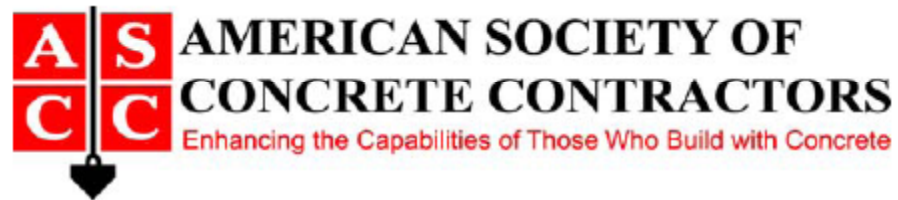


AVOIDING TOLERANCE TRAPS

Ward R. Malisch

Technical Director



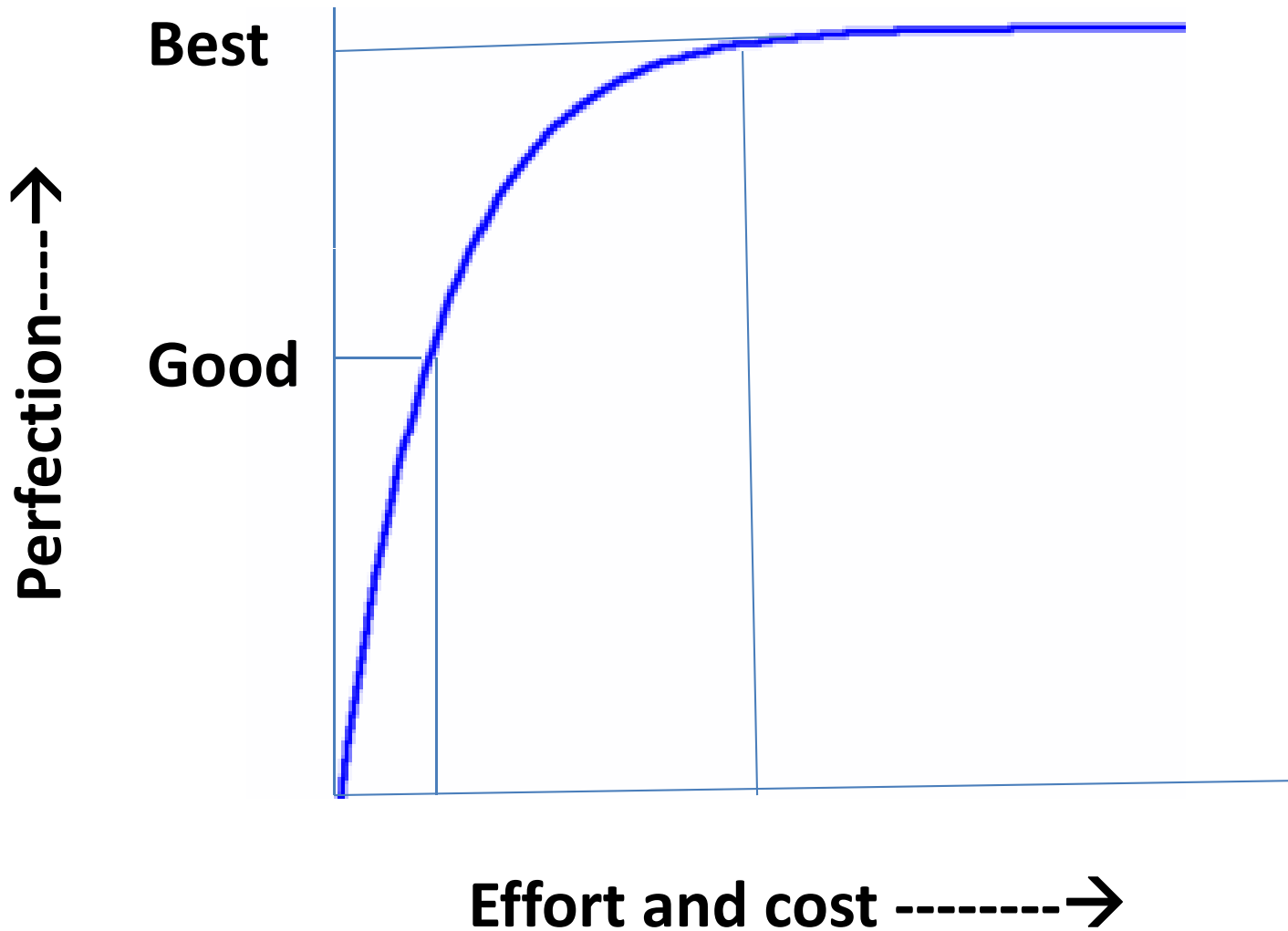
What is a tolerance?

