Portland Cement
vs.
Expansive Cement
in
Post-Tensioned
Concrete Structures

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INTRODUCTION

All concrete structures are affected by shrinkage and creep; post-tensioning introduces elastic shortening as well. This paper will compare the effect of this shortening on structures using expansive cement concrete and conventional cement concrete.

Many engineers who design post-tensioned or reinforced structures concern themselves only with the final forces or reinforcing in the individual members. They sometimes tend to overlook the effects which volume changes of the members themselves have on the structure.

The primary focus of the paper is to show that the use of expansive cement concrete can minimize the induced moments created by volume changes. A structural example will be used to compare these effects.

CRITICAL LOCATION FOR VOLUME CHANGE

Shortening of the concrete structure is the most severe at the first framed floor or roof above the foundations. The foundations are fixed and do not undergo volume changes such as the floor and roof structures undergo. Whether the structure is one story or 20 stories tall, the first framed floor or roof and column above the foundation will have very large moments due to volume changes. Floors above the first framed floor are affected mainly by the relative volume change, floor-to-floor, in terms of time between their placement. The relative movement is due to elastic shortening plus only that part of creep and shrinkage which occurs between placement of successive floors, which is assumed to be 7 days.

Restated: the floors above the first framed floor shorten essentially together; the important effects of movement occur between the foundation (which cannot move) and the first framed floor.

POST-TENSIONING STEEL LOSS CALCULATION METHOD

Having pin-pointed where the most severe shortening effects occur, we may now determine the method by which to calculate the amount of shortening that occurs at different time intervals. This paper will assume that the construction time cycle between different slab castings will be 7 days. The time intervals that will be used in the calculations of shortening will be 7, 14, 21, 28, 35, 42, 90, 180, 270, 365 days, and 30 years, the assumed life of the structure. The period of 7 to 42 days is the assumed construction time of a six-story structure such as the example that is being used in this paper. The other time intervals are being used to show the effects on the structure as the concrete ages.

The concrete modulus of elasticity for this example was varied for time intervals 7, 14, 21, and 28 days. The time intervals after 28 days were assumed to have a modulus of elasticity corresponding to 4,000 psi concrete strength. Concrete strength does continue to gain after 28 days, and may even be higher than required at 28 days, but this is an unknown amount of gain. The engineer should use his own judgment about which modulus of elasticity to use after 28 days.

The method used to calculate the losses on the prestressing steel was the PCI's "Recommendations for Estimating Prestress Losses" (Reference 1). This method figures the losses in the post-tensioning steel, which can also be used to figure the shortening of the structure. When using this method to calculate the amount of shortening, we must assume that the losses (elastic shortening, shrinkage, creep) occurring in the post-tensioning steel are occurring simultaneously in the concrete at the same rate at which shortening of the concrete occurs.

Figures 1 and 2 show the building plan and cross section through the building. The plan indicates the assumed construction joints, column locations, large openings, etc.

The structural example is an office building with a plan dimension of 152' by 252', six stories high. The structure has the normal floor openings due to stairs, elevators, mechanical shafts, electrical chases, etc. Since there are no shear walls in this building, the column slab frames will be designed to resist lateral loads.

DESIGN PROCEDURE OF SLABS

The prestressing force in the slab will be determined by the "Load-Balancing Method" and ACI 318-71, plus current supplements. The slabs will be load-balanced for nine-tenths (9/10) of their weight. The unbalanced load will be used to calculate moments in the slab and columns. The unbalanced load moment in the columns will be shown later, when the columns are designed.

Figure 3 shows the post-tensioning steel profile for an end bay as well as the typical interior bay. The end bays will have a higher force F per foot of slab than the interior bays. The higher force in the end bays is due to the smaller h dimension, since the post-tensioning anchorage is located at the center of gravity of the slab. This higher force F will be continuous across the end bay plus 1/4 of the span of the first interior bay. The average post-tensioning force in the east-west direction is 17.207 kips per foot of width of slab. The average compressive stress in the slab is 191 psi.

