Design Solutions Utilizing the Staggered-steel Truss System

MICHAEL P. COHEN

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During the conceptual design stages of most building projects, the structural engineer must consider many different factors before selecting the final structural system. While some basic building properties such as height, shape, usage, etc. lead the structural designer toward certain proven systems, it is not infrequent that architectural constraints, owner requirements and/or building location render these systems unacceptable. Other factors which enter into the selection process include: local economic conditions (both of materials and labor), construction schedule, design loads (vertical and lateral), building behavior and occupant comfort, foundation considerations and coordination with mechanical systems. While these general considerations are required on all projects, each specific building usually presents the designer with an additional set of its own unique problems.

This paper outlines the conceptual design and selection process by which the staggered-truss system of structural framing was selected for one particular project. The subsequent design process encountered problems, and their associated resolutions are also reviewed.

CONCEPTUAL DESIGN AND SYSTEM SELECTION

At the start of design, the following parameters were immediately defined: The building was to be a high-rise, luxury hotel located on the oceanfront in Atlantic City, N.J. Designed around a double-loaded center corridor, the width would be approximately 70 ft. An Atlantic City zoning ordinance limited the height of the building to about 420 ft. The lower four floors would be public spaces, their elevations coinciding with those of an adjacent low-rise convention facility to be built around the base of the tower.

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The remaining upper floors would be guest room levels. The total number of rooms required by the owner was about 1,200. Given the luxury hotel status with 24-hour occupancy and the oceanfront wind exposure, occupant comfort (i.e., building drift and acceleration) was of prime concern from the beginning.

Geotechnical investigation at the site determined that subsoil was made up of three distinct sand layers separated by two relatively thin, clay layers. The project soils engineers determined that under anticipated column loads in excess of 11,000 kips, the clay layers would experience excessive consolidation, resulting in unacceptable building settlements. The foundation, therefore, was to be deep piling penetrating through the clay layers and bearing in the deepest, dense sand layer located about 90 ft below grade.

Minimum design loads for the structure were governed by the BOCA *Basic National Building Code*, which is New Jersey's Building Code. Typical live loads of 40 psf for guest rooms and 100 psf for corridors and lobbies were applied. Live loads in the public spaces at the lower levels were, however, increased to 150 psf to account for special uses and large assemblies possible at a convention and casino facility of this type. A question was raised as to whether lateral wind loads, as outlined by BOCA, would have to be modified to account for the building's unusually exposed location in an open coastal region. The design team (owner, architect and engineer) decided to have wind-tunnel testing conducted to confirm lateral design loads, measure building response, determine cladding pressures and study effects on pedestrian traffic at the building base.

A preliminary design analysis and subsequent cost study was made of four basic structural systems. Starting with the 1,000+ rooms as a requirement, building dimensions of each of the systems were varied to optimize each structural system. These systems were (see Fig. 1):

1. **Steel: Staggered Truss**—A basic steel building frame with concrete floor system.

