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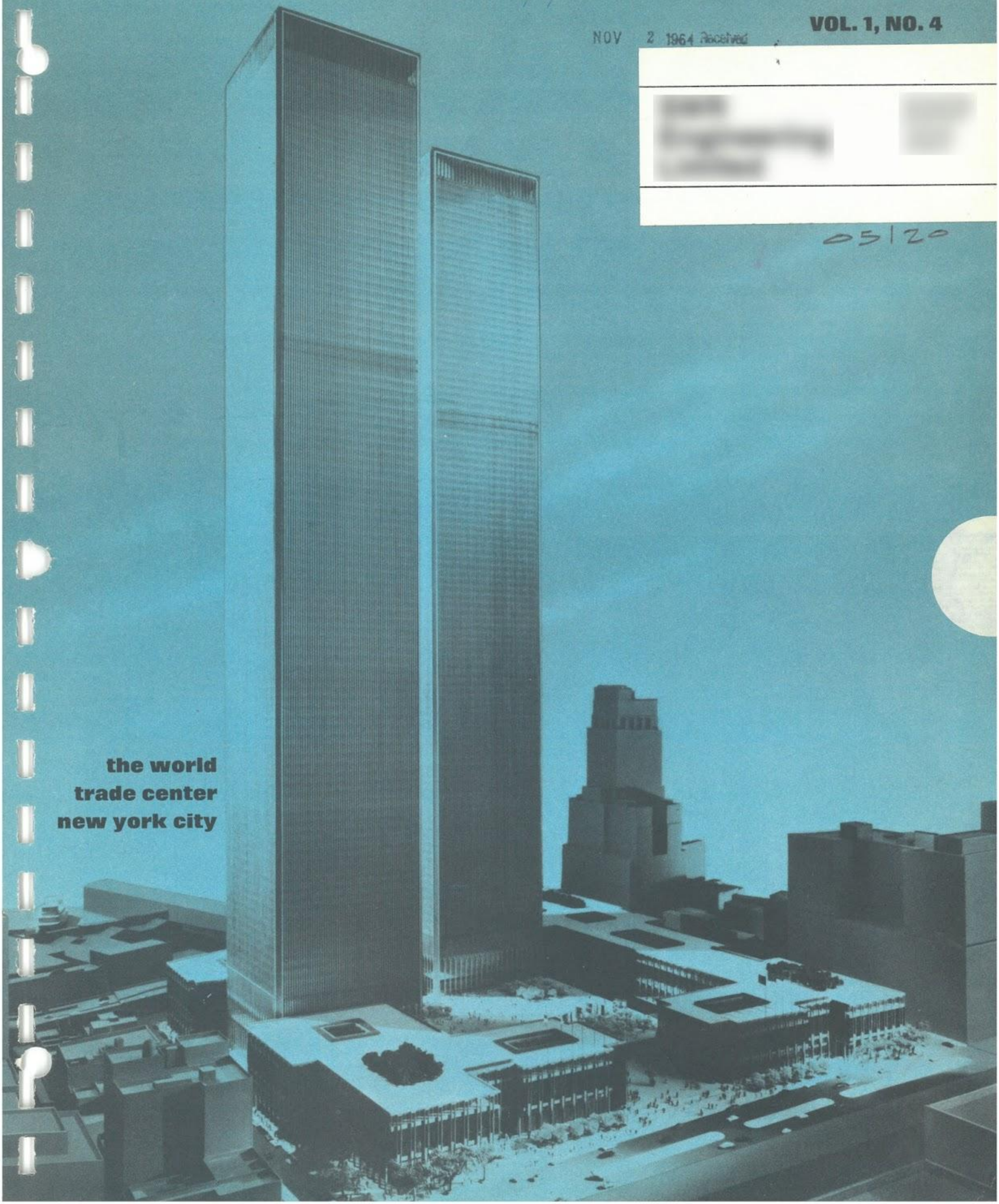


the world trade center new york city

the world trade center:

AN ARCHITECTURAL AND ENGINEERING MILESTONE

by Robert E. Rapp, P. E.

The World Trade Center, to be built by the Port of New York Authority on the lower West side of Manhattan in New York City, has been referred to by the Authority as an innovation in steel design. It may also be described as a major milestone in structural steel design. The remarkable features incorporated into the design of the towers for the Trade Center promise to set the direction and scope for a new class of high-rise buildings.

The 110-story twin towers will soar over New York City to a height of more than 1350 feet, higher than any building ever constructed. Each tower will be 209 feet square with 43,000 square feet per floor. The total rentable area for the Center will be 10,000,000 square feet.

A structural engineer receiving specifications for such a building just four years ago would have been faced with an almost impossible task. Today, however, this engineering wonder is being made possible by the engineering ingenuity of John Skilling and Leslie E. Robertson of Worthington, Skilling, Helle and Jackson, through the use of various grades of steel made available only in recent years.

Because of the specified design concepts and erection procedures, shop fabrication and field erection costs will be reduced to a minimum for a structure of this magnitude.

The towers require approximately 40 per cent less structural steel than would be required for buildings designed by more conventional methods; yet the structure has been designed to resist wind loads of 45 pounds per square foot over the entire face from the street to roof line. This is more than two times the New York City Code requirements and far in excess of the design load for any other New York City building. Likewise, there is built-in reserve strength to resist damage from an explosion or an extensive fire. This has been accomplished by continuity of construction and unique employment of high strength steels. If one area of the building becomes overstressed, the overstress is evenly distributed throughout the entire structural system. This system has enough reserve strength to withstand between 400 and 2200 per cent increase in live loads based on factors of safety from 1.8 to 5.4 respectively. Yet the weight of steel in this structural system does not exceed 37 pounds per square foot. This weight is exceptionally low for a building of this size.

This article will explain the basic engineering principles that will be employed to achieve the required aesthetic features, function, economy, speed of erection and maximum stability.

THE WORLD TRADE CENTER DESIGN TEAM

Two of the world's leading architectural firms, Minoru Yamasaki and Associates of Birmingham, Michigan, and Emery Roth & Sons of New York City, developed the plans for the World Trade Center. They were assisted by the World Trade Center Planning Division under the direction of Malcolm P. Levy, Chief, and the Port Authority Engineering Department under the direction of John M. Kyle, Chief Engineer. Also assisting them have been the consulting firms of Jaros, Baum & Bolles, mechanical engineers and Joseph R. Loring and Associates, electrical engineers, both of New York City. The structural consultants are Worthington, Skilling, Helle & Jackson of Seattle, Washington.

