A Modified Tube Concept for Tall Buildings

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Framed tubes (beam-column frames on the perimeter) are among the most widely used structural systems for providing lateral stability and resistance to lateral loading in tall buildings. This system has been used successfully in many of the world's tallest structures. However, the efficiency of the framed tube is limited by two factors:

1. Shear lag in the flanges of the tube reduces the effectiveness of columns away from the corners;
2. The axial stiffness of columns in the webs of the tube, especially the columns well away from the corners, is not used effectively for resisting lateral load.

The loss of tube efficiency from these sources can be reduced by concentrating a large part of the total column area at the corners of the tube. However, while this might make the tube more efficient for lateral loads, it would not result in improved overall structural efficiency unless the large corner columns are also used to support a large part of the gravity load on the tube.

The desirability of transferring gravity load to the corners of the tube has been recognized by designers of tall buildings. Various means to achieve this objective have been tried. Some engineers have attempted to transfer floor load to the corners through the layout of the floor framing, usually with long diagonal girders that span from the building core to the corners of the perimeter tube. This approach is of limited effectiveness and can result in awkward connection details in the floor system. Another approach is to interrupt the continuity of all vertical members in the perimeter frame, except for one (or a few) at each corner. This results in all vertical loads being transferred to the corners. There are many variations and refinements of this concept, including the superframe system.

This paper will present and examine a different method of improving the efficiency of framed tubes for tall buildings. As in the techniques mentioned before, the basic concept is to concentrate a large part of the column area and gravity load at the corners of the tube. This is achieved by assignment of strength and stiffness among the members on the perimeter of the building to create a structure that could be labeled a soft-sided tube.

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PROPOSED STRUCTURAL CONCEPT

The member layout, connections, erection procedures and other architectural and constructional considerations in the soft-sided tube are the same as in conventional framed tubes. The improved efficiency is achieved simply by appropriate member selection, together with more detailed analysis than is customarily performed on building structures. In the design of framed tubes for tall buildings, the usual design intent is to duplicate the lateral load behavior of a flexural cantilever of tubular cross section. The desired result of lateral loading is equal axial stress in columns on the flanges of the tube and linearly varying axial stress in the web columns. There is no systematic attempt to optimize the tube to attain any particular distribution of forces due to gravity loads.

In the proposed modification of the tube concept, a primary design objective is the transfer of gravity load through the tube from the sides to the corners. The corner columns are intended to support a very large proportion of both the gravity load and the overturning forces due to lateral load. To achieve this objective, the members on the perimeter of the building are selected as follows:

1. The side columns (i.e., all columns except those at the corners) are designed to have minimal axial stiffness and just enough flexural stiffness to prevent excessive shear-wracking deformation of the building under lateral loading.
2. The beams are selected to work with the side columns in limiting shear-wracking deformation under lateral loading, as in any framed tube.
3. The corner columns are proportioned to support all the vertical loads (gravity and overturning forces) not supported by side columns.

It is advantageous to use high-strength steel for the side columns. Rolled sections of 60 ksi F_y, or even three-plate weldments of 70 or 100 ksi F_y, could be considered. The corner columns should be of lower-strength steel than the side columns since the level of stress is likely to be lower at the corners. Structural analysis to determine forces, moments and stresses due to gravity loads is far more critical for the proposed structure than for conventional framed tubes. It might be necessary not only to analyze the completed structure for gravity loads but also to consider the progression of loading on the partially completed structure during construction.

EXAMPLE

A 60-story steel-framed building, 155 ft square in plan, will be considered in this example. The floors span 45.75 ft from a 60-ft square service core to a 151.5-ft square perimeter frame or tube. The floor-to-floor height is 12.75 ft.

The framing plan for a typical floor is shown in Fig. 1 (only main members are shown). Columns on the perimeter are nominally 15 ft apart; floor beams 10 ft apart. The floor is 2-in. metal deck with 3.25 in. of lightweight concrete over it. The criss-cross arrangement of beams at the corners of the floor was selected to avoid having a long-span beam adjacent and parallel to the outer wall, which could cause troublesome floor deflection patterns.