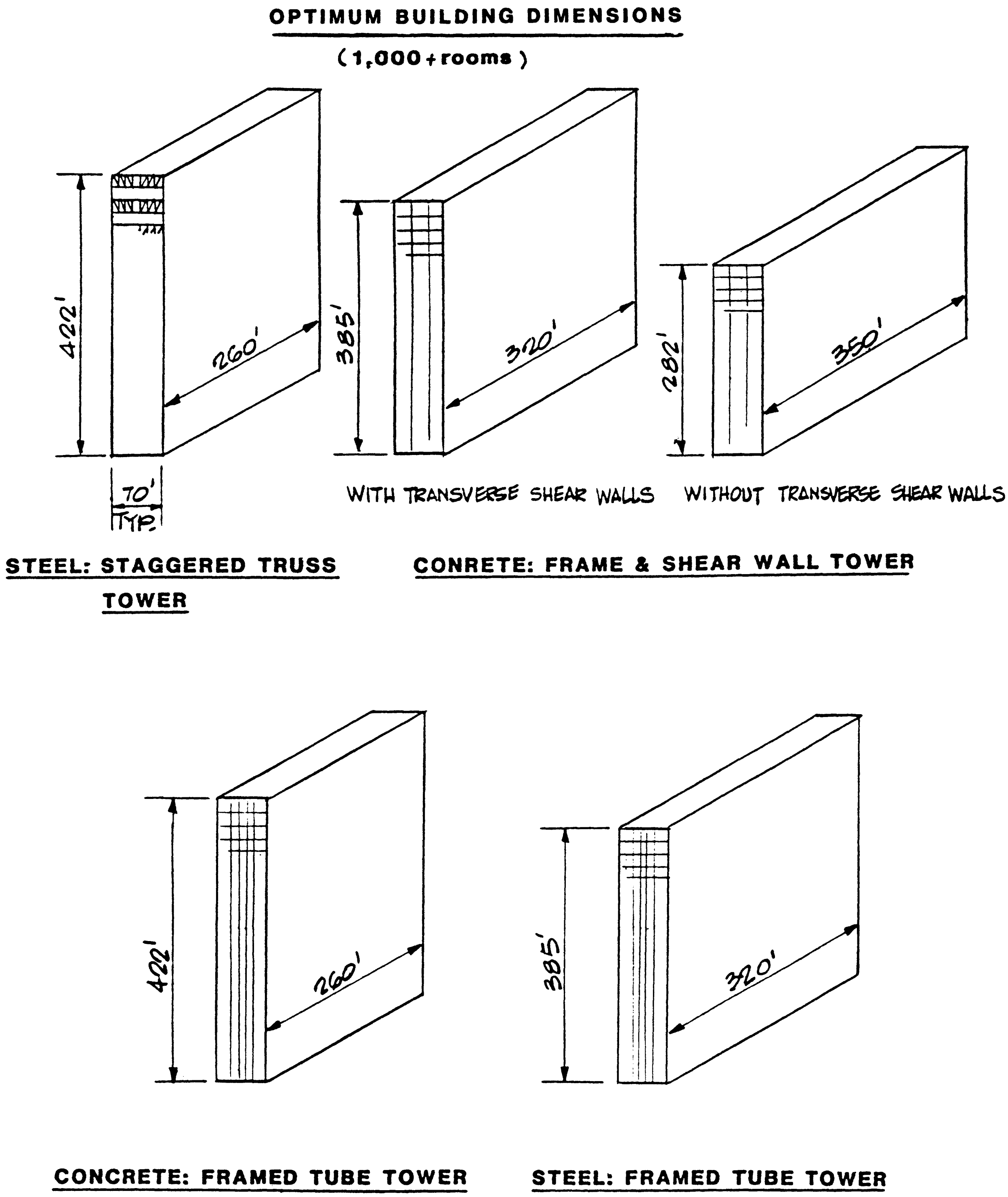

OPTIMUM BUILDING DIMENSIONS
(1,000+rooms)
422'
260'
70'
TYP.
385'
320'
282'
350'
WITH TRANSVERSE SHEAR WALLS
WITHOUT TRANSVERSE SHEAR WALLS
STEEL: STAGGERED TRUSS TOWER
CONRETE: FRAME & SHEAR WALL TOWER
422'
260'
385'
320'
CONCRETE: FRAMED TUBE TOWER
STEEL: FRAMED TUBE TOWER

Figure 1

2. **Concrete: Frame and shear wall**—This system was a combination of shear walls and frames to resist lateral wind loads. Two schemes of this type were considered, one with shear walls at the central elevator core only and the other with additional transverse shear walls.
3. **Concrete: Framed Tube**—This consisted of rigid concrete frames with closely spaced columns in combination with shear walls at the central elevator core.
4. **Steel: Framed Tube**—This system utilized rigid steel frames with closely spaced columns in combination with shear walls at the central elevator core.

The preliminary analysis confirmed the structure's relatively high height/width ratio of about 6.0 controlled the design. All of the schemes, except the staggered truss, required relatively large shear walls to control drift. Aside from the negative architectural implications, a large price is paid for these heavy walls in the foundation. The total concrete schemes had substantially higher foundation costs, were more labor intensive and thus had longer construction time. Resistance to overturning and the resulting uplift force was a problem for the steel-framed tube scheme. The structural unit costs per square foot of building area, on a relative basis, were determined to have been as follows:

1. Steel staggered-truss	1.0
2. Concrete frame to shear wall	1.25
3. Concrete-framed tube	1.10
4. Steel-framed tube	1.40

From this study, it became apparent the staggered-truss system was the most economical choice for this particular project. Construction time for this system was anticipated to be among the fastest with the smallest foundation of the group and the relatively fast erection inherent in the staggered truss (shop fabricated) system. Architectural benefits included the elimination of all shear walls and the large, column-free spaces provided at the public levels. Considering all of the above, the decision was made to proceed with the design of the steel staggered truss tower.

THE STAGGERED-TRUSS SYSTEM

The staggered-truss framing system was developed by a USS-sponsored research team working at Massachusetts Institute of Technology in the mid 1960s. The object of the study was to arrive at a new, efficient, structural steel system which would also provide architectural benefits. The result was the staggered-truss system which has since been used typically in a variety of mid-rise (15- to 20-story) hotel/motel and housing structures. While the initial study envisioned buildings of greater height, it is only recently the design and construction of staggered-truss, high-rise buildings greater than 30 stories has been realized.

The basic element of the staggered-truss system is the story-deep truss which spans the full transverse width of the building at alternate floors on each column line. These trusses are supported only at their ends on the two longitudinal rows of exterior columns and are arranged in a staggered pattern on adjacent column lines. The gravity loads are delivered to the truss from the floor slab system which spans from the top chord of one truss to the bottom chord of its adjacent truss. Therefore, each truss is loaded at its top and bottom chord and the total gravity load of the building is transferred to the building's exterior columns.

The main structural benefit and subsequent efficiency is in the system's resistance to lateral loads acting parallel to the trusses. In long, narrow rectangular buildings of this type, lateral resistance in the transverse direction is often a problem since the wind forces developed on the large face of the building are substantial and must be resisted by the smaller building dimension or weak axis. The inherent benefit of the staggered truss system is that the entire building weight is mobilized in resisting the overturning moment. The large gravity loads on the exterior columns are often sufficient to counteract the uplift due to wind.

Lateral forces are transmitted through the floor, acting as a diaphragm or deep beam, to the top chord of an adjacent truss. The force is then transferred down between floors through the truss web members, with the truss acting as a shear wall. Once at the lower chord, the load cannot continue straight down because there is no truss immediately below (no stiffness) and so the load must once again be transferred through the floor system to the top chord of the adjacent trusses. In this manner, lateral forces are transferred back and forth all the way down to the lateral resisting system at the building base.

Since the trusses have been sized to carry two floors of building gravity loads and span the entire building width, their member sizes are often sufficient to provide the required lateral stiffness and, due to the one-third increase in allowable stresses, may not have to be increased in weight for the wind forces.

The floor system is an element critical to the proper functioning of the staggered-truss system. As noted above, the floor must function as a shear diaphragm to resist lateral loads. A truss at any level carries the cumulative lateral load from the total building above over a two-bay width. The floor area on each side of the truss must transfer half of this load to the top chord of the adjacent truss in the story below. The floor system must be designed to provide sufficient in-plane diaphragm strength and stiffness to sustain these horizontal forces as well as gravity loads.