Figure 4 is a cross section of the 7-1/2" slab in the east-west direction. The cross section gives the location 'point x' which was used to calculate the average frictional losses of the post-tensioning steel; also shown is the parabolic configuration of the post-tensioning steel and its center-line from slab surfaces.

Design procedure for determining amount of shortening

The post-tensioning steel losses at different time intervals were inserted into the following equation to arrive at the amount of slab shortening.

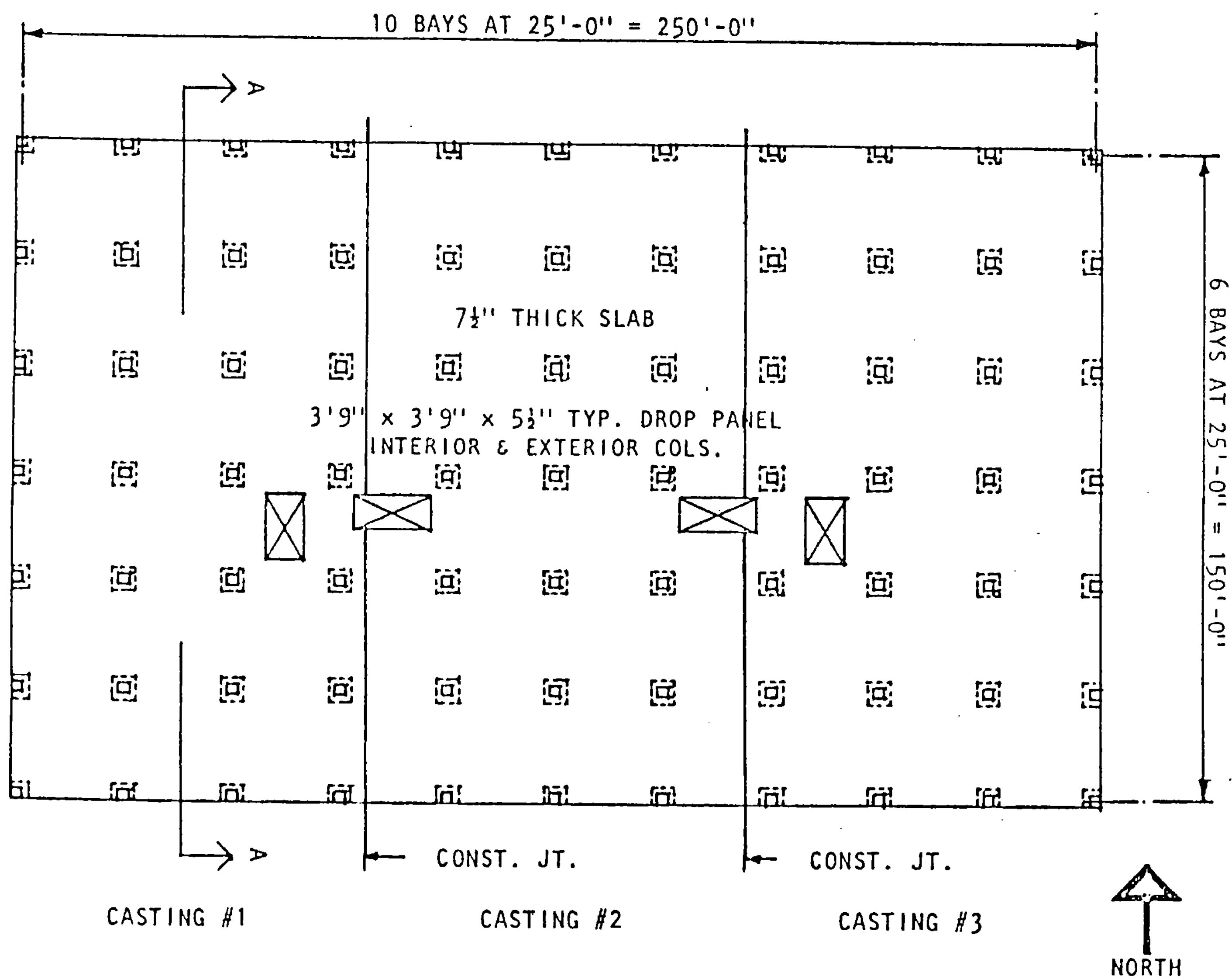


FIGURE 1 TYPICAL FLOOR PLAN OF AN OFFICE BUILDING

