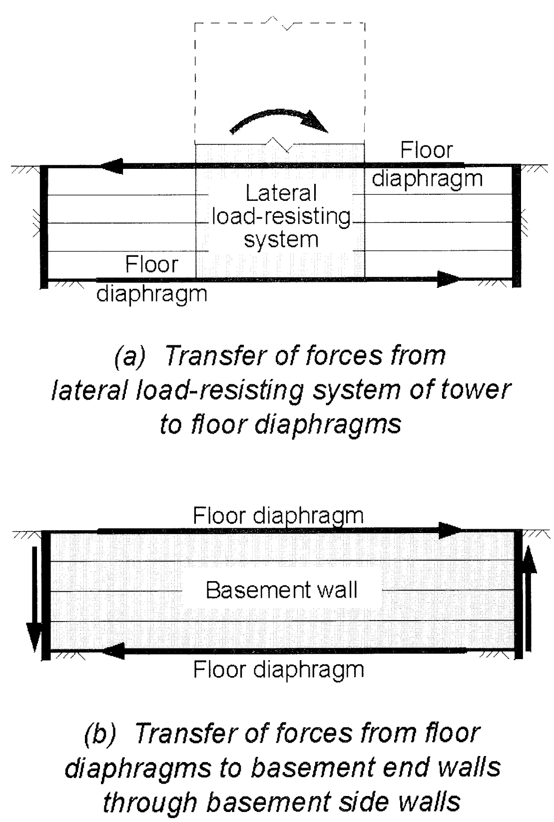

Fig. 3. "Virtual" outrigger action at basement of tall buildings.

straints 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.

EXAMPLE 1

A 40-story steel-framed office tower will be used to investigate how different base support idealizations affect the results of lateral-load analysis of the structure and to illustrate the use of a basement as a virtual outrigger.

General Layout of the Building

An elevation of the building is shown in Figure 4. There are 40 above-ground stories extending to 512 ft above ground level, and four basement levels extending down 52 ft below ground level.

A simplified typical tower floor plan, typical basement floor plan and sectional elevation though the basement and part of the tower are shown in Figure 5. The tower floor is nominally 120 ft wide and 210 ft long (to column grid lines). The longer dimension of the tower floor is in the north-south direction. The basement floor measures 300 ft in the east-west direction and 270 ft in the north-south direction.

The lateral load-resisting system is a braced steel shear core measuring 40 ft east-west by 90 ft north-south. There are four 40-ft deep K-braced trusses in the east-west direction and two 90-ft deep trusses (of three bays each) in the north-south direction. This bracing system continues from the tower down through the basement to the foundation.

Columns along the exterior edges of the tower are at 30-ft centers. Interior spans in the tower are 40 ft east-west and 30 ft north-south. Spans in the basement outside the tower footprint are 30 ft in both directions.

Suspended floors in the tower and in the basement consist of metal deck and concrete topping supported on steel framing. The ground level and lower floor slabs are attached to the basement walls; there are no expansion joints anywhere in the floors. The basement walls are of cast-in-place reinforced concrete.

Tower columns are supported on concrete caissons (cast-in-place drilled piers) bearing on rock. The caissons are 100 ft long.

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 30 psf at the top (512 ft above ground level).

Design of Components

Members were proportioned with enough accuracy to provide a reasonable indication of the behavior of the structure. Members were designed on the basis of the support idealization indicated in Figure 1(a); then the same sizes were retained for

