Efficiency of Tubular Framing for Medium-Height Buildings

ROBERT E. LEFFLER

A tubular-framed high-rise building has its main structural frame on its perimeter. The columns are closely spaced, so that the structural behavior of this perimeter frame will approximate that of a tube in resisting applied loads.[1] This type of framing is generally applied to tall structures with 40 or more stories, although it has been used for buildings as low as 22 stories.[2] This is because its main advantage is in resisting wind loads, which become more important as the height of the building increases. Furthermore, shear lag,* which reduces the effectiveness of the tubular frame in resisting wind loads, is smaller in tall buildings.

To evaluate this framing method for medium-height buildings ranging between 20 and 40 stories, comparative designs were made of a 20-story building whose arrangement was representative of this type of structure. Three types of frames were compared: (1) a simple building frame, (2) a rigid building frame, and (3) a tubular building frame. Cost estimates were obtained for the latter two designs.

The simple frame, which included no provisions for lateral loads, was included to show the amount of material required to carry gravity loads alone. Since the rigid frame was designed to resist both gravity and wind loads, a comparison of the amounts of material in the two types of frames shows how much material is required to carry wind loads in a 20-story rigid frame building. A similar comparison shows how much material is required for wind loads in a 20-story tubular frame. A comparison of this amount with the amount for a rigid frame shows whether the tubular frame is effective in reducing the material required for wind loads. The most important comparison, of course, is the comparison between the costs for the tubular and rigid frames, since this indicates whether the tubular frame is likely to be competitive for 20-story buildings.

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* *Due to shear distortions, the longitudinal stress in wide beam flanges decreases as the distance from the web or webs increases, and this stress diminution is called shear lag.*

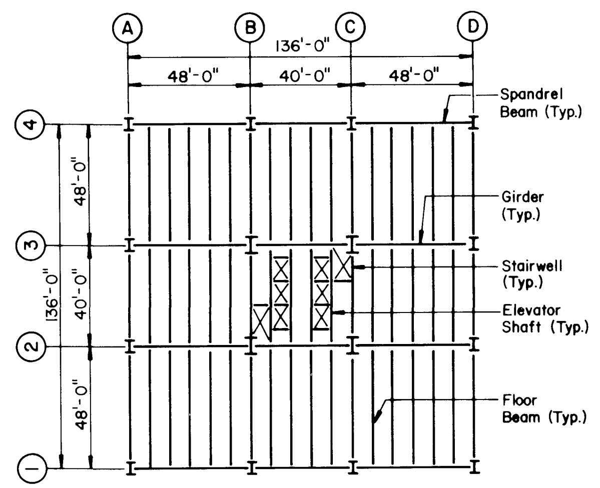


Fig. 1. Typical floor plan of building

BASIC STRUCTURE AND DESIGN CRITERIA

A building height (20 stories) at the bottom of the range of interest was chosen for the study because tubular framing is expected to be more competitive at greater heights. The story height selected was 12 ft-6 in. throughout. The basic floor-framing plan for the studied structures is shown in Fig. 1. The chosen building was square to take advantage of symmetry and antisymmetry,* which simplifies the analysis. Spans and column spacings were selected to be representative of normal design practice.

ASTM A572 Grade 50 steel was generally used throughout the structure. However, where stiffness rather than strength controlled the selection of the member, ASTM A36 steel was used. Also, where the selected column section was too heavy to be available in A572 Grade 50 material, A588 steel (50 ksi yield strength available for all shapes) was used.

* *Antisymmetry is a condition in which the loads and stresses at locations equidistant on opposite sides of an axis of symmetry are equal in magnitude but opposite in sign.*

The floor beams were designed for composite action with the concrete floor slab. The design method assumed the beams to be unshored during the pouring of the floor. Composite construction is not advantageous for the spandrel beams and most beams in the building core, because the floor slab is only on one side of the web in such beams. Noncomposite design was used for these beams. Dead and live loads for a machinery floor on top of the roof were included in the design of the columns supporting the building core. Its members are not shown because the machinery floor details were not considered important to this study. Because of the roofing system used, the roof beams were designed as noncomposite members.

The designs are based on the AISC Specification,[3] including Supplement 3. Gravity and wind loads applied to the structure are as specified in the Uniform Building Code[4] for office buildings. A nominal wind pressure of 30 lb/ft^2 was applied to one face of the building at a time. A summary of the design parameters appears in Appendix A. The Uniform Building Code permits reduction of the design live load based on the area contributing to the load on the member. The live-load reduction was used where it was applicable in the design. This included most floor members and columns. Live-load reduction is not applicable to the roof structure.

The drift ratio is defined as the horizontal displacement per unit of height. The numerical value of the drift ratio is not limited by the specification, and is left to the engineer's judgment. For this study, the drift ratio was limited to a value of 0.003, or 0.0375 in. per story.

SIMPLE FRAME

The simple building frame was designed to resist gravity loads only. No design provisions were made to resist lateral loads. The purpose of this design was to determine the amount of material required to carry the gravity loads alone. Then, in subsequent designs, the amount of material used to resist the lateral load could be evaluated, and the relative efficiency of these subsequent designs could be determined.

This design was accomplished with hand calculations. The design was then confirmed with a computer program that designs planar framed structures. The accuracy of the simple frame design was thus assured, as was the gravity load input for the design of the rigid frame building.

All the bending members (spandrels and floor beams) for this case were designed as simple beams. Lateral stability was assumed to be provided. Therefore, in accordance with the AISC Specification,[3] the effective length coefficient (K-value) used in the column design was 1.0, and the columns are designed for axial load only.

The design of the simple frame building is summarized in Figs. 2 through 4. The roof framing is shown in Fig. 2; the floor framing, except for the building core, is shown in Fig. 3; and the framing for the core is shown in Fig. 4. The column schedule is shown in Appendix B, Table B1. Table 1 summarizes the required number of pieces (beams and columns) in the structure and their weights. No allowance for connections, fasteners, welds, base plates, splice plates, or other miscellaneous details is included in these quantities.

