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**Structuring the commercial environment**

L'aménagment de l'environnement commercial

Planung der kommerziellen Umwelt

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**SUMMARY**

The architectural and structural engineering design of highrise, commercial office buildings to meet the needs of the commercial environment in the world's major cities is one of the most challenging aspects of building design today. Unlike many other types of construction projects, such as highways, bridges, water-front facilities, and institutional buildings, the commercial highrise office building environment and the facilities built to meet its needs must immediately turn a profit for the owner/developer.

**RESUME**

Le projet architectural et structurel de bâtiments élevés répondant aux besoins commerciaux est un des aspects actuels les plus passionnants dans le projet de bâtiments, dans les villes principales du monde. A l'opposé d'autres types de construction, tels que routes, ponts, aménagements côtiers et bâtiments gouvernementaux, les bâtiments élevés à l'usage commercial, et leur environnement, doivent remplir leurs fonctions immédiatement, tout en offrant un revenu au propriétaire.

**ZUSAMMENFASSUNG**

Das Architektur- und Ingenieurprojekt für Bürohochhäuser zählt heute in den meisten Weltstädten als eine der herausforderndsten Aufgaben des Bauingenieurwesens. Im Gegensatz zu anderen Bauten wie Strassen, Brücken, Bauwerke am Meer und Regierungsgebaude müssen Bürohochhäuser ihren Dienst sofort erfüllen und gleichzeitig eine Rendite für den Bauherrn abwerfen.

## A. INTRODUCTION

The architectural and structural engineering design of highrise, commercial office buildings to meet the needs of the commercial environment in the world's major cities is one of the most challenging aspects of building design today. Unlike many other types of construction projects, such as highways, bridges, waterfront facilities, and institutional buildings, the commercial highrise office building environment and the facilities built to meet its needs must immediately turn a profit for the owner/developer.

In this kind of economic climate, the building must be designed with the "bottom-line" as the top priority. The pressures that exist in this environment cause the designers of the building to constantly be faced with delivering the most functional, durable, aesthetically pleasing and commercially competitive structure at the lowest construction cost.

Ten years ago, when the prevailing interest rates in the United States were in the single digit range, the time required to construct a building was not nearly as important as it is today with double digit interest rates and inflation. With interim construction financing presently costing approximately 2 to 3 percentage points above the prime lending interest rate (e.g., 20% to 23% in 1980), the shortest construction time is of paramount importance to the owner so that rental income can be generated as early as possible.

All of these factors combine to make the design of the commercial environment for highrise buildings a most challenging experience.

## B. BASIC STRUCTURAL SYSTEMS

Highrise commercial office buildings, from a structural point of view, consist of two major systems: The floor and the lateral load resisting system. The analysis, design and cost evaluation of the alternate framing approaches for the floor system for commercial buildings is generally an objective and well established procedure. For a structural steel building, the floor system including the columns to support the floor system usually ranges between 8 to 10 pounds per square foot (psf). For a structure with about 10 stories, the total weight of structural steel including the floor system, columns and lateral load resisting system usually amounts to about 10 to 12 psf. The distribution of steel weight and cost changes when highrise construction is contemplated. The following example shows what happens:

a. Assume that the floor system and columns, i.e. the amount of steel required to support vertical gravity dead and live loads, is 10 lbs. per sq. ft.

b. Thus, all additional steel in the building frame is related to lateral load resisting requirements. Assuming that a braced central core approach is utilized for a series of buildings having 30, 40, 50 and 60 stories, the following becomes apparent:

30 stories - gravity load system - 10 lbs. per sq. ft.
lateral load system - 15 lbs. per sq. ft.

$$\frac{\text{lateral}}{\text{gravity}} = \frac{15}{10} = 1.5$$

40 stories - gravity load system - 10 lbs. per sq. ft.
lateral load system - 20 lbs. per sq. ft.

