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**LOAD BALANCED BEAMS IN PERIMETER FRAMES
OF HIGH-RISE BUILDINGS FOR EFFICIENT
TRANSFER OF COLUMN LOADS**

by

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ABSTRACT:

Using post-tensioned concrete perimeter frames for transferring columns in high-rise structures is an effective solution to strength and serviceability. These load balanced transfers allow columns to be transferred without the use of deep girders or walls and allow forces to be shared throughout the building facade.

Post-tensioned facade transfers were designed, constructed and monitored at the 500 West Monroe Project located in Chicago, Illinois. 500 West Monroe is a 45-story, 600-foot-tall concrete office tower/parking complex. Thirty-five stories of office space are located above 10-stories of parking.

Columns at the exterior wall of the structure required transferring before entering the parking areas within typical structural floor depths and without the use of transfer girders or walls which were architecturally unacceptable. Every other column on the north elevation of the structure required transferring. Each column accepted a post-tensioned beam spanning 45'-6". Columns at the north elevation were spaced at 15'-0" on-center and carried 35 stories of load. Similar transfers were used on the west elevation. In all cases, post-tensioned load balancing was used to transfer loads. The design allowed post-tensioning to be done on a floor-by-floor basis without the use of staged post-tensioning.

Post-tensioning was used to control behavior of the perimeter frames. Deflection control of the frame, which would receive the exterior wall granite system, was closely evaluated. Analysis was performed on a floor-by-floor, step-construction, time-history basis and was monitored during construction. Creep and shrinkage studies were also performed to evaluate the frames' behavior relative to other areas of the structure. Construction corrections were made and as-built conditions were surveyed.

I. INTRODUCTION

It seems appropriate that the structure which would occupy the 500 West Monroe site would be designed and constructed of post-tensioned concrete. The parking garage which occupied the site from the middle 1960's to 1990 was constructed of post-tensioned concrete and designed by T. Y. Lin and Associates. The parking garage was the first post-tensioned structure built in Chicago. Many of the same engineering fundamentals developed by T. Y. Lin were incorporated into the design of the post-tensioned floor framing and more importantly, the post-tensioned facade transfers for the 500 West Monroe structure.

Functional and aesthetic requirements for the building were the factors which defined the need for an innovative means of transferring perimeter column loads. Every other column along the north facade required transferring above the parking area. Without transfers, 39 parking spaces would be lost and services entering through the loading dock area would be severely limited. A large transfer girder at the top of the parking garage was not possible because it would interfere with the primary routing of the tower's mechanical systems. Every other column along the west facade carrying loads from the upper portion of the building and three neighboring columns along the west facade carrying loads from the middle portion of the building required transferring above office spaces located in an area where the building stepped out. In each case, a large transfer girder under the entire column line was not acceptable because it would make a large portion of office space unusable. In all areas, the size of the transfers were limited by established floor-to-floor heights, lease spans and massing of the building.

II. LOCATION OF POST-TENSIONED FACADE TRANSFERS IN THE HIGH-RISE STRUCTURE

Transfers at North Facade

Facade transfers exist along the entire north face of the building from Level 10 to Level 45. Every other column spaced at 15'-0" on-center, or a total of 5 column lines, required transferring before entering the parking garage. Each column accepts a 24" x 18" post-tensioned beam spanning 45'-6" which carries a 6" thick reinforced concrete slab, a floor live load of 80 psf and a superimposed dead load of 25 psf. In addition, columns accept 24" x 32" perimeter spandrels and carry the granite clad facade weighing 30 psf.

Transfers at West Facade

Facade transfers exist along the west face of the building from Level 18 to Level 45. Every other column spaced at 12'-6" on-center, or a total of 2 column lines, required transferring before entering office space. Each column accepts a 6" thick reinforced concrete slab spanning 15'-0" which carries a floor live load of 130 psf. In addition, columns accept 24" x 32" perimeter spandrels and carry the granite clad facade weighing 30 psf.

From Level 12 to Level 18, facade transfers exist along the west face of the building. Three columns spaced 12'-6" on-center required transferring before entering office space. The column loads are transferred to 2 columns spaced 50'-0"

apart. Each column accepts loads which are the same as those for the transferred columns on the west facade from Level 18 to Level 45.

See Figure 1 for plan location of the transfers and Figure 2 for the location of the transfers in elevation.

III. STRUCTURAL ANALYSIS OF POST-TENSIONED FACADE TRANSFERS

Transfers at North Facade

A finite element model was created using 24" x 32" spandrel beams, 24" x 36" columns, a unit post-tensioning force and a specified tendon drape to determine applied forces to columns in all locations along the facade. The parabolic drape was maximized, having its lowest position under the column requiring transferring and highest position at columns which would continue through the parking garage. Figure 3B illustrates the applied post-tensioning forces to the transfers as well as tendon geometry.

The unit post-tensioning force was factored to provide the upward force required to balance applied gravity loads. Full dead load, superimposed dead load, exterior wall and 50% of the design live load comprise the total applied load which was balanced. The upward force initiated by the post-tensioning was 90% of the total applied load from any one floor. This design approach allowed the transferred column to remain in compression. Also, 90% of the total load corresponded approximately to the actual load on the transfers at the time of construction. Figure 3C shows the applied forces due to gravity loads and post-tensioning.

The concrete stress level in the post-tensioned transfers was checked for code compliances at both transfer and at service loads. The stress level was evaluated based on applied loads at each level and the effective prestressing force with the parabolic tendon profile.

A floor-by-floor finite element model was created to simulate applied forces and post-tensioning forces superimposed on the frame at every step of construction. The following analysis was performed:

1. The 10th floor frame geometry along the north facade was created with section properties of the spandrel beams (24" x 32") and columns (24" x 36").
2. Design loads were applied to the frame.