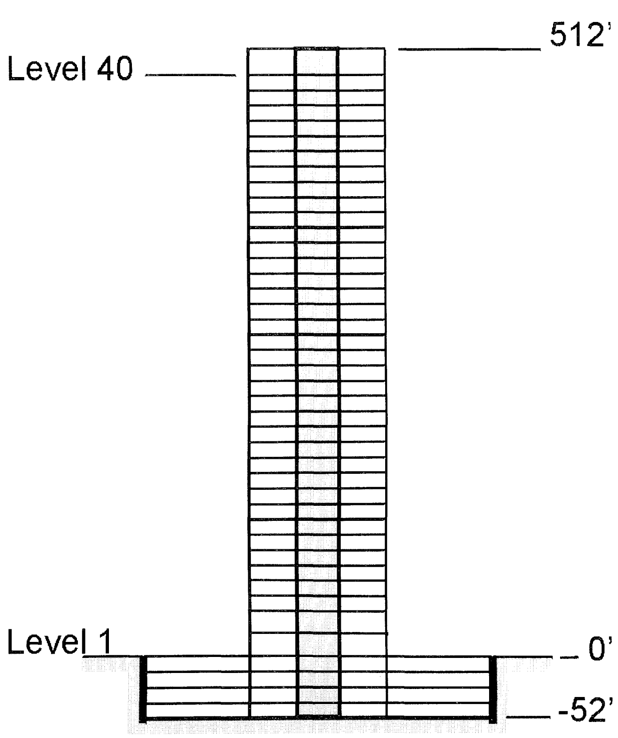

Fig. 4. Elevation of building studied in Example1.

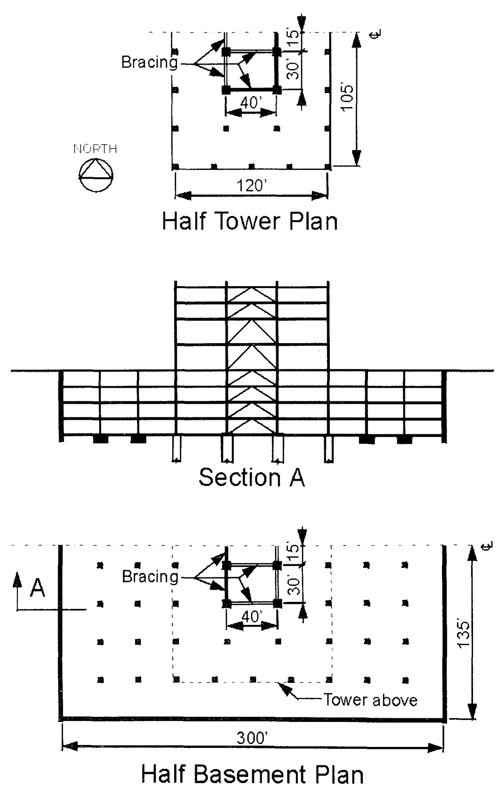

Fig. 5. Plans and section of building studied in Example 1.

the analyses using other support models. This design, intended to allow direct comparison of the various support idealizations, is defined as the "original" design.

A "modified" design, intended to better illustrate and demonstrate the virtual outrigger effect, was obtained by resizing some components.

Suspended floors in both the tower and the basement have 3¼ in. of lightweight concrete over 2-in. composite metal deck. The lowest basement floor is a 6-in. slab on grade. The basement walls are 12 in. thick. The caissons supporting the core columns are 8 ft in diameter.

The eight core columns are built-up members with a cross sectional area of 860 in.^{2} each at the base of the structure. The largest core bracing members are W12×190 sections.

In the "modified" design, there is an approximately fourfold increase in the area of diagonal bracing members within the basement. Also, the ground-level slab is changed from 3¼ in. of lightweight concrete (above the metal deck) to 8 in. of regular-weight concrete and the thickness of the slab on grade is increased to 8 in. There is no change in other components.

Analysis

The building was analyzed for east-west wind loading as a three-dimensional elastic structure, using the LARSA computer program. The "original" structure was analyzed seven times, with seven different support conditions at the base.

The first six analyses corresponded to the six models indicated in Figures 1 and 2. Basement slabs (outside the core) and basement walls were not included in these six analyses. The vertical supports in the Figure 1 models were applied at the top-of-caisson elevation. For the Figure 2 models, the caissons were represented by linear members of appropriate length and cross section, supported at the bottom. The lateral restraints in all six models were applied at the center of each east-west braced frame.

The seventh analysis of the "original" structure included a complete three-dimensional representation of conditions at the base of the building. The Level 1 and basement floor slabs were represented by planar finite elements; beams on east-west column lines were represented by linear members; other beams outside the core were not included. Basement walls were represented by planar finite elements and the caissons by linear members.