CONSTRUCTION OF SUPERSTRUCTURE*—The occupancy space requirements will be met by what the architects and engineers refer to as the "sky lobby" system. The "sky lobby" acts as an elevated station to change from high speed express elevators for local elevators. It is estimated that transportation time to any point in the building, including transfer, will not exceed two minutes. Likewise, the estimated maximum waiting time, even during rush hours, will not exceed two minutes.*

Comparison of elevator shaft areas to usable space areas is shown in Figure 1. There is approximately 75 per cent of the total floor area available for tenant occupancy in the "sky lobby" system compared to only 52 per cent in a more conventional design.

CONVENTIONAL: *approximately 52 per cent of total floor area available for occupancy.*

SKYLOBBY: *approximately 75 per cent of total floor area available for occupancy.*

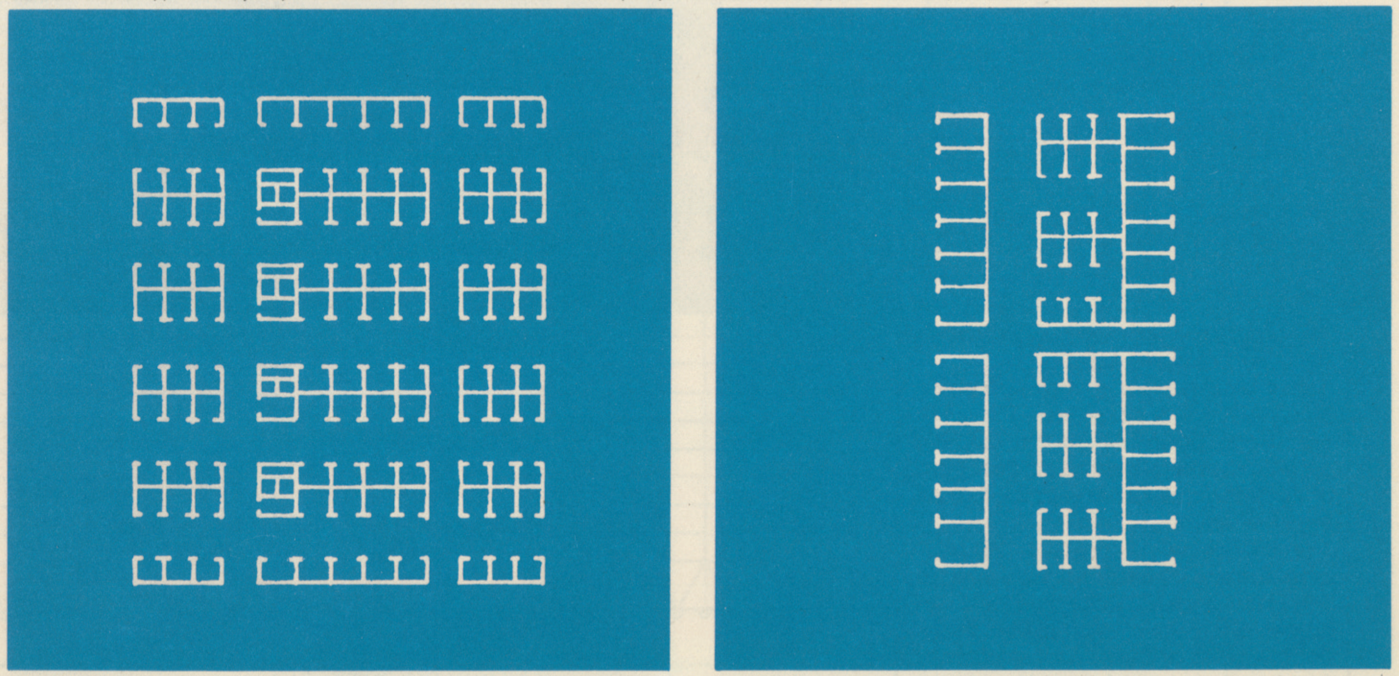


Figure 1

The occupancy floor area is completely free from interior columns.
Figure 2 illustrates a typical framing plan, for floors nine to sixteen. The building core is rectangular so that the long span truss floor system has a clear span of 60 feet on two sides and 35 feet on the other sides.
The floor system consists of 33 inch-deep trusses spanning from the core to the exterior walls. These members are spaced 3 feet-3 inches on center. Bridging is applied at 6 feet-6 inch intervals. The trusses are prefabricated in sections 13 feet wide and 35 or 60 feet long.