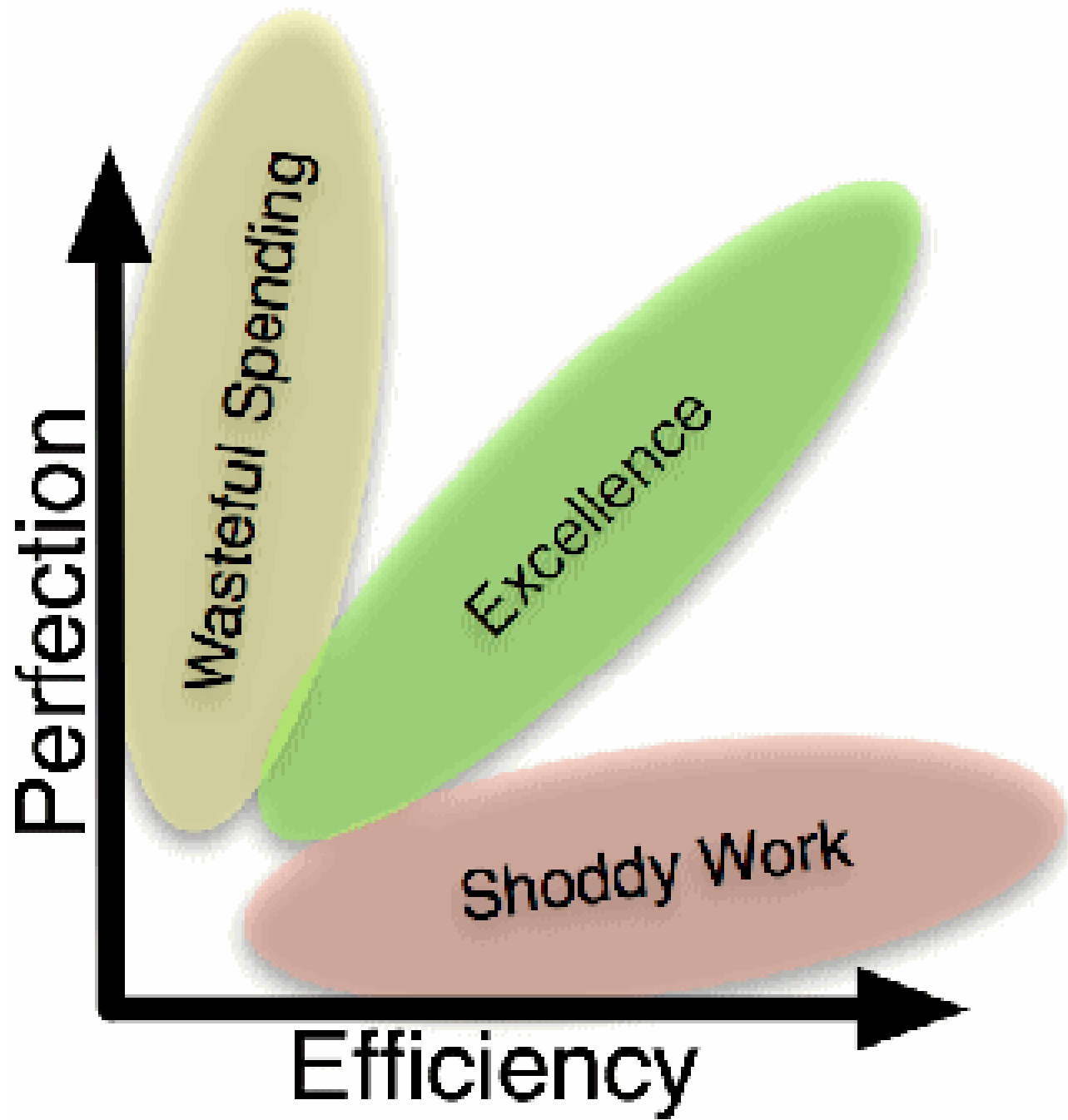
Permitted variation from a specified dimension or location

“No building is ever plumb, level, straight, and true to dimension — that is, not exactly.”

John R. Nichols, 1940

The best is the enemy of the good





In the beginning...