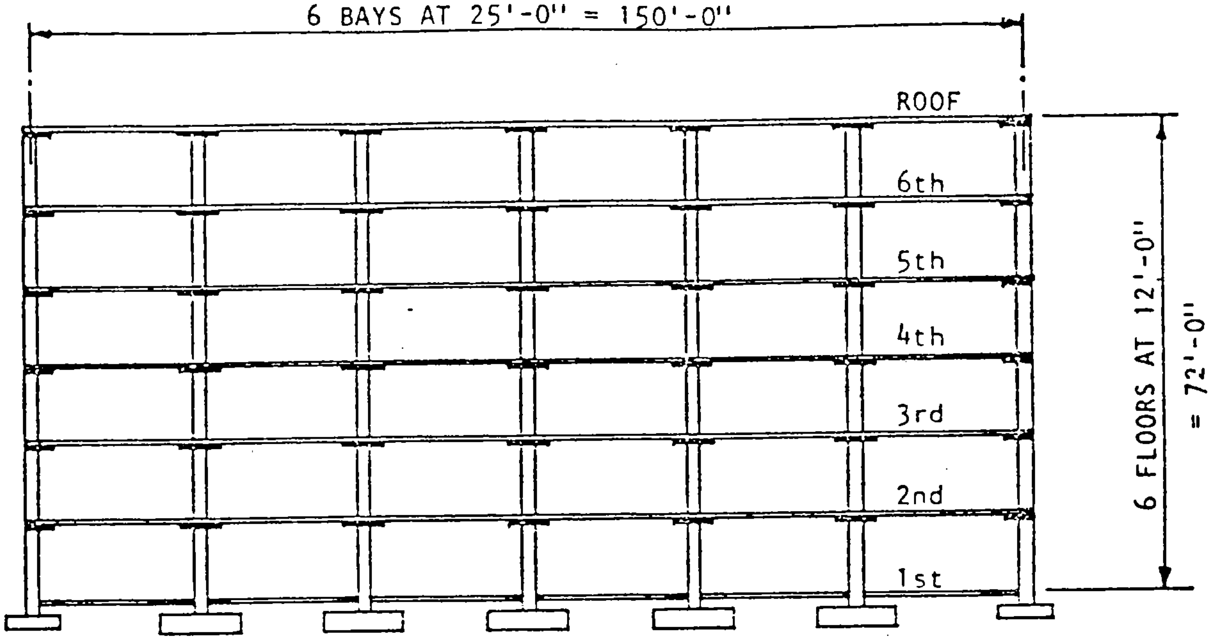


FIGURE 2 CROSS SECTION A-A

DESIGN PARAMETERS THAT WILL BE USED ON THE STRUCTURE

Roof Loads (pounds per square foot)

Live 30 ; Dead 115

Floor Loads (pounds per square foot)

Live 80 ; Dead 125

Wind Loads (pounds per square foot, vertical surface)

20psf up to 30' , 25psf to 50' , 30psf to 72'

Concrete Strength 4,000 psi normal weight

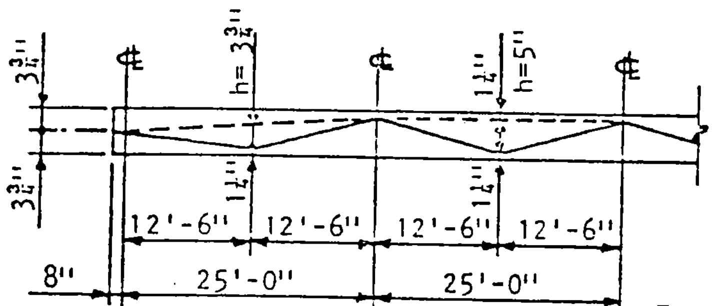
Prestressing Steel 270,000 psi, 7 wire strand

Prestressing Forces will be determined by the "Load-Balancing Method" using criteria for stresses and strength from ACI 318-71 and current supplements.

