Some Recent Problems in Applying ACI 318 Deflection Criteria

By

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Flexural Deflection in ACI 318-02

- Controlled in Section **9.5**
  - **9.5.2** Non-prestressed one-way construction
  - **9.5.3** Non prestressed two-way construction
  - **9.5.4** All prestressed concrete construction
  - **9.5.5** Composite construction
- Many comments apply to all four sections.
- This discussion will focus on Section 9.5.3
  - Two-way slabs without interior beams

Two-Way Slabs w/o Interior Beams

- Addressed in Sections **9.5.3.1**, **9.5.3.2** and **9.5.3.4**
- Section **9.5.3.1**:

*"The thickness of slabs without interior beams spanning between the supports on all sides shall satisfy the requirements of **9.5.3.2** **or** **9.5.3.4**"*

NOTE!

Section **9.5.3.2** – Minimum Thickness

- Specifies minimum thickness for two-way slabs per Table **9.5(c)**:

TABLE 9.5(c)—MINIMUM THICKNESS OF SLABS WITHOUT INTERIOR BEAMS

Yield strength, f_y, psi*	Without drop panels†			With drop panels†		
	Exterior panels		Interior panels	Exterior panels		Interior panels
	Without edge beams	With edge beams‡		Without edge beams	With edge beams‡	
40,000	$\frac{\ell_n}{33}$	$\frac{\ell_n}{36}$	$\frac{\ell_n}{36}$	$\frac{\ell_n}{36}$	$\frac{\ell_n}{40}$	$\frac{\ell_n}{40}$
60,000	$\frac{\ell_n}{30}$	$\frac{\ell_n}{33}$	$\frac{\ell_n}{33}$	$\frac{\ell_n}{33}$	$\frac{\ell_n}{36}$	$\frac{\ell_n}{36}$
75,000	$\frac{\ell_n}{28}$	$\frac{\ell_n}{31}$	$\frac{\ell_n}{31}$	$\frac{\ell_n}{31}$	$\frac{\ell_n}{34}$	$\frac{\ell_n}{34}$

* For values of reinforcement yield strength between the values given in the table, minimum thickness shall be determined by linear interpolation.

† Drop panel is defined in 13.3.7.1 and 13.3.7.2.

‡ Slabs with beams between columns along exterior edges. The value of α for the edge beam shall not be less than 0.8.

Definition of ℓ_n

- *“length of clear span in **<u>long</u>** direction of two-way construction, measured face-to-face of supports in slabs without beams and face-to-face of beams or other supports in other cases, in.”*

- Commonly interpreted to mean the longest of the two orthogonal spans in rectangular panels.

Section **9.5.3.4** - Calculations

- Permits the use of slab thicknesses ***LESS*** than the minimum specified in Table **9.5(c)** if…
  - *"…it is shown by computation that the deflection will not exceed the limits stipulated in Table* ***9.5(b)****."*

9.5.3.4 Also Provides Guidance

- For appropriate concrete modulus of elasticity $\boldsymbol{E_c}$
- For appropriate moment of inertia for instantaneous deflection calculations
- Long-term creep and shrinkage multipliers (cites **9.5.2.5**)

Therefore Calculations

- Can be used to justify slab thicknesses less than the minimums specified in Table 9.5(c)
- No calculations required if slab thickness satisfies minimums Table 9.5(c)

Table 9.5(b) – Maximum Permissible Computed Deflections

TABLE 9.5(b) — MAXIMUM PERMISSIBLE COMPUTED DEFLECTIONS

Type of member	Deflection to be considered	Deflection limitation
Flat roofs not supporting or attached to nonstructural elements likely to be damaged by large deflections	Immediate deflection due to live load ***L***	$\ell/180$*
Floors not supporting or attached to nonstructural elements likely to be damaged by large deflections	Immediate deflection due to live load ***L***	$\ell/360$
Roof or floor construction supporting or attached to nonstructural elements likely to be damaged by large deflections	That part of the total deflection occurring after attachment of nonstructural elements (sum of the long-term deflection due to all sustained loads and the immediate deflection due to any additional live load)†	$\ell/480$‡
Roof or floor construction supporting or attached to nonstructural elements not likely to be damaged by large deflections		$\ell/240$§

* Limit not intended to safeguard against ponding. Ponding should be checked by suitable calculations of deflection, including added deflections due to ponded water, and considering long-term effects of all sustained loads, camber, construction tolerances, and reliability of provisions for drainage.