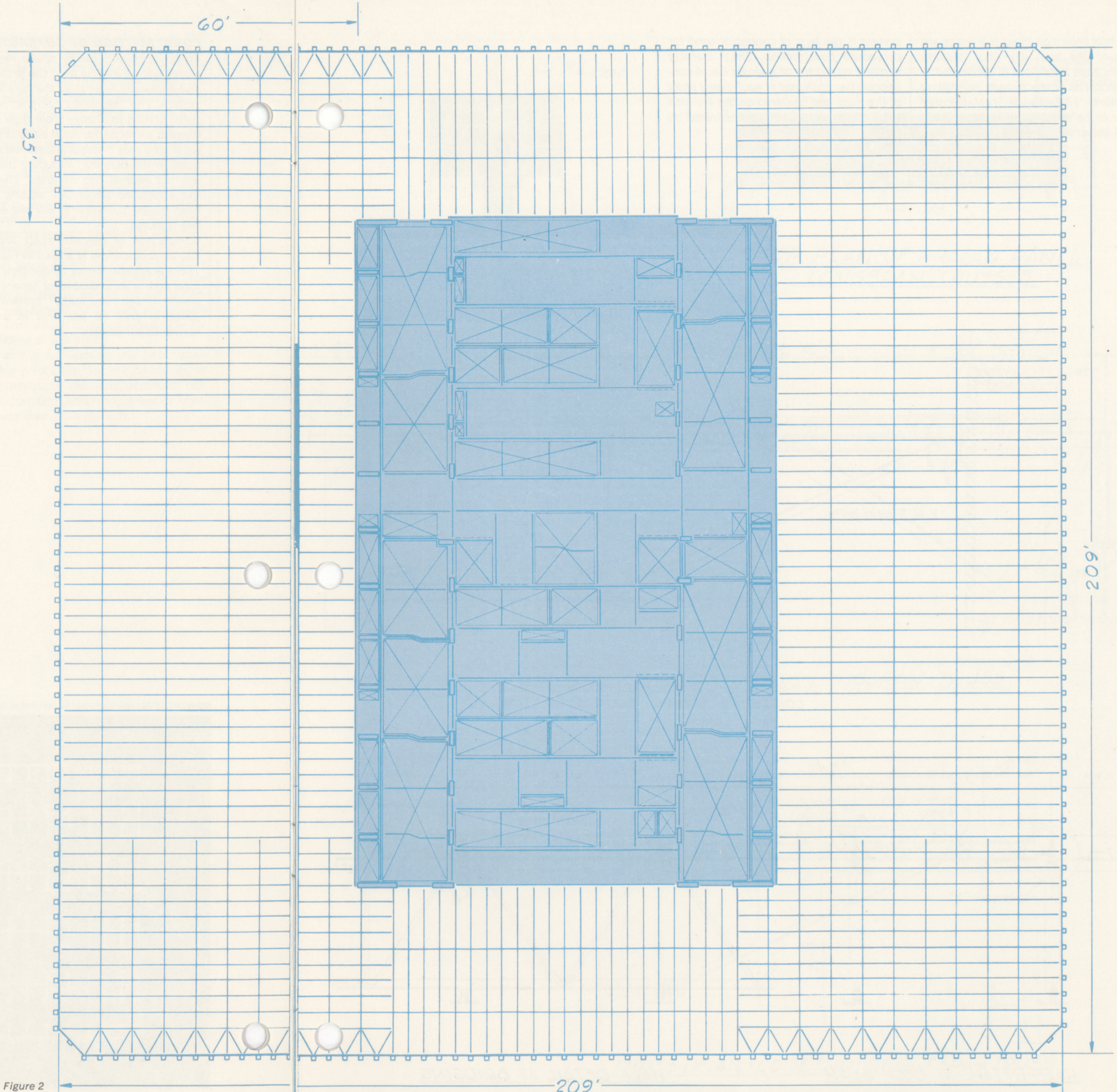
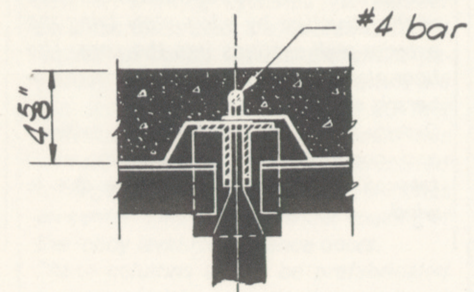


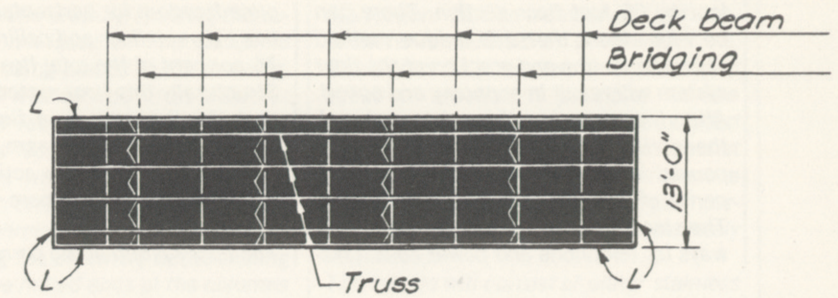
Figure 2

FRAMING PLAN

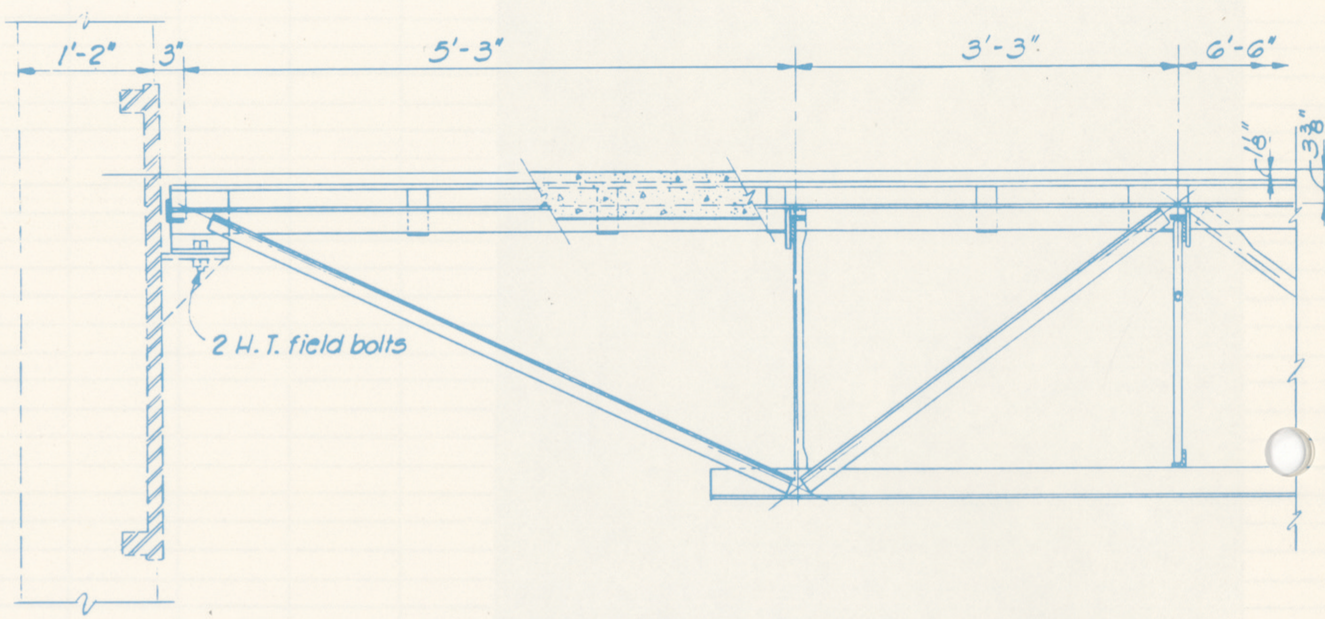
The details shown on these two pages are typical of the one way floor system. The light gage floor deck is connected to the top chords of the trusses permitting the entire 13-foot-wide prefabricated section to be erected in one operation. One of the unique features of this floor system is the type of connector used for composite construction. Shear transfer is made by means of a single No. 4 continuous bar anchored at each panel point of the truss and centered on the 4⅝ inch thick floor slab. This is illustrated in detail.