Prestress Losses "Recommendations For Estimating Prestress Losses" reference 1

Mild Reinforcement 60,000 psi

Structure Assumptions column end at foundation, pinned; structure movements will be symmetrical about its center; there are no stiff elements in the structure that would prevent the frame from expanding or shortening.



Wpre	0.0846 k/ft.	0.0846 k/ft.
h	3.75 in.	5.0 in.
F	21.15 kips	15.863 kips
F/A	235 psi	176 psi

$$F = \frac{W_{pre} L^2}{8h} \times 12$$

FIGURE 3 FORCES AND PROFILES FOR FLEXURAL DESIGN

CONCRETE AND STEEL DESIGN REQUIREMENTS

SLAB; A = 90 sq. in./ft. ; I = 422 in^4

E_s = 27,000,000 psi ; E_c = 3,605,000 psi ; f'_c = 4,000 psi

E_{ci} = 2,550,000 psi ; f'_{ci} = 2,000 psi ; f_y = 60,000 psi

f_{pu} = 270,000 psi

F = post tensioning steel force, kips/ft.

h = post tensioning steel sag, in.

Wpre = uniform upward load applied to concrete by post tensioning steel, kips/ft.

L = center to center spacing of columns, ft.

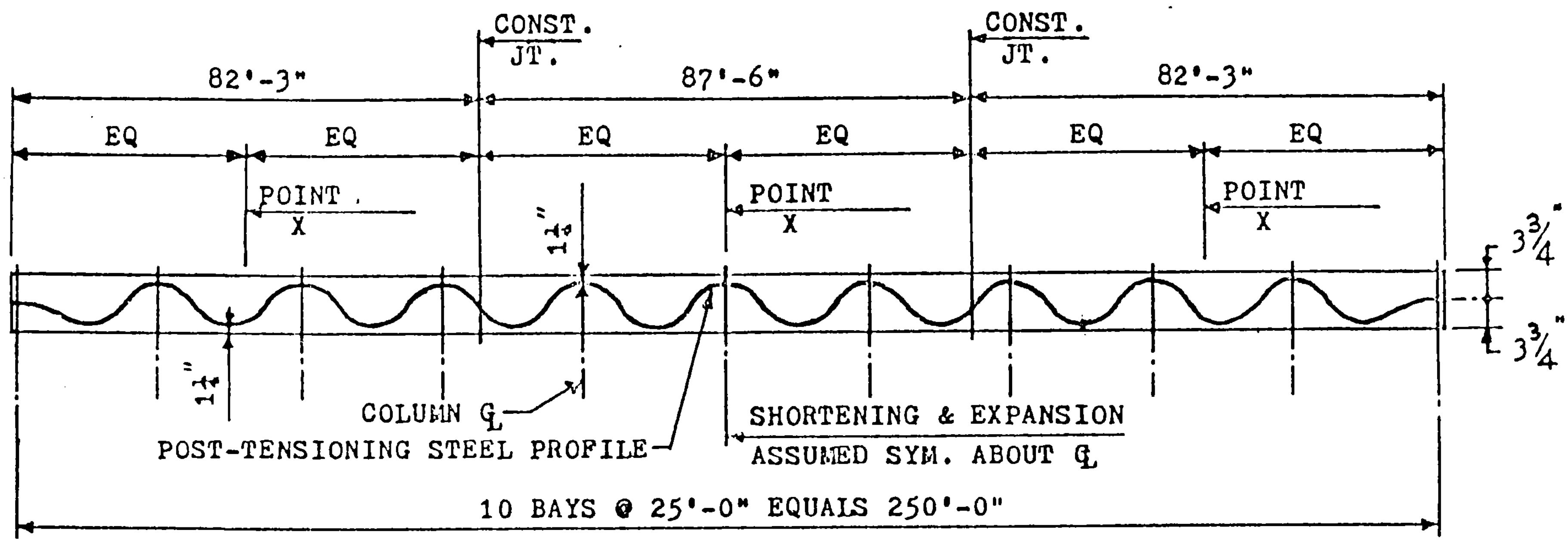


FIGURE 4 EAST-WEST CROSS SECTION THROUGH FLOOR SLAB

Equation 1

$$\Delta = \left(\frac{\text{TOT.LOSS ES+CR+SH+REL}}{\text{Tx (@point x)}}\right)\left(\frac{\text{TOT.LOSS ES+CR+SH}}{\text{TOT.LOSS ES+CR+SH+REL}}\right)\left(\frac{f_{st}(12)L}{Es}\right)$$