The framing shown in Fig. 1 is for even-numbered floors. At odd-numbered floors, the framing in the corners is inverted north-south to east-west. This is done purely to simplify the analysis and the presentation of data in this study by making the effective loading on all four sides of the tube identical.

The floor framing system discussed before is denoted as Framing Plan A. An alternative arrangement for the corners—Framing Plan B—is shown in Fig. 2. This type of beam arrangement has been used in some buildings in an attempt to transfer more floor load to the corners of the tube. The effectiveness of this approach will be evaluated as part of this study.

The tube structure consists of rigidly connected columns and beams on the perimeter of the building. The corner columns are welded built-up members. Other columns (the side columns) and all beams are rolled sections. Beam and column sizes are shown in Table 1. The corner column shape is shown in Fig. 3. Plate thicknesses in the corner column vary from 2 in. in X694 to 6 in. in X1837 and X2205. The corner columns are of A572 Gr. 42 steel; side columns A572 Gr. 60. All beams in the tube structure are A36.

Loadings

The dead load includes the weight of the steel framing and the floor structure, with an additional allowance for ceilings, ductwork and finishes. The exterior wall is assumed to

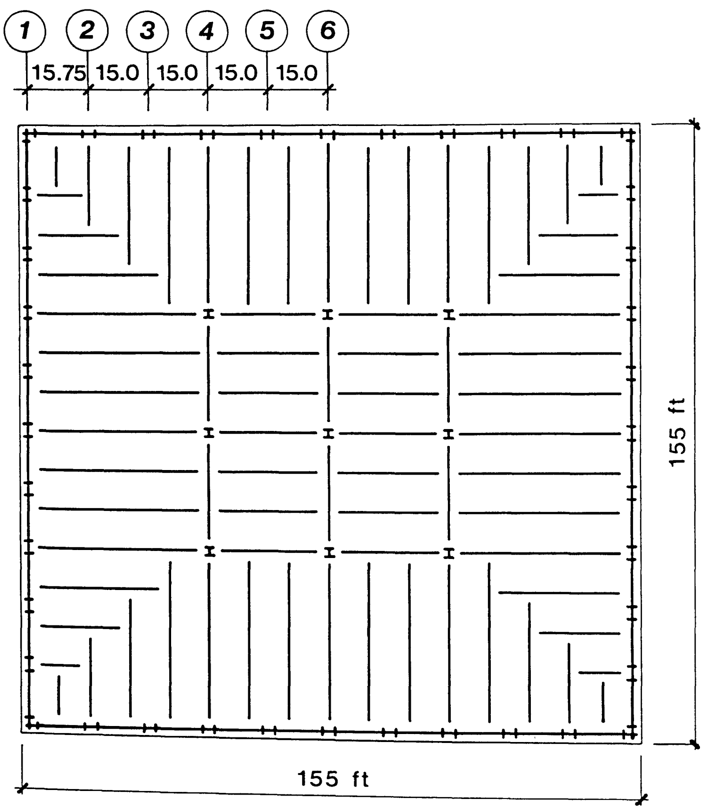

Fig. 1. Structural plan of typical floor (Framing Plan A)

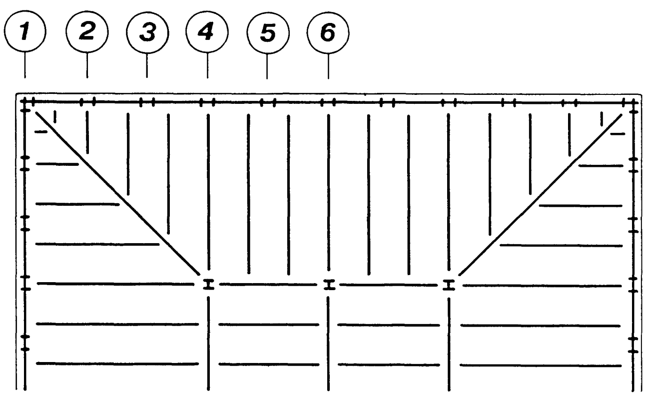

Fig. 2. Alternate framing for corners (Framing Plan B)