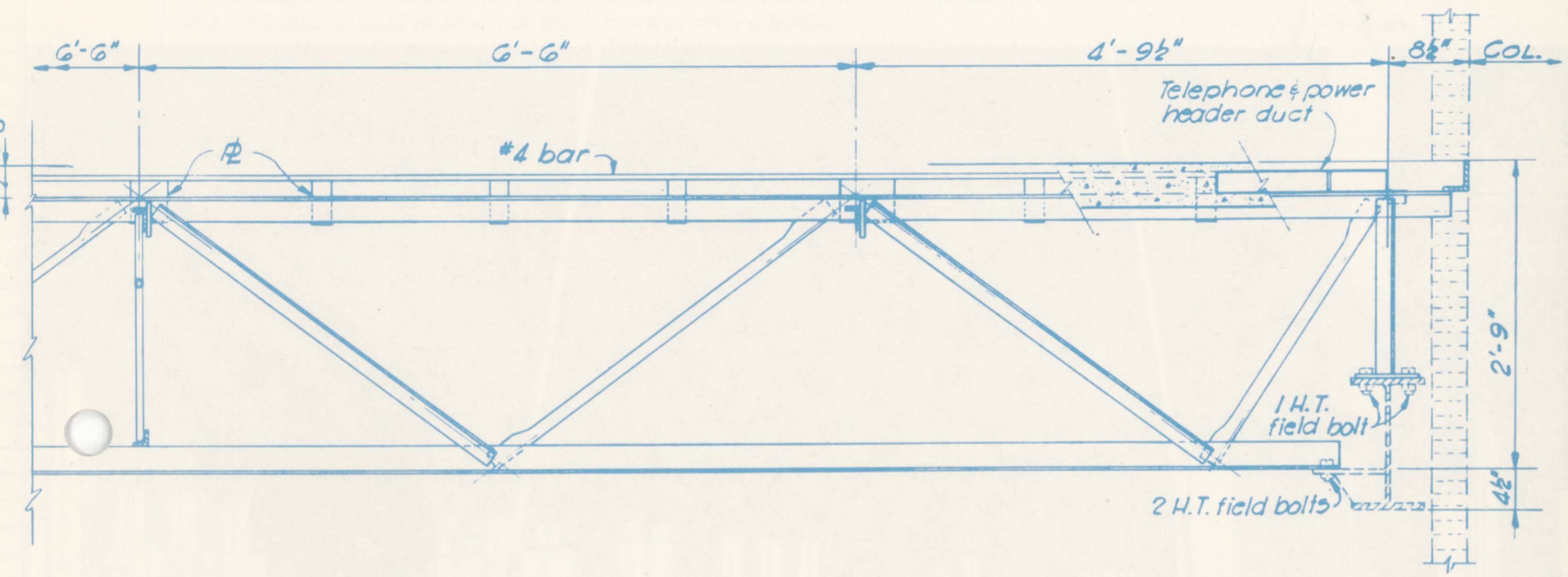
DETAIL "X"



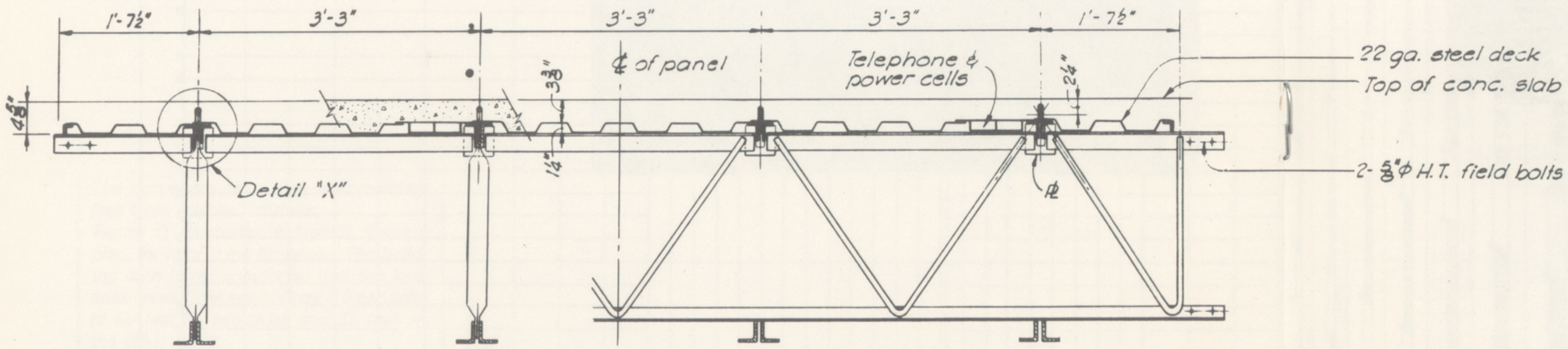
TOP PLAN OF PREFAB PANEL
LONGSPAN TRUSSES



TRUSS DETAIL · OUTSIDE WALL END
LONGSPAN SHOWN · SHORTSPAN SIMILAR



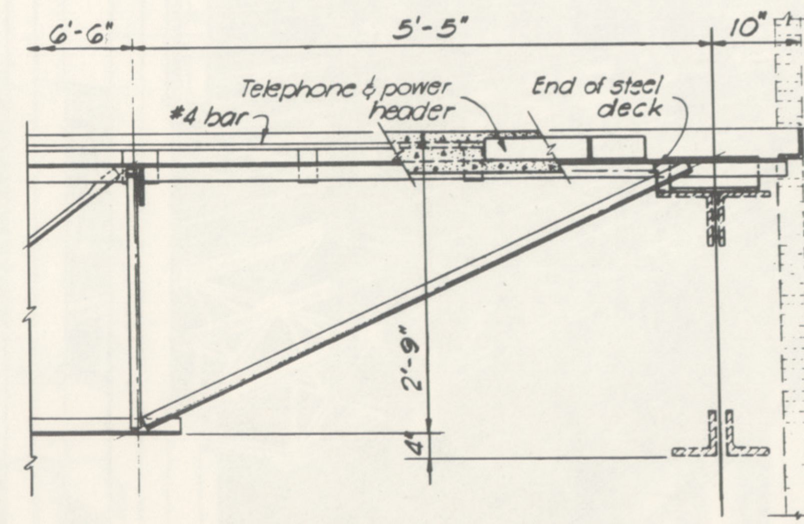
TRUSS DETAIL · CORE END · LONGSPAN TRUSS



HALF DETAIL AT DECK BEAM

HALF DETAIL AT BRIDGING

CROSS SECTION · PREFAB PANEL · ONE WAY FRAMING



TRUSS DETAIL · CORE END · SHORTSPAN TRUSS

Figure 4 illustrates the placing of a 13 foot by 60 foot floor section. There can be little doubt that this unique method of prefabrication and erection of the floor system will result in economy and speed. After these sections have been placed, the entire concrete floor deck can be poured in one operation without the expense of employing shores.