$$\frac{\text{lateral}}{\text{gravity}} = \frac{20}{10} = 2.0$$

50 stories - gravity load system - 10 lbs. per sq. ft.
lateral load system - 25 lbs. per sq. ft.

$$\frac{\text{lateral}}{\text{gravity}} = \frac{25}{10} = 2.5$$

60 stories - gravity load system - 10 lbs. per sq. ft.
lateral load system - 30 lbs. per sq. ft.

$$\frac{\text{lateral}}{\text{gravity}} = \frac{30}{10} = 3.0$$

From the above, it is apparent that for a low-rise building, the ratio of lateral load resisting steel to gravity load resisting steel components of the building is small while for a 60 story building, the ratio can be three (3.0) or greater.

Thus, for tall buildings the key to an economic solution is the structural system selected by the designer to resist the lateral loads on the building.

The purpose of this paper is to depict the relative comparative approaches that can be utilized in the design of highrise buildings. It is important, however, to remember that the aim in highrise design is to achieve the true cost effective structure which makes a positive contribution to the total building system by minimizing the overall cost and maximizing its efficiency. The lateral load system should not only be a self-serving, low cost support system which jeopardizes the other systems of the building, such as architectural and mechanical and electrical systems.

## C. STRUCTURAL AND ARCHITECTURAL FORM

With most major American cities already full of rectangular box-like and prismatic towers, the tendency on the part of today's architectural designers is to introduce variations in form and shape. Curved tops, cuts, sculptured silhouettes and other geometric expressions are utilized to capture a distinctive image for the building and to attempt to reduce the visual impact of these large monoliths very real size to the pedestrian and observer at street level. Architectural commentators are referring to this direction as the "post-modernist" school.

These various changes in geometrical form contribute an additional complexity to the selection of a structural solution to resolve the lateral load on tall towers. Generally, for buildings less than 40 stories, a central core bracing system is efficient and economical to adequately resist lateral loads. When the height of a building exceeds 40 stories, then an exterior bracing solution begins to make economic sense. Once an exterior bracing solution is arrived at as the most economical method to resist lateral loads, variations in exterior geometry of the building introduce significant impact and cost penalty on the building. The best compromise arrived at by the design team is to attain the most efficient lateral load resisting system with the most aesthetically appealing and acceptable exterior geometry.

In 1979, The American Society of Civil Engineers through the Council on Tall Buildings and Urban Habitat published Volume SB, "Structural Design of Tall Steel Buildings". This definitive volume is one of a set of five comprehensive volumes of a Monograph on the Planning and Design of Tall Buildings. This reference classified various structural systems into four types as follows:

| | |
|---|---|
| Type I | - semi-rigid and rigid connected structural frame works generally less than 30 stories. |
| Type II | - braced core and braced core with outrigger and frame with braced core generally less than 60 stories. |
| Type III | - framed end channel or framed middle I exterior braced systems generally less than 70 stories. |
| Type IV | - exterior framed tube, bundled tubes and exterior diagonally braced tubes generally acceptable above 70 stories. |

Figure 1 shows a diagrammatic comparison of these four structural systems. Based upon the multitude of possibilities and the subjective aspects of the selection of the lateral load resisting system, there is tremendous controversy among designers surrounding which, if any, system is best. Claims are made by many designers that one system is more advantageous than another. Should a tube or a braced frame be used? Should a steel shear wall system or a concrete shear wall system be used? Is a structural steel system more economical than reinforced concrete system? Should moment connected steel frames be used or should K-braced or knee-braced steel frames be utilized? Unfortunately, no two commercial buildings are alike, and as such, the needs and constraints of each project are never the same. It is often very misleading to utilize facts, figures and quantities from one project as a datum of comparison with another project.

Figure 2 shows the general variation in steel weight for Type I and II systems while Figure 3 shows the general variation in steel weight for Type III and IV systems. For these figures, it can be noted that the economic domain for which each type of system is economically feasible varies from 30 stories for Type I, 50 stores for Type II, 70 stories for Type III and greater than 70 stories for Type IV. It becomes obvious that as buildings grow taller, the only economical way to solve the structural problems and achieve an economical solution is to utilize a Type IV solution; an exterior braced system, or exterior tubular approach.

