

# TEMPERATURE DESIGN OF POST-TENSIONED FLOORS<sup>1</sup>

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## APPENDIX

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## REFERENCES

Daily temperature changes, differences in the ambient temperature between when a building is under construction and when it is in service, and differences in ambient temperatures on different levels can all create stresses in a concrete frame building. This Technical Note discusses the effects of temperature change on concrete floor slabs with and without post-tensioning and shows how to design for temperature change using the ACI 318 building code. The Note concludes with a design example for a multi-story building.

## 1 – TEMPERATURE LOAD

Temperature change can result in stresses and deformation in concrete frame buildings. In most cases, the effects of temperature change are within the acceptable range of the building's in-service response. However there are conditions where the effects of temperature change are large and must be evaluated and accounted for, to mitigate their adverse impact on the building's performance.

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**1.1 Daily Changes in Temperature**

Daily ambient temperature changes for exposed roof slabs can lead to temperature gradients through the slab depth. The daily change in temperature subjects the slab to “short term” but repetitive temperature effects. The gradient will depend on the exposure and slab thickness but can exceed 10 °C (50 °F)

**1.2 Seasonal and Other Long-Term Temperature Changes**

When construction takes place in one season, but the building is placed in service during a different season, and possibly, in a temperature-controlled environment, there can be a change of up to 20 °C in the ambient temperature of a slab’s environment. A change of this type typically leads to uniform temperature change through the thickness of the slab with “long-term” effects that are reduced by concrete creep.

In multi-story buildings, there can be a difference between the ambient temperature above and below a slab, such as between a mechanical floor that is not air-conditioned and a floor above or below that is. Over time, the difference between the two ambient temperatures results in a temperature gradient through the depth of the slab, with “long-term” temperature effects. The effects of a “long-term” temperature gradient differ from those of a “short-term” gradient caused by daily temperature changes, since the effects of long-term exposure are partly mitigated by concrete creep.

**2 TEMPERATURE LOAD EFFECTS**

Stresses and deformations from temperature changes are additive to those of other loads, such as dead, live and prestressing. However, temperature change only causes internal forces if the structure is restrained against temperature-induced deformation. Figure 2-1(c) shows an object fixed in position at two supports. A rise in temperature will result in the internal forces at, and around, the supports as shown in part (c) of the figure. A similar rise in temperature will not cause internal forces in the unrestrained object shown in 2.1(b).

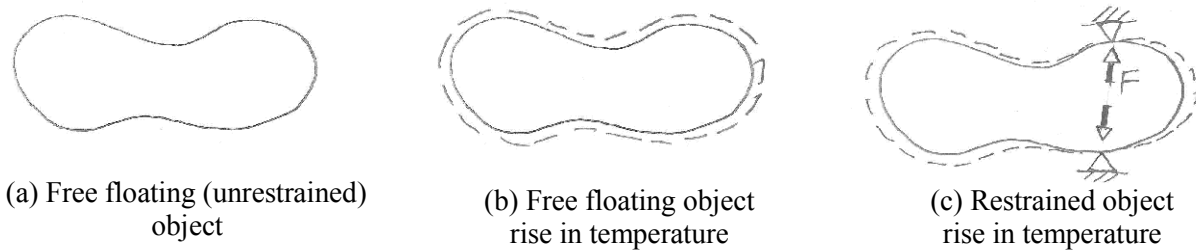


FIGURE 2-1 Free floating (unrestrained) and restrained homogeneous objects subjected to a temperature rise. In part, (c) the object is not free to deform, hence internal stresses are generated.

Figure 2-2 is a schematic of the lower levels of a multi-story frame. The connection shown in Figure 2-2a (a fixed connection to the foundation) will create restraint forces in the frame due to temperature changes, whereas the connection shown in Fig. 2-2-b, which is free to rotate and move laterally does not result in such forces.

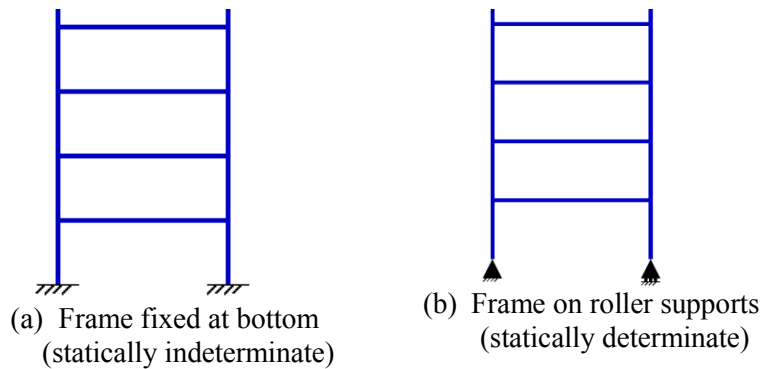


FIGURE 2-2 Partial Elevation of Multi-Story Frame. Because the statically determinate connection to the supports shown in (b) allows free movement of the structure, there are no internal stresses from temperature change, whereas the restrained (indeterminate connection) in (a) leads to internal stresses.

For building frames, the global constraints are generally the connections to the foundations. The restraint forces decrease rapidly with distance from the foundation. Figure 2-3 illustrates this concept for a multistory frame subjected to a uniform change in temperature. Note that by the second elevated slab, the forces will no longer be significant for design. The distribution shown in Fig. 2-3 assumes that the frame will respond elastically and there is no cracking. In practice, minute cracks are likely to develop at the floor connections to its supports, and along the columns and walls. These cracks relieve the temperature-generated forces so that concrete structures are rarely subjected to the level of internal stresses that are calculated from a non-cracked elastic analysis.