3. Post-tensioning loads were applied to the frame.
4. Forces, moments and net displacements were recorded.
5. The 11th floor frame was added to the original model. Design loads as well as post-tensioning loads were applied at the 11th floor. Forces, moments and net displacements were recorded at the 10th floor and 11th floor.
6. This procedure of applying forces and recording data for all superimposed conditions was continued through the 45th floor.

Transfers at West Facade

The analysis for the facade transfers between Level 18 and Level 45 was executed in the same manner as the analysis for the north facade with the appropriate applied loads and spans. The spandrel size used in the analysis was 24" x 32" and the column section sizes were 24" x 36".

The analysis for the facade transfers between Level 12 and Level 18 was performed in the same manner as the north facade with the following exceptions:

1. The finite element model created to determine the distribution of post-tensioning forces to intermediate columns reflected the geometry of this transfer. The parabolic drapage was maximized, having its lowest position under the center column, its intermediate position under the neighboring columns and its highest position at the columns which would continue through the office space below. The tendon geometry and the applied forces on the concrete members, due to the post-tensioning only, are shown in Figure 4B.
2. The unit post-tensioning force was factored to provide an upward force required to balance gravity loads at each of the three transferred columns. Because of the tendon geometry and the level of prestressing required to balance the system, the upward force initiated by the post-tensioning was 117% of the total applied load at the center column and 71% at the neighboring transferred columns. The net tension force applied to the center column developed a stress state well below the allowable tension stress in the concrete; therefore, no cracking would be realized. Since the post-tensioning force applied to the neighboring transferred columns does not fully balance the applied load, these columns are always subjected to compression. The overall upward force on the three column system initiated by the post-tensioning

was 87% of the total applied system load. The applied forces due to gravity loads and post-tensioning are shown in Figure 4C.

IV. STRUCTURAL DESIGN OF POST-TENSIONED FACADE TRANSFERS

The primary consideration for structural design of the post-tensioned facade transfers was gravity load. Transfer forces due to post-tensioning, service loads and ultimate factored loads were considered for strength design. Since the transfer frames also resisted lateral loads, the system was considered for factored loads with wind effects. Lateral loads to the exterior frame were not significant because of the large difference in relative stiffness between the shear wall core and the exterior frame. Longitudinal steel in transfer beams, required for gravity loads, was continuous and in all cases satisfied any requirements for lateral load combinations.

Post-tensioning Tendons in Transfer Beams

The design of the post-tensioning tendons for each frame was based on load balancing requirements. Design stresses at transfer and service load were within allowable ACI Code requirements. The post-tensioning tendons were also considered for contributing to the ultimate design strength of transfer beams.

Longitudinal Mild Reinforcement in Transfer Beams

Post-tensioned transfer beams on each floor were designed to satisfy mild reinforcement requirements for transfer, service and ultimate loads. Minimum mild reinforcement was used in many cases.

Since the total gravity load applied to the transfer frames on any facade was not fully balanced, beam members at the lower portion of the transfer system were designed for larger loads. Mild longitudinal reinforcement was added to resist these additional loads.

Stirrups in Transfer Beams

Since the transfer beams were precompressed, the ACI requirements for shear reinforcing in prestressed concrete could be used. No significant torsion existed on the transfer beams; therefore, additional stirrups for torsion were not required.

Columns

Columns throughout the facade transfers were designed based on net applied forces when considering post-tensioning. Therefore, columns which were transferred typically were reinforced with minimum steel, whereas columns receiving transferred loads were more heavily reinforced and increased in size near the bottom of the transfer system.

V. CONSTRUCTION OF POST-TENSIONED FACADE TRANSFERS

A construction procedure for the post-tensioned facade transfers was developed and executed as follows:

1. Floor framing members were post-tensioned prior to post-tensioning the transfer beams.
2. Formwork for the floor system was dropped (except for formwork supporting exterior transfer beams).
3. Columns above transfer beams were poured.
4. Perimeter transfer beams were post-tensioned.
5. Formwork for perimeter transfer beams was dropped.

The construction procedure was designed to ensure that all of the design dead loads from the framing and the columns were applied to the transfers at the time of stressing. Without this construction procedure, overstressing of the transfer beams may have occurred.

Staged post-tensioning of the facade frames was not used. The system was designed to be stressed at each level as it was constructed. Loads were balanced by post-tensioning at the time of load application to the frames.

Corrections of individual components of the perimeter frames such as cambering were not necessary. Corrections of some specific column locations at the perimeter were made to account for relative concrete creep and shrinkage between the shear wall core and columns.

An extensive field survey program of the facade transfers was designed and implemented. Each column within the frames was surveyed as follows:

North Facade (Level 10 - Level 45)

West Facade (Level 18 - Level 45)

1. Each column at the first transfer level was surveyed immediately after forms were stripped. Every subsequent fifth floor was surveyed immediately after forms were stripped.
2. Columns at lower levels of the transfer frame were surveyed at one week intervals until the 20th floor on the north face and 25th floor on the west face were poured.
3. All columns identified above were then surveyed on a 4-week interval basis until the exterior wall was placed to Level 45.

West Facade (Level 12 - Level 18)

1. Every column in the frame was surveyed after removal of forms. After each floor was constructed and surveyed, each floor below that newly constructed floor was surveyed.
2. After erection of the exterior wall, the frame was surveyed on a weekly basis until the wall was erected at Level 18.

VI. DISCUSSION OF THEORETICAL AND AS-BUILT RESULTS

Transfers at North Facade

At Level 10, the total long-term deflection of the transferred columns relative to columns continuing through the parking garage was calculated to be 1 1/2" without post-tensioning the facade. With the exterior wall being erected 10 stories behind concrete construction, 3/4" of relative column deflection would be realized by the system after the exterior wall was erected. The behavior was attributed to the influence of additional dead and live load from upper floors on previously constructed floors.