† Long-term deflection shall be determined in accordance with 9.5.2.5 or 9.5.4.3, but may be reduced by amount of deflection calculated to occur before attachment of nonstructural elements. This amount shall be determined on basis of accepted engineering data relating to time-deflection characteristics of members similar to those being considered.

‡ Limit may be exceeded if adequate measures are taken to prevent damage to supported or attached elements.

§ Limit shall not be greater than tolerance provided for nonstructural elements. Limit may be exceeded if camber is provided so that total deflection minus camber does not exceed limit.

Limits in Table 9.5(b)

- Based on a span "***ℓ***" divided by a numerical coefficient (***ℓ****/360,* ***ℓ****/240 etc.)*
- Definition of ***ℓ:***
  - *"span length of* ***beam or one-way slab****, clear projection of cantilever"*
- *2-way slabs?*
- Definition of ***ℓ*** implies that table applies only to beams or one-way slabs

But Table 9.5(b) Clearly Applies to 2-Way Slabs

- Cited in **9.5.3.4**, a section which applies only to 2-way slabs
- Need definition of ℓ for 2-way slabs
  - Shortest span?
  - Longest span?
  - Diagonal span?
- All have been used
- Recommendation will follow

Computed Deflections in Table 9.5(b)

- Roof or floor members
- Supporting non-structural elements likely/not likely to be damaged by large deflections
- “Not likely to be damaged”
  – Limit applies to instantaneous live load deflection
- “Likely to be damaged”
  – Limit applies to part of total deflection occurring after attachment of nonstructural elements

Summary: Code Deflection Requirements for 2-Way Non-Prestressed Slabs

- Are satisfied by conformance to ***either***:
  - Table 9.5(b) – Computed Deflections
  - Table 9.5(c) – Minimum Thickness
- Conformance to both is not required
- Table 9.5(c) is independent of loading and E_c
  - Any slab, regardless of load, satisfies the code deflection criteria if it satisfies minimum thicknesses of Table 9.5(c)

Supported Emphatically

- By **PCA** ***Notes on ACI 318-02***
  - Page 10-10
  - *"Deflections of two-way slab systems with and without beams, drop panels, and column capitals **need not be computed** when the minimum thickness requirements of 9.5.3* [Table 9.5(c)] *are met."*
- Deflection calculations are ***NEVER*** required
  - All code deflection criteria can be satisfied by providing minimum thicknesses.

Is This Wise?

- Code deflection requirements are independent of applied load and concrete properties (***E_c***)
- 2-way slab, 12” thick, spanning 30 feet
  - – ***ℓ_n/30***, therefore code deflection criteria are satisfied (remember ***ℓ_n*** defined as ***longest*** span)
  - – Applied load could be 50 psf or 500 psf
  - – Calculations (not required) could show clear ***non-compliance*** to Table 9.5(b)
- This does not seem rational

Commentary to Minimum Thickness Table 9.5(c)

- **R9.5.2.3** – *The minimum thicknesses in Table 9.5(c) are those that have been developed through the years. Slabs conforming to those limits have not resulted in systematic problems related to stiffness for short and long-term loads.* ***These limits apply to only the domain of previous experience in loads, environment, materials, boundary conditions, and spans.***