Since the flow of the transverse lateral loads is strictly through the trusses and the floor system, there is no bending of the building columns in the transverse direction. Drift of the structure in this direction is solely a function of the slab and truss stiffnesses and the column cross-sectional areas. It is advantageous, therefore, to orient the columns with their weak axis parallel to the longitudinal direction. In this manner the columns (bending in their strong axis) can be rigidly attached to the spandrel beams to create portal frames to resist lateral loads in the longitudinal direction.

The staggered-truss system is a relatively new structural concept based on the sound principle of using the same structural elements to resist gravity and lateral loading. It has been proven to be very efficient and, where conditions are proper to warrant its use, can yield the most economical and architecturally flexible structure possible.

DESIGN APPLICATION

Once the decision was made to proceed with the staggered-truss design, the building dimensions were finalized. Preliminary gravity analysis indicated the chord members could consist of large W10 shapes. Combined with the assumed floor system depth of 8 in., a typical floor-to-floor height of 8′-10″ was determined to be the smallest practicable. Accordingly, to accommodate the required number of hotel rooms, the overall number of floors and building dimensions were fixed. The building would be comprised of four public floors, 38 guest room floors, an attic space and a high roof level. The building length is 350 ft and the main width is 68 ft, with projections at the elevator core (see Fig. 2). The height from grade to the high roof is approximately 420 ft.

With the geometrical information and a preliminary idea of the building's dynamic properties, a wind tunnel study was conducted. The building, as well as its local surroundings (including possible future buildings) was modeled and monitored through the series of tests. Both a pressure model, used to measure local wind pressures and a dynamic model to study building response were used (see Fig. 3). The results of these tests helped establish design wind loads which were used in the final design. A modified BOCA code wind was established in each direction which produced wind shears, moments, and torsional effects equivalent to those indicated by the wind study. Average wind forces in the transverse direction exceeded 50 psf.

One of the first and most critical design steps was the selection and design of the floor system. A typical and efficient system used in previous staggered-truss buildings is a hollow-core, precast concrete plank with a thin cast-in-place concrete topping. It was readily apparent, in this case, the combination of the building height and the high wind forces were resulting in slab shears through much of the lower part of the building which would exceed the capacity of such a hollow plank system. After study of several alternate schemes, a solid composite, concrete-slab system was chosen. The system is a precast prestressed solid concrete slab with a cast-in-place topping. The precast units have a roughened top surface and extended horizontal ties which insure bond with the cast-in-place concrete topping. The net result is a solid, composite concrete slab which spans the building's typical 30-ft bay.

At the lower floors, with the large public live loads and high wind shears, a 12-in. total slab thickness was used. The typical hotel floors employed an 8-in. thick slab. The profile of the precast panel varies from about 3-in. thick at the ends

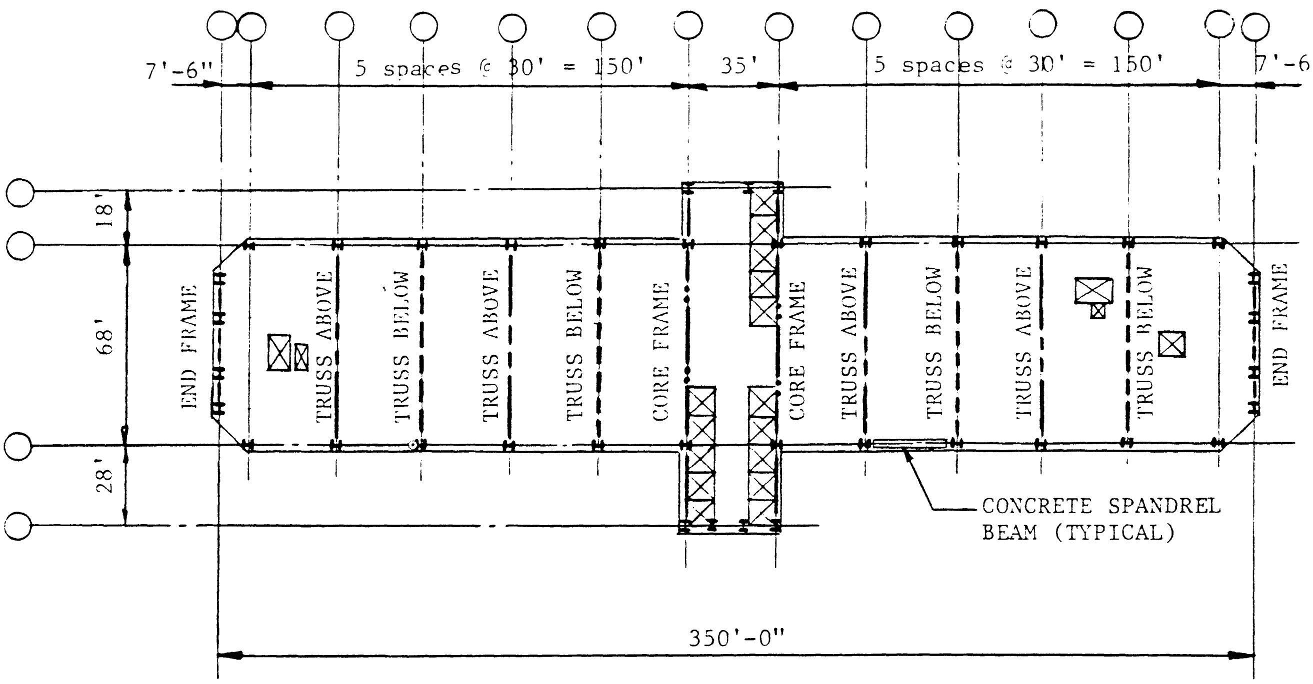
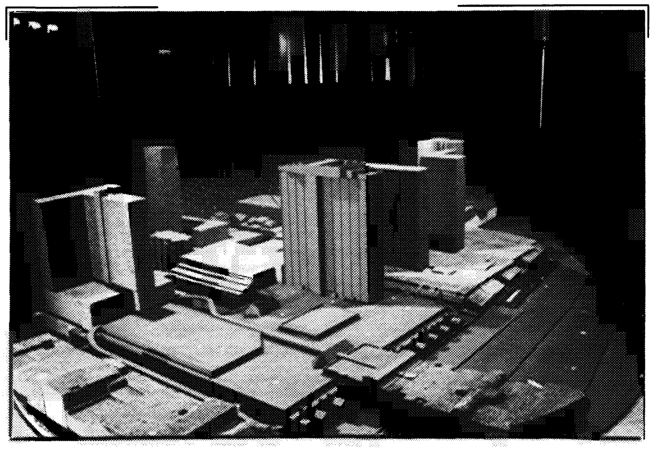
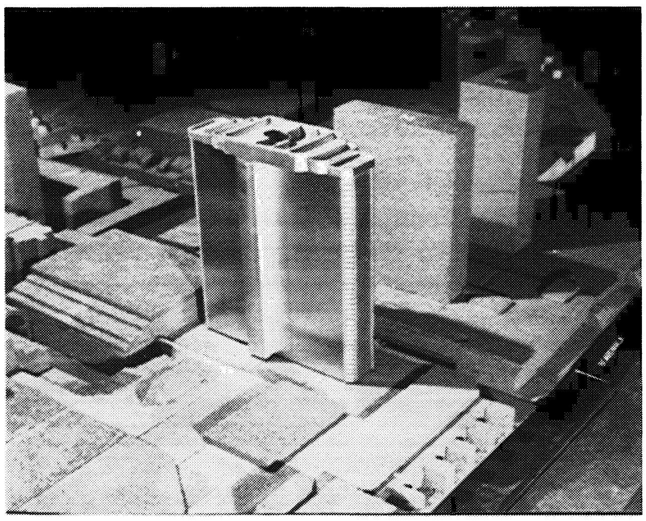