The 1 1/2" of relative movement between columns 15"-0" on-center was far from acceptable for the office environment. Also, this relative movement would have created slab moments and shears which could not be designed for. Cracking in slabs would most likely have occurred. In addition, 3/4" of relative movement of columns supporting the exterior wall was not acceptable since the stone joint size was designed as 3/4", allowing 3/8" of movement in any direction.

With the facade post-tensioned, the relative long-term deflection of the transferred columns to columns continuing through the parking garage was calculated to be $3/16$ " at Level 10. Slightly over $1/16$ " of relative column deflection was calculated for the system after the exterior wall was erected.

At Level 10, a field survey of the neighboring columns, recorded 1 year and 4 months after the floor was poured, indicated that the maximum relative displacement between transferred columns and columns continuing through the parking garage was $1/16$ ".

Figure 5 illustrates the relationship of stories of frame constructed to displacement for a typical transfer column at Level 10. The graph presents theoretical data for a post-tensioned and non-post-tensioned frame as well as recorded field data. Theoretical creep and shrinkage of columns were considered in the presentation of the displacements.

Transfers at West Facade

An analysis similar to that of the north facade was performed for the transfers from Level 18 to Level 45. Behavior with and without post-tensioning of the frame was similar. Since applied loads to this transfer system were not as great in magnitude as those on the north facade, relative displacements between column lines were not as severe. The maximum recorded relative displacement of a transferred column to a continuing column was $1/8$ " at Level 20. This surveyed relative displacement was recorded five months after Level 20 was constructed.

At Level 12, the total long-term deflection of the center transferred column to the columns continuing through the office space below was calculated to be 2" without post-tensioning the facade. With the exterior wall being erected after the transfer frame was completed, $3/4$ " of relative column deflection would be realized between the center transferred column and the columns continuing through the office space below.

Again, the relative displacement of 2" was not acceptable for office use. This 2" displacement was associated with columns spaced 25'-0" apart. Also, this displacement would have created adverse strength and serviceability requirements for the reinforced concrete slab. A relative movement of $3/4$ " would have exceeded the allowed movement of $3/8$ " for the exterior wall.

The relative displacement of the center column to the columns continuing through the office space below was calculated to be

1/4" at Level 12 with the facade post-tensioned. The relative deflection of the center column to the continuing columns was calculated to be 1/8" after the exterior wall was erected.

At Level 12, a field survey of the relative columns, recorded three months after the floor was constructed, indicated that the maximum relative displacement was 1/16".

Figure 6 illustrates the relationship of stories of frame constructed to displacement for the center transfer column of the frame at Level 12. The presentation shows theoretical data for a post-tensioned and non-post-tensioned frame as well as recorded field data. Theoretical creep and shrinkage of columns were considered in the presentation of the displacements.

VII. CONCLUSIONS

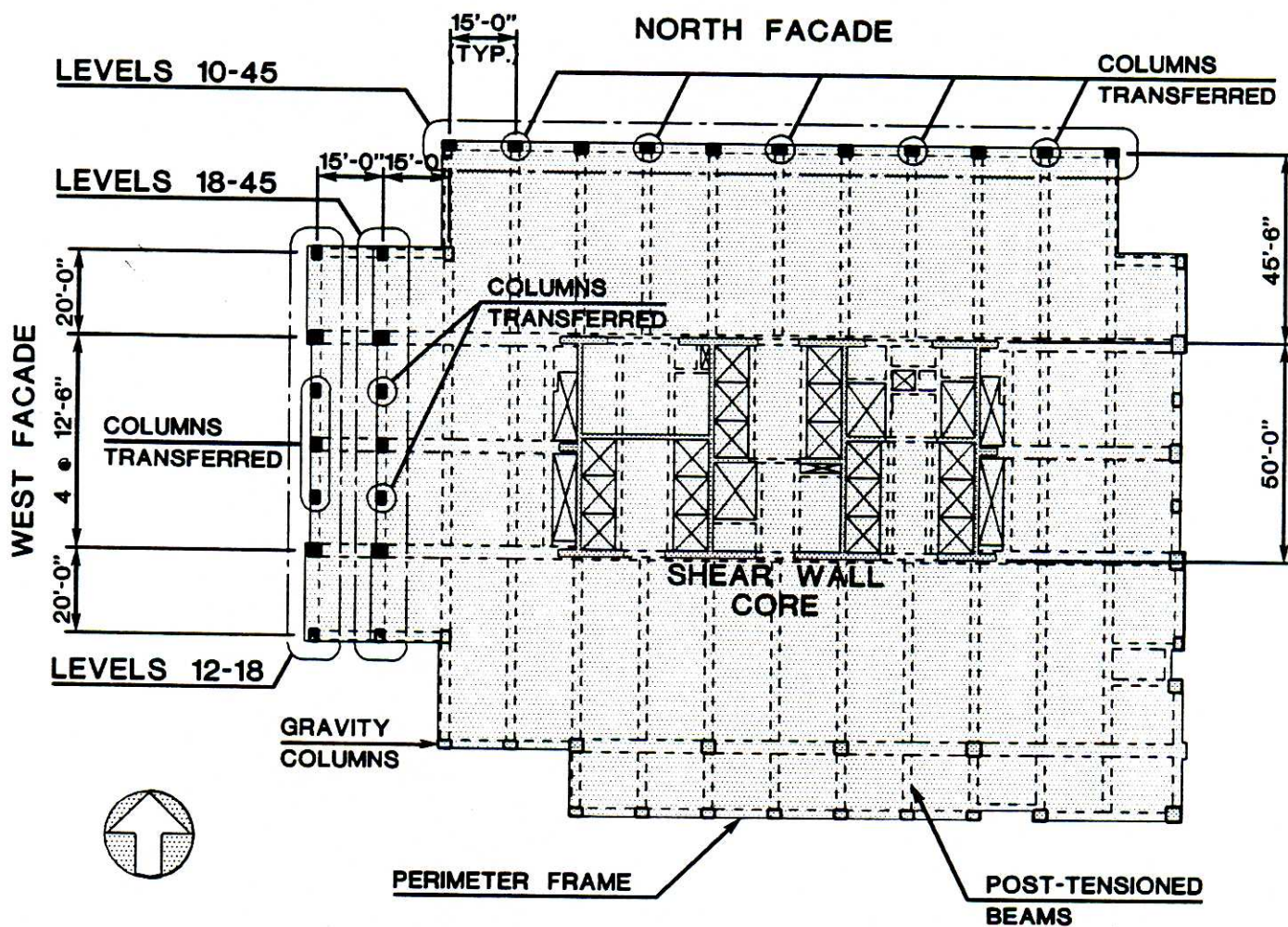
Post-tensioned beams in the perimeter frames of 500 West Monroe provided an efficient solution to strength and serviceability. The quantity of mild reinforcement required for transferring the column loads was reduced, leading to the building's minimal rebar quantity of 6.0 psf. Deflections of the frames were controlled with the balancing of load. A relative deflection between columns in a 15'-0" bay not exceeding 1/8" met strict office floor flatness requirements. In all cases, relative deflections between transferred and continuing columns were equal to, or less than, 1/8" in both the calculated and as-built conditions. In addition, the maximum relative column deflection of 1/8" was less than the required maximum relative displacement of 3/8" for the base building structural supporting elements of the exterior wall.