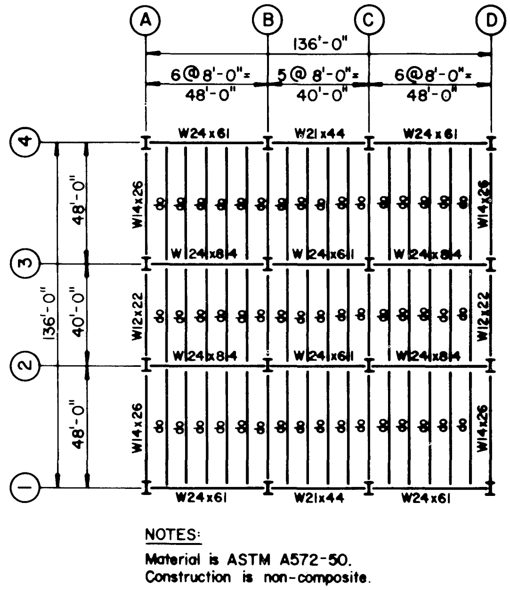


Fig. 2. Simple frame 20-story building—roof framing

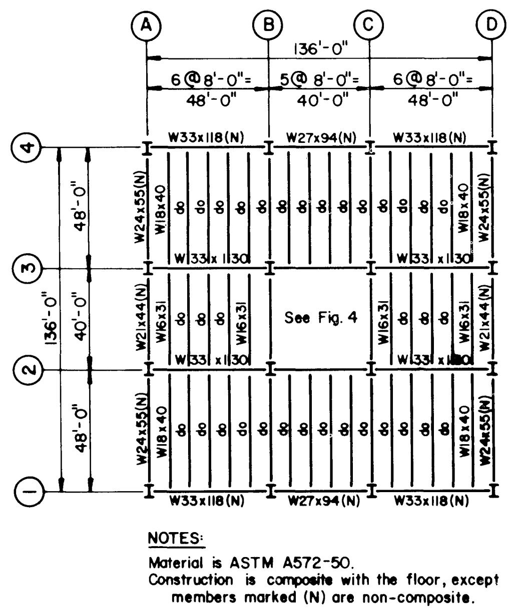
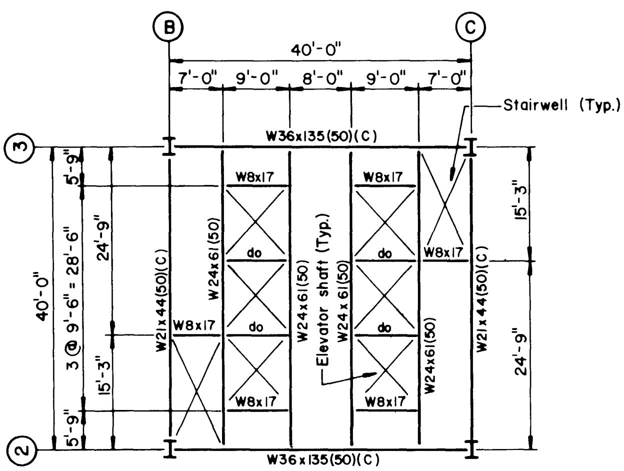


Fig. 3. Simple frame 20-story building—floor framing (floors 2–20)

Table 1. Quantity Summary—Simple Frame 20-Story Building

	A36						A572-50						A588	
	Beams Noncomp.		Beams Comp.		Columns		Beams Noncomp.		Beams Comp.		Columns		Columns	
Item	No.	Wt.	No.	Wt.	No.	Wt.	No.	Wt	No.	Wt.	No.	Wt.	No.	Wt.
Roof							66	48.5	—	—	—	—		
Floors 2–20	190	13.9	—	—	—	—	304	513.2	950	1074.6	—	—		
Cols. A1, A4, D1, D4	—	—	—	—	8	4.6	—	—	—	—	32	65.6		
Cols. B1, B4, C1, C4	—	—	—	—	4	2.2	—	—	—	—	36	89.5		
Cols. A2, A3, D2, D3	—	—	—	—	4	2.2	—	—	—	—	36	92.4		
Cols. B2, B3, C2, C3	—	—	—	—	—	—	—	—	—	—	24	67.8	16	117.5
Totals	190	13.9	—	—	16	9.0	370	561.7	950	1074.6	128	315.3	16	117.5
Total Wts.	22.9						1951.6						117.5	

Notes: All weights are in tons.
Total weight of framing: 2,092.2.
Total number of pieces: 1,670.



NOTES:
Material is ASTM A36 except members marked (50) are ASTM A572-50.
Construction is non-composite except members marked (C) are composite with the floor.

Fig. 4. Simple frame 20-story building—core framing (floors 2–20)

RIGID FRAME

In a rigid frame building, resistance to lateral loads is provided by the frame itself. Moment-resisting capability is required in the connections between the beams and the columns. This type of framing is often used for high-rise buildings. Therefore, it was included in this study for comparison with the simple frame and the tubular frame.

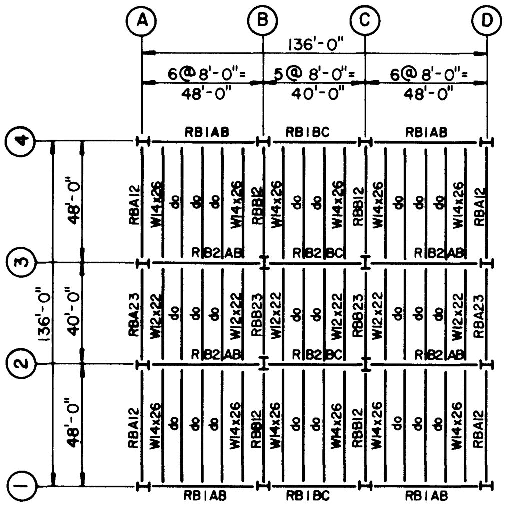
The design of the basic roof beams and floor beams was taken from the simple frame design. A new design was required for the rest of the structure. The previously mentioned structural-design computer program was used in developing this design. Since the program is written for planar structures only, the structure was divided into eight planar bents* which are assumed to behave independently. As shown in Fig. 5, these are bents A, B, C, D, 1, 2, 3, and 4. Due to symmetry, only bents A, B, 1, and 2 were designed. The computer program was used in the analysis mode; i.e., members were manually selected and the program was used to calculate the stresses for the in-plane girders and the drift ratios. It also calculated in-plane axial forces, moments, and effective length factors, K, for the columns. Results for the two axes of a column were obtained from runs of the structural design program for two orthogonal bents. These data were entered into an AISC Column Design Program[5] to confirm the adequacy of the selected sections. In addition to this program, a column-analysis program was developed to check the columns in the final stages of the design. This program determines the K-values, allowable and actual stresses, and actual-to-allowable stress ratios for the column sections from the base to the roof at a specific column location.