Fig. 2. Typical floor plan



PRESSURE MODEL



DYNAMIC MODEL

Fig. 3. Completed wind tunnel models

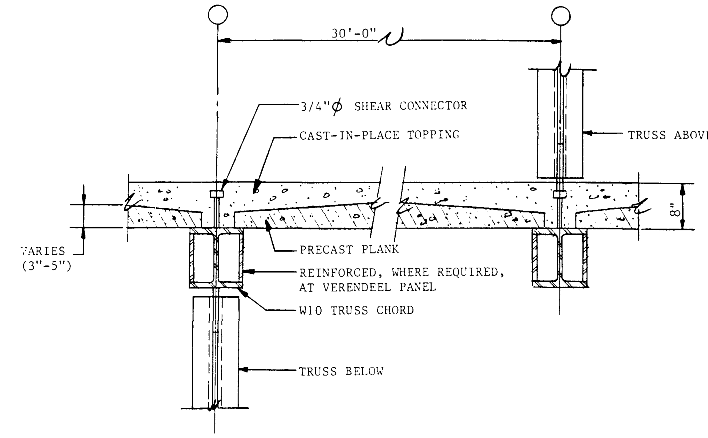


Fig. 4A. Typical bay section

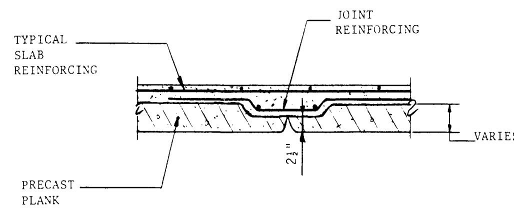


Fig. 4B. Plank joint detail

to 5-in. thick in the middle (Fig. 4a). With the resulting section properties, the panel is capable of spanning the 30-ft bay unshored until, just prior to casting the concrete topping, a minimal amount of shoring was applied to carry the wet concrete weight. This method greatly aided the erection process, since the trusses were able to be erected and the plank simply laid in place and erection bolted to the trusses. This requirement for minimal shoring meant several floors could be erected without depending on the completion of the floor below to serve as a shoring base.

The tapered plank ends over the truss chords provided a further structural benefit. Since the horizontal shears being carried down the building through the trusses are transferred through the slab, the point of transfer between the two elements is critical. In this case, ¾-in. dia. shear connectors welded to the top of the truss chord and embedded in the slab are used for this transfer. The detail of the tapered plank on both sides of the shear studs results in a large area of cast-in-place concrete at this point, ensuring proper embedment and aiding in the shear transfer process.

Architectural and other disciplinary restraints prevented the typical staggered truss bent from being used on all column lines. Accordingly, three types of framing were employed: the typical staggered truss, a core frame and an end frame (Fig. 5).