## D. STRUCTURAL STIFFNESS AND DRIFT CRITERIA

In a design of a tall structure for lateral loads, including seismic and wind loads, the structural engineer must design the system to meet three criteria:

1. To provide a structure with adequate strength to safely resist all expected forces.

2. To provide adequate rigidity to prevent damage to non-structural elements due to building motion, thus reducing maintenance costs and improving serviceability of the structure.

3. To eliminate perception to sway (movement) or undesirable drift and unpleasant response by the occupants within the building.

There are no established drift criteria for the design of tall buildings. In general, each structural engineer designing a tall building must develop his own design criteria. The reason for this is that the wide variation in geometrical configurations and the mixture of materials, structural systems and exterior cladding systems can either significantly increase or decrease the amount of drift. Generally, drift is limited to approximately .002 H where H is the building height. Another way to look at drift limitation is to relate it to a relative drift or movement between adjacent floors. This is called interstory drift.

The interstory drift becomes quite important relative to the interaction and impact of structural movement or drift of the overall building on the exterior enclosure system. With the modern trend toward the use of lighter, high performance glass and metal exterior walls, the drift of buildings tends to be much more dependent upon structural stiffness of the major wind resisting system, the structure. Very little resistance results from the exterior wall. As a result, the calculations for drift of buildings become quite important and the actual calculated amounts are very close to reality. Since the normal floor to floor height in highrise office buildings is generally 12'-0" to 12'-6" high, the interstory drift at .002 times the story height becomes approximately 3/8". Exterior wall systems must be capable of absorbing this movement without damage. If the drift of the building were to be significantly higher than .002 H (where H is the story height) which has actually happened in several major highrise buildings in the United States, severe curtain wall deformation and failure occurs.

It is difficult to set a definitive criteria for drift limitation in a highrise building. More important, the drift control and behavior must be related to the natural period of vibration and dynamic motion of the building.

## E. EXAMPLES

In order to attempt to show how the above factors have impacted on the design of several highrise buildings in the United States, two projects are described in this section. The Continental Center, a 42-story building located in New York City, contains approximately 1.1 million square feet, and a 54-story United States Steel Realty Corporation, Dravo Building, in Pittsburgh contains 1.7 million square feet. Each of these buildings utilizes a different lateral load resistance system.

### 1. The Continental Center, New York, N.Y.

The Continental Center is a 1.1 million square foot commercial office building located at Maiden Lane in the business district of lower Manhattan. The owner of the project is a joint venture of Rockefeller Center Development Corporation and the Continental Corporation, a large American insurance company.

The architect for the project is Swanke, Hayden, Connell & Partners and the structural engineer is Thornton-Tomasetti, P.C., the Office Of Lev Zetlin Associates, Inc. The general contractor is Tishman Construction Corporation.

The project is located adjacent to the South Street Seaport and is sited diagonally on the parcel of land in order to allow vistas on the Seaport and the surrounding waterfront. Because of space dedicated to the public at the lower levels and the desire to architecturally express the large atria on three sides, the elevation from the ground to the first occupied office floor is approximately 100 feet. As a result, the unsupported length of structural columns around the exterior of the building is quite long. With long unsupported lengths of exterior columns at the base of building, the utilization of exterior moment connected frames or the use of an exterior tube type structure is not economically or technically desirable. Since the building is only 42 stories high, a braced steel core utilizing knee braces in one direction and K-braces in the other direction is utilized. This corresponds to a Type II building. The weight of structural steel per square foot for this project is 23 lbs. per sq. ft. This compares favorably with the chart shown in Figure 2. Alternate schemes were studied using moment connected frames, exterior tube framing and central reinforced concrete shear wall system but all proved to have no technical or cost advantage.

