Basic Questions

- When does it happen?
- What are the consequences?
- How to predict it?
- How to compensate it?
- Other considerations.
When does it happen?

- Height of the building
- Construction sequence
- Difference in axial stress
- Difference in cross sectional shapes
- Reinforcement quantities
What are the consequences?

- Differential shortening between core & columns.
- Distortion of slab
- Redistribution of vertical loads
- Additional moments in the slab
- Effects on non-load bearing elements such as Partitions, cladding, finishes & piping
How to predict it?

- Estimated axial load in vertical elements based on uncracked section properties for all the elements
- Construction Sequence is assumed
- Material properties of concrete Elastic Modulus, ultimate shrinkage and specific creep (use experimental values if not then use codified values)
- Methods to estimate strength gain of concrete, shrinkage and creep with time
- Use Mark Fintel et al to calculate shortening
- Difference between core and columns is shortening of columns
How to compensate it?

- At design stage try to balance the loads (equal stresses in core and columns)

- During construction phase:
  - Composite or steel framing
    - For columns with steel cross sections either fabricate them longer or use site steel shims
    - Alternatively put the beam connection points in the core at a lower level
  - For concrete frame columns adjust formwork to the required length
Other Considerations

- Additional effects
  - Wind loading
  - Temperature effects
  - Differential foundation movements
- Performance Criteria
- Material Testing
Elastic Shortening

Up to Casting of Solution-Floor Level (denoted by subscript \( p \))

\[
\Delta_{1,p}^e = \sum_{j=1}^{N} \sum_{l=j}^{N} \frac{P_i h_j}{A_{1,ij} E_{ct,ij}}
\]

with

\[
E_{ct,ij} = 33 \cdot w^{1.5}/f'_{ct,ij}
\]

\[
f'_{ct,ij} = \frac{f'_{c,f}(t_i - t_j)}{4.0 + 0.85(t_i - t_j)}
\]

and

\[
A_{t,ij} = A_{g,ij} + A_{s,ij}(m_{ij} - 1)
\]

\[
m_{ij} = \frac{E_s}{E_{ct,ij}}
\]

Subsequent to Casting of Solution-Floor Level (denoted by subscript \( s \))

\[
\Delta_{1,s}^e = \sum_{j=1}^{N} \sum_{l=N+1}^{n} \frac{P_i h_j}{A_{1,ij} E_{ct,ij}}
\]
Ec of High Strength Concrete

- For normal strength concrete of
  - \( Ec = 33 \, w^{1.5} \sqrt{f'c} \) about \( 57,000 \sqrt{f'c} \)
  - \( w \) in \( \text{lb/ft}^3 \) = 145 \( \text{lb/ft}^3 \)
  - \( f'c \) in \( \text{psi} \) (valid to about 6,000 psi)
  - \( Ec \) in \( \text{psi} \)

- For high strength concrete
  - \( Ec = 3320 \sqrt{f'c} + 1.0 \times 10^6 \)
  - \( 3,000 < f'c < 12,000 \, \text{psi} \)
Creep

**Due to Initial Loads (denoted by subscript 1)**

Up to Casting of Solution-Floor Level (denoted by subscript \(p\))

\[
\Delta_{t_{1,p}} = \sum_{j=1}^{N} \sum_{i,j} \frac{P_i CR_{LA,ij}}{A_{t,ij}} \cdot \epsilon_{c_{c,ij}} \cdot h_j \cdot CR_{VS,ij} \cdot CR_H \cdot CR_{t,ij} \cdot CR_{R,ij}
\]

(18)

where

\(CR_{LA,ij} = 2.3(t_i - t_f) - 0.25\) — from equation (7) (18a)

\(A_{t,ij}\) has been defined by equations (13a), (13a'), (13b), and (13b')

\(CR_{VS,ij} = \frac{0.044(v,s)_j + 0.934}{0.1(v,s)_j + 0.85}\) — from equation (8) (18b)