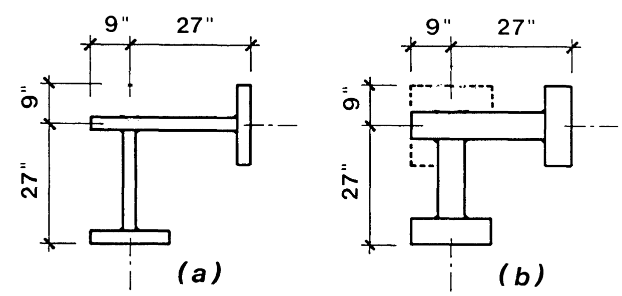

Fig. 3. Corner column sections: (a) X694 through X1582; and (b) X1837 and X2205

Table 1. Tube Members

Floors	Corner Columns[a] $(F_y = 42)$[b]	Side Columns $(F_y = 60)$[b]	Beams $(F_y = 36)$[b]
52–61	X694	W30 × 99	W36 × 135
42–51	X1011	W33 × 118	W36 × 160
32–41	X1307	W36 × 135	W36 × 182
22–31	X1582	W36 × 160	W36 × 210
12–21	X1837	W36 × 182	W36 × 245
G–11	X2205	W36 × 210	W36 × 280

[a]See Fig. 3 for shape. The number after X is the weight in lb./ft.
[b]Yield stress in ksi

weigh 40 lbs. per sq. ft of wall area. The design floor live load is 50 psf, with an additional allowance for 20 psf for partitions. For loads on columns, the live load is reduced by a maximum of 50%. The partition load is not reduced. These loadings are in accordance with the Chicago Building Code.

The wind loading is taken as 25% higher than specified in the Chicago Building Code. The wind pressure (including the 25% increase) is 25 psf from ground level to 300 ft above the ground. It increases linearly from this point to 40 psf at the top of the building, 765 ft above the ground.

Analysis

Forces in the tube structure due to gravity load were determined by three alternative analyses—labeled Analysis I, II and III, respectively—as follows:

Analysis I. In this analysis, the force in a column due to gravity load is determined by summation of the loads applied on the column above the location being considered.

Analysis II. Forces and moments in columns and beams due to gravity load are determined by linear elastic analysis of the framed tube. All loads are applied on the completed 60-story structure.

Analysis III. The forces and moments due to gravity load are determined by linear elastic analysis. The live load and partition load are applied on the completed framed tube. The dead load (other than partition load) is applied in stages as follows: loads at floors 2 through 21 are applied on the structure assembled to floor 21; loads at floors 22 through 41 are applied on the structure assembled to floor 41; loads at floors 42 through 61 (roof) are applied on the completed tube structure.

Analysis I is the traditional way of accumulating loads for column design in buildings. Analysis III is at the opposite extreme in refinement; it simulates (albeit in a highly simplified manner) the progression of loading on the partially completed structure during construction.

Analyses II and III for gravity loads and the analysis for wind loading were performed by means of the computer program for three-dimensional analysis of multi-story buildings described in Ref. 1. The analysis is exact in that the axial, flexural and shear stiffnesses of columns and the flexural and shear stiffnesses of beams are modeled accurately and all equilibrium and compatibility conditions are satisfied (except for second-order large-deformation effects). Finite column widths and finite beam depths are taken into account in the analysis.

Selected results of the analysis are presented in Tables 2, 3 and 4. The results shown do not include overall lateral stability (P-delta) effects. These effects were evaluated using the amplification factor technique described in Ref. 2. The maximum amplification factors (applicable to the effects of lateral loading) were found to be about 1.10 at service loads and 1.21 at a load factor of $^{23}/_{12}$.

Comparison of Methods of Analysis

Column forces due to gravity load indicated by the three methods of analysis—I, II, and III—are compared in Table 2. The forces indicated by Analysis I (simple summation of loads applied on each column) bear little resemblance to the results of the more refined analyses. It is obvious the simple analysis is not applicable to this type of structure, since it does not account for the redistribution of gravity load forces among the columns in the tube.