The steel deck also serves as access runways for telephone and power cells. Likewise, the open web trusses allow complete freedom for horizontal runs of utilities between floor and ceiling throughout 75 per cent of the total floor system.

Structurally this floor system acts to support the live and dead floor loads and also serves as a diaphragm, substantially stiffened by composite action, to tie the exterior columns and core at each story level.

The floor system at the corners will be reinforced by a two-way truss acting as a double layer grid. This stiffens the corners of the structure by adequately tying the exterior wall sections into the core. The floor plan showing these transverse members is shown in Figure 2.

Gravity loads are taken by the exterior and core columns. The exterior walls take all the moments and shear due to wind.

Figure 4

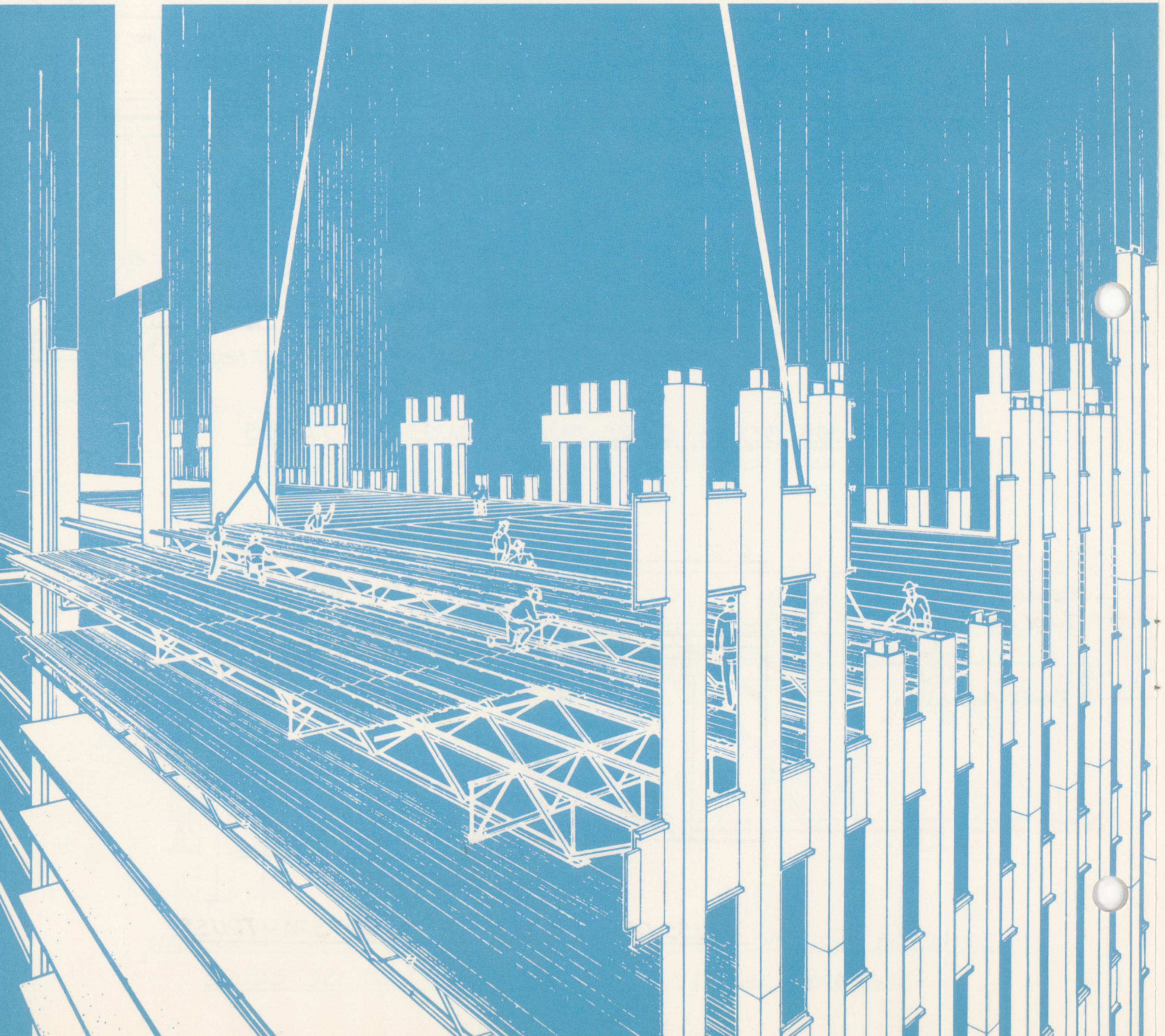


Figure 5 shows a plan and detail of the exterior framing system. The exterior columns illustrated are spaced 3 foot-3 inches on center around the entire periphery of each tower. These columns will run uninterrupted from about 80 feet above street level to the roof. Below this 80 foot level loads are to be transferred to larger columns spaced 9 feet-9 inches on center. This provides wider spacing at the lobby level for entrance doors.

These columns are to be prefabricated from steel plate using various grades of high strength steel ranging from low alloy heat treated steel with yield points up to 100,000 psi to ASTM Designation A-441 steel with a minimum yield point of 42,000 psi.

At each floor level a spandrel is provided, also fabricated of plate as shown in the elevation section in Figure 5.