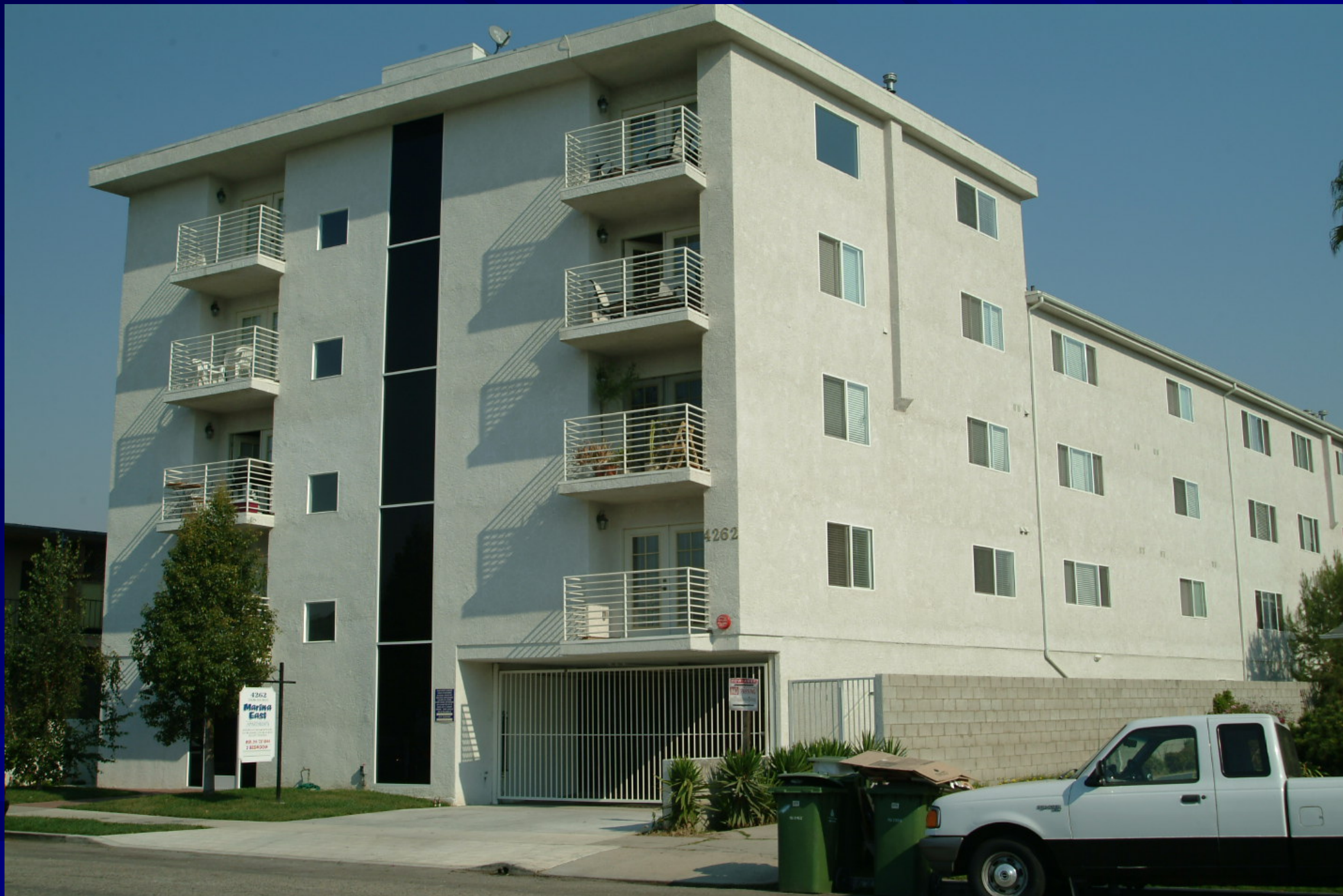
Unfortunately…

- The "*domain of previous experience*" is not quantified or described

- Therefore, for all practical purposes, code deflection criteria are ***independent of applied load***

A Practical Example

- Subterranean apartment buildings with “podium slabs”
- 2-way reinforced concrete slab, prestressed or non-prestressed
  - Supporting 2 to 4 stories of wood-framing above
  - Parking below, generally below grade
- Slab supported on concrete columns (round, 12-16”ϕ) and perimeter CMU walls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Typical Details