The design is summarized in Figs. 5 through 7. The roof framing and the floor framing are shown in Figs. 5 and 6, respectively. The framing for the core is shown in Fig. 7. A beam schedule for members that change with building height is shown in Appendix B, Table B2. Table B3 is the column schedule. Built-up column sections indicated in Table B3 are described in Fig. 8. Table 2 summarizes the number of pieces in the structure and their weights. No allowance for connections, fasteners, welds, base plates, splice plates, or other miscellaneous details is included in these quantities.

TUBULAR FRAME

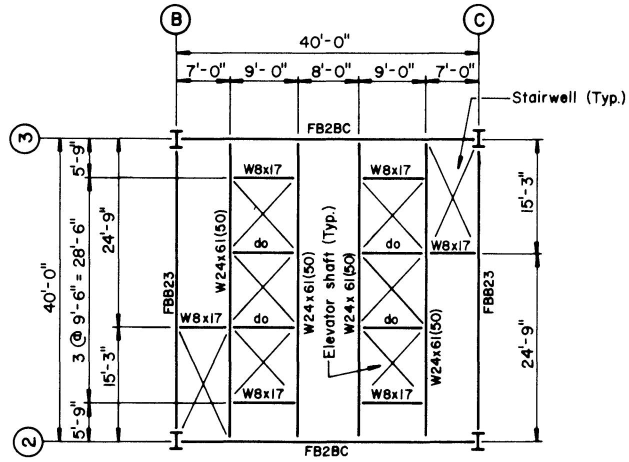
The main frame in a tubular building is located on its perimeter. The perimeter frame provides support for most of the gravity load and resistance to wind load. Interior

* *A bent is a two-dimensional structural frame.*



NOTES:
Material is ASTM A572-50.
Construction is non-composite.
For Beam Schedule for members RB XXX, see Appendix B, Table B2.

Fig. 5. Rigid frame 20-story building—roof framing

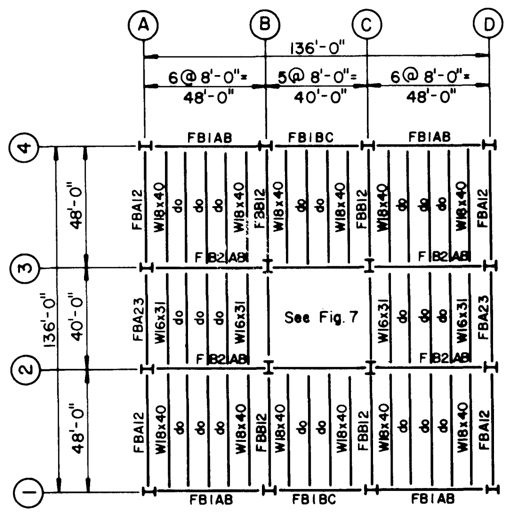


NOTES:
Material is ASTM A36 except members marked (50) are ASTM A572-50.
Construction is non-composite
For Beam Schedule for members FBXXX, see Appendix B, Table B2.

Fig. 7. Rigid frame 20-story building—core framing (floors 2–20)

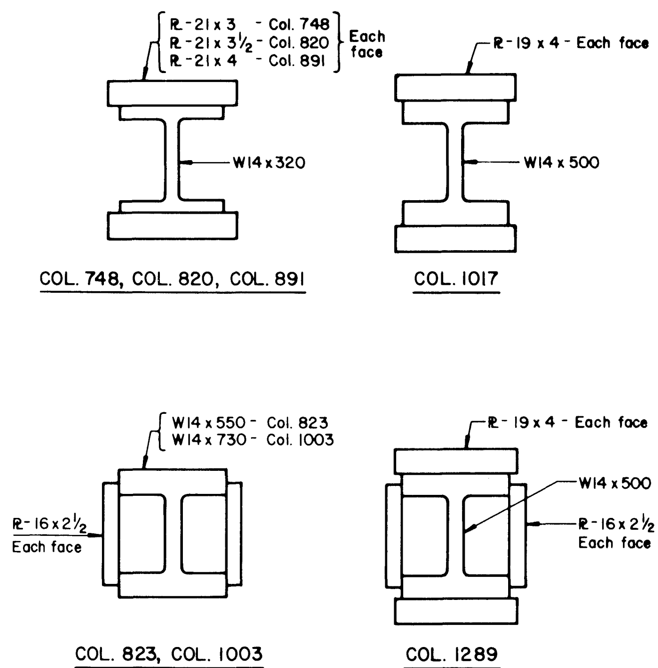
columns are used to support the remainder of the gravity load. The columns in the perimeter frame are closely spaced, which improves the efficiency of the frame in resisting wind load and tends to distribute the gravity load among the columns.[1]

The general arrangement for a typical floor in the tubular-framed building is shown in Fig. 9. This arrangement results in a non-uniform application of load to the various columns. Columns on lines A and V carry floor beams, whereas columns on lines 1 and 18 do not. Columns



NOTES:
Material is ASTM A572-50.
Construction is composite with the floor except members FBXXX which are non-composite.
For Beam Schedule for members FBXXX, see Appendix B, Table B2.

Fig. 6. Rigid frame 20-story building—floor framing (floors 2–20)



NOTE:
For Column definition, see Appendix B, Table B3.