The building's typical transverse column lines consist of the basic staggered-truss framing system. Lowest of the trusses is at the first or second level, with remaining trusses at every alternate floor from there up. The top guest room floor (42nd) was to have provisions for large, open luxury suites, so all trusses were omitted there. The cumulative wind shear is so low at this high level that only the core and end frames were required to resist the wind. At the roof level, trusses of varying heights cantilever over the main

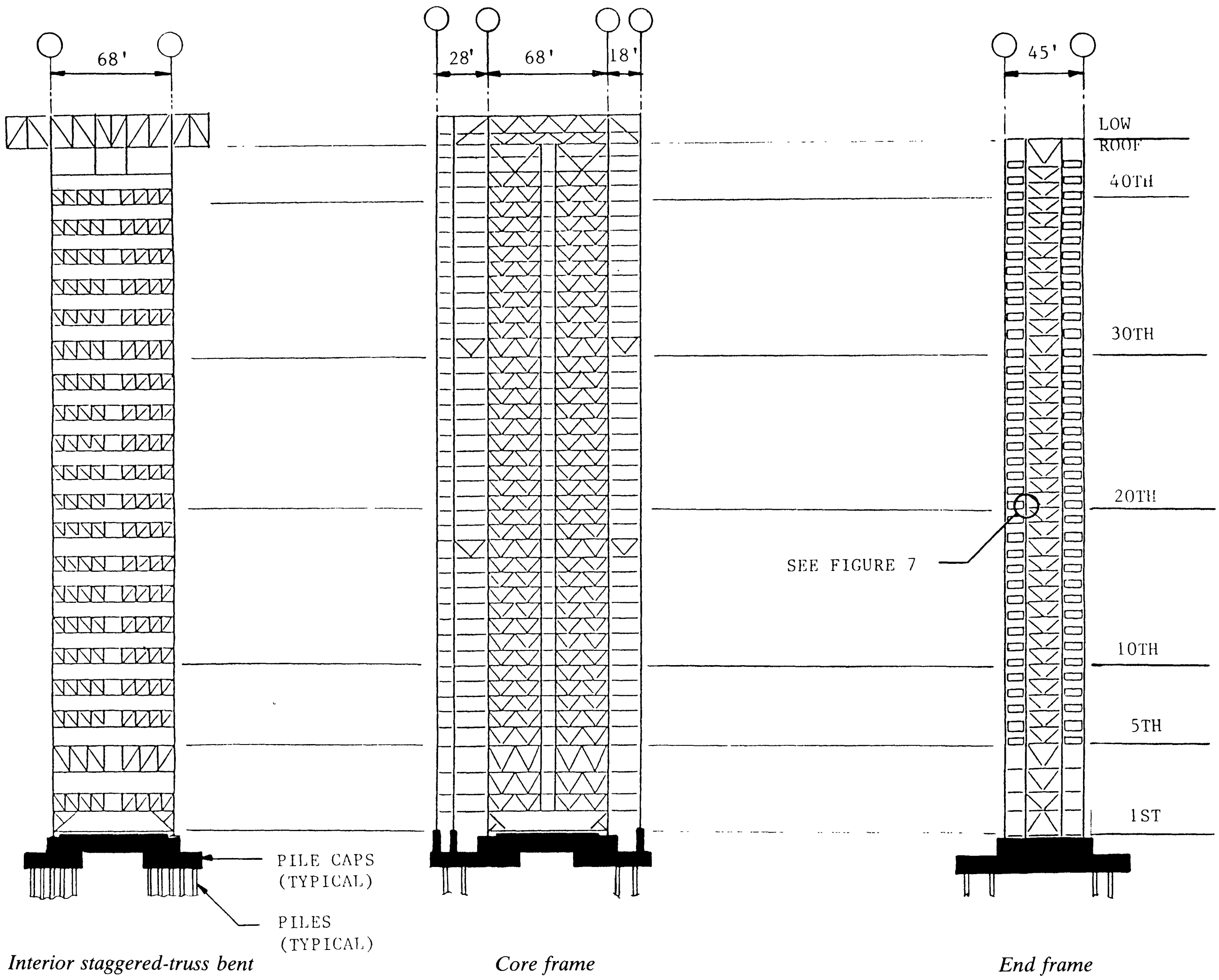


Figure 5

building line to provide for the distinctive roof crown of the architectural design.

At the base of the building, the cumulative total of the wind shear is brought into the foundation by embedding the bottom chord of the lowest truss in a large concrete grade beam. This beam and truss connects the pile caps on opposite sides of the building. In order to distribute the lateral load evenly between all the building bays at the base, diagonal braces were added at those column lines where no truss exists at the lowest level. The diagonal braces transfer the alternate bay's lateral load down to a steel beam embedded in the foundation, similar to the adjacent truss bottom chord.

Foundation piles are 165-ton capacity, 14-in. diameter, steel shell, mandrel-driven cast-in-place concrete filled. A pile cap at the typical staggered-truss bays contains 36 piles and is 25 ft $\times$ 25 ft $\times$ 8 ft deep. The lateral capacity of the piles and cap system is sufficient to resist the applied wind shears.

Architectural features, corner balconies and fenestration, prevented use of the typical staggered truss in the two end bays of the building. However, torsional motion of such a long, thin building, called for the creation of stiff lateral resisting elements at the ends of the structure. To provide this stiff end, a 3-bay braced frame was introduced. The center bay of this 3-bay frame is diagonally braced with steel channels and then rigidly connected to deep, stiff, spandrel beams on each side connected to large columns. These end frames are short (45 ft) compared to the 68-ft span of the staggered truss, and once made stiff enough to attract their required share of the load, exterior columns experience a substantial amount of uplift. To resist this uplift, columns are embedded into the foundation which consists of one large pile cap. This 100-ft long cap spans the width of the building and encases 110 piles. The large resulting moment arm of this long pile cap reduces the net uplift on the end piles to a minimal amount.

The center bay of the building, which contains the elevator core, presented another series of problems. Ten passenger and five service elevators would properly service this luxury hotel. The associated elevator shaft openings, in addition to other slab openings required for mechanical ducts, reduced to a fraction of its capacity the slab diaphragm so critical to the staggered-truss system. On one side of the core, the slab necked down to a thin 14-ft width through which all of the lateral shear would have to be transferred. At the lower floors, this proved extremely difficult. Several attempts were made to substantially reinforce this area, but this proved to be unfeasible.