\(CR_H\) is given by equation (9)

\(CR_H = 1.40 - 0.01H\)

(9)

where \(H\) is the relative humidity in percent. Again, it is suggested that the average annual value of \(H\) should be used.

\[CR_{t,ij} = \frac{(t_N - t_f)^{0.6}}{10.0 + (t_N - t_f)^{0.6}}\] if \(t_N \geq t_f\)

\[= 0\] if \(t_N \leq t_f\)

— from equation (10) (18c)

and

\[CR_{R,ij} = \frac{1 - e^{-p_j m_{ij} \cdot \epsilon_{c_{c,ij}} \cdot E_{c,ij}}}{p_j \cdot \epsilon_{c_{c,ij}} \cdot E_s}\]

— from equation (11) (18d)

\[\epsilon_{c_{c,ij}} = \epsilon_{c_{c,ij}} \cdot CR_{LA,ij} \cdot CR_{VS,ij} \cdot CR_H\] (18d'')

\[p_j = A_{s,ij} / A_{g,ij}\] (18d''')

**Subsequent to Casting of Solution-Floor Level**

(denoted by subscript \(s\))

\[
\Delta_{t_{1,s}} = \sum_{j=1}^{N} \sum_{i,j} \frac{P_i \cdot CR_{LA,ij}}{A_{t,ij}} \cdot \epsilon_{c_{c,ij}} \cdot h_j \cdot CR_{VS,ij} \cdot CR_H \cdot (1 - CR_{t,ij}) \cdot CR_{R,ij}
\]

(19)
Specific Creep

Let $\epsilon_{c\infty}$ denote the specific creep (basic plus drying) of 6-in.-diameter (150-mm) standard cylinders ($v:s = 1.5$ in. or 38 mm) exposed to 40% relative humidity following about 7 days of moist-curing and loaded at the age of 28 days. In the absence of specific creep data for concretes to be used in a particular structure, the following likely values of $\epsilon_{c\infty}$ may be used:

$$\epsilon_{c\infty} = \frac{3}{f'_{c}} \text{ (low value) to } \frac{5}{f'_{c}} \text{ (high value)} \quad (6)$$

where $\epsilon_{c\infty}$ is in inch per inch per kip per square inch if $f'_{c}$ is in ksi; or in inch per inch per pound per square inch if $f'_{c}$ is in psi. The lower end of the proposed range is in accord with specific creep values suggested by Neville.\(^{(16)}\) The upper end agrees with laboratory data obtained by testing concretes used in Water Tower Place\(^{(7)}\) in Chicago, Illinois.

Low value = $1.5 \times 10^{-3}/f'_{c}$
High value = $2.1 \times 10^{-3}/f'_{c}$
$f'_{c}$ in psi
Shrinkage

Up to Casting of Solution-Floor Level (denoted by subscript \( p \))

\[
\Delta^s_p = \sum_{j=1}^{N} h_j \cdot \epsilon_{s_{\infty},j} \cdot SH_{v:s,j} \cdot SH_H \cdot SH_{t,j} \cdot SH_{R,j} \quad (16)
\]

with

\[
SH_{v:s,j} = \frac{0.037(v:s)_j + 0.944}{0.177(v:s)_j + 0.734} \quad \text{—from equation (3)} \quad (16a)
\]

and

\[
SH_{t,j} = \frac{t_N - t_j - t'_j}{26.0e^{-0.36(v:s)_j} + (t_N - t_j - t'_j)} \quad \text{—from equation (5)} \quad (16b)
\]

where \( t'_j \) is the period of moist-curing of column \( j \), \( SH_{jH} \) is from equation (4), and \( SH_{R,j} \) (see equation 12) is defined as follows:

\[
SH_{R,j} = \sum_{i=j}^{n} CR_{R,ij} \quad \frac{n}{n - j + 1} \quad (16c)
\]

\( CR_{R,ij} \) is given by equation (18d).