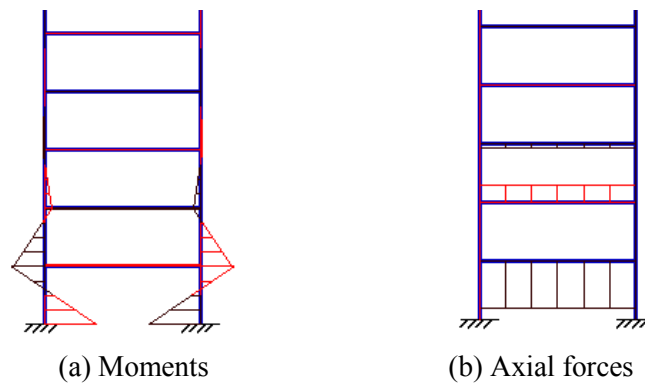


FIGURE 2-3 Partial elevation of a concrete frame with restrained supports subject to a uniform change in temperature over the entire frame. The change in temperature results in forces in wall/column supports and floors at or near the supports but these forces decrease rapidly with distance from the supports.

The following temperature change example illustrates the impact of temperature load on post-tensioned members. Note that the coefficients of thermal expansion for concrete and steel are similar, and for design purposes, they can be considered to be the same. The following parameters are used to represent a typical post-tensioned floor slab:

$$\alpha = 12 \times 10^{-6} / ^\circ\text{C} \quad ; \text{ coefficient of thermal expansion of both concrete and steel } (54 \times 10^{-6} / ^\circ\text{F}) \quad ;$$

- $f'_c = 35 \text{ MPa}$  ; 28 day concrete cylinder strength (5,076 psi) ;
- $E_c = 35,000 \text{ MPa}$  ; modulus of elasticity of concrete (5,076 ksi) ;
- $C_{cr} = 2$  ; creep coefficient of concrete, for long-term effects of temperature;
- $f_r = 0.33\sqrt{f'_c}$  ; cracking stress of concrete under uniform tension ( $f_r = 4\sqrt{f'_c}$ );
- $E_s = 200,000 \text{ MPa}$  ; modulus of elasticity of prestressing steel (29,008 ksi) ;

- ❖ Post-tensioned floors are typically designed for 1 MPa (145 psi) precompression for service condition.
- ❖ The change in ambient temperature over long-term for illustration purposes is assumed 20 °C (68 °F) .
- ❖ The daily temperature gradient through the depth of an exposed post-tensioned slab, such as roof slab is assumed 10 °C (50 °F).
- ❖ Concrete strain to cause 1 MPa stress is  $\varepsilon = 1/35,000 = 28.6 \times 10^{-6}$  28.6 micro strain
- ❖ Temperature change to cause strain associated with 1 MPa stress in concrete is:  
 $T = 28.6 \times 10^{-6} / 12 \times 10^{-6} = 2.38 \text{ }^\circ\text{C}$  (4,28 °F)

Using the preceding values and the expression  $f_r = 0.33\sqrt{f'_c}$  ( $f_r = 4\sqrt{f'_c}$ ), for concrete with  $f'_c = 35 \text{ MPa}$  (5,076 psi), the cracking stress,  $f_r = 1.95 \text{ MPa}$  (283 psi).

$\varepsilon_c = f_r / E_c = 1.95 / 35000 = 56 \times 10^{-6}$  ; Thus the concrete strain at the initiation of cracking will be 56 micro-strains

The instantaneous drop in temperature that will lead to cracking of restrained concrete is therefore:

$$T = \varepsilon_c / \alpha = 56 \times 10^{-6} / 12 \times 10^{-6} = 4.67 \text{ }^\circ\text{C}$$
 (8.41 °F)

Long-term drop in temperature to cause through crack of restrained concrete = 2 x 4.67 = 9.33 °C (16.79 °F)

Where 2 is the assumed ultimate creep coefficient of concrete

Figure 2-5 illustrates the response of a concrete element under different conditions of temperature change, support restraint, and post-tensioning.

### 3 DESIGN FOR TEMPERATURE EFFECTS

#### 3.1 Temperature Reinforcement

The load combination for temperature design is the “sustained” (quasi permanent) condition, to which the temperature effect is added.

$$U = 1.00DL + K_iLL + K_iT \quad (\text{Exp 3.1-1})$$

Where  $K_i$  is the coefficient of temperature effects. For a change in ambient temperature,  $K_i=0.5$ . This is based on the assumption that the temperature change takes place over a month or longer, so that the creep response of concrete governs. The ultimate creep factor for concrete is generally taken as 2 – hence the 0.5 factor for  $K_i$ . For a temperature gradient taking place on daily basis  $K_i=1$ .