The typical floor plan of the building is shown in Figure 4 for both architectural and structural systems. The exterior architectural elevation of the building is depicted in Figure 5. The wind loadings for the structural system of this building are shown in Figure 6 along with the curtain wall wind pressures and their correspondence to New York City Wind Pressure Code specified values. A wind tunnel test was undertaken for the building which showed that in all cases the pressures for structural design would be less than the code specified values. This was not true for the pressure distributions developed from the wind tunnel for the exterior cladding or curtain wall design. In this case, the wind pressures were significantly in excess of what would be expected by code. Figure 7 shows a diagrammatic depiction of the wind bracing system utilized in the building. The structural analysis of the structure for the lateral loads on the building showed that the deflection or drift at the top of the building would be 14". This corresponds to a drift ratio of about .0021H. Figure 8 shows a deflected shape diagram, generated by computer, of the structure's behavior under wind loading. By utilizing computer graphics, the actual deformed shape of the structure was studied and where deviations from expected behavior were observed, member sizes were changed and the analysis redone so that an acceptable design could be finally achieved.

## 2. The United States Steel Realty, Dravo Building, Pittsburgh, Pa.

The structural system of the 1,700,000 sq. ft. 54-story Dravo Tower utilizes an exterior framed steel tube with a unique exposed steel stressed skin as both a structural bracing system and the facade. This approach eliminates the need for a separate non-structural exterior wall, reduces the steel in the primary lateral load resisting frame, and maximizes interior space by reducing the size of the central core structure. This stressed skin tube structural system both reduces cost while increasing the ratio of net to gross floor area, which is extremely important to the real estate developer.

The architect for the project is Welton Becket Associates of New York and the structural engineer is Lev Zetlin Associates, Inc. of New York. The owner is United States Steel Realty Corp., the major tenant is the Dravo Corporation and the general contractor is Turner Construction Corporation of Pittsburgh.

The exterior framed steel tube with columns spaced 10 feet on center, together with moment connected spandrel beams, provides all necessary lateral resistance to maintain stresses within code allowables. However, designing a highrise building with members sized to resist lateral loads based only on allowable stresses results, predictably, in a building with an unacceptable amount of sway - in this case, a sway equal to building height divided by 300 or .0033H where the height of the building is 729 feet.

The building is shown in exterior elevation in Figure 9. The typical floor plan is shown both architecturally and structurally in Figure 10.

In a conventional framed steel tube structure, steel is added to the spandrels and columns, and often to the core, to provide the additional lateral stiffness required to develop an acceptable sway in the order of the height divided by 500 or .002H. This lateral stiffness is accomplished in the Dravo Tower with the stressed skin steel facade which interacts with the primary tube structure to minimize sway.

The 5/16" steel skin, with precut openings for windows, is applied in three-story high units. Its dual function of acting as facade and a structural element is the key to the cost savings achieved with this design. Figure 11 shows the approach to the exterior facade structure.

By establishing the stressed skin exterior tube as the structural component that will resist all lateral loads, the core is designed to transmit only gravity loads. This significantly reduces the size of the core walls, adds approximately 18" of additional rentable floor space around the core's perimeter on all floors, and results in further cost effectiveness of the design. Figure 12 shows the deformed shape of a typical exterior panel as drawn by a computer aided device.

Since the degree of a building's sway is not related to structural integrity, there are no code requirements dictating its amount. With the Dravo Tower's core resisting some of the gravity loads and the primary tube structure resisting the rest of the gravity loads and all lateral loads within code allowables, the building is structurally sound without the stressed skin. The steel skin adds the significant additional structural stiffness necessary to eliminate an unacceptable amount of sway.

Therefore, by maintaining this distinction of function between the steel skin and the rest of the structural framing in both the design and analysis, the steel skin can be exposed, without fire protection, thus adding to still further cost savings.