There is remarkably little difference between the results of Analyses II and III. (All load is applied on the completed structure in II. The progression of loading during construction is simulated in III.) The difference is greater near the top of the structure than near the bottom, but even at the 45th floor the maximum difference is only about 10%. The absence of major differences between the results of Analyses II and III indicates that there would be very little benefit to further refinement in the analysis, beyond that represented by Analysis III.

Comparison of Floor Framing Systems

The data in Table 2 include a comparison of the column forces that result from floor Framing Plans A and B. The more accurate analyses indicate virtually no difference between the two framing arrangements in terms of the column force distributions that they produce near the bottom of the building. (The total load on the tube is slightly higher for Plan A.)

It is evident from this comparison that Framing Plan B is not effective for transferring a larger proportion of the total load to the corners. It can be concluded that the floor framing layout in a tube-type building should be selected on the basis of serviceability and economy *of the floor*, without concern for the distribution of floor reactions on the tube.

Stresses

The stresses in columns near the bottom of the building due to gravity load and wind are summarized in Table 3. Note, the overall stress level is very nearly equal in all the side columns. The high-strength steel (Gr. 60) in these columns

Table 2. Axial Forces in Columns Due to Gravity Load

Floor	Framing Plan	Analysis Type	Column Forces (kips) Col 1	Col 2	Col 3	Col 4	Col 5	Col 6
45	A	I	479	560	734	942	729	850
		II	3350	404	425	443	453	455
		III	3054	398	450	488	508	513
25	A	I	1077	1260	1650	2119	1640	1912
		II	8180	851	889	920	939	946
		III	7806	845	921	976	1007	1018
5	A	I	1675	1960	2567	3296	2551	2974
		II	12211	1284	1421	1520	1572	1589
		III	12055	1280	1431	1543	1602	1623
5	B	I	3544	1643	1997	2884	2551	2974
		II	12021	1243	1359	1451	1505	1524
		III	11883	1240	1368	1472	1534	1555

Table 3. Stresses in Columns at 5th Floor Due to Gravity Load[a] and Wind

Loading	Stress Component	Stresses (ksi) Col 1	Col 2	Col 3	Col 4	Col 5	Col 6
Gravity	f_a	18.6	20.7	23.1	25.0	25.9	26.3
	f_b	1.0	4.2	3.5	2.1	0.9	0.0
	$f_a + f_b$	19.6	24.9	26.6	27.1	26.8	26.3
Wind	f_a	6.1	3.9	2.6	1.7	0.8	0.0
	f_b	3.0	12.9	13.5	13.4	13.4	13.4
	$f_a + f_b$	9.1	16.8	16.1	15.1	14.2	13.4
Combined[b]	f_a	18.5	18.4	19.3	20.0	20.0	19.7
	f_b	3.0	12.8	12.7	11.6	10.7	10.1
	$f_a + f_b$	21.5	31.2	32.0	31.6	30.7	29.8

[a]Gravity load stresses are for Framing Plan A, Analysis III
[b]Combined loading = 0.75 (Gravity + Wind)

Table 4. Displacements Due to Gravity Load[a] and Wind

Floor	Loading	Vertical Displacements (in.) Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Horizontal Displacement (in.)
61	Dead[b]	3.25	3.64	4.07	4.40	4.58	4.63	0.0
	Live[c]	1.40	1.48	1.60	1.69	1.73	1.75	0.0
	Wind[d]	0.96	0.73	0.54	0.36	0.18	0.00	15.9
41	Dead[b]	2.68	2.99	3.32	3.57	3.72	3.76	0.0
	Live[c]	1.14	1.22	1.31	1.38	1.42	1.44	0.0
	Wind[d]	0.89	0.65	0.48	0.31	0.15	0.00	11.2
21	Dead[b]	1.49	1.65	1.82	1.95	2.03	2.05	0.0
	Live[c]	0.62	0.67	0.73	0.78	0.80	0.81	0.0
	Wind[d]	0.58	0.39	0.28	0.18	0.09	0.00	5.0

[a]Gravity load displacements are for Framing Plan A, Analysis III
[b]Dead load, excluding partitions
[c]Live load (50 psf, reduced 50%) plus partition load (20 psf)
[d]Wind load (Chicago Code + 25%)

is used effectively. The level of stress in the corner column (which is of Gr. 42 steel) is lower, primarily because of lower flexural stresses.