Δ = total shortening in a concrete member of length L, inches

TOT.LOSS = summation of losses being considered at time interval

ES = loss of prestress due to elastic shortening, psi

CR = loss of prestress due to creep of concrete, psi

REL = loss of prestress due to steel relaxation, psi

Es = modulus of elasticity of prestressing steel, psi

Tx = steel stress at any point x, psi

f_{st} = stress in prestressing steel at time interval (day) being checked, psi

L = length of structure being checked for movement, ft

The amount of slab shortening that occurred after 30 years is almost exactly the same amount that would be calculated from approximate methods of shortening. The following approximate equations can be used to estimate the various shortening effects:

1. Elastic shortening: $\varepsilon_e = \frac{F}{AE_c}$

2. Shrinkage: $\varepsilon_s = 0.0003$ for normal weight concrete,
$\varepsilon_s = 0.0005$ for lightweight concrete

3. Creep: ε_c may be estimated as twice the elastic shortening.

Equation 2

$$\Delta = L\ (\varepsilon_e + \varepsilon_s + \varepsilon_c)$$

(L to be in units of inches.)

The reason for using PCI's method of calculating losses was that at any given time interval, a shortening effect could thus be determined. The frame moments that occurred using these shortening effects will be shown later, which will demonstrate the effect time has on a structure. If the engineer is not interested in the interim time, he may use the above approximate equation to determine shortening effects.

Shortening of frame elevation and table

In Figure 5, elevation of building frame after shortening has taken place, shows column movement due to shortening effects. The dotted lines indicate the plumb column prior to shortening effects of the slab. The solid line shows the column after shortening movements have taken place. The elevation shows the column joint at the foundation being pinned and the rest of the joints being fixed; also shown is