This approach requires an in-depth analysis. The entire structure must first be analyzed as a tube system without the skin to be sure that all stress levels are within code allowables. The tube system generated by computer aided device is shown in Figure 13. The tube structure must be analyzed again with the addition of the skin as a shear membrane to be sure that an acceptable level of sway is obtained. Also, stresses must be re-analyzed to assure that in all areas of the structure they are indeed further reduced by the application of the skin and there are no local areas where increases have been induced.

In addition, the skin must be designed for a combination of in-plane shear forces, wind forces perpendicular to the skin, some compressive forces transferred from the columns due to elastic shortening, residual stresses due to the window openings, thermal forces, as well as overall and local shear buckling.

This complex analysis is required only for design; fabrication and erection, however, is executed in a conventional manner.

Between the core and the exterior tube, 47 ft. clear spans are achieved with 24 in. wide flange beams which are penetrated for mechanical distribution systems to minimize floor to floor heights. The floor typically consists of 2 in. composite electrified deck spanning 10 feet between the beams with 2½ in. stone concrete fill. The total weight of primary structural steel is limited to only 23 psf. The added stiffness due to the exterior skin is achieved within a cost of exterior skin less than that expected for a conventional curtain wall.

The 17-story low-rise bustle appended to the tower is not tall enough to act as a tube. However, it utilizes a similar structural system to provide lateral resistance, supplemented by some internal bracing that is required due to its unsymmetrical relationship to the tower. The structural system of the bustle is "tuned" to behave in a manner compatible with the movements of the tower. This permits the elimination of expensive expansion joints between the bustle and the tower.

The net result of this integrated and efficient architectural and structural design is to provide cost effective column free interior space with a high ratio of net to gross floor area. The heart of the cost effectiveness lies in the dual function of the stressed skin exterior wall which provides a facade as well as the stiffness required to minimize sway.