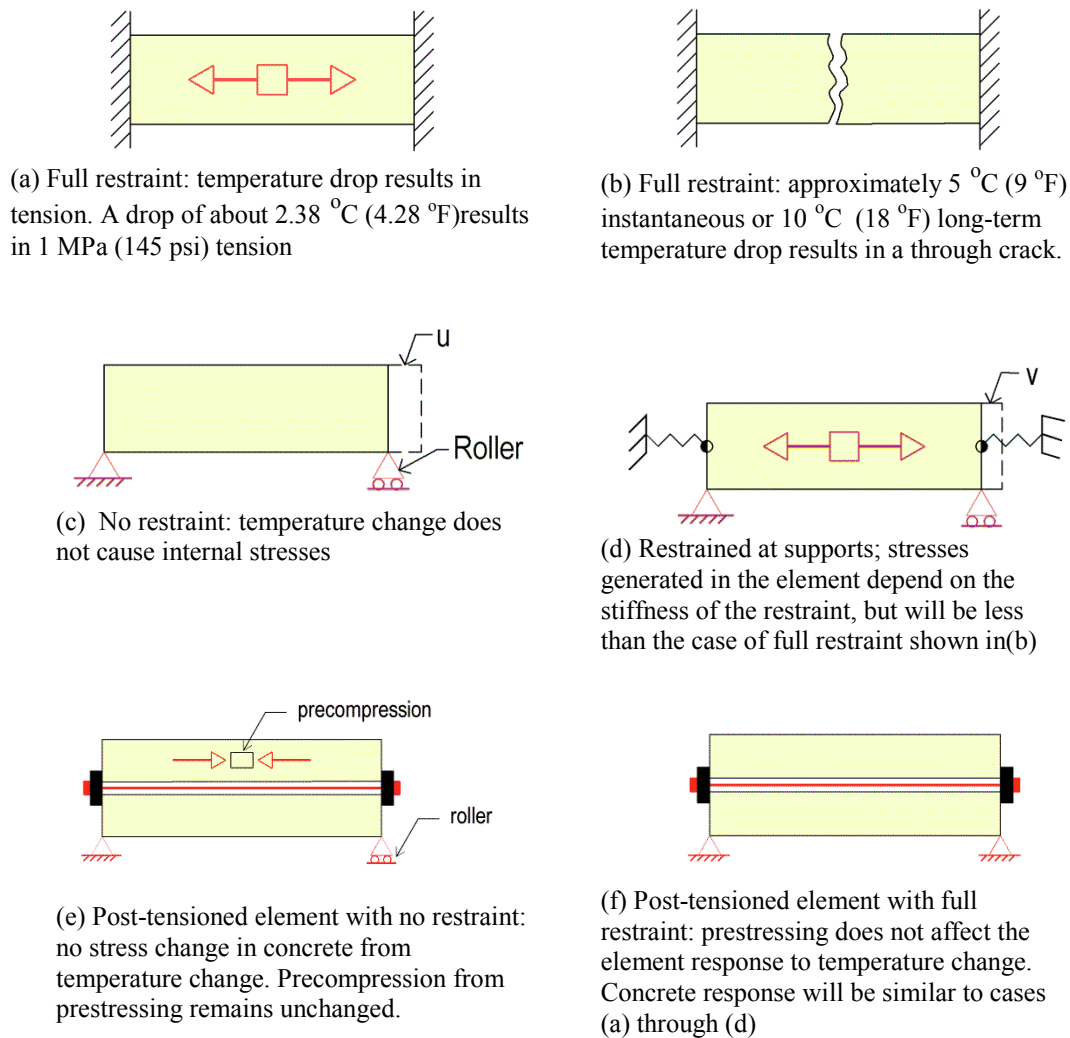


FIGURE 2-5 Concrete Element Subjected to Temperature Change  
 The impact of support restraint and prestressing on a concrete element is illustrated. The coefficients of thermal expansion for concrete and steel are assumed to be the same.  
 (PTS804;PTS805)

The fraction of live load for the sustained (quasi permanent) condition depends on the building code used. ACI 318 leaves it to the judgment of the design engineer. The common practice is to use  $K_l=0.3$  for common residential and commercial buildings.

Temperature drop and shrinkage have similar effects on concrete elements. ACI 318-11, §7.12.2 requires the following when members are designed using post-tensioning to control cracking from temperature and shrinkage.

*“Tendons shall be proportioned to provide a minimum average compressive stress of 100 psi (0.69 MPa) on gross concrete area using effective prestress, after losses ...”*

For conventionally reinforced members, ACI 318-11’s recommendation is to provide deformed bars or welded wire mesh of not less than 0.18% of the section’s gross cross-sectional area. For post-tensioned members, the temperature and

shrinkage requirements can be satisfied with a combination of prestressed and non-prestressed reinforcement, as shown in Fig. 3-1 (graphical presentation of ACI 318-11 §7.12.2).

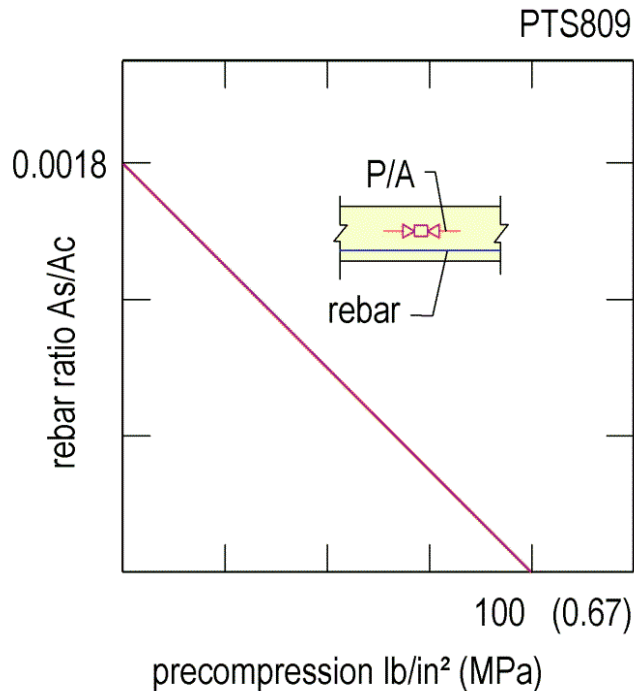


FIGURE 3-1 Minimum Temperature and Shrinkage Requirement for Post-Tensioned Members  
A combination of precompression and non-prestressed reinforcement can be used to meet the minimum temperature and shrinkage reinforcement required by ACI 318-14 (§7.12.2)

From Fig. 3-1, the following applies when unbonded reinforcement is used:

$$100/(P/A) + (A_s/A_c)/0.0018 \geq 1 \quad (\text{Exp 3-1.2})$$

When bonded post-tensioning is used, the area of the strands can be included in accordance with Exp 3.1-3, provided the tendon layout meets the detailing requirements outlined in Section 4.

$$100/(P/A) + [(A_s + A_{ps})/A_c]/0.0018 \geq 1 \quad (\text{Exp 3-1.3})$$

Where;

- $P/A$  = average precompression;
- $A_s$  = nonprestressed steel cross-sectional area;
- $A_c$  = concrete cross-sectional area; and
- $A_{ps}$  = cross-sectional area of bonded prestressing.

### 3.2 Cracking and Deflection Check

Possible consequences of changes in temperature are extreme fiber cracking and enlargement of existing cracks. Either condition can cause an increase in member deflection. Where deflection of a member is critical, its value under temperature load should be computed and verified for compliance.