Fig. 8. Rigid frame 20-story building—special columns

Table 2. Quantity Summary—Rigid Frame 20-Story Building

Item	A36						A572-50						A588	
	Beams Noncomp		Beams Comp		Columns		Beams Noncomp		Beams Comp		Columns		Columns	
	No.	Wt.	No.	Wt.	No.	Wt.	No.	Wt.	No.	Wt.	No.	Wt.	No.	Wt.
Roof	18	20.0	—	—	—	—	48	32.4						
Floors 2–5	136	586.7	—	—	—	—	16	19.5	152	132.3	—	—	—	—
Floors 6–9	112	341.8	—	—	—	—	40	78.3	152	132.3	—	—	—	—
Floors 10–13	88	142.1	—	—	—	—	64	156.1	152	132.3	—	—	—	—
Floors 14–17	88	127.8	—	—	—	—	64	143.6	152	132.3	—	—	—	—
Floors 18–20	66	74.3	—	—	—	—	48	107.7	114	99.2	—	—	—	—
Cols. A1, A4, D1, D4	—	—	—	—	4	34.3	—	—	—	—	36	115.4	—	—
Cols. B1, B4, C1, C4	—	—	—	—	4	43.3	—	—	—	—	24	74.2	12	77.8
Cols. A2, A3, D2, D3	—	—	—	—	4	43.3	—	—	—	—	24	77.9	12	78.0
Cols. B2, B3, C2, C3	—	—	—	—							24*	88.0	16*	212.3
Totals	508	1292.7	—	—	12	120.9	280	537.6	722	628.4	108	355.5	40	368.1
Total Wts.	1413.6						1521.5						368.1	

* Number of pieces is listed in accordance with the column core material. The weight of the core material and cover material is listed in the appropriate material column.

Notes: All weights are in tons.
Total weight of framing: 3,303.2.
Total number of pieces: 1,670.

on lines G and M carry girders that support floor beams, whereas columns on lines 7 and 12 carry only floor beams. To minimize this column load variation, the floor framing on successive floors was oriented orthogonally. Beams oriented in a north-south direction on even-numbered floors were oriented in an east-west direction on odd-numbered floors. This floor framing arrangement resulted in gravity loads that were approximately the same on corresponding columns on all faces.

Nevertheless, the gravity loads applied to the eight columns that supported girders were considerably greater than the loads applied to other columns. The gravity loads applied to the corner columns were considerably less than the loads applied to the other columns. On the other hand, the corner columns carry most of the wind load.[1] Therefore, several different sizes of columns were used in the design, including: one for the corner columns, one for the girder columns, one for the columns flanking the girder columns, and one for all other columns.

Bending of the columns is significant only in the plane of the building face. Therefore, the strong axis of the column was oriented in this direction, and the minor axis K-values were taken as 1.0. The major axis K-values were defined by the interaction of the column and spandrel stiffnesses.

The analysis of the tubular frame was performed with the NASTRAN finite-element computer program.[6] Symmetry and antisymmetry were used, so that only one-quarter of the building had to be analyzed. The gravity loads are symmetrical about the building center lines (Fig. 9). The wind load is symmetrical about the building center line parallel to the direction of the wind. The wind load produces moments that are resisted by forces in the columns that are antisymmetrical about the building center line normal to the direction of the wind. The floors are assumed to be rigid diaphragms. This assumption has been verified in a previous report.[7] Therefore, the grid-point displacements on any one floor were coupled in the north-south and east-west directions.

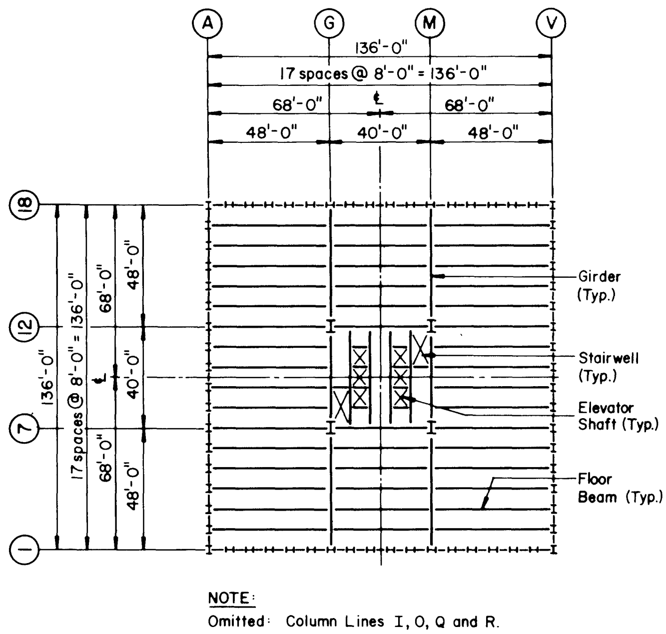
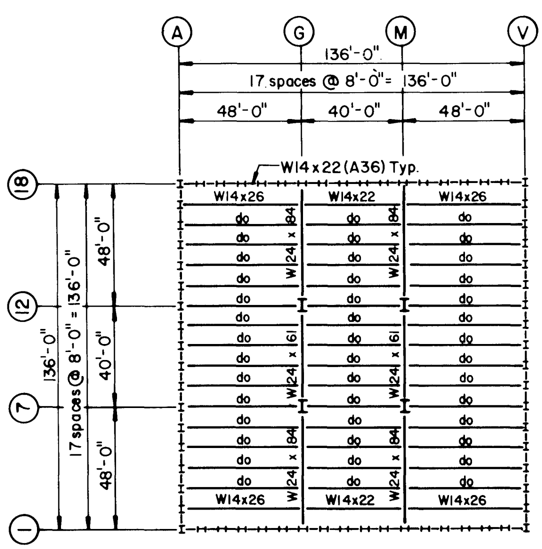


Fig. 9. Tubular frame 20-story building—general arrangement

The sizes of the roof beams, floor beams, and interior columns were taken from the simple-frame design. The design of the columns and spandrel beams was accomplished with the aid of NASTRAN. This program does not design members. Consequently, member sizes were assumed for each run and checked upon its completion. For the spandrel beams, design adequacy was easily verified with hand calculations. Control of drift due to wind forces governed the size of these members. The adequacy of the columns was verified by the column analysis program. Two designs were prepared—one using A572 Grade 50 steel columns, and one using A36 steel columns.