Analytical techniques used to evaluate the transfer systems considered the behavior of individual transfer elements at each floor level, as well as each frame as a whole. Each step of construction was evaluated for the influence of applied loads. It was proven that post-tensioning could be performed on a floor-by-floor basis without the need for staged post-tensioning which would have increased construction costs as well as created uncertainty in the actual magnitude of applied post-tensioning forces.

The post-tensioned facades were designed for all requirements defined in the ACI Code. Minimum requirements for mild reinforcement and post-tensioning were utilized where allowed by code. Since the relative column deflections were minimized, no additional reinforcement was required for interior slabs or beams.

Post-tensioned facade transfers were built in accordance with the designed construction process. This process had no adverse effect on the construction schedule, allowing an unusually fast 3-day construction cycle for typical upper floors. Loads were balanced upon application, resulting in no adverse cracking of transfer beams or columns. No tendon breakage, due to stressing or fabrication errors, occurred within the transfer facades. All facade transfers were monitored on a periodic, as-designed, basis. Surveys confirmed that the relative displacements between transferred and continuous columns were controlled and were minimal.

Using post-tensioning to load balance beams in perimeter frames of high-rise buildings for transfer of column loads provided a highly efficient structural solution without compromising the architecture.



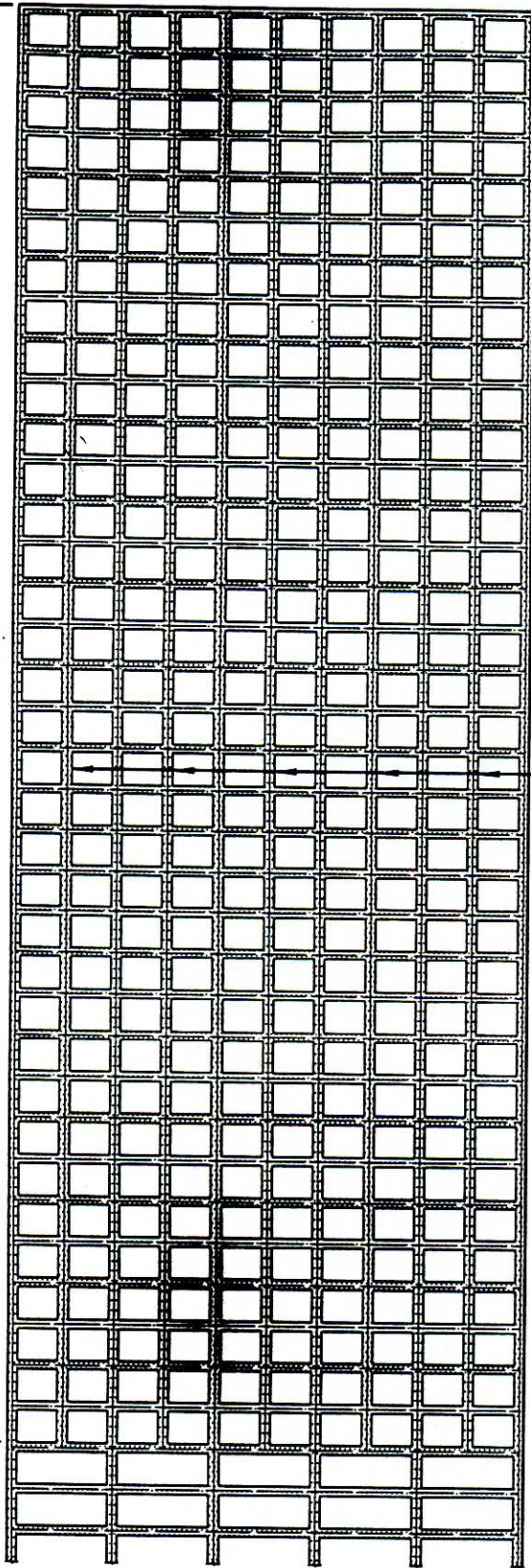
TYPICAL STRUCTURAL FRAMING PLAN - LEVELS 12-45

PLAN LOCATION OF TRANSFERS

FIGURE 1

LEVEL

45



COLUMNS
TRANSFERRED
(LEVELS 10-45)