## 4 DETAILING

Temperature and shrinkage reinforcement is designed to control crack width. For slab dimensions common in residential and commercial construction ACI 318-11<sup>3</sup> recommends a maximum spacing of 18 in (450 mm) or 1.5 times the slab thickness. ACI 318-11<sup>4</sup> also has a maximum spacing for unbonded tendons that are intended for temperature control, but in the author's opinion, the spacing of unbonded tendons does not relate to the control of cracking from temperature and shrinkage effects – rather, it is the resulting precompression that affects the cracking. This requirement can be waived if necessary to simplify the tendon placement.

The European code EC2 recommends a maximum spacing of 450 mm<sup>5</sup> between reinforcement intended for shrinkage and temperature control.

Where bonded tendons are used, for spacing requirements, each bonded tendon is viewed equivalent to a non-prestressed reinforcement. Hence, the applicable clear spacing between adjacent sheathing of bonded tendons, or a post-tensioned bonded tendon and the next non-prestressed reinforcement is the same as stipulated above.

For post-tensioned members, temperature reinforcement, where required, is placed on the side of the member with smaller compression. This is generally the side, where tendons are located.

## 5 DESIGN EXAMPLE

The high-rise building shown in Fig. 5-1 extends above the plaza level at the base. The building will be constructed in an environment where there will be a significant change in the ambient temperature between the construction in open air and the completed, air-conditioned building. The change in ambient temperature between construction and the completed building is estimated to be 20 °C (36 °F). In addition, at the roof level, the daily change between the exposed surface and the uppermost floor is expected to result in a temperature gradient of 10 °C (18 °F) through the depth of the roof slab.

It is necessary to determine whether the reinforcement specified for the gravity and lateral design of the building is adequate for the temperature load; and if deficient, to determine the reinforcement needed to account for the effects of temperature load.

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<sup>3</sup> ACI 318-11, Section 7.12.2.2

<sup>4</sup> ACI 318-11 Section 7.12.3.4

<sup>5</sup> EC2 1992-1-1:2004, Section 9.3.1.1



FIGURE 5-1 High-Rise Tower Subject to Temperature Loading (P1002)

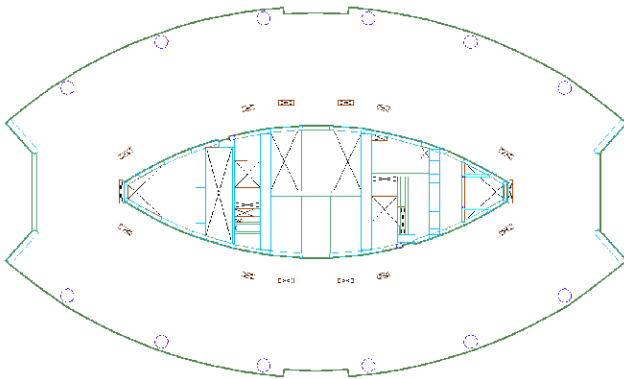
The floor plan of the typical level is shown in Fig. 5-2. The principal parameters of the construction are:

- Slab thickness            220 mm (8.66-in.)
- Concrete strength;  $f'_c$     34 MPa (4,930 psi)
- Reinforcement:            bonded post-tensioning and non-prestressed reinforcement

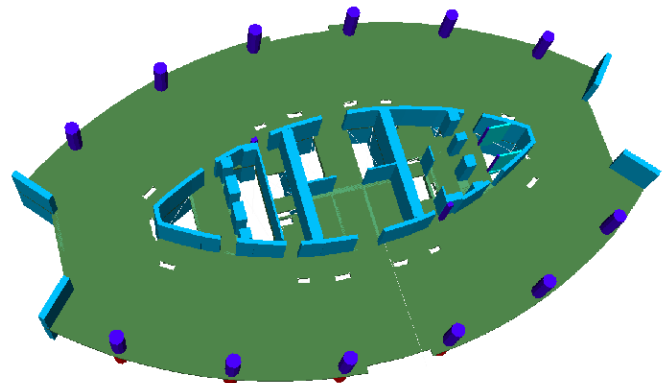
- Loads:
- SDL = 3.3 kN/m<sup>2</sup> (68.90 psf)
  - Perimeter load = 10 kN/m (737 lb/ft)
  - LL = 2.5 kN/m<sup>2</sup> (52.2 psf) ; in certain areas LL is increased to 5.5 kN/m<sup>2</sup> (114.8 psf)

- Change in ambient temperature
- 20 °C (36 °F) drop between construction and service conditions for typical level
  - Daily temperature gradient in roof level due to 10 °C (18 °F) rise at the exposed top surface





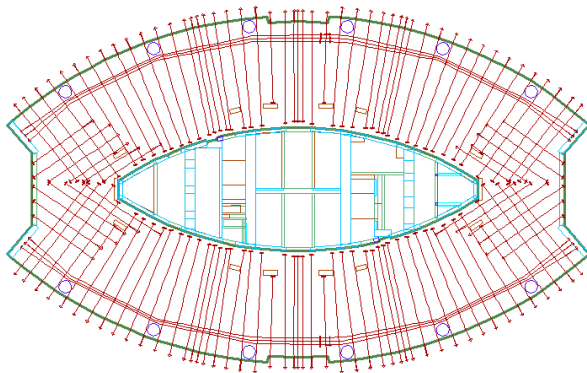
(a) Plan of a typical level (P1005)



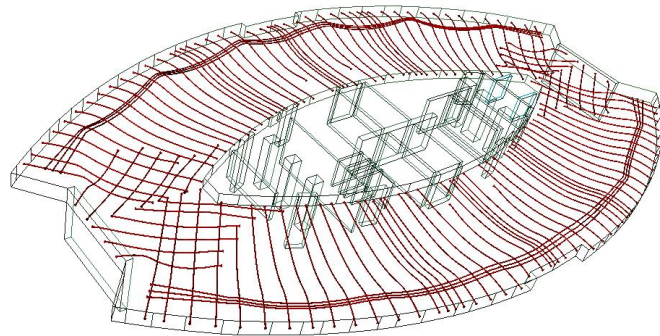
(b) 3D view of the typical level (P245)

FIGURE 5-2 Plan of Typical Level

The tendon layout of the typical floor is shown in Fig. 5-3. In addition to the tendons shown, the slab has a bottom mesh of 8 mm at 200 mm (#5 @ 7.87" o.c.) in each direction.