A modification of the typical staggered-truss bent was required to solve the problem of the concentration of shear in this area. The resulting so-called core frame consists of a similar type truss spanning across the building width. In the core, however, a truss is located at each floor level. Trusses at each level produce a lateral system of similar stiffness to that of the staggered truss, however, the presence of a lateral resisting element at each level means that shears which enter the system do not have to be transferred out. Therefore, the shears which must be transferred through the core slab are not the cumulative total of the shear over the building height but simply the shear of one story. Even the relatively small area of core slab remaining can easily carry this shear. Several of the trusses in the core at intermediate levels and at the roof were extended out to the elevator wings. By using these as belt and hat trusses, the building columns furthest apart are mobilized to give additional stiffness to these core frames.

Once the exact configurations of the transverse frames were determined, computer models of them were generated. The various systems were linked together, and the design loads applied. From this analysis of the relative stiffnesses of the various elements, a more accurate determination of the shear flow through the slabs and into the trusses was arrived at. Combining this analysis with the relatively simple gravity analysis, the final design of the trusses was completed. In the typical staggered truss bent, the trusses at the lower public floors and at the roof were each specifically designed. To help achieve economy of fabrication, detail and erection, the trusses through the middle 30 floors of the building were designed and detailed into only three different types covering 10 floors each. The core and end frames were designed in a similar manner so as to achieve a similar degree of economy through repetition of units. The core frame, with its solid wall of trusses, was detailed to result in an erection sequence similar to the typical staggered truss. This was done by having the trusses on every alternate level shop assembled as were the typical staggered trusses. After these were erected, the web members of the intermediate levels were infilled in the field.

Results of the computer analysis of the traverse lateral loading was used for the final design of the floor system. Using a similar theory to that of the truss designs, the slabs were designed in groups consisting of the twelve-inch thick slabs of the lower floors and three separate designs of ten floors each for the eight-inch thick slabs of the typical hotel floors. Gravity loads were added to the critical wind loads at each design level and the resulting stresses were checked and the slabs reinforced as required. The typical slab bay throughout the hotel floors includes several duct and pipe openings at the center of the 30-ft span where bathrooms of back-to-back rooms meet. In addition, there are openings at the corners adjacent to the spandrels and the exterior columns. It has been proven that slab stresses are highest at openings and at the corners. Thus, considering the slab openings of this building, an in-depth study of this typical bay was warranted. Therefore, a detailed finite-element computer model and stress analysis was made of this bay. The results of this analysis were used in the final detailing of the slab system. Reinforcing quantities and patterns were determined at typical locations and at all openings. Another related item, critical to the performance of the slab system, which was detailed during this analysis, was the plank-to-plank joint. This joint must be such as to maintain the integrity of the floor diaphragm and transfer in-plane forces from plank to plank. In order to minimize the amount of additional field work required, consideration of a welded joint (as often used) was eliminated. Instead, a detail was devised whereby the edges of adjacent plank taper down to a minimum 2½ in. thickness over a 6-in width. The final result is a 1-ft wide section largely of cast-in-place concrete which is reinforced, as required, to resist the forces through the joint (Fig. 4b).

Another integral part of the floor system, particularly with regard to its diaphragm design as a deep beam, is the spandrel beam. By connecting integrally the slab and the spandrel beam, the spandrel acts as the flange of the deep beam. This increases the lateral stiffness of the system and has been shown to reduce stresses in the slab at areas where they are known to be the highest. However, the spandrel beam was also to be part of the moment frame in the longitudinal direction so its design was to be based on the critical case of lateral loads in both directions.

The initial selection of the type of spandrel beam to be used was based on architectural as well as structural considerations. Both structural steel and concrete spandrel beams were considered, since both were capable of meeting the structural requirements. Architecturally, an upturned concrete spandrel beam provided a fireproof, smooth, finished surface to which the interior window and sill details would adapt readily. The resulting 12-in. wide by 4-ft deep spandrel beam provided architectural benefits as well as an extremely stiff element contributing to the rigid longitudinal frame. The combination of this stiff spandrel beam moment connected to the large building exterior columns and the relatively shallow floor to floor height created a rigid frame easily capable of resisting the relatively small