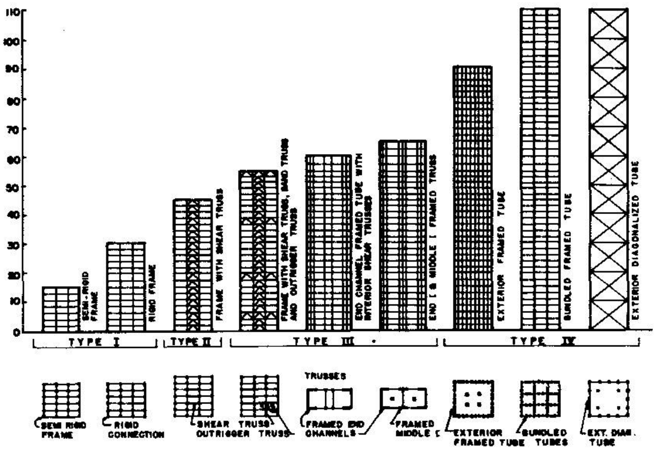


FIGURE 1 - VARIOUS STRUCTURAL SYSTEMS

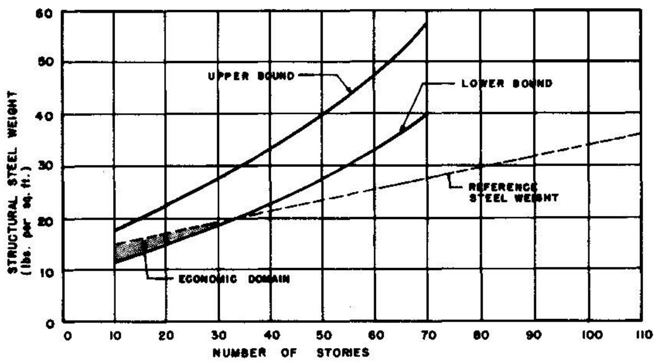


FIGURE 2A - TYPE I

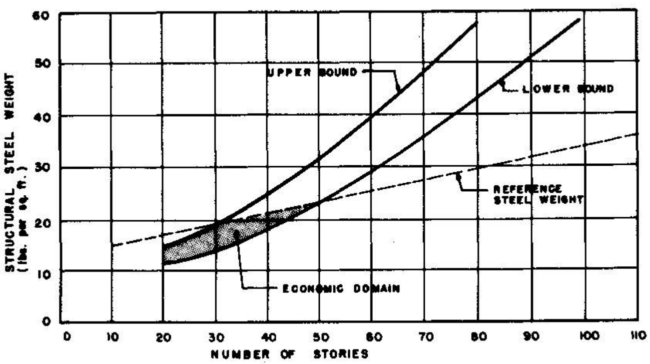


FIGURE 2B - TYPE II

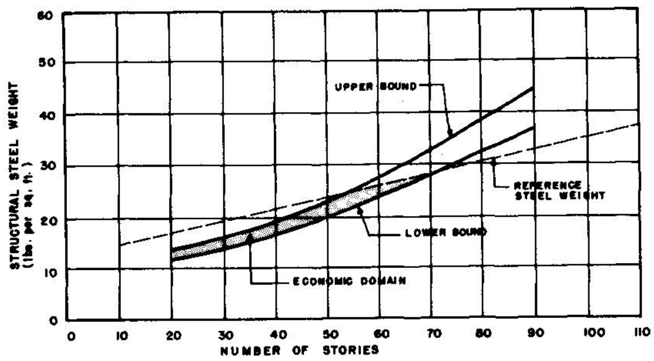


FIGURE 3A - TYPE III

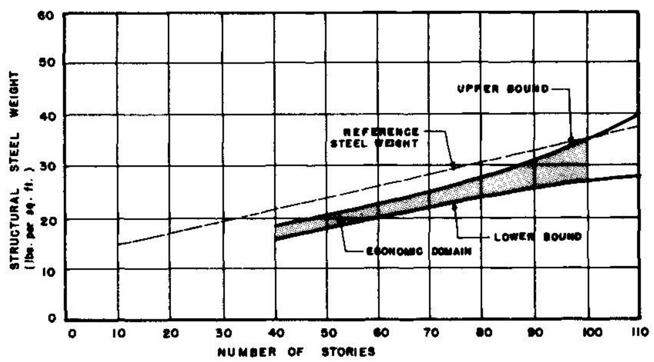


FIGURE 3B - TYPE IV

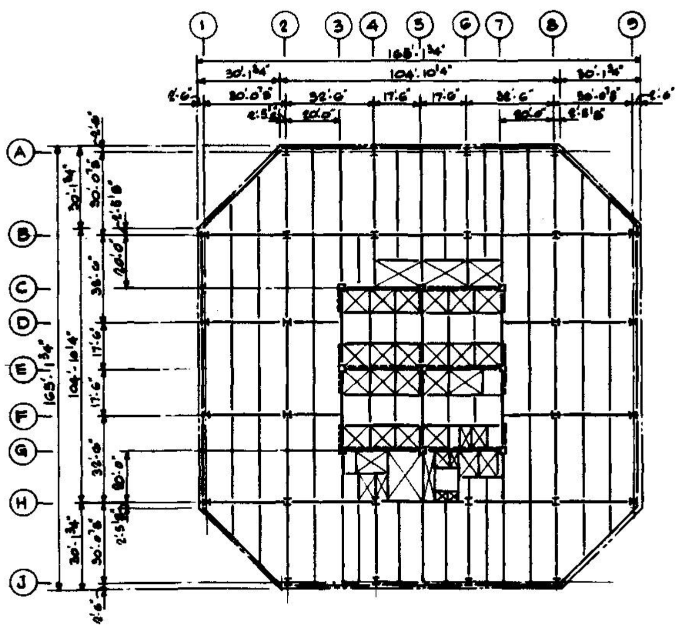