(a) Plan of tendon layout (P1006)



(b) 3D view of tendon layout (P1007)

FIGURE 5-2 Tendon Layout of Typical Floors

The post-tensioning is a bonded system with each duct containing 3 to 5 strands of 13 mm (0.5-in.) diameter;  $f_{pu} = 1860$  MPa (270 ksi)

The design for temperature and shrinkage uses the same modeling scheme and load path selection that is used for gravity design. The floor slab is subdivided into design strips and design sections are chosen for each design strip. Force demands are calculated at each of the design sections and the required reinforcement is determined [Aalami, 2014].

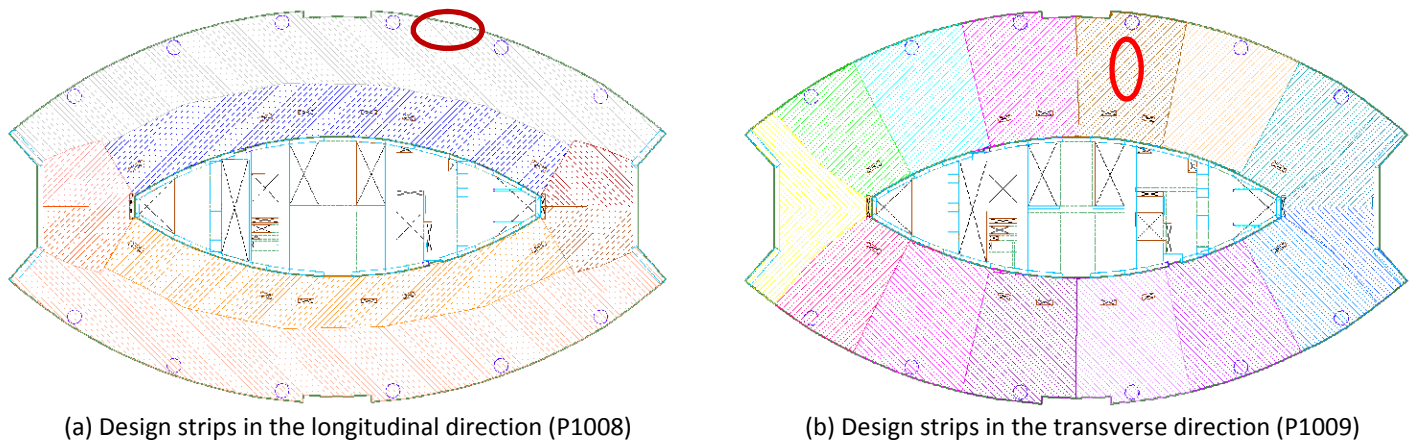


FIGURE 5-3 Division of the Floor Slab into Design Strips  
 Typical spans for detailed temperature design are identified  
 in the longitudinal direction (part a) and transverse direction (part b)

Three separate temperature designs are typically done for high-rise buildings with similar floor plans. These are: (i) the design of first level above the plaza/podium construction or the foundation, where there is no podium construction; (ii) design of a typical level; and (iii) design of the roof level.

### 5.1 First Slab above the Plaza Construction

For this level, because of the more robust construction of the plaza structure, the bottom of the walls and the columns are conservatively assumed to be fixed against movement and rotation at their connection to the plaza.

Specifics of the design strips are:

In the transverse direction (Y-Y)

Average width of the design strip	=	5,650 mm (18' 6")
Slab thickness	=	220 mm (8.66-in.)
Cross-sectional area of the design section	=	5,650x220 = 1.243x10 <sup>6</sup> mm <sup>2</sup> (1,926-in <sup>2</sup> .)

In the longitudinal direction (X-X)

Average width of the design strip	=	9,000 mm (354.33-in.)
Slab thickness	=	220 mm (8.66-in.)
Cross-sectional area of the design section	=	9,000x220 = 1.98x10 <sup>6</sup> mm <sup>2</sup> (3,069-in <sup>2</sup> .)

Figure 5.1-1 shows the distribution of axial stress in the slab caused by a 20 °C (36 °F) long-term drop in ambient temperature.

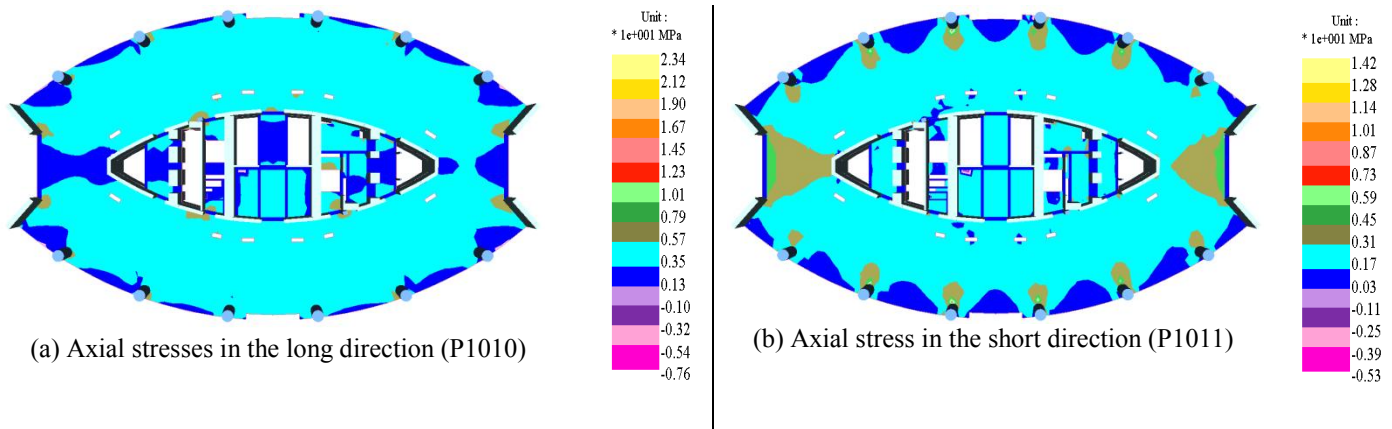


FIGURE 5.1-1 Distribution of axial stress in the first level above the plaza construction from a drop of 20 °C (36 °F) in ambient temperature. Stresses shown are in MPa. Tension is shown positive. The wall and column supports are assumed fixed against movement and rotation at their connection to the podium. The axial stresses shown are additive to those from gravity and other loads. (1 MPa = 145 psi)