Column stresses throughout the tube structure are generally within allowable limits, with a maximum overstress of no more than 5% when overall lateral stability effects (computed at a load/resistance factor of 23/12) are included. All beam stresses are well below allowable limits. Only one cycle of member sizing and analysis was performed in this study. There was no redesign and re-analysis and no attempt to optimize the structure beyond the initial selection of members.

Displacements

Vertical and horizontal displacements at selected locations due to gravity load and wind are shown in Table 4. As might be expected, the vertical displacement due to gravity load is greater near the center of the side of the tube (column 6) than at the corner. If a 1.38-in. difference in elevation between the center and the corner is architecturally objectionable, column fabrication lengths could be adjusted to produce a level beam line in the finished structure. The horizontal displacement of 15.9 in. at the roof due to wind loading is about 1/580 of the height of the building. The maximum drift between adjacent floors (not shown in Table 4) is about 1/500 of the story height. Inclusion of overall lateral stability effects in the analysis would increase these horizontal displacements by less than 10%.

General Evaluation

It is evident from the data in Table 2 that the soft-sided tube in this example satisfies the design intent of transferring load to the corners of the building. The stresses in Table 3 show all material in the side columns and the very heavy corner columns is used very effectively for resisting both gravity and wind loading. The overall result should be a very efficient structure.

The analysis of this example did not reveal any displacement or deformation patterns that are likely to be a problem. The structure has ample lateral stiffness. Beam sizes in the tube probably could be reduced without causing excessive lateral displacements (and with only slight effect on the force distribution among the columns). The 15-ft spacing of tube columns in this example is close to the upper limit on tube column spacing in North American practice. Large column spacing was selected for the example since it represents the most severe test of the proposed concepts. These concepts could be expected to work at least as well (possibly even better) for tubes with more closely-spaced columns and also for taller buildings.

SUMMARY AND CONCLUSIONS

A variation of the tube concept for tall buildings has been proposed and evaluated. In the proposed type of structure, a large part of the total column weight in the tube is concentrated at the corners while the sides of the tube are made as soft as possible (in terms of vertical stiffness). Large corner columns are advantageous for resisting lateral load. The corner columns in the proposed structure are expected also to absorb a large part of the total *gravity* load on the tube, resulting in full utilization of the column material and an efficient overall structure. Study of an example has led to the following conclusions:

1. The proposed design concept is very effective for transferring gravity load to the corners of the tube.
2. It is advantageous to use very high strength material in the side columns (i.e., all exterior columns except those at the corners) and somewhat lower strength material in the corner columns.
3. The capacity of all the tube columns, including the large corner columns, can be used effectively.
4. Forces in tube columns due to gravity load *cannot* be determined by simple summation of loads applied on particular columns. Elastic analysis of the tube frame is essential.
5. For accurate determination of forces in tube columns due to gravity load, the progression of loading on the partially completed structure during erection should be simulated in the analysis.
6. Applying all gravity loads on the completed structure in the analysis results in small errors in column forces near the bottom of the building and moderate errors (about 10% in the example considered) in the upper part of the building.
7. Use of the proposed design concept does not result in objectionable displacements or deformations in the structure.
8. There is *no* benefit to floor framing arrangements that impose a larger proportion of the total floor load reaction on the corners of the tube.

It is important to note that the proposed design method and the conclusions drawn from study of the example apply only to steel-framed buildings. Any attempt to extend these concepts to concrete buildings must include rigorous evaluation of time-dependent effects.

REFERENCES

1. *Nair, R. S.* Linear Structural Analysis of Multistory Buildings *ASCE Journal of the Structural Division, March 1975.*
2. *Nair, R. S.* A Simple Method of Overall Stability Analysis for Multistory Buildings *Developments in Tall Buildings, Council on Tall Buildings and Urban Habitat, Hutchinson Ross Publishing Co., 1983.*