Subsequent to Casting of Solution-Floor Level (denoted by subscript \( s \))

\[
\Delta^s_s = \sum_{j=1}^{N} h_j \cdot \epsilon_{s_{\infty},j} \cdot SH_{v:s,j} \cdot SH_H \cdot (1 - SH_{t,j}) \cdot SH_{R,j} \quad (17)
\]

\[
SH_H = 1.40 - 0.010H \text{ for } 40 \leq H \leq 80 \quad (4)
\]

\[
= 3.00 - 0.030H \text{ for } 80 \leq H \leq 100
\]
Attempts have been made in the past to correlate $\epsilon_{s, \infty}$ with parameters such as concrete strength. In view of experimental data now available,\textsuperscript{(7)} it appears that no such correlation may in fact exist. The only possible correlation is probably that between $\epsilon_{s, \infty}$ and the water content of a concrete mix (Fig. 7). In the absence of specific shrinkage data for concretes to be used in a particular structure, the value of $\epsilon_{s, \infty}$ may be taken as between $500 \times 10^{-6}$ in. per inch (low value) and $800 \times 10^{-6}$ in. per inch (high value). The latter value has been recommended by ACI Committee 209.\textsuperscript{(2)}
Subsequent Load

Elastic Shortening

Due to Subsequent Load Application(s) (denoted by subscripts 2, 3, and so on)

$$\Delta_e^2 = \sum_{j=1}^{N} \sum_{k} \frac{P_k \cdot h_j}{A_{i,k} \cdot E_{ci,kj}}$$  \hspace{1cm} (15)

with

$$E_{ci,kj} = 33 \cdot 1.5 \sqrt{\frac{f'_{ci,kj}}{f'_{cl,kj}}} \quad \text{— from equation (1)}$$  \hspace{1cm} (15a)

$$f'_{ci,kj} = \frac{f'_{ci}(t_k - t_j)}{4.0 + 0.85 (t_k - t_j)} \quad \text{— from equation (2)}$$  \hspace{1cm} (15a')

Creep

Due to Subsequent Load Application(s) (denoted by subscripts 2, 3, and so on)

$$\Delta_c^2 = \sum_{j=1}^{N} \sum_{k} \frac{P_k \cdot CR_{LA,kj} \cdot \epsilon_{\infty,j} \cdot h_j \cdot CR_{v,s,j}}{A_{i,kj}} \cdot CR_H \cdot CR_R,kj$$  \hspace{1cm} (20)
Rules of thumb for Total Shortening

- **Steel Columns**
  - Only Elastic Shortening about 1.5 to 2mm/floor

- **Concrete Columns**
  - Elastic Shortening about 0.5 to 0.8mm/ floor
  - Creep about 1 to 2 x Elastic Shortening
  - Shrinkage about 0.2 to 0.5 mm/ floor

- Overall very similar but happening at different times.
Al Mas Tower
160,000 sq.m
5B+3Podiums+60Floors+3Plants
71 levels
360m in Height
Office, retail & diamond exchange
Al Mas Tower
Al Mas Tower
Al Mas Tower
Al Mas Tower

- Elastic Shortening
- Long term effects (creep and shrinkage)
- Principles (effects before and after casting a slab)
  - Self compensating effects
  - Adjustments have to be made
- Theoretical methods
  - Paper by Mark Fintel, et al.
  - ACI 209
  - ACI 363
- Computer Programs
  - SMA program
Al Mas Tower - Core
Al Mas Tower - Column

Column 3TC3-1

Graph showing data for different columns.
Al Mas Tower

Differential Shortening

- Core Total
- Column Total
- Differential
Al Mas Tower

Controlling Factors:

- Column size/ length
- Concrete strength
- Conc. properties
- Member sizes
- Reinforcing amount
- Floor dead loads
- Superimposed loads
- Construction time
- Construction loads
- Humidity at curing
- Temperature