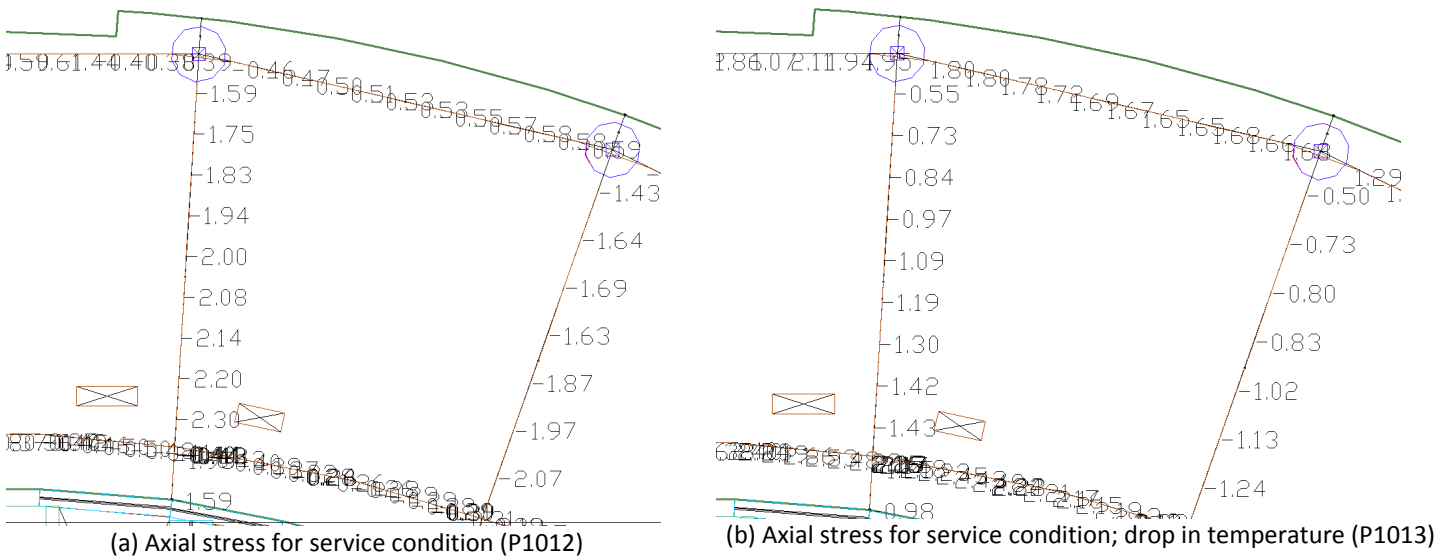


FIGURE 5.1-2 Distribution of axial stress in the first level above the podium. The values shown are the stresses along the support lines of the design strips in Fig. 5-3 for the sustained service (quasi permanent) load combination plus 20 °C drop in ambient temperature. Stresses shown are in MPa. Tension is positive. At the critical location of the longitudinal direction (X-direction), the initial precompression of -0.52 MPa at midspan has become a tensile stress of 1.69 MPa. Temperature reinforcement will be required at this location. (1 MPa = 145 psi)

**A- Transverse Direction:** In the transverse (Y-Y) direction, the precompression at midspan is reduced from 2.00 MPa compression to 1.09 MPa compression. The reduced amount still exceeds the threshold of 0.67 MPa compression that would trigger the requirement of additional reinforcement for temperature control. Hence, no additional rebar is necessary in the radial direction.

**B – Longitudinal Direction:** In the longitudinal direction (X-X), the value of 0.52 MPa compression is reduced to 1.69 MPa tension by the drop in temperature. ACI 318’s provision for temperature and shrinkage reinforcement is based on the premise that shrinkage and a drop in temperature will result in crack formation, which will mobilize the recommended reinforcement to control crack width. In this case, since there will be no contribution from precompression, the required reinforcement is given by:

$$A_s = 0.0018A_c = 0.0018 \times 220 \times 1000 = 396 \text{ mm}^2/\text{m}$$

Reinforcement from the provided bottom mesh of 8 mm@200 mm each way

$$A_{s,provided} = 5 \times 50.3 = 251.1 \text{ mm}^2 < 396 \text{ mm}^2/\text{m}$$

Hence, additional reinforcement is required.

Per ACI 318, the spacing of the reinforcement should not be greater than 450 mm. Since the bonded tendons are grouped along the boundary of the floor, their contribution at distances farther than 450 mm is not accounted for in crack control. Distributed reinforcement is required to cover the shortfall of reinforcement on this level.

Provide 10 mm bars @ 150 mm o.c.

$$A_{s,prov} = 523 \text{ mm}^2/\text{m} > 396 \text{ mm}^2/\text{m} \text{ OK}$$

### 5.2 Typical Levels

With respect to design, the primary difference between the typical levels and the first level above the podium are the support conditions at the far end of the supports. For the typical levels, the far end of the supports is effectively free to move horizontally, since they rest on a slab of similar conditions with respect to the tendency to shorten. However, as with the first level above the podium, the ends of the supports are assumed rotationally fixed.