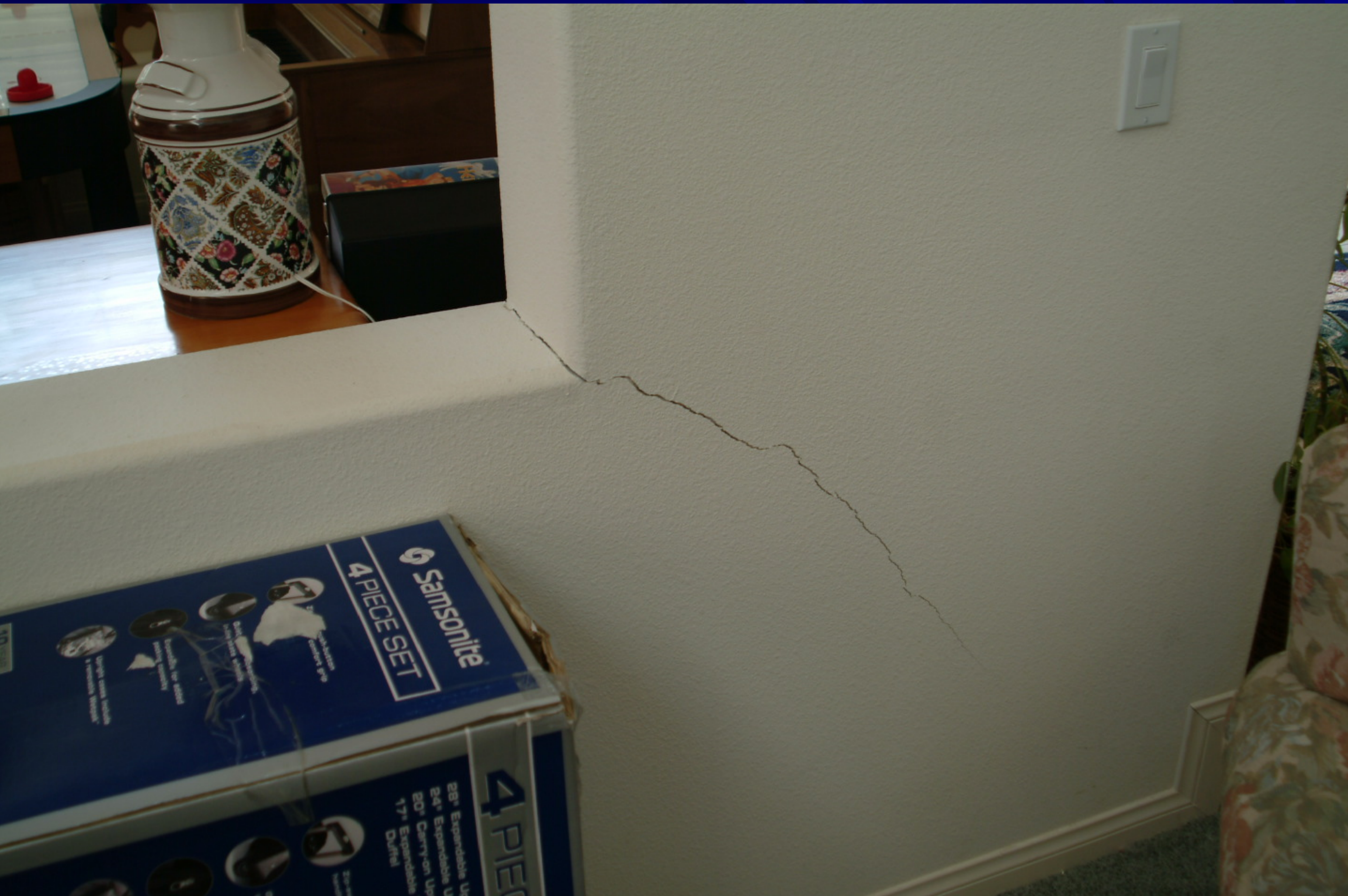
- Maximum bay sizes ± 30’
- Slab f'_c = 3,000 – 4,000 psi
- Superimposed dead loads 100-200 psf
- Live loads 70-100 psf
- Typical slab thickness
  - Non-prestressed 12-14”
  - Post-tensioned 10-12”
- Non-prestressed slabs satisfy code deflection criteria ***by inspection***