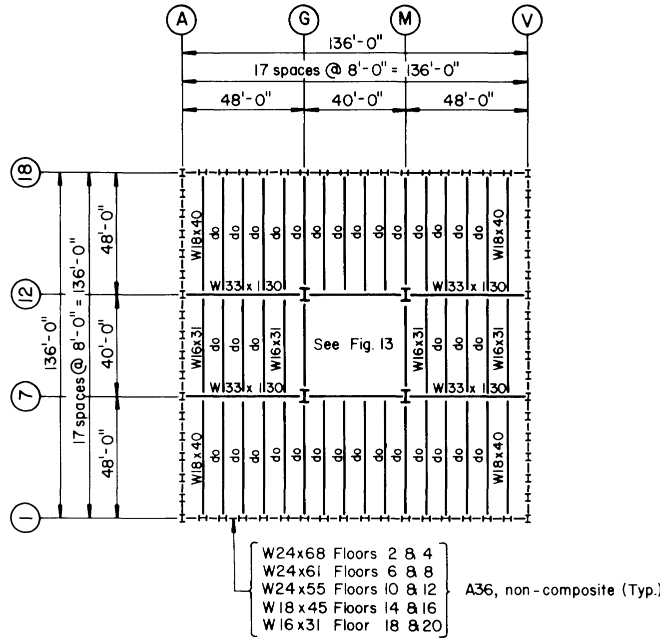
Drift control governed the column size in the tubular frame design that used A572 steel columns. Although these columns were lighter than the A36 steel columns, the weight savings were offset by weight increases for the spandrel beams. The heavier spandrel beams were needed to assist in the control of drift. The total estimated weight for A572 steel design was about the same as that for the A36 steel design. Since the material cost is higher for the A572 steel and all other construction costs would be the same, the cost of the building with A36 steel columns would be lower. Therefore, the design using A572 steel columns is not presented.

Stress governed the column size in the tubular frame design that used A36 steel columns. This design is summarized in Figs. 10 through 13. The roof framing is shown in Fig. 10; the floor framing, except for the building core, is shown in Figs. 11 and 12; and the framing for the core is shown in Fig. 13. The column schedule is shown in Appendix B, Table B4. Table 3 summarizes the number



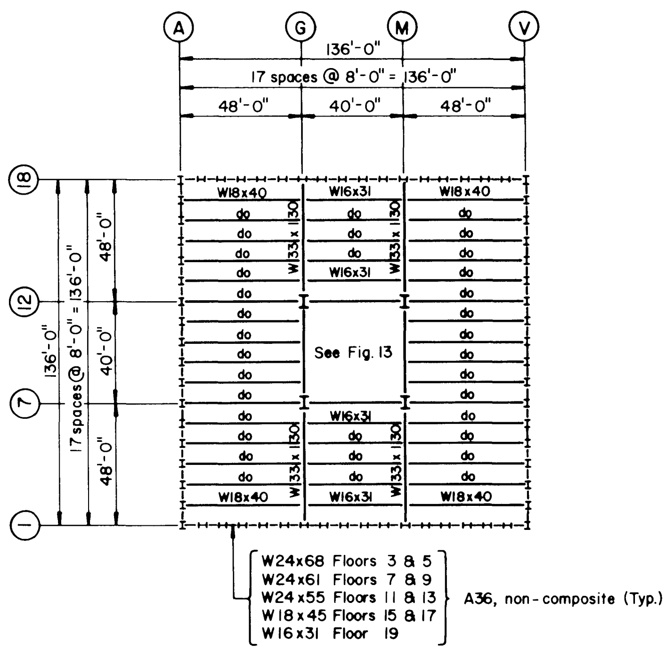
NOTES:
Material is ASTM A572-50, unless noted.
Construction is non-composite.
Omitted: Column Lines I, O, Q and R.

Fig. 10. Tubular frame 20-story building—roof framing



NOTES:
Material is ASTM A572-50 unless noted.
Construction is composite with the floor unless noted.
Omitted: Column Lines I, O, Q and R.

Fig. 11. Tubular frame 20-story building—floor framing (even-numbered floors 2–20)



NOTES:
Material is ASTM A572-50 unless noted.
Construction is composite with the floor unless noted.
Omitted: Column Lines I, O, Q and R.

Fig. 12. Tubular frame 20-story building—floor framing (odd-numbered floors 3–19)

Table 3. Quantity Summary—Tubular Frame 20-Story Building

	A36						A572-50						A588	
	Beams Noncomp.		Beams Comp.		Columns		Beams Noncomp.		Beams Comp.		Columns		Columns	
Item	No.	Wt.	No.	Wt.	No.	Wt.	No.	Wt.	No.	Wt.	No.	Wt.	No.	Wt.
Roof	68	6.0	—	—	—	—	54	37.5	—	—	—	—	—	—
Floors 2–5	312	76.9	—	—	—	—	16	19.5	200	226.3	—	—	—	—
Floors 6–9	312	69.2	—	—	—	—	16	19.5	200	226.3	—	—	—	—
Floors 10–13	312	62.8	—	—	—	—	16	19.5	200	226.3	—	—	—	—
Floors 14–17	312	52.0	—	—	—	—	16	19.5	200	226.3	—	—	—	—
Floors 18–20	234	27.6	—	—	—	—	12	14.6	150	169.7	—	—	—	—
Cols. Ext.	—	—	—	—	680	634.4	—	—	—	—	—	—	—	—
Cols. Int.	—	—	—	—	—	—	—	—	—	—	24	67.8	16	117.5
Totals	1550	294.5	—	—	680	634.4	130	130.1	950	1074.9	24	67.8	16	117.5
Total Wts.	928.9						1272.8						117.5	

Notes: All weights are in tons.
Total weight of framing: 2,319.2.
Total number of pieces: 1,670.

of pieces in the structure and their weights. No allowance for connections, fasteners, welds, base plates, splice plates, or other miscellaneous details is included in these quantities.