The 20 °C drop in ambient temperature will result in the distribution of axial stresses shown in Fig. 5.2-1

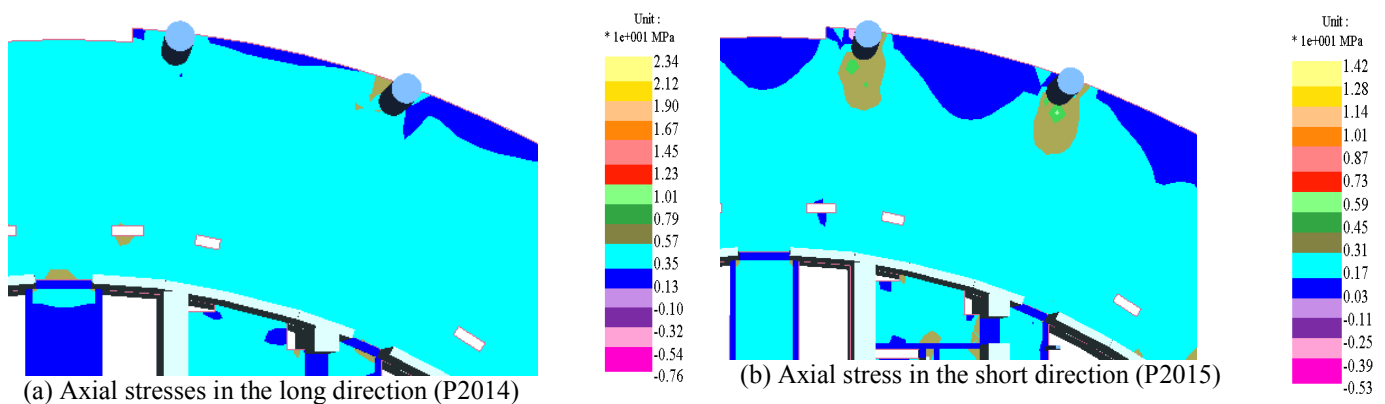


FIGURE 5.2-1 Distribution of axial stress from a drop of 20 °C in ambient temperature in the typical level. Stresses shown are in MPa. Tension is shown positive. The bottom of the wall and column supports are assumed free to move horizontally, but are rotationally fixed. The distributions show development of tension in both the longitudinal and transverse direction from the temperature drop.

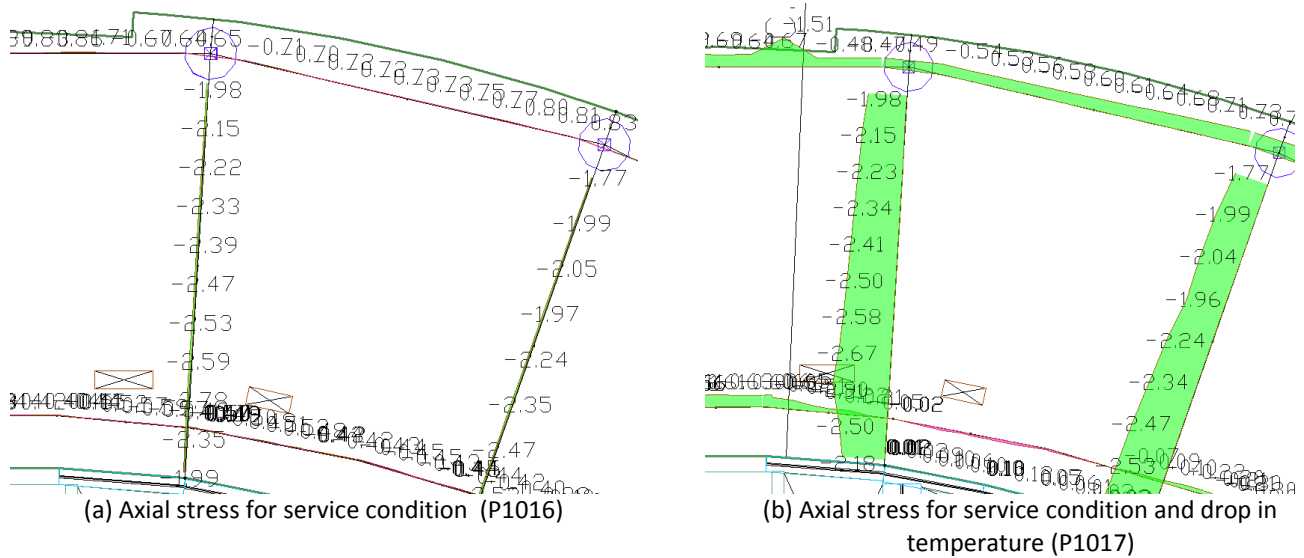


FIGURE 5.1-2 Distribution of Axial Stress from Drop of 20 °C in Ambient Temperature  
 The drop in temperature has negligible impact on the stresses in the transverse direction, but reduces the precompression in the longitudinal direction due to the greater impact of core walls on the shortening in this direction. (1 MPa = 145 psi)

**A- Transverse Direction:** In the transverse direction (Y-Y), the compressive stresses at midspan increase from 2.39 MPa compression to 2.41 MPa compression. The increase in compression is not significant.