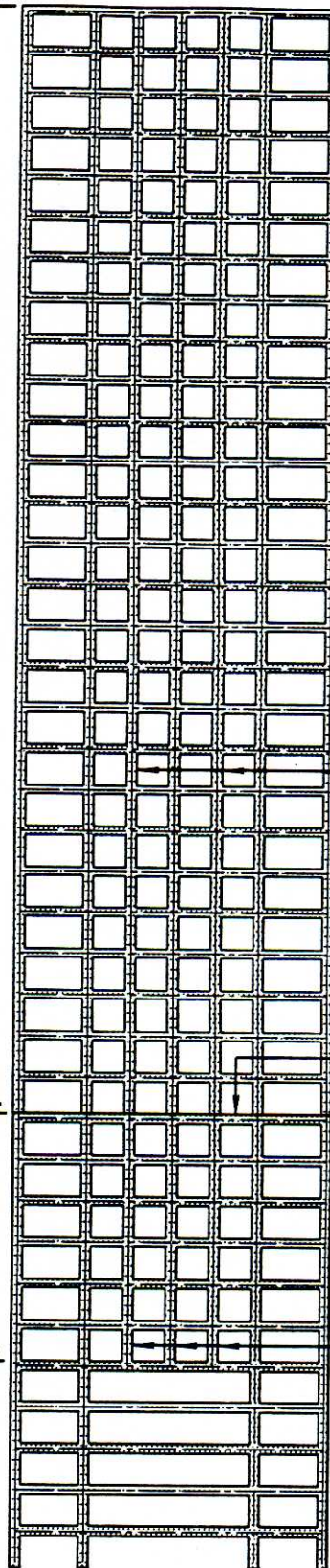
LEVEL

10

NORTH FACADE

LEVEL

45



COLUMNS
TRANSFERRED
(LEVELS 18-45)

SETBACK
LOCATION

LEVEL

18

LEVEL

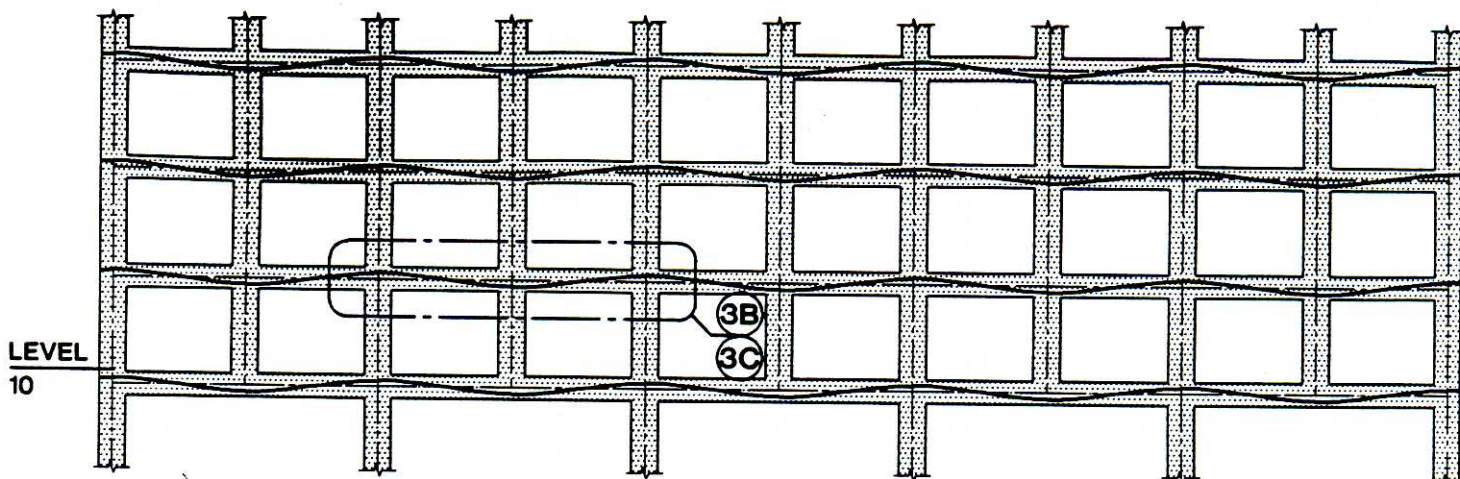
12

COLUMNS
TRANSFERRED
(LEVELS 12-18)