The boundary conditions or restraints in the seventh analysis included vertical restraints along the bottom edges of all the basement walls and horizontal restraints in the east-west direction at the bottom edges of the north and south basement walls. (Other horizontal restraints that could, reasonably, have been considered include springs distributed over the height and width of the leeward wall, representing passive earth resistance against that wall, and restraints distributed over the height and width of the side walls, representing soil friction at those walls. These restraints, the effects of which would have been highly dependent on the assumed soil properties, were neglected in the present analysis to avoid introducing additional variables into the study. Except with very stiff or dense soil, the restraints adopted in the present analysis could be expected to provide a good picture of the overall behavior of the structure.)

The complete three-dimensional analysis was repeated for the "modified" building, with appropriately modified properties for the Level 1 slab, the slab-on-grade at the bottom of the basement, and the diagonal bracing members within the basement.

Results of Analysis

The results of the eight analyses (seven on the "original" building and one on the "modified" structure) are summarized in Table 1. The lateral displacement at the top, the maximum column reaction at the foundation, and the maximum force in any diagonal bracing member below the ground floor, all due to wind load alone, are indicated in the tabulation.

Also shown in Table 1 is the maximum "design" uplift on a core column foundation. This is the column reaction due to a combination of full wind load, in the direction that produces uplift, and two-thirds of dead load.

Evaluation of Alternative Support Idealizations

Comparing the results for the Figure 1 models with those for the Figure 2 models, it is evident that caisson length changes can have a very large effect on the wind-induced lateral displacement of a building. For instance, comparing the 1(a) and 2(a) models, caisson deformation is found to increase the drift/height ratio from 1/465 to 1/320. Clearly, caisson length changes cannot reasonably be neglected in the lateral load analysis of the structure.

The results obtained using the complete three-dimensional model of the base of the building could be regarded as the "correct" results in that they are based on the most realistic representation of the actual structure. Comparison with the correct results shows that none of the simple idealizations provides a very good indication of the behavior of the structure, even when caisson deformations are included in the analysis.

The Figure 2(a) model is conservative (i.e., it would lead to a safe, though uneconomical, design) for lateral displacement at the top and for column loads at the foundation. It does not indicate the force reversal that occurs in the bracing below the ground floor. (The result is conservative in this example, but it may not be so in other cases.)

The Figure 2(b) model is reasonably accurate for drift at the top and conservative for column loads at the foundation, but it misrepresents conditions in the lateral load-resisting system below the ground floor. (If the bracing member sizes required above the ground floor were continued in the base-

Table 1. Results of Analysis of 40-story Building, Example 1						
		Effects of wind loading				
Building design	Support idealization in analysis	Lateral displacement at top of building (inches)	Maximum column reaction at foundation (kips)	Maximum force in bracing below ground floor[c] (kips)	Algebraic minimum design load on column foundation[d] (kips)
Original[a]	Figure 1(a)	14.5	5217	396	–2049
Original[a]	Figure 1(b)	13.7	4378	7	–1210
Original[a]	Figure 1(c)	13.6	4184	–169	–1016
Original[a]	Figure 2(a)	21.1	5165	384	–1997
Original[a]	Figure 2(b)	18.7	4287	18	–1119
Original[a]	Figure 2(c)	17.4	3434	–490	–263
Original[a]	Complete 3-D model	18.3	3863	–296	–695
Modified[b]	Complete 3-D model	17.1	3146	–636	+22

[a]Member sizes based on analysis using the support idealization in Figure 1(a).
[b]Thicker ground floor slab; heavier bracing below ground floor.
[c]Negative value denotes change in direction of force below ground floor.
[d]Due to (2/3)D+W; negative value indicates uplift.

ment, the analysis using the Figure 2(b) model would result in a reasonable design in this example. However, this may not be true for other structures.)

The Figure 2(c) model is conservative in its representation of forces in the bracing, but it slightly understates lateral drift at the top of the building and significantly understates column reactions and uplift at the foundation.