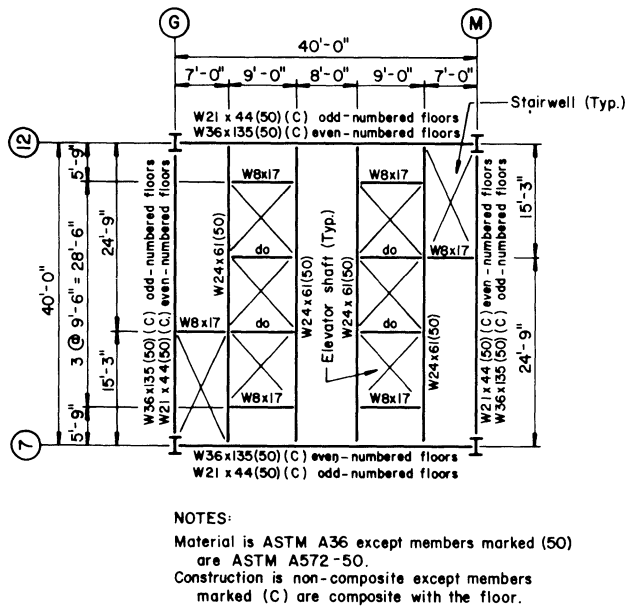


Fig. 13. Tubular frame 20-story building—core framing (floors 2–20)

COMPARISONS

Material Quantities—Quantities for the comparative designs, including weights and total number of pieces, are compared in Table 4. The weight per square foot, which is often used to measure the efficiency of a building frame, and the number of field connections for each design are also included in the table.

There are two tubular frame designs listed in Table 4. The basic design of these two frames is the same, but their fabrication and erection schemes are different. In Tubular Frame A, the columns and the spandrel beams are fabricated as separate pieces. These pieces are field-erected using moment-resisting connections. In Tubular Frame B, one-half of each spandrel beam is shop-connected to a column section, forming a tree-shaped unit. The trees are then field-erected using shear and moment connections for the spandrels at mid-span. This latter fabrication and erection scheme reduces the number of pieces to be shipped. Furthermore, there are fewer field connections, and their assembly is less complicated. However, the amount of shop fabrication and shipping complexity is increased.

As discussed previously, the difference between the weights of the simple frame and the rigid frame shows how much material is required to carry wind loads in a rigid frame. Since tubular framing is mainly advantageous in resisting wind loads, it is expected to be competitive with conventional rigid framing only in buildings where a large proportion of the material is required for wind loads. As shown in Table 4, 37 percent of the rigid-frame weight in a 20-story building is required for wind loads. In taller (and to a lesser extent, narrower) buildings, this percentage is expected to be higher. Thus, a large potential for weight savings through tubular framing exists for medium-height buildings in the 20- to 40-story range. Table 4 shows that only 10 percent of the weight was required for wind loads in the 20-story tubular frame. This means that the tubular frame was able to realize most of the potential weight savings.

Weight, however, is only one factor in the in-place or total cost of a building frame. The number of pieces to be

Table 4. Comparison of Quantities

Description	Simple Frame	Rigid Frame	Tubular Frame A*	Tubular Frame B*
Weight (tons)	2090	3300	2320	2320
Wt/sq ft (lbs/ft^2)	11.9	18.8	13.2	13.2
Weight Needed for Wind Load (tons)	—	1210	230	230
Percent of Total Weight (for Wind Load)	—	37	10	10
Number of Pieces for Fabrication	1670	1670	3350	4710
Percent Increase in No. of Pieces for Fabrication**	—	—	101	182
Number of Pieces for Erection	1670	1670	3350	1990
Increase in No. of Pieces for Erection**	—	—	101%	19
Number of Field Connections				
a) Simple	3020	2060	2540	3900
b) Moment	—	960	2720	—
c) Column Splices	144	144	648	648
d) Column Bases	16	16	72	72
e) Total Connections	3180	3180	5980	4620
Percent Increase in Total Field Connections**	—	—	88	45

* Fabrication and erection for Frame A: Separate spandrels and columns.
Fabrication and erection for Frame B: Tree-shaped spandrels and column assemblies.
** Compared with rigid frame.

handled, the size and shape of the pieces, and the degree of complexity of the connections, especially the field connections, also affect the total cost. The number of pieces and the number and type of field connections are compared in Table 4 for the various frame designs. Columns are assumed to be two stories in length. The rigid frame has the same number of pieces (1,670) for fabrication and erection as the simple frame. Tubular Frame A has 101 percent more pieces than the rigid frame. Tubular Frame B has 182 percent more pieces for fabrication, but only 19 percent more pieces for erection than the rigid frame. Tubular Frame A has 88 percent more field connections than the rigid frame, most of which are moment-resisting connections. Tubular Frame B has a 45 percent increase in field connections over the rigid frame; none of these connections are moment resisting. The 2,720 moment-resisting field connections in Tubular Frame A are accomplished as shop connections, which are more economical than the moment-resisting field connections in Tubular Frame B.

Estimated Costs—Three fabricators prepared cost estimates for the rigid-frame and tubular-frame designs. For the tubular-frame estimate, the fabrication and erection scheme of Tubular Frame B was used. A comparison of the cost estimates is presented in Table 5.

Each fabricator provided his own weight estimate. These weight estimates are greater than those made in the design study, because they include base plates, connection material, stiffeners, fasteners, and other miscellaneous materials.