WEST FACADE

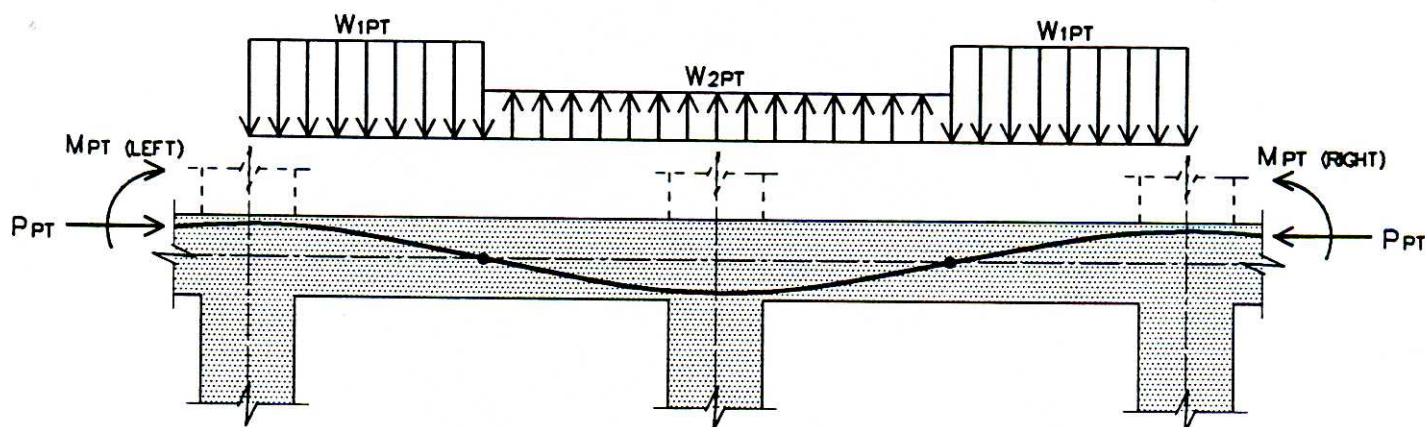
ELEVATION LOCATION OF TRANSFERS

FIGURE 2



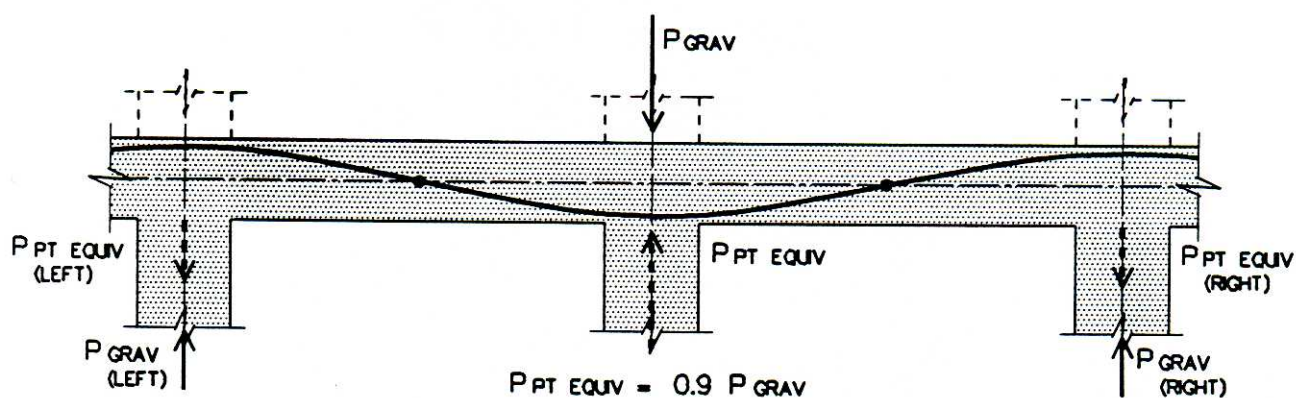
NORTH FACADE TRANSFER - LEVELS 10-45

FIGURE 3A



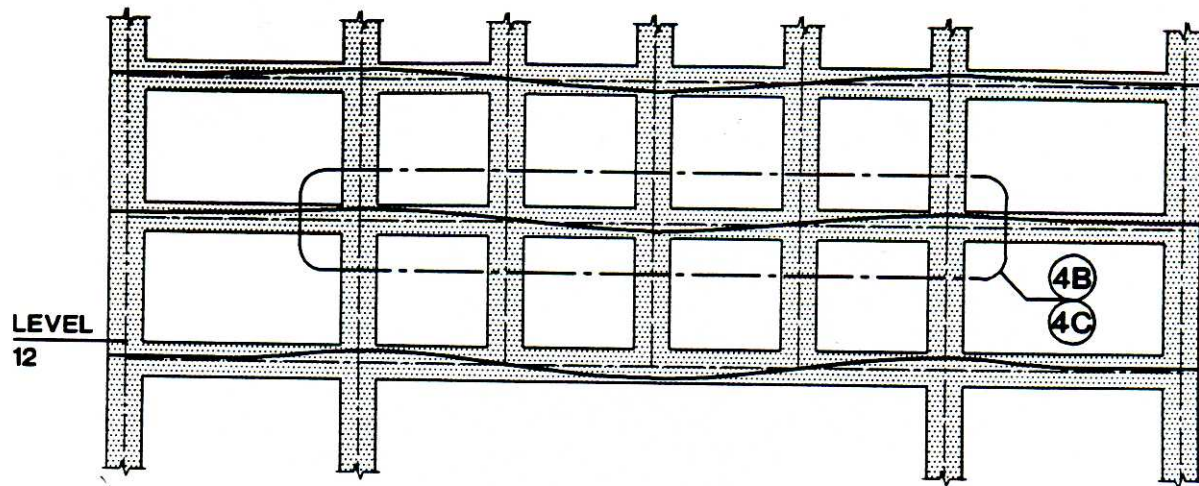
EFFECTS OF POST-TENSIONING ONLY

FIGURE 3B