Following is Based on a True Story

- Names omitted to protect the guilty
- Scenario presented is not unusual

Investigation

- Five year old rental apartment building
  - – 4 stories of wood framing over parking
- Building owner complains of cracking in drywall, difficulty in operating doors and windows
- Slab soffit survey shows 3-4” of ***apparent*** deflection in bays below superstructure distress
- Similar floor surface shape in apartments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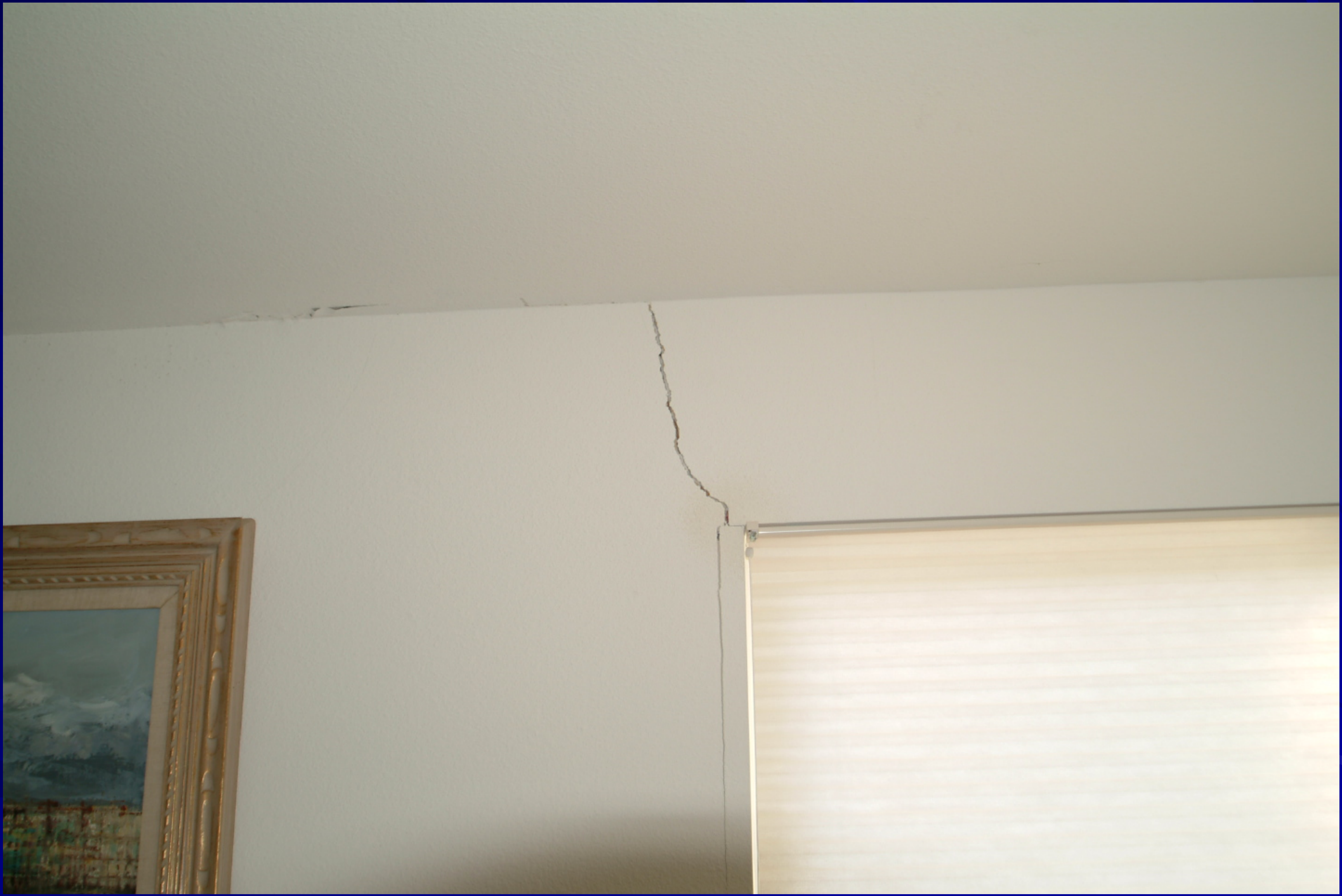

Structural Analysis

- Slab t = 13", normal weight, bay size 29'x29', f_y = 60 ksi, f'_c = 3,000 psi
- SDL = 128 psf
- Total DL = 128 + 163 = 291 psf
- LL = 84 psf
- Computed instantaneous deflections in exterior panel (DL=291 psf, LL=84 psf)

  Δ_{DL} **= 1.10 in.**

  Δ_{LL} **= 0.32 in.**
- Deflection calcs by equivalent frame and FE

After 5 Years

- Using DL creep coefficient (2.0) from 9.5.2.5

$\Delta_{5\ yrs}$ = 1.10 + 2(1.10) + 0.32 = **3.63 in.**

- Consistent with results of slab soffit survey

Deflection Limits in Table 9.5(b)