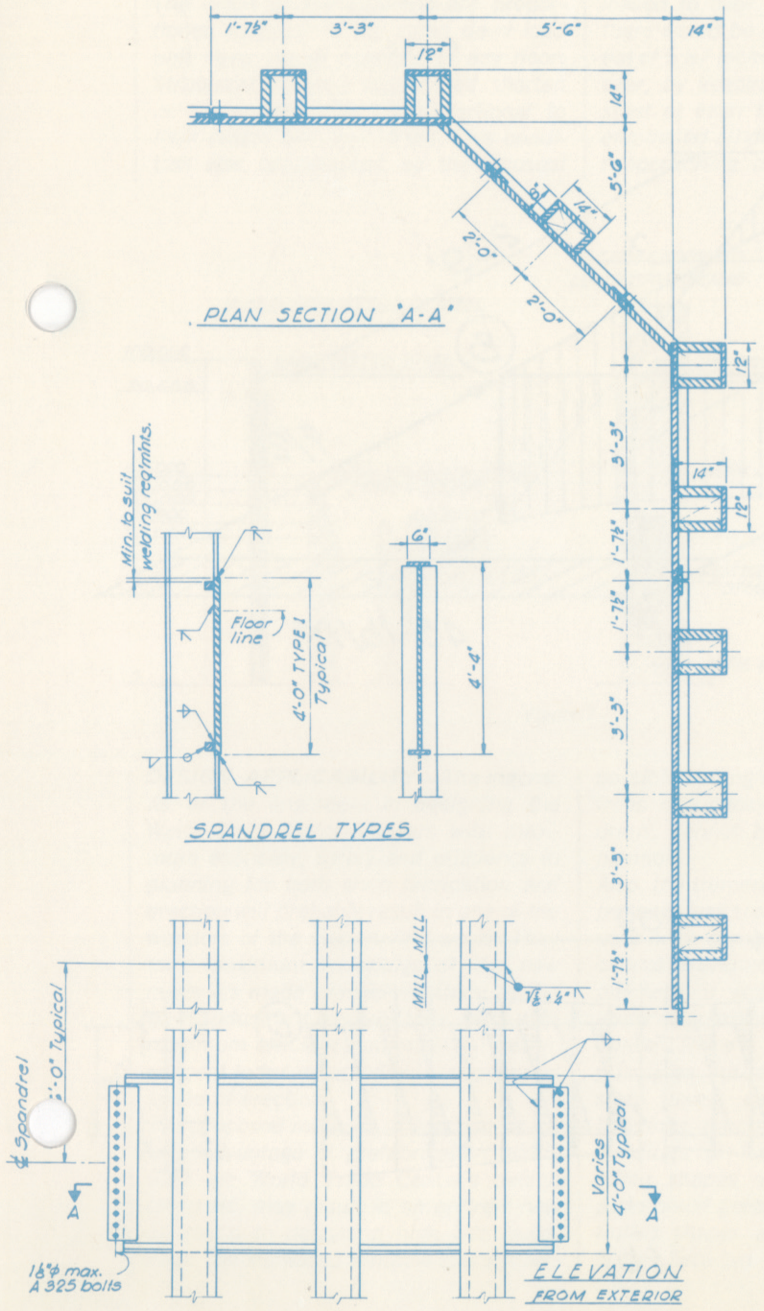
The spandrel and column sections are to be prefabricated into units as illustrated in the schematic drawing showing the exterior view in Figure 5. The complete unit, shown being placed in the drawing, will be shop welded into three modules measuring 9 feet 9 inches wide, by 24 feet (two stories) high.

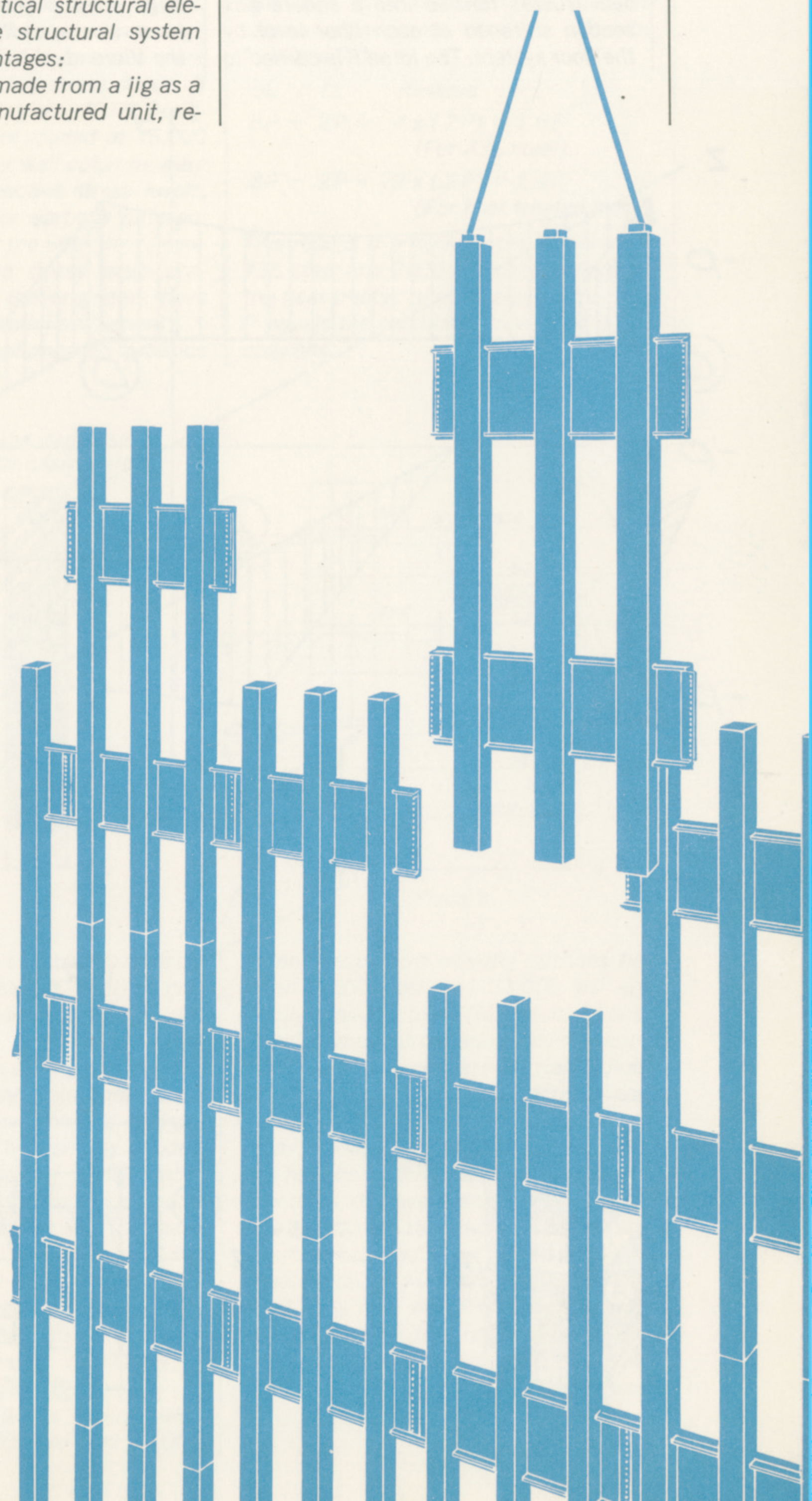
The columns will be milled simultaneously at both ends on special equipment in order to eliminate inaccuracies due to repositioning the assembly in the milling machine. The milled ends of the columns will be field welded and every third module of the spandrel will be field bolted by a splice plate as illustrated in the exterior section shown in Figure 5.