Table 5. Comparison of Cost Estimates

	Fabricator No. 1		Fabricator No. 2		Fabricator No. 3		Average of Estimates	
	Rigid	Tubular	Rigid	Tubular	Rigid	Tubular	Rigid	Tubular
Weight Estimated in Design Study (tons)	3300	2320	3300	2320	3300	2320	3300	2320
Weight Estimated by Fabricators (tons)	3410	2560	3490	2500	3420	2470	3440	2510
Increase in Weight Fabricators Estimates Over Design Study Estimate (tons)	110	240	190	180	120	150	140	190
Estimated Cost ($)								
Fabrication	1,983,000	2,092,000	1,943,000	1,750,000	—	—	1,963,000*	1,921,000*
Erection	567,000	517,000	349,000	313,000	—	—	480,000*	415,000*
Total	2,550,000	2,609,000	2,292,000	2,062,000	2,426,000	2,690,000	2,423,000	2,454,000
Percent Variation from Avg.								
Fabrication	+1	+9	−1	−9	—	—	—	—
Erection	+24	+25	−24	−25	—	—	—	—
Total	+5	+6	−5	−16	0	+10	—	—
Percent Increase in Cost Compared With Rigid Frame	—	+2	—	−11	—	+11	—	+1

* Based on two estimates only.

Even though there is some variation in the estimated weight of the construction details, it is only a small portion of the total weight—3 to 6 percent for the rigid frame, and 6 to 10 percent for the tubular frame.

Fabricators 1 and 2 produced separate cost estimates for fabrication and erection. Fabricator 3 provided only an estimated total cost. The two fabrication cost estimates for the rigid frame vary only by ±1 percent from the average. There is a ±24 percent variation in estimated erection cost. The three estimated total costs for the rigid frame vary by ±5 percent from the average. The two fabrication cost estimates for the tubular frame vary by ±9 percent from the average, and the variation in the two erection cost estimates is ±25 percent. The variation in the three estimated total costs for the tubular frame ranges from +10 through −16 percent from the average. Thus, the highest variations occur in the erection costs for both types of frames. The total costs vary more for the tubular design than for the rigid-frame design.

Fabricator 1 estimated the total cost of the tubular frame to be 2 percent higher than that of the rigid frame; Fabricator 2 estimated the cost of the tubular frame to be 11 percent less than that of the rigid frame; and Fabricator 3 estimated the cost of the tubular frame to be 11 percent higher than that of the rigid frame. The average estimated cost of the tubular frame is one percent higher than the average estimated cost of the rigid frame. The lowest estimate for the tubular frame is 11 percent less than the lowest estimate for the rigid frame. This latter comparison is more pertinent than the comparison of average estimates, because in practice the cost of a building is based on the lowest bid price.

CONCLUSIONS

The study showed that in medium-height buildings in the 20- to 40-story range there is a considerable potential for reducing the weight of the material required to carry the wind loads, and that a tubular frame is able to realize most of this potential. Thus, the weight of a 20-story tubular frame was about 30 percent less than that of a similar rigid frame. The cost advantage of the tubular frame was considerably less because of higher fabrication costs. Based on the lowest of the three cost estimates by different fabricators, the tubular frame costs 11 percent less than the rigid frame. However, based on the average of the three estimates, the tubular frame costs 1 percent more than the rigid frame. Thus, it appears that neither type of frame has a clear cost advantage over the other at the 20-story height. Consequently, it is expected that in practice tubular framing would be cheaper for some particular 20-story buildings, and rigid framing would be cheaper for others. In taller buildings, the cost comparison is expected to be more favorable for tubular framing.

REFERENCES

1. *Leffler, R. E.* Tubular Framing for Medium-Height Buildings—Parameter Study *Research Laboratory Bulletin, U.S. Steel Corp., May 23, 1979.*
2. Tubular Design Cuts Mid-Rise Framing Weight *Engineering News Record, Vol. 198, No. 18, April 29, 1976.*
3. Specification for the Design, Fabrication and Erection of Structural Steel for Buildings *American Institute of Steel Construction, 1969.*
4. Uniform Building Code *Vol. 1, International Conference of Building Officials, 1973.*
5. User's Manual: Computer Program for Steel Column Design *CDA-1-69.1, American Institute of Steel Construction, 1971.*
6. NASTRAN *National Aeronautics and Space Administration.*
7. *Leffler, R. E.* Stresses in Floors of Staggered-Truss Buildings: Precast Prestressed Concrete Floor Plank *Research Laboratory Report 46.019-400(5), U.S. Steel Corp., Dec. 31, 1973.*

APPENDIX A—DESIGN PARAMETERS

Building: Office

No. Floors: 20

Height/Floor: 12 ft-6 in.

Specifications: Uniform Building Code

Live Loads:	Roof:	20 psf
	Office:	50 psf*
	Corridor:	100 psf
	Mechanical:	150 psf
Dead Loads:	Steel Deck & Concrete:	47 psf**
	Ceiling:	5 psf
	Partitions:	20 psf
	Miscellaneous:	5 psf
	Roof and Deck:	10 psf†
	Curtain Wall:	30 psf
Wind Loads:	0 to 30 ft:	25 psf
	30 to 50 ft:	30 psf
	50 to 100 ft:	40 psf
	100 to 250 ft:	45 psf
Lightweight Concrete:	Weight:	120 psf
	f'_c:	3000 psi
	E_c:	2.38×10^6 psi

* *Concrete load of 2.0 kips.*

** *$3\frac{1}{4}$-in. lightweight concrete on 3-in. composite steel floor deck, similar to H. H. Robertson QL-99.*

† *5-ply built-up roof and $1\frac{1}{2}$-in. rigid insulation over $1\frac{1}{2}$-in. wide rib steel deck.*

APPENDIX B

Table B1. Simple Frame 20-Story Building—Column Schedule

Story*	A1, A4, D1, D4		B1, B4, C1, C4		A2, A3, D2, D3		B2, B3, C2, C3	
	Sect.	Mat'l	Sect.	Mat'l	Sect.	Mat'l	Sect.	Mat'l
1-2 2-3	W14×219	50	W14×342	50	W14×342	50	W14×730	50
3-4 4-5	W14×193	50	W14×314	50	W14×314	50	W14×665	50
5-6 6-7	W14×176	50	W14×264	50	W14×287	50	W14×500	50
7-8 8-9	W14×150	50	W14×228	50	W14×237	50	W14×455	50
9-10 10-11	W14×127	50	W14×193	50	W14×202	50	W14×398	50
11-12 12-13	W14×111	50	W14×158	50	W14×167	50	W14×314	50
13-14 14-15	W14×87	50	W14×127	50	W14×136	50	W14×264	50
15-16 16-17	W14×68	50	W14×95	50	W14×95	50	W14×184	50
17-18 18-19	W14×61	36	W14×68	50	W14×68	50	W14×127	50
19-20 20-RF	W14×30	36	W14×43	36	W14×43	36	W14×68	50

* Story height = 12′-6″.
Notes: Material marked 36 is ASTM A36.
Material marked 50 is ASTM A572-50 except sections heavier than W14×426 are ASTM A588.