Conditions Revealed by Complete Analysis

The complete three-dimensional analysis showed that the ground floor and all below-ground floors offer some lateral restraint to the building, but less than indicated by the Figure 2(c) model. The in-plane flexibility of the floors and, to a much lesser degree, the in-plane flexibility of the basement side walls cause some relaxation of the restraint to lateral displacement of the core.

The maximum horizontal force transfer from the core bracing to the ground floor slab was found to be 718 kips at each of the four planes of bracing. The maximum in-plane shear force in the ground floor slab is 6.6 kips per linear foot. These forces are high enough to require special design and detailing.

Some degree of "virtual outrigger" action does occur, even though the structure was not specifically designed to create outrigger action. About 26 percent of the total overturning moment at the base of the building is supported by the basement walls acting as a virtual outrigger system; the remaining 74 percent is supported by the core. The outrigger action reduces the maximum design uplift on the core caissons from 1,997 kips to 695 kips.

The forces and stresses in the basement walls due to outrigger action are small. The maximum in-plane shear is 9.3 kips/ft. The vertical force on the walls (up on the windward half, down on the leeward half) is 770 kips. These forces could be neglected in the design of the walls and their foundations.

Behavior of Building Modified to Increase Outrigger Effect

The complete three-dimensional analysis was also performed on the "modified" structure. This was the same structure as in the other analyses, except that the slabs at the top and bottom of the basement and the core bracing within the basement were made stiffer. This was done to increase the outrigger effect.

In this modified design, about 41 percent of the total overturning moment at the base of the building is supported by the basement walls acting as a virtual outrigger system (up from 26 percent in the original design), and the design uplift on the core caissons disappears altogether. The lateral displacement at the top of the building is reduced by about 7 percent.

The maximum horizontal force transfer from the core bracing to the ground floor slab is 1,392 kips at each of the four planes of bracing. The maximum in-plane shear force in the ground floor slab is 12.8 kips per linear foot.

The forces and stresses in the basement walls due to outrigger action are larger than in the original design, but are still fairly small. The maximum in-plane shear is 13.0 kips/ft. The vertical force on the walls (up on the windward half, down on the leeward half) is 1,198 kips. These forces should not affect the design of the walls.

Elimination of Outrigger Effect

It has been noted that basements tend to act as virtual outriggers regardless of the designer's intent. It is possible, however, to eliminate outrigger action through certain deliberate design choices.

In this example, outrigger action of the basement could be suppressed by deleting all bracing diagonals below the ground floor. The Figure 2(b) model would, then, accurately represent the behavior of the structure. All the horizontal shear in the tower would be transferred from the shear core to the basement walls through the ground floor slab (which must, of course, be designed to accomplish this force transfer with complete reliability). All the overturning moment in the tower at the ground floor level would be carried down to the foundation without increase or attenuation.

Outrigger action could also be eliminated by isolating the core from the basement walls by providing joints in the floors. The Figure 2(a) model would, then, be correct.

SUMMARY AND CONCLUSIONS

Alternative ways of modeling supports in the analysis of tall buildings have been evaluated with the help of an example. It has been shown that for a tall building with a basement, the traditional idealized representations of the lateral restraints at the base of the structure can lead to flawed results. Designs based on analyses using these simple support models can be both uneconomical and unconservative.

Complete three-dimensional representation of conditions at the base of the building is necessary to obtain an accurate picture of the behavior of the structure. Given the computational power that is readily available to structural designers today, there is little justification for using the traditional simple models for buildings with deep basements.

In many (if not most) tall buildings with basements, complete three-dimensional analysis will show that part of the overturning moment in the lateral load-resisting system of the tower is transferred to the basement walls through "virtual" outrigger action. Recognition and exploitation of the outrigger action, which creates a wider effective base for resisting the overturning effects of lateral loading, can lead to more economical structural designs.

Regardless of outrigger action and the lateral restraint model used, and regardless of the presence or absence of basements, vertical foundation deformation must be taken into account in the lateral-load analysis of tall buildings (except possibly for foundations of near-perfect rigidity, such as shallow footings on bedrock).

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