This prefabricated method of construction of the most critical structural elements of the entire structural system provides many advantages:

1. Each unit can be made from a jig as a prefabricated or manufactured unit, resulting in greatly increased speed of fabrication. 2. The number of field connections is reduced to a minimum. 3. Close erection tolerances with maximum speed of erection is possible. 4. The units serve not only as the principal load carrying members of the structure but also as a base for the facade of the entire exterior walls. Therefore, individual curtain or load bearing walls are completely eliminated.

The facade will consist of either stainless steel or aluminum.





DESIGN PRINCIPLES—Actually, the World Trade Center exterior will be a bearing wall-space frame system which offers high efficiency in resisting wind loads.

Each tower structure will act as a large cantilever beam having a square cross section measuring 209 feet. This can best be shown by the stress distribution due to wind diagrammatically illustrated in Figure 6a.

As the horizontal force F is applied to section A B C D acting on plane A B, tensile forces are applied to columns in this plane and compressive forces are applied to the columns in plane C D.

The exterior walls act as gigantic Vierendeel trusses formed into a square box section stiffened at each floor level by the floor system. The force F is carried to the corners where it is absorbed in planes A C and B D respectively. With wind in the direction shown, the exterior Vierendeel truss walls in planes A C and B D are designed to carry moments and shear to the foundation. The stress distribution in a row of columns for one floor section is illustrated in Figure 6b where each column portal is spaced 3 feet-3 inches on center. There are 300 columns per floor to analyze; with 110 floors there would be 33,000 columns per tower; therefore, the analysis of the columns was carried out by electronic computer. The floor system is not designed to carry any moments due to applied horizontal forces. The structure, then, becomes a huge internally-braced cantilever box beam where, as illustrated in Figure 6a, the Vierendeel truss walls in planes A C and B D act as web members taking shear; while the walls in planes A B and C D act as flanges to absorb compressive and tensile forces.

The maximum loads on the external columns will be relatively light for a structure of this magnitude. The 3 foot-3 inch and the 9 foot-9 inch column module will carry maximum loads of 2000 and 5800 kips respectively. However, the corner core columns at the base of the structure will carry maximum gravity loads of 25,000 kips.

The foregoing simplified illustration and explanation provides some insight into the basic design concepts employed to analyze this structure. Actually, many hundreds of pages of calculations were made and many alternate methods were considered before the plans were finalized.

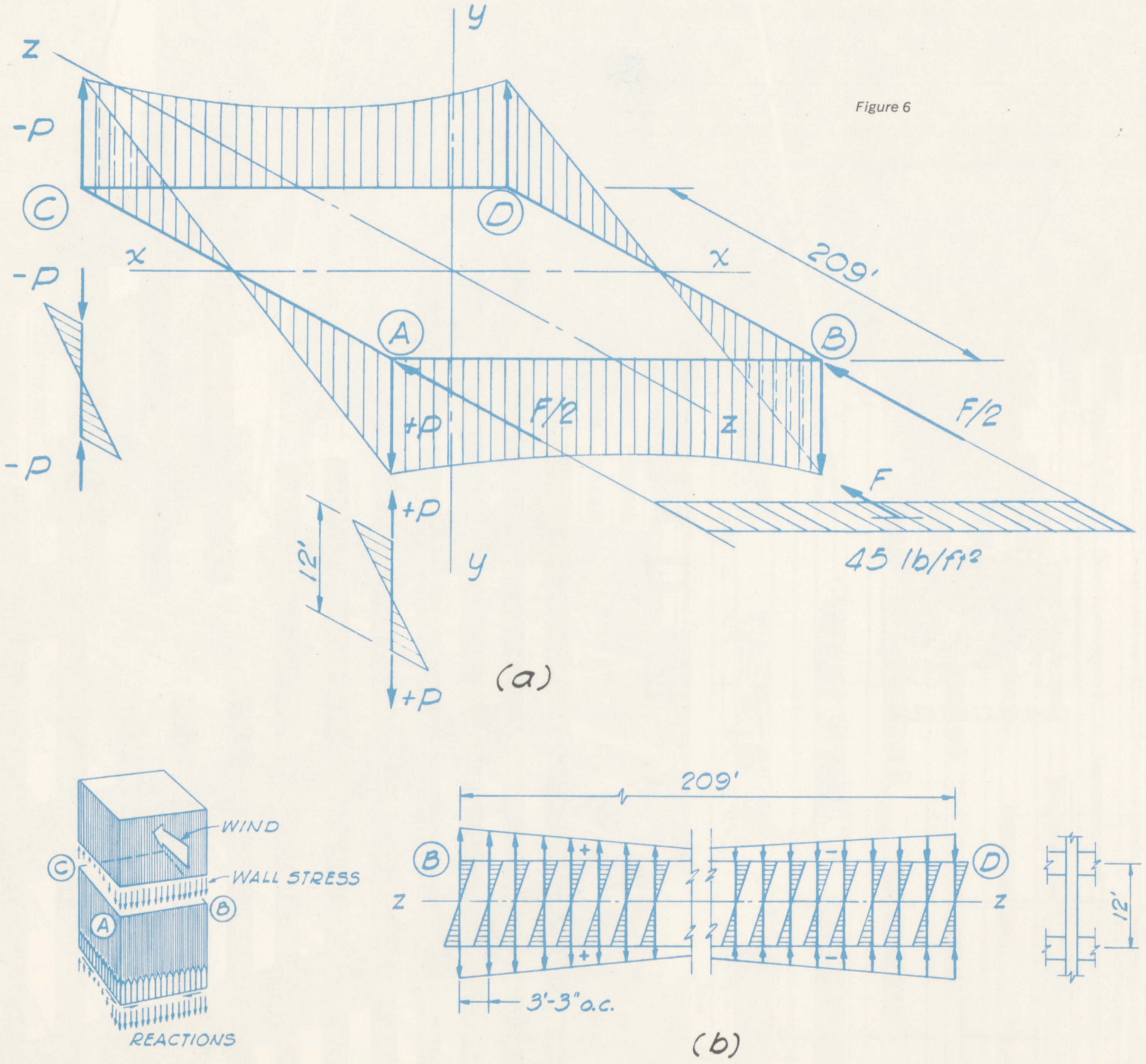


Figure 6

VARIETY OF STEELS—Another very interesting design feature in this structure is the employment of various grades of steel. All steel used in the core columns will be ASTM Designation A36. However, the steel plate to be used in the columns of the Vierendeel truss walls will include 12 different grades having yield points between 42,000 psi and 100,000 psi, with allowable working stresses as high as 45,000 psi.