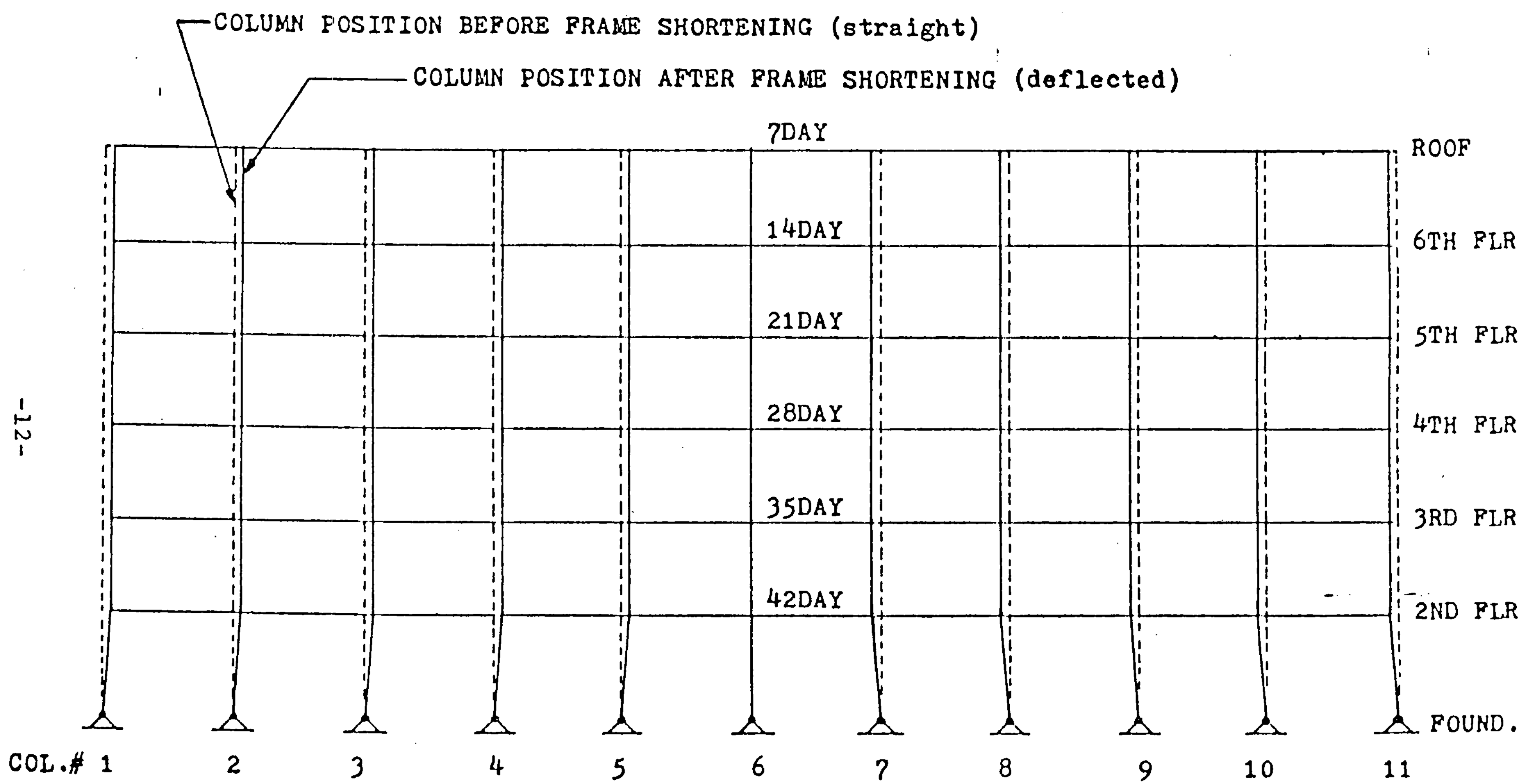


FIGURE 5 ELEVATION OF BUILDING FRAME AFTER SHORTENING HAS TAKEN PLACE

D \ C	1	2	3	4	5	6	7	8	9	10	11	FIG.
7	+0.199	+0.159	+0.119	+0.080	+0.040	0.0	-0.040	-0.080	-0.119	-0.159	-0.199	5
14	+0.270	+0.216	+0.162	+0.108	+0.054	0.0	-0.054	-0.108	-0.162	-0.216	-0.270	5
21	+0.307	+0.245	+0.184	+0.123	+0.061	0.0	-0.061	-0.123	-0.184	-0.245	-0.307	5
28	+0.335	+0.268	+0.201	+0.134	+0.067	0.0	-0.067	-0.134	-0.201	-0.268	-0.335	5
35	+0.354	+0.283	+0.212	+0.142	+0.071	0.0	-0.071	-0.142	-0.212	-0.283	-0.354	5
42	+0.372	+0.298	+0.223	+0.149	+0.074	0.0	-0.074	-0.149	-0.223	-0.298	-0.372	5
90	+0.459	+0.368	+0.276	+0.184	+0.092	0.0	-0.092	-0.184	-0.276	-0.368	-0.459	5
180	+0.498	+0.398	+0.299	+0.199	+0.100	0.0	-0.1[illegible]	-0.199	-0.299	-0.398	-0.498	5
270	+0.547	+0.437	+0.328	+0.219	+0.109	0.0	-0.109	-0.219	-0.328	-0.437	-0.547	5
365	+0.597	+0.478	+0.358	+0.239	+0.119	0.0	-0.119	-0.239	-0.358	-0.478	-0.597	5
30 YR	+0.673	+0.538	+0.404	+0.269	+0.135	0.0	-0.135	-0.269	-0.404	-0.538	-0.673	5

D = Days Old ; C = Column ; FIG. = Related Figure Showing Movement of Frame
Units of measurement, INCHES ; + = Movement to right ; - = Movement to left

TABLE 1 CONVENTIONAL CONCRETE COLUMN JOINT SHORTENING MOVEMENTS the assumption that the frame shortens about its center, column number 6. The 7 day through 42 day notations on the elevation will be discussed later in the paper when the frame moment calculations are presented.