Table B2. Rigid Frame 20-Story Building—Beam Schedule

Memb.	Floor	Sect.	Mat'l	Memb.	Floor	Sect.	Mat'l
FB1AB	2-5	W36×230	36	FBA12	2-5	W36×230	36
	6-9	W30×108	50		6-9	W36×160	36
	10-13	W30×108	50		10-13	W33×130	36
	14-20	W30×99	50		18-20	W27×84	36
RB1AB	Roof	W24×61	36	RBA12	Roof	W21×44	36
FB1BC	2-5	W36×230	36	FBA23	2-5	W36×280	36
	6-9	W30×108	50		6-9	W36×170	36
	10-20	W27×84	50		10-13	W30×99	36
RB1BC	Roof	W21×44	36		14-17	W27×84	36
FB2AB	2-5	W36×300	36		18-20	W24×68	36
	6-9	W36×230	36	RBA23	Roof	W21×44	36
	10-13	W36×150	50	FBB12	2-5	W36×300	36
	14-20	W36×135	50		6-9	W36×230	36
					10-13	W36×135	36
RB2AB	Roof	W24×68	50		14-17	W33×118	36
FB2BC	2-5	W36×300	36		18-20	W27×84	36
	6-9	W36×230	36	RBB12	Roof	W21×44	36
	10-13	W36×135	50	FBB23	2-5	W36×300	36
	14-20	W33×130	50		6-9	W36×230	36
RB2BC	Roof	W24×55	50		10-13	W36×135	36
					14-20	W33×130	36
				RBB23	Roof	W24×55	36

Notes: Material marked 36 is ASTM A36.
Material marked 50 is ASTM A572-50.

Table B3. Rigid Frame 20-Story Building—Column Schedule

Story*	A1, A4, D1, D4		B1, B4, C1, C4		A2, A3, D2, D3		B2, B3, C2, C3	
	Sect.	Mat'l	Sect.	Mat'l	Sect.	Mat'l	Sect.	Mat'l
1-2	COL823**	36	COL1003**	36	COL1003**	36	COL1289**	50
2-3	W14X550	36	W14X730	36	W14X730	36	COL1017**	50
3-4 4-5	W14X398	50	W14X550	50	W14X605	50	COL891**	50
5-6 6-7	W14X370	50	W14X550	50	W14X500	50	COL820**	50
7-8 8-9	W14X342	50	W14X455	50	W14X455	50	COL748**	50
9-10 10-11	W14X287	50	W14X398	50	W14X398	50	W14X730	50
11-12 12-13	W14X246	50	W14X342	50	W14X342	50	W14X550	50
13-14 14-15	W14X219	50	W14X287	50	W14X287	50	W14X455	50
15-16 16-17	W14X176	50	W14X211	50	W14X228	50	W14X342	50
17-18 18-19	W14X142	50	W14X150	50	W14X176	50	W14X219	50
19-20 20-RF	W14X127	50	W14X95	50	W14X127	50	W14X103	50

* Story height = 12'-6".
** Built-up column, see Fig. 8.
Notes: Material marked 36 is ASTM A36.
Material marked 50 is ASTM A572-50, except sections heavier than W14X426 and thicker than 2 in. are ASTM A588.

Table B4. Tubular Frame 20-Story Building—Column Schedule

Story*	A1, A18, V1, V18		A2, A3, A4, A9, A10, A15, A16, A17, B1, B18, C1, C18, D1, D18, J1, J18, K1, K18, S1, S18, T1, T18, U1, U18, V2, V3, V4, V9, V10, V15, V16, V17		A5, A14, E1, E18 V5, V14, P1, P18		A6, A13, F1, F18, V6, V13, N1, N18		A7, A12, G1, G18, V7, V12, M1, M18		A8, A11, H1, H18, V8, V11, L1, L18		G7, G12, M7, M12	
	Sect.	Mat'l	Sect.	Mat'l	Sect.	Mat'l	Sect.	Mat'l	Sect.	Mat'l	Sect.	Mat'l	Sect.	Mat'l
1-2 2-3	W14X142	36	W14X103	36	W14X103	36	W14X136	36	W14X167	36	W14X119	36	W14X730	50
3-4 4-5	W14X127	36	W14X95	36	W14X103	36	W14X127	36	W14X142	36	W14X119	36	W14X665	50
5-6 6-7	W14X103	36	W14X95	36	W14X95	36	W14X111	36	W14X127	36	W14X103	36	W14X500	50
7-8 8-9	W14X84	36	W14X84	36	W14X84	36	W14X103	36	W14X103	36	W14X95	36	W14X455	50
9-10 10-11	W14X74	36	W14X74	36	W14X74	36	W14X95	36	W14X95	36	W14X78	36	W14X398	50
11-12 12-13	W14X61	36	W14X68	36	W14X74	36	W14X78	36	W14X78	36	W14X68	36	W14X314	50
13-14 14-15	W14X48	36	W14X53	36	W14X61	36	W14X78	36	W14X78	36	W14X53	36	W14X264	50
15-16 16-17	W14X38	36	W14X43	36	W14X48	36	W14X61	36	W14X61	36	W14X43	36	W14X184	50
17-18 18-19	W14X30	36	W14X34	36	W14X34	36	W14X43	36	W14X48	36	W14X34	36	W14X127	50
19-20 20-RF	W14X30	36	W14X30	36	W14X30	36	W14X30	36	W14X30	36	W14X30	36	W14X68	50

* Story height = 12'-6".
Notes: Material marked 36 is ASTM A36.
Material marked 50 is ASTM A572-50 except sections heavier than W14X426 are ASTM A588.