**B – Longitudinal Direction:** In longitudinal (X-X) direction, the temperature drop reduces the axial compression of the service condition from 0.72 to 0.58 MPa. Hence, temperature reinforcement is required. Since the post-tensioning tendons are banded along the perimeter (Fig. 5-2), they do not meet the requirement for a maximum spacing of 450 mm. Hence, the entire reinforcement will be provided by well-distributed non-prestressed reinforcement.

$$A_s = 0.0018A_c = 0.0018 \times 220 \times 1000 = 396 \text{ mm}^2/\text{m}$$

The plans show a bottom mesh of 8 mm@200 mm each way.

$$A_{s,provided} = 5 \times 50.3 = 251.1 \text{ mm}^2 < 396 \text{ mm}^2/\text{m}$$

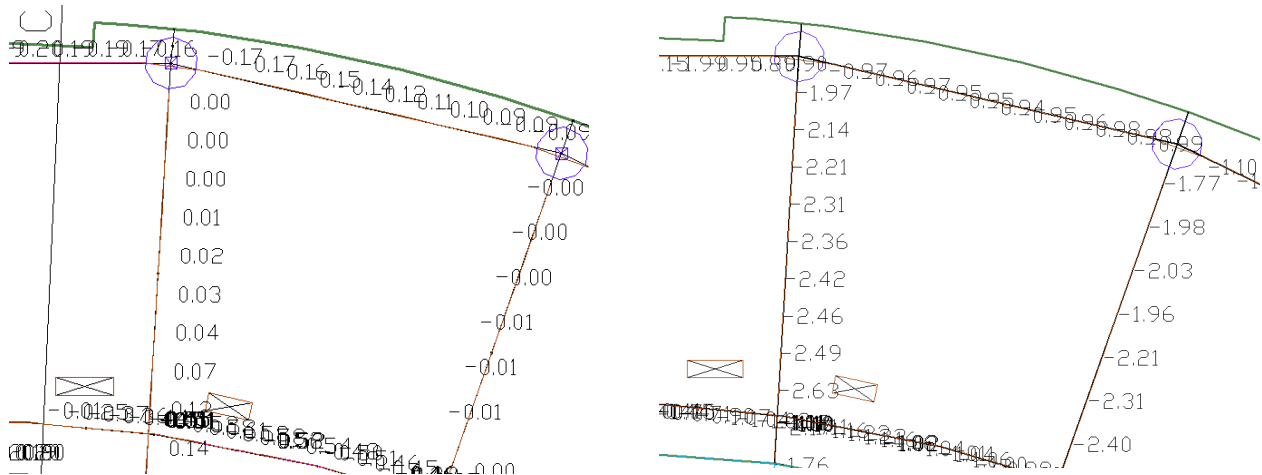
Additional bottom steel is required. Change the bottom mesh to 10 mm @150 mm o.c.

$$A_{s,prov} = 523 \text{ mm}^2/\text{m} > 396 \text{ mm}^2/\text{m} \text{ OK}$$

### 5.3 Roof Level

The exposed surface of the roof slab experiences a daily change of temperature through its depth. The temperature gradient will depend primarily on the insulation of the roof cover and the slab depth. In the absence of specific data for the project, a 10 °C temperature difference between the two faces of the roof slab is considered. In effect, the roof slab will be subject to a temperature gradient with 10 °C.

The distribution of stress due to the rise in temperature at the top surface of the roof slab is shown in Fig. 5.3-1



(a) Axial stress in the roof slab from 10 °C temperature gradient; higher value at top (MPa) (P1018)

(b) Axial stresses in the roof slab from sustained service load combination and temperature gradient of (a) (P1019)

FIGURE 5.3-1 Distribution of axial stress from 10 °C daily temperature rise at the top surface of the roof slab.

The distribution of temperature rise through the roof slab is assumed linear – maximum at the exposed top surface and zero at the bottom surface. Values shown are in MPa; tension is shown positive. The rise in temperature results in the development of slight tension stresses in the radial (Y-Y) direction and compression stresses in the longitudinal direction (X-X).

From Fig. 5.3-1(b) The combined effects of gravity load and temperature gradient does not change the distribution of the axial stress enough to trigger the requirement for temperature reinforcement. In both directions, the average stress is precompression in excess of 0.67 MPa. (1 MPa = 145 psi)

## APPENDIX

### TEMPERATURE ANALYSIS AND DESIGN AID

Stresses arising from changes in temperature are similar to those arising from other loads, such as superimposed dead, live and wind load. Temperature effects are combined with those from other loads acting concurrently. In addition to stresses, temperature change can result in deformation, and possibly cracking. The following are the central analysis and design requirements for temperature analysis and design software.

#### 1 – Application of temperature effects.

As with other loads, temperature effects can affect specific regions of a floor slab or building. Depending on occupancies, there can be significantly different temperatures in adjacent regions of a floor, or in the floors on either side of a slab (Fig. A-1).

#### 2 – Change in temperature through the depth of the structural element.

The distribution of temperature through the depth of the member can be uniform, or linear as indicated in Fig. A-2

- 3 - The change in temperature can take place over a relatively long period, such as seasonal changes, or can be short term, such as daily. The effects will be different and need to be accounted for differently in load calculations.
- 4 – Temperature effects must be combined with the effects of other loads on the structure. Reinforcement specified for other load conditions should be evaluated and adjusted as required for temperature effects.
- 5 – When detailing temperature reinforcement, bonded post-tensioning tendons should be taken into account. Their effectiveness is limited to the distance recommended for spacing of temperature reinforcement,

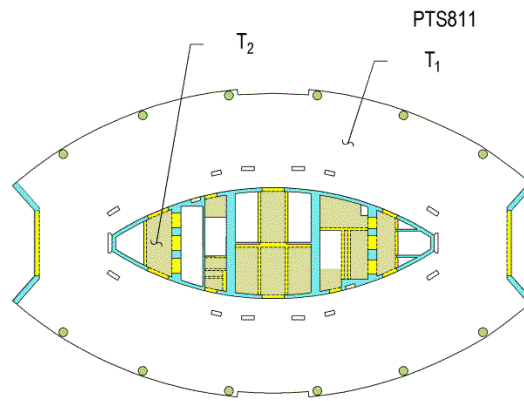


FIGURE A-1 Plan: Different Regions of a Floor Subject to Different Temperatures

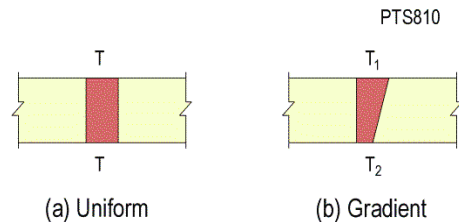


FIGURE A-2 Distribution of Temperature through Depth of Member  
 (a) shows uniform distribution of temperature. (b) shows a linear distribution of temperature through the depth

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