Table 1, conventional concrete, lists the slab shortenings for each column in the east-west direction; these shortenings were calculated from equation 1. Again, column line 6 was assumed to have zero movement, whereas column lines 1 and 11 are assumed to have the greatest movement. The table shows at 365 days (1 year) that the amount of shortening taking place in 125 feet of slab length is equal to about 9/16 of an inch, and at 30 years age the shortening is equal to about 11/16 of an inch. From the results shown in the table, about 89 percent of the shortening has taken place by the end of a year. The remaining 11 percent of shortening will take place very slowly, hence allowing the frame to redistribute any shortening forces through the creep of concrete.

EXPANSION BAR TESTS

A series of 3" x 3" x 10" concrete bars were tested according to ASTM, "Proposed Method of Test for Restrained Expansion of Shrinkage Compensating Concrete" (Reference 2), for the amount of expansion that would occur for restrained and unrestrained conditions. These tests were conducted for both regular-weight and light-weight concrete. The tests were run by the Medusa Cement Company at the request of the author. The results of the tests are included in the appendix.

The concrete being assumed for this paper is normal-weight (regular) concrete. The author assumes that the slabs are unrestrained by columns, walls, etc. The structure does not have any stiff walls or deep columns that would prevent the slab from expanding. The slab has some mild reinforcement in areas where required to satisfy ultimate strength requirements, but this is not continuous. This reinforcement plus formwork and column stiffnesses will give some restraint to the expansion of the concrete but not enough to seriously reduce the amount of expansion.

From the test expansion bars that were run by Medusa Cement Company, the normal-weight concrete at 7 days age had an unrestrained expansion of 0.038 percent. The results of this test will be used to calculate the amount of expansion in our sample structure slab. Columns 1 and 11, 125 feet from the center of the structure, will have an expansion movement of $\Delta = 125 \times 12 \times 0.00038 = 0.57$ inches (this is the same number that is shown in Table 2 under the "days old" heading of EC7).