FIGURE 4 - CONTINENTAL CENTER TYPICAL FLOOR

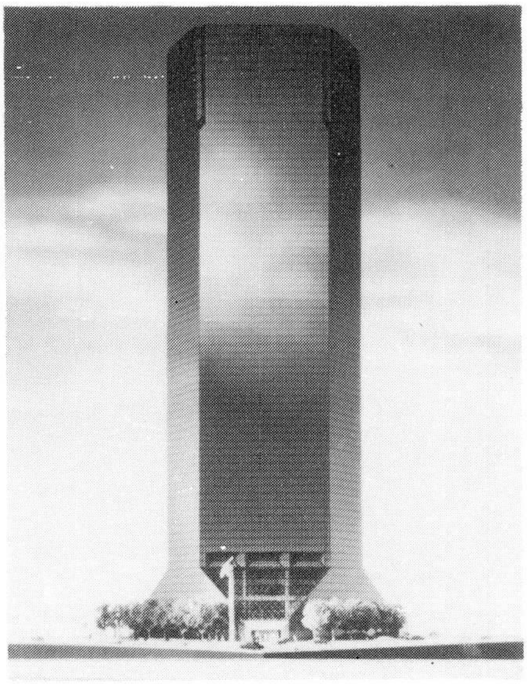

FIGURE 5 - CONTINENTAL CENTER MODEL

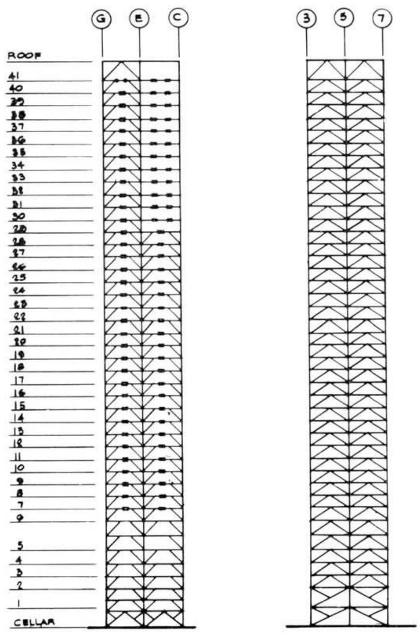


FIGURE 7 - WIND BRACING
CONTINENTAL CENTER

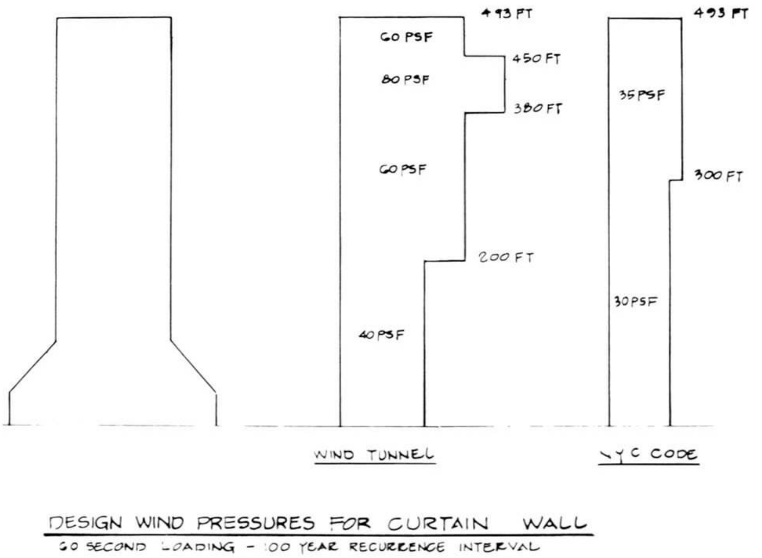


FIGURE 6 - WIND PRESSURES - CONTINENTAL CENTER

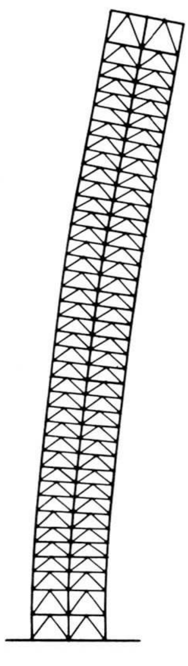

FIGURE 8 - DEFLECTED SHAPE - CONTINENTAL CENTER