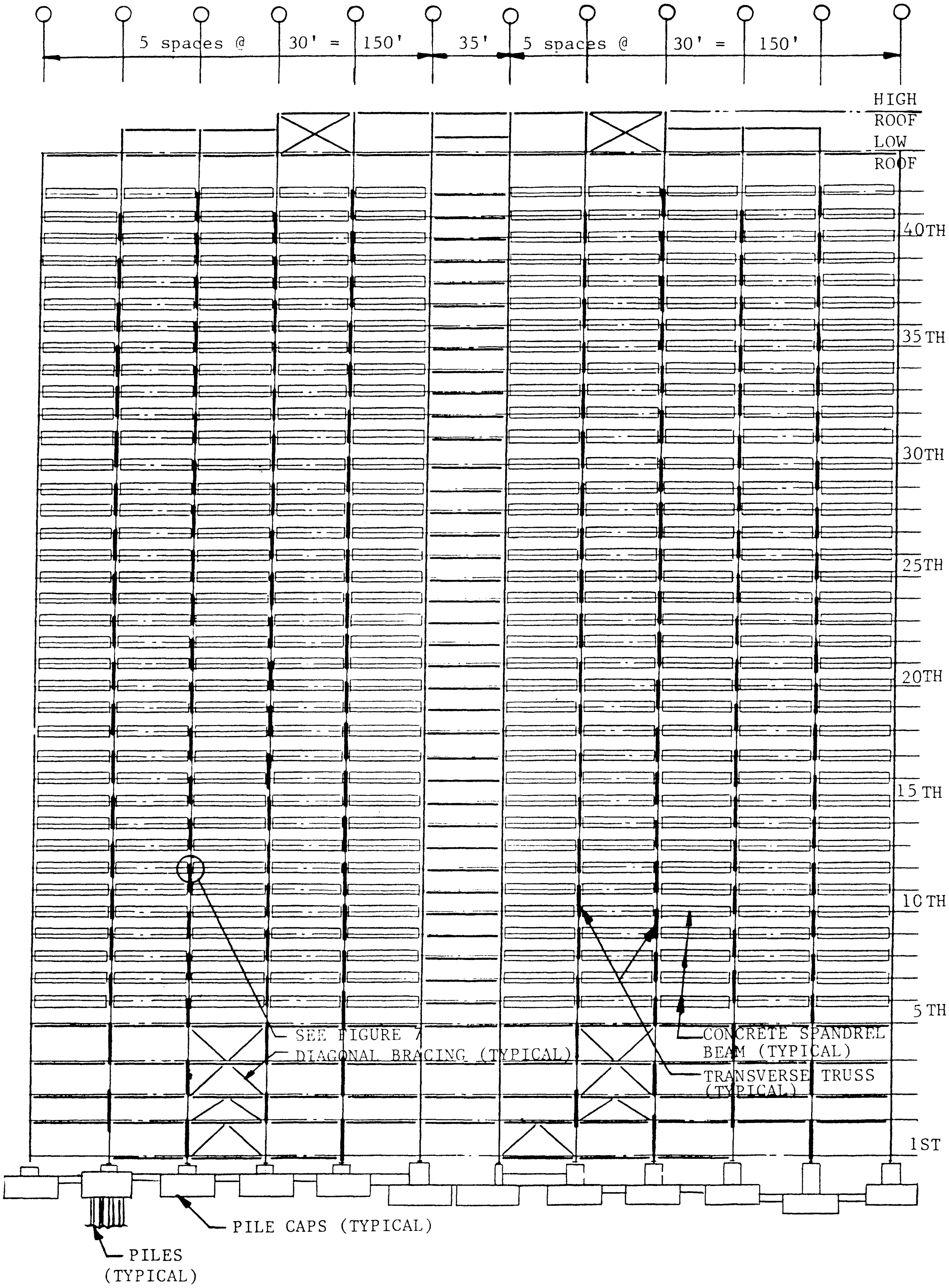


Fig. 6. Longitudinal frame

longitudinal wind loads with more than ample stiffness in that direction (Fig. 6). At the lower levels, where an upturned spandrel beam was not possible, steel spandrels below the slab were combined with several bays of diagonal bracing to complete the lateral resisting system in the longitudinal direction and carry the wind shear down to the foundation.

The detailing of the spandrel beam itself went through several different stages. Among the options considered were: a steel beam encased in concrete, a cast-in-place concrete beam with mild reinforcing steel and several versions of precast concrete beams both prestressed and nonprestressed. The design of the beam itself was not as much a concern as was the detail of its connection to the column. The tight erection tolerances inherent in the staggered truss system dictate that the beam-to-column connection adhere to tight steel tolerances. Normal concrete construction tolerances cannot be worked with or accepted during the erection of this system. It was critical that the detail and fabrication of this beam be such as to adhere to the tolerances of structural steel. The final result, as shown in Fig. 7, was a combination of the basic engineering design and discussions with the steel erector. Similar smaller versions of this precast concrete beam with a modified end connection had been used in previous staggered-truss construction. A precast concrete beam is shop fabricated and reinforced with large (#14 and #18) rebars. The rebars are cadwelded to a structural tee shape at each end which is also fitted with ¾-in. dia. shear studs to be embedded in the concrete. The rebar cutting and cadwelding was done by the structural steel fabricator who also provided jigs for setting the cages to the precaster. The resulting product did indeed maintain the required steel tolerances and its field-bolted connection to a shear plate welded to the column was performed smoothly on the job without incident. Also, by casting into the spandrel beam a shear key and a specified quantity of dowels, the floor slab was sufficiently locked into the spandrel by means of the topping pour.

Once the design and detailing of the major structural elements was completed, attention was turned to the number of miscellaneous conditions throughout the building and coordination items with the other disciplines. Miscellaneous stair, duct and pipe floor openings were provided by either sufficiently reinforcing the slab or, where required, by framing the openings with structural steel. In either case, it was imperative that the diaphragm capacity of the slab system was not significantly impaired.

The major mechanical systems run vertically through the structure and are accommodated by the slab penetrations. However, there are fire suppression and electrical elements which are required to run horizontally through each level. This presented some problems because of the relatively small floor-to-floor height and the inability of these elements to bend around the truss chords. The sprinkler pipe