Figure 7 shows the employment of high strength steels in the structure. The illustration locates the grade of steel at various levels of the structure.

The engineers made a detailed study to determine what combination of cross sectional area and grade of steel would produce the most economical and structurally sound design. The column sizes and steel grades were determined for the exterior walls of the structural system by formulae developed to produce the maximum structural efficiency and economy. The areas of the columns are proportioned to produce the same dead load unit stress in all columns at any floor. Structural columns under load shorten in an amount directly proportional to their length and unit stress. This condition was accentuated by the unusual 1400 foot long columns used in the World Trade Center structures.

The principal objective was to prevent uneven settlement throughout the structure as loads were applied. For example, columns 1400 feet long proportioned strictly on an allowable stress relationship would shorten 8 inches stressed at 15,000 psi for ASTM A36 steel. However, for heat treated low alloy steel, they would shorten 24 inches at 45,000 psi. This uneven settlement as construction proceeded would make it relatively impossible to keep the floors level. This would be a serious and costly problem to correct in a building of lesser size, let alone one of the magnitude and proportions of the World Trade Center towers. Figure 8 illustrates the uneven warpage at various stories if the columns were loaded at their working stress levels. If the core columns using only ASTM Designation A36 steel were loaded at 15,000 psi, while the exterior wall columns were loaded to their respective stress levels, there would be a floor warpage differential of 5.87 inches at the 66th floor. However, by keeping the stress levels constant at each floor the engineers have eliminated all differential settlement.

Proportioning the columns to produce the same unit stress due to gravity loads also achieved the built-in increase in safety factor mentioned earlier. The Vierendeel truss walls are utilized to distribute the stress from points of over-load to areas of strength. This reserve strength can be drawn upon should the structure suffer severe damage for any reason.

For example, an ASTM Designation A36 column at an allowable stress of 15,000 psi has a factor of safety of 1.8. A heat treated high alloy steel column stressed at 15,000 psi rather than its allowable 45,000 psi has an effective factor of safety of 5.4. Based on yield strength and assumed gravity load distribution of 80 per cent dead load and 20 per cent live load, the maximum live load increase at ultimate strength may be found as follows:

DL LL Reserve

$.8P + .2P + 4 \times (.2P) = 1.8P$ (For A36 steel).

$.8P + .2P + 22 \times (.2P) = 5.4P$ (For heat treated steel).

This results in a 400 per cent reserve for A36 steel and 2200 per cent reserve for the heat treated alloy steels. In this case, P equals the calculated axial load in the columns.

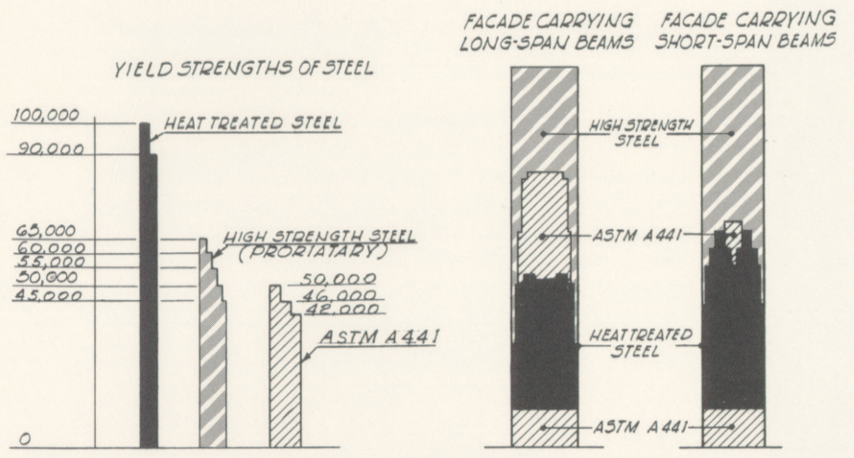


Figure 7

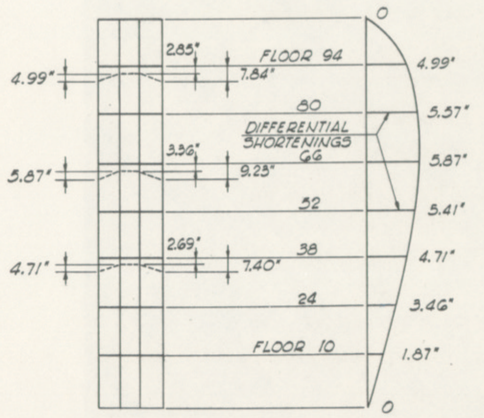


Figure 8

DESIGN APPLICABILITY—The ingenuity of the engineers in designing the World Trade Center Towers with maximum economy, safety and efficiency in planning for both shop fabrication and erection will probably result in one of the wonders of the engineering world. They took maximum advantage of the new materials made available to them by the steel industry. Likewise, they used with maximum efficiency an excellent design concept to insure stability, economy and speed of erection.

The proposed methods of erection which take advantage of prefabrication, along with the World Trade Center's design concepts, may result in an entirely new approach to designing high rise buildings. The increased rentable space made possible by long span construction, which frees occupancy areas of internal columns, cannot be overlooked by future planners.

Also, the tremendous saving in steel (40 per cent less steel than would have been used with a more conventional design) cannot be overlooked by economy-minded planners of structures of considerably lesser proportions than the World Trade Center. There is no reason why the same principles utilized to design these 110-story towers cannot be employed for buildings much lower in elevation. In buildings of less magnitude, ordinary rolled shapes or shapes fabricated of plate could probably be used.

Rolled shapes and plates having yield points between 36,000 psi and 50,000 psi and respective working stresses between 22,000 psi and 33,000 psi are readily available to ASTM Specifications. Likewise, many proprietary rolled shapes and plates are available with yield points of 45,000, 50,000, 55,000, 60,000 and 65,000 psi.

Today, the engineer designing steel buildings has the materials and tools to create structures that were considered impossible even in the recent past. The revised specification and new structural materials provide him with passport and ticket to a new world of structural design—a world to be explored as the engineers of the World Trade Center have, with careful efficiency and bold imagination.

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