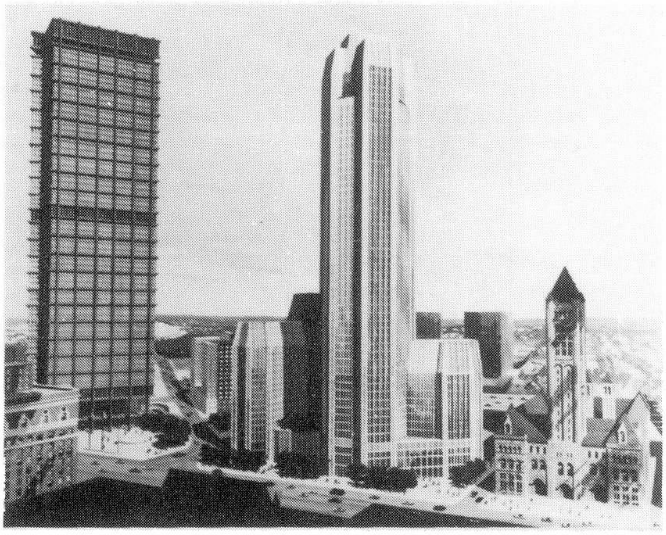

FIGURE 9 - DRAVO BUILDING

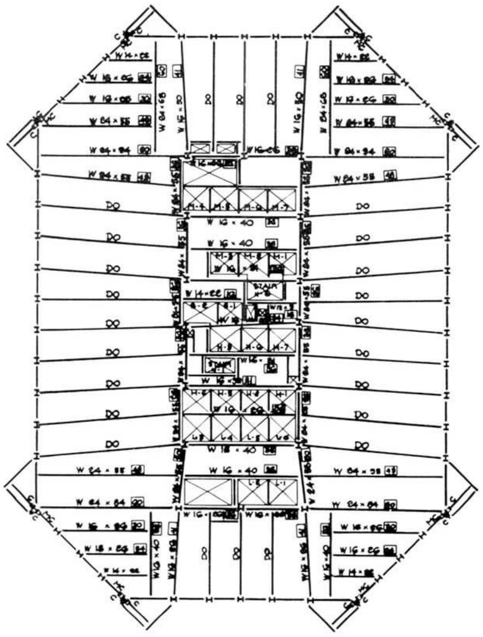

FIGURE 10 - DRAVO BUILDING TYPICAL FLOOR

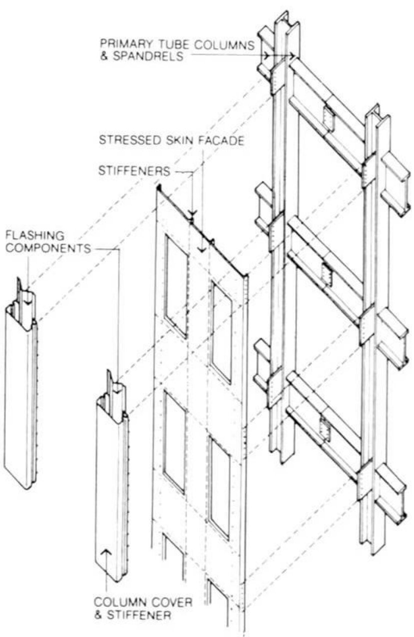


FIGURE 11 - EXTERIOR WALL SYSTEM

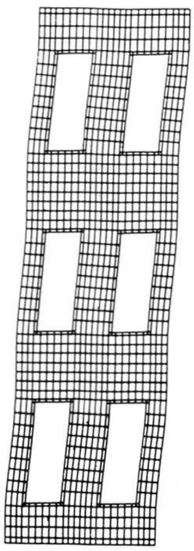

FIGURE 12 - DEFORMED SHAPE OF EXTERIOR WALL

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