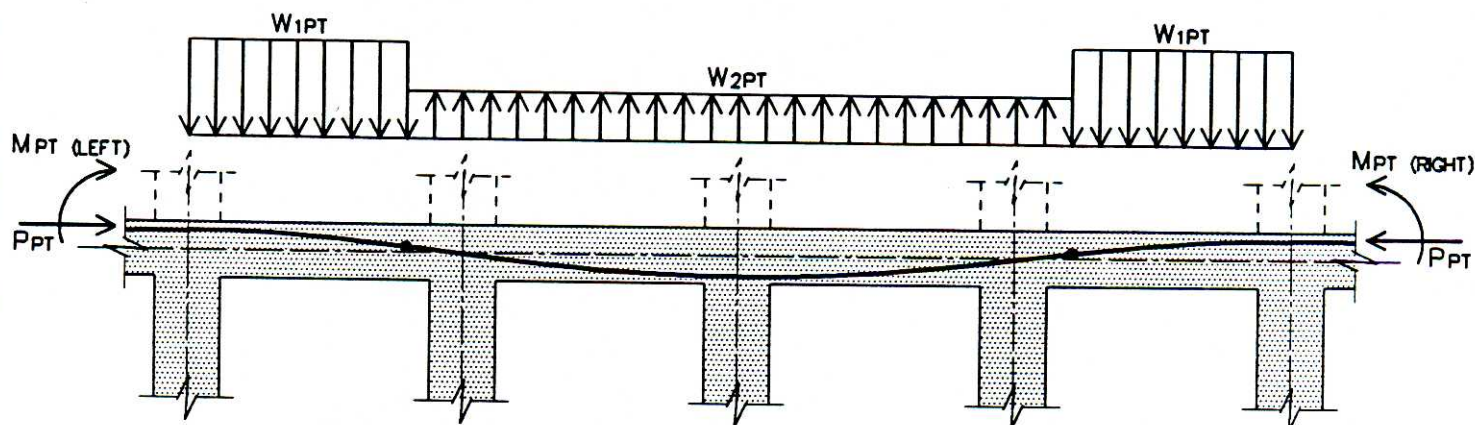
LOAD BALANCING OF APPLIED GRAVITY LOADS

FIGURE 3C



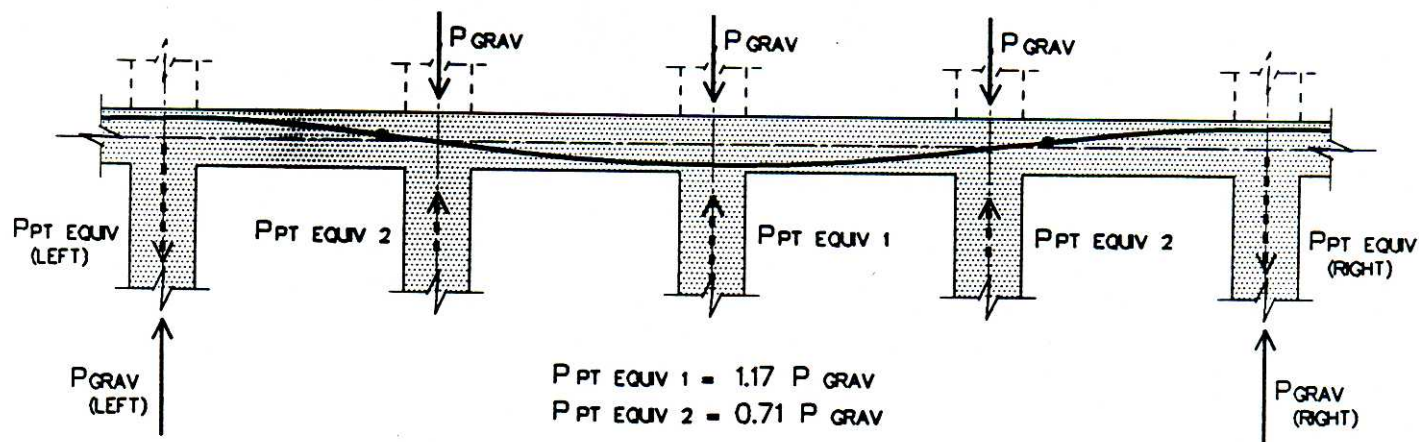
WEST FACADE TRANSFER - LEVELS 12-18

FIGURE 4A



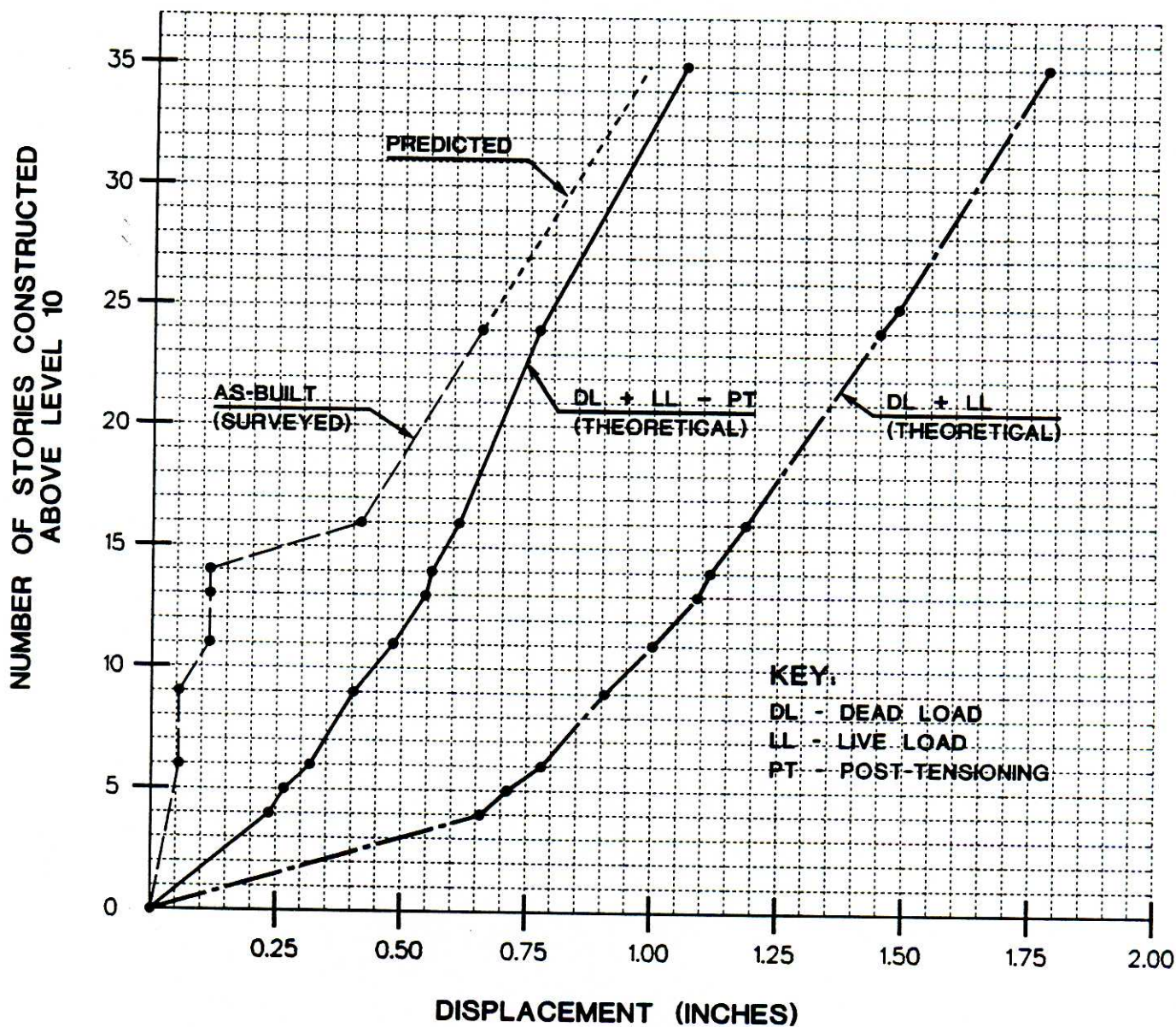
EFFECTS OF POST-TENSIONING ONLY

FIGURE 4B



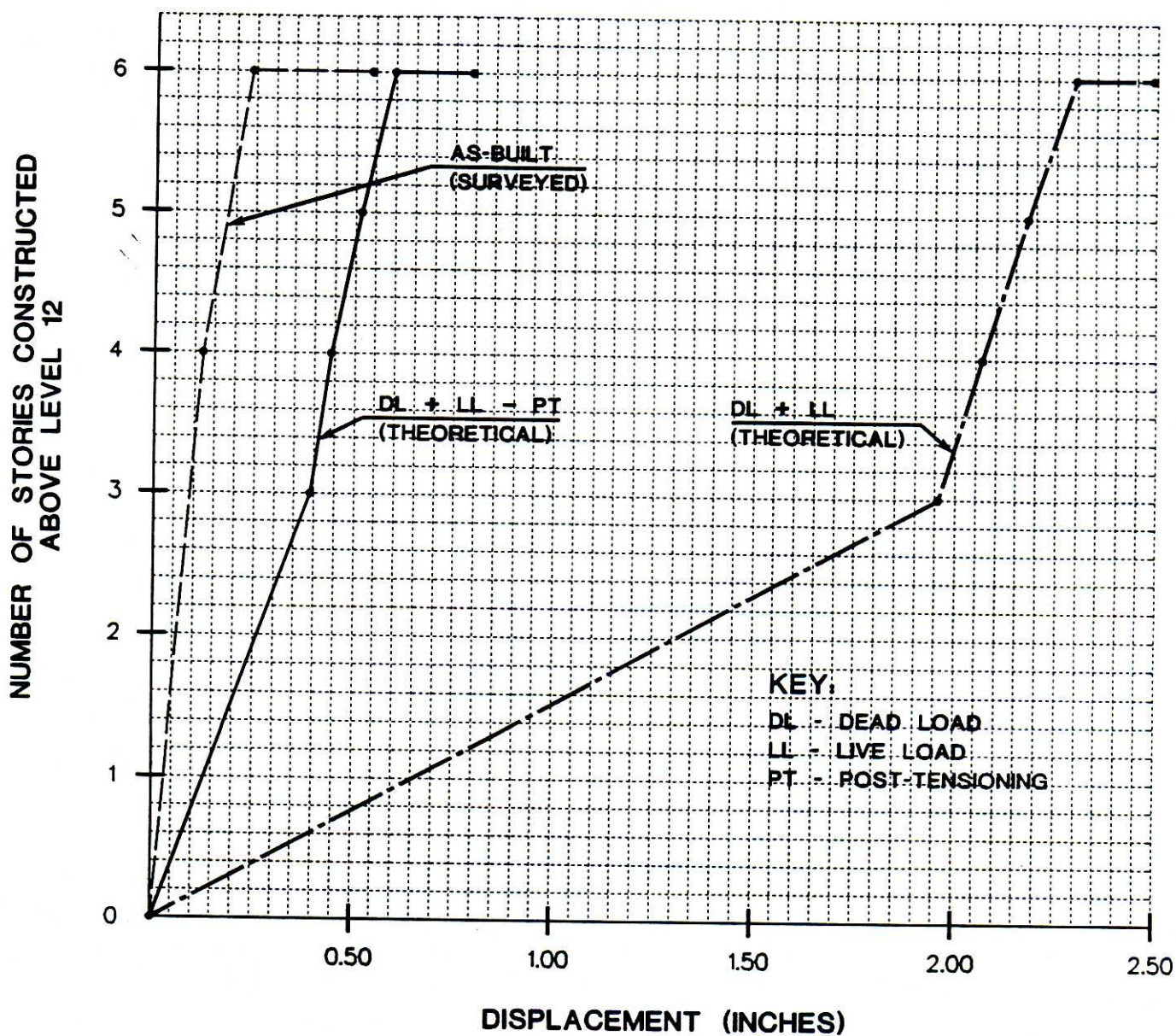
LOAD BALANCING OF APPLIED GRAVITY LOADS

FIGURE 4C



RELATIONSHIP BETWEEN STORIES CONSTRUCTED AND DISPLACEMENT

DISPLACEMENT OF TYPICAL TRANSFERRED COLUMN AT NORTH FAÇADE



RELATIONSHIP BETWEEN STORIES CONSTRUCTED
AND DISPLACEMENT

DISPLACEMENT OF CENTER TRANSFERRED COLUMN
AT WEST FACADE

FIGURE 6