- Are based upon the part of the deflection that occurs ***after*** attachment of non-structural elements likely to be damaged by large deflections
- Engineer must determine the time at which the damaging deflections start; and the slab deflection that exists at that time
- Involves considerable judgment on the part of the engineer

Some Generalities About This Type of Construction

- Wood framing starts immediately after podium slab is cast
  - Some is in place when slab forms are removed (typically @ 28 days)
- Installation of framing (gypsum wallboard is last element) is complete within 3 months
- Time at which damaging deflections start is not easy to define

Parameters Affecting Start Time for Damaging Deflections

- Time at which (or over which) non-structural elements (partitions) are attached to slab
- Time at which damaging deflections are assumed to start
- Creep factors applying to remaining portion of SDL between time of attachment and time that “damaging deflections” start

Our Investigation

- Slab weight = 163 psf
- Superimposed Dead Load (SDL) = 128 psf
- Total Dead Load = 291 psf (***Δ_{DL}*** = 1.10”)
- Live Load = 84 psf (***Δ_{LL}*** = 0.32”)

One Common Assumption

- Damaging deflections start at age 3 months (when all partitions are in place)
- Full SDL applied instantaneously at that time (no creep factor on deflections caused by SDL)

$$\Delta_{3\,mo} = \underbrace{163/291(1.10)(2)}_{\substack{\text{Slab deflection}\\ \text{with creep factor}\\ = 1.0\text{ (3 mo.)}}} + \underbrace{128/291(1.10)}_{\substack{\text{Instantaneous}\\ \text{deflection from}\\ \text{SDL (no creep)}}} = \mathbf{1.73\ in.}$$

Another Common Assumption

- Damaging deflections start at age 3 months (when all partitions are in place)
- Full SDL applied at time zero (3-month creep factor [1.0] on deflections caused by SDL)

$$\boldsymbol{\Delta_{3\ mo}} = (1.10)(2) = \mathbf{2.20\ in.}$$

Would Not be Unreasonable

- To assume that “damaging deflections” start when framing starts, rather than ends (at this point deflection is produced only by slab weight):

$$\boldsymbol{\Delta_0} = 163/291(1.10) = \mathbf{0.62\ in.}$$

Range of Possibilities

Partitions Attached @ Time	Damaging Deflections Start @ Time	Slab Deflection @ Start Time	Deflection Occurring After Start Time
0 months	0 months	0.62”	3.01”
3 months	3 months	1.73”	1.90”
0 months	3 months	2.20”	1.43”

Smallest Possible Rational Value

- For deflection occurring ***after*** connection of partitions:

1.43”

Allowable Computed Deflection?

- Computed deflection is based upon contributions from two orthogonal spans
- Logical to base governing span $\boldsymbol{\ell}$ from Table 9.5(b) on ***diagonal*** (function of both spans)
- $\boldsymbol{\ell}$ = 1.414x29 = 41 ft
- For floors supporting partitions "likely to be damaged"

$$\Delta_{allow} = 41 \times 12/\mathbf{480} = \mathbf{0.83\ in.} \ll \mathbf{1.43\ in.\ NG}$$

So This Building

- Seriously violates computed deflection criteria of Table 9.5(b)
  - – Actual/Allowable = 1.72 minimum
- Has significant deflection-related distress in superstructure
- Has measured apparent deflections which are consistent with computed deflections
- ***<u>Easily</u> satisfies code deflection criteria***

$$t_{min} = 29 \times 12/30 = 11.6" < 13"$$

Recommendations

- Revise definition for ℓ:
  - *"span length of beam or one-way slab, as defined in 8.7;* ***diagonal dimension between column centerlines in two-way slab panels****; clear projection of cantilever, in."*

Recommendations

- Reverse the current deflection criteria
- Require deflection calculations and compliance to Table 9.5(b) in all cases
- Review and perhaps modify minimum thicknesses in Table 9.5(c)
  - Do not permit thicknesses less than those in Table 9.5(c)

More Rational

- Deflection criteria should be based on all things known to affect deflection (loads, modulus of elasticity, etc.)
- No real penalty for designers
  - Computers make complicated deflection calculations transparent
- Minimum thickness criteria should not permit thinner slabs than required by computation

Thank You!