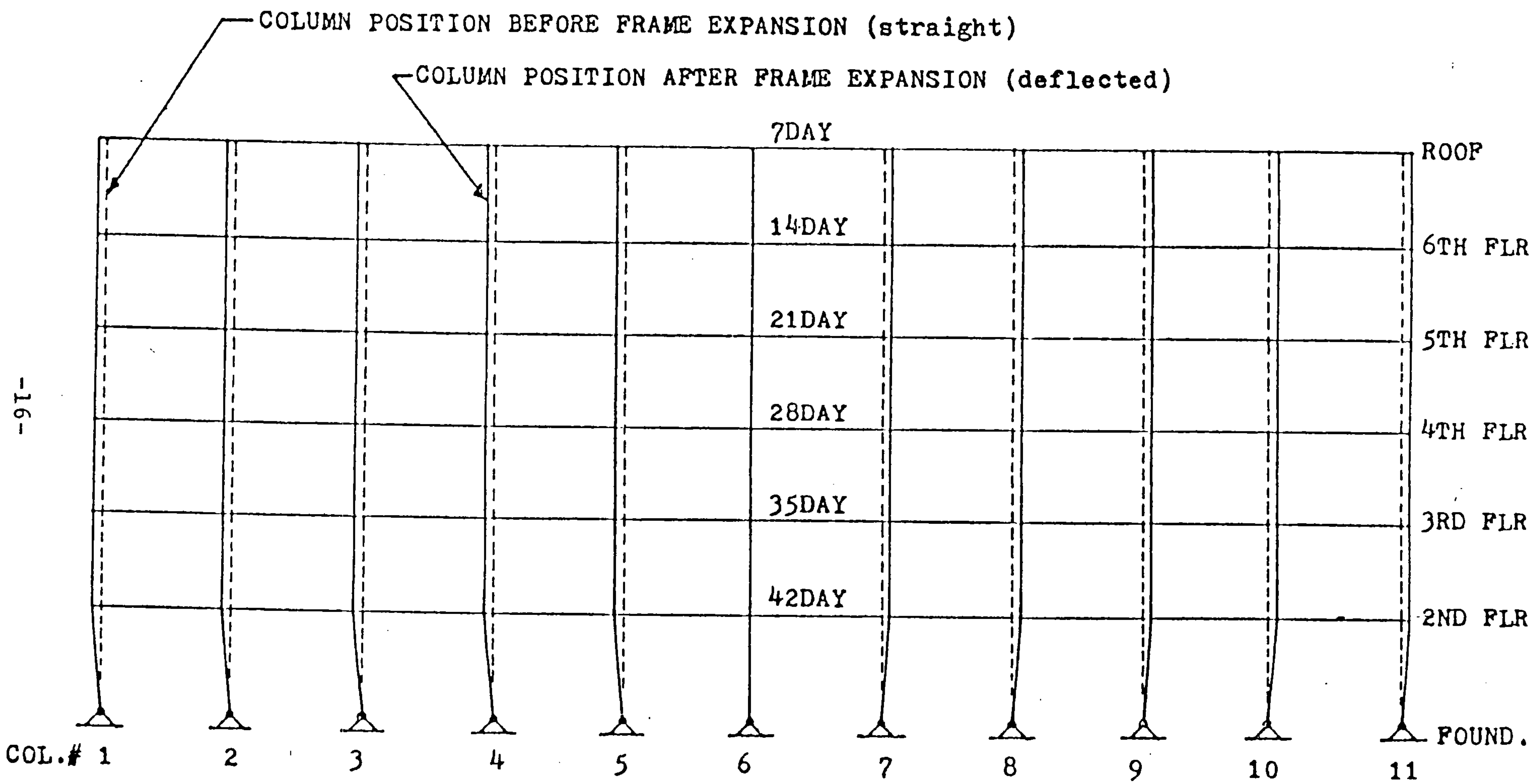


FIGURE 6 ELEVATION OF BUILDING FRAME AFTER EXPANSION HAS TAKEN PLACE

D \ C	1	2	3	4	5	6	7	8	9	10	11	FIG.
EC7	-0.570	-0.456	-0.342	-0.228	-0.114	0.0	+0.114	+0.228	+0.342	+0.456	+0.570	6
7	-0.371	-0.297	-0.223	-0.148	-0.074	0.0	+0.074	+0.148	+0.223	+0.297	+0.371	6
14	-0.300	-0.240	-0.180	-0.120	-0.060	0.0	+0.060	+0.120	+0.180	+0.240	+0.300	6
21	-0.263	-0.211	-0.158	-0.105	-0.053	0.0	+0.053	+0.105	+0.158	+0.211	+0.263	6
28	-0.235	-0.188	-0.141	-0.094	-0.047	0.0	+0.047	+0.094	+0.141	+0.188	+0.235	6
35	-0.216	-0.173	-0.130	-0.086	-0.043	0.0	+0.043	+0.086	+0.130	+0.173	+0.216	6
42	-0.198	-0.158	-0.119	-0.079	-0.040	0.0	+0.040	+0.079	+0.119	+0.158	+0.198	6
90	-0.111	-0.088	-0.066	-0.044	-0.022	0.0	+0.022	+0.044	+0.066	+0.088	+0.111	6
180	-0.072	-0.058	-0.043	-0.029	-0.014	0.0	+0.014	+0.029	+0.043	+0.058	+0.072	6
270	-0.023	-0.019	-0.014	-0.009	-0.005	0.0	+0.005	+0.009	+0.014	+0.019	+0.023	6
365	+0.027	+0.022	+0.016	+0.011	+0.005	0.0	-0.005	-0.011	-0.016	-0.022	-0.027	5
30 YR	+0.103	+0.082	+0.062	+0.041	+0.021	0.0	-0.021	-0.041	-0.062	-0.082	-0.103	5

D = Days Old ; C = Column ; FIG. = Related Figure Showing Movement of Frame
Units of measurement: INCHES ; + = Movement to right ; - = Movement to left

TABLE 2 EXPANSIVE CONCRETE COLUMN JOINT EXPANSION & SHORTENING MOVEMENTS