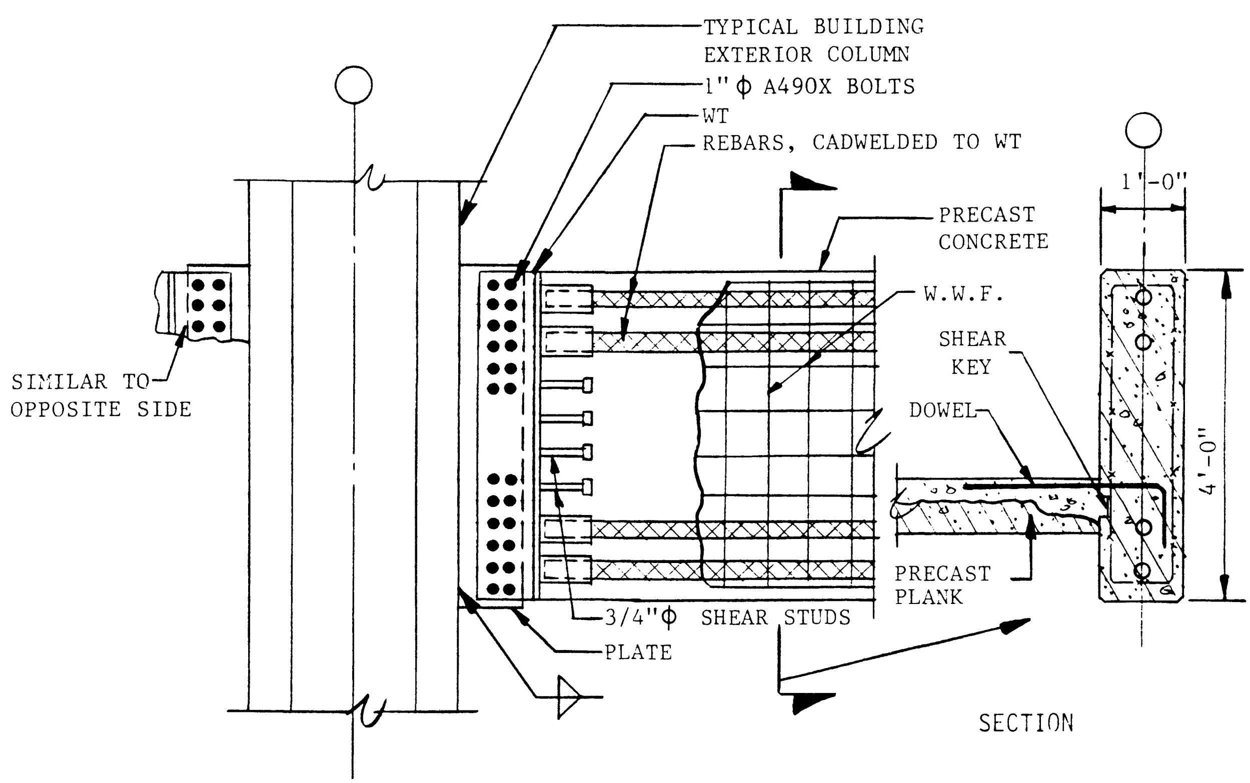


Fig. 7. Spandrel beam detail

detail was solved by predetermining the pipe locations and shop cutting 4-in. dia. holes through the webs of the W10 truss chord members. Where required, these holes were reinforced with either a pipe or sufficient plates to maintain the integrity of the truss member (Fig. 8). The main electrical cable, which typically runs along tight to the underside of the slab, also had trouble passing through the trusses since it is not flexible enough to bend down and wrap around the sides and bottom of the truss chord. This situation was rectified with a relatively simple detail. Again at predetermined locations, thin slots were cast into the bottom of the ends of the precast panels. In this manner, once two of these panels were set across from each other over a truss, a small continuous slot was formed in the underside of the floor slab just over the chord (Fig. 9). Accordingly, the electric conduit could run directly, veering only slightly to pass over the top of the truss. Other similar detailing problems were solved in similar manners.

CONCLUSIONS

Every individual project has its own set of particular parameters which generally dictate the elimination of considering certain structure types and lead to the selection of others. Given the proper circumstances, as was the case reported here, the staggered-steel truss system proved to be a desirable, economical structural system. The recent design and construction of the first high-rise buildings of this type have shown the system is compatible with these, and even taller, structures. The resulting structure, as defined in this report, is capable of efficiently resisting high wind loads and inherently exhibits the stiffness and dynamic levels required to maintain even the strictest of occupant comfort levels. This was confirmed by results of the wind tunnel dynamic test which indicated a sluggish structure with low acceleration levels. While occasional modifications to the typical staggered-truss framing may be necessary to meet other requirements, this does not necessarily change the basic system behavior or efficiency. Details can be worked out so that all the various systems of the total building can be integrated within the framework of the truss system. The net result is a highly efficient structural system which is relatively quickly and economically erected and yields a high degree of architectural and planning flexibility.

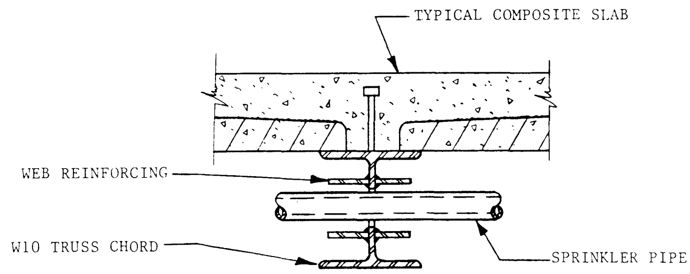


Fig. 8. Pipe penetration detail

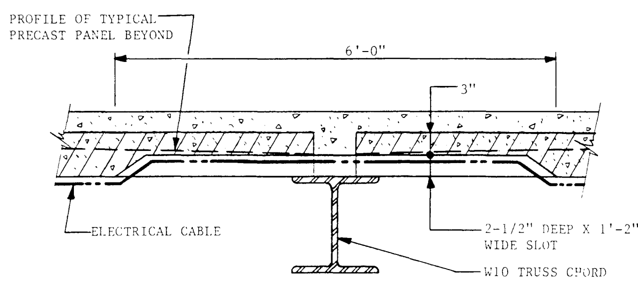


Fig. 9. Electrical slot detail