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APRIL, 1940

Tolerances in Building Construction*

BY JOHN R. NICHOLS†

MEMBER AMERICAN CONCRETE INSTITUTE

S Y N O P S I S

Tolerances are proposed tentatively, allowable variation from the exactly plumb, straight, level and true, for lines, levels and dimensions of reinforced concrete buildings and it is suggested that eventually, after discussion, a set of some such tolerances be adopted as standard by the American Concrete Institute.

Nichol's paper was the first attempt to provide tolerance values for reinforced concrete construction.

In judging any proposed tolerance, however, he suggested that two questions must be asked

First question

Is it necessary and sufficient to build within the tolerance so the structure...

- Has a suitable appearance?**
- Satisfies the purpose for which it was erected?**
- Is structurally safe?**
- Accommodates tiling, plaster, or other finishes?**

Second question

Can the tolerances be achieved reasonably; that is, without unjustified cost?

Nichols then suggested tolerance values for properties such as:

- **Member dimensions.. minus 1/4 , plus 1/2 in.**
- **Plumbness 1/4 in. in any story**
- **Reinforcing bar placement ... 1/4 in. vertical**
- **Cover over reinforcement**
(under 1 ft. member thickness)..1/4 in.
(over 1 ft. member thickness)1/2 in.

But he added that discussion of his tolerances would be needed before they were adopted as an ACI standard

In the discussion of the Nichols paper, we find the first instance of intelligent design being debated in a scientific meeting. The debate was related to the 1/4 in. tolerances on positioning of reinforcement.

1st engineer: Does that $\pm \frac{1}{4}$ in. bar placement tolerance applicable before or after the concrete is placed? Because the bars move a bit when workers walk on them.

Nichols: The final position of the bar is all that matters.

2nd engineer: I don't see why the workers can't keep bars in their theoretical positions. We don't have any trouble keeping the bars exactly where they were placed.

Contractor: Do you go down to the bottom of the column with your ruler to see if the bars have 1½ in. of cover? You have to take what you get and trust to God that it is all right.

2nd engineer: That does not place our engineers on a very sound basis. Trusting to God is not good engineering practice.

An apt quote from Daniel Cuoco

“Generally speaking, perfection in design or construction is rare. Nor is it the standard of care in our industry. Any construction site can be converted into a science project in which everything is inspected under a magnifying glass and parts of the structure are physically demolished , resulting in a certainty that instances of imperfect construction will be discovered.”

Letter to the editor

Civil Engineering

July 2009

Nichols' goal was that:

“...eventually, after discussion, a set of some such tolerances be adopted as standard by the American Concrete Institute.”

Fast forward to 1963

ACI 347-63, “Recommended Practice for Formwork” was the first ACI document to state some tolerances.

The committee, in some cases, agreed on even tighter tolerances than those suggested by Nichols.

But all was not well in tolerance land. In 1971, Birkeland and Westhoff published a paper that illustrated some problems.

Some of their conclusions

- **Tolerances obtained in construction are much larger than commonly expected.**
- **Most tolerance problems arise from unrealized expectations.**
- **Nobody knows what tolerances are realistically obtainable, or what tolerances are actually required to obtain a satisfactory building.**

Fast forward again to August 1980

**Proposed ACI Standard: Tolerances
for Concrete Construction and
Materials appears in *Concrete
International* for public discussion.**

Statement in the Introduction

The stated tolerances in this document were, in many cases, derived by consensus opinion due to the lack of definitive data; *and should be used with judgment* as a range of acceptability and not a limit for rejection.

And in October 1980, Mary Hurd, editor of *Concrete Construction* magazine, gave her readers a look at the proposed tolerances so they could send comments to ACI.

The result:

8 pages

**of discussion and 1 page of closure
published in the February 1981
issue of *Concrete International***

A sampling of the responses

- The tolerances are generally attainable and , “if used with judgment ...and not as a limit for rejection would in most cases serve their purpose. This idealism, although admirable, would probably be ignored.**
- There is too much controversy over tolerance magnitudes, and too few field measurements of actual construction achievement to justify the tolerances.**

- **Document should be published as an ACI report of recommended practice rather than as a standard.**
- **Experience on nuclear power plant construction has shown that these tolerances are too tight and very difficult to meet.**
- **Has anyone checked the listed tolerances for their practical meaning and application?**
- **Have those who established these unrealistic limits ever had to erect a 10-ft high column that conformed to the 1/4 in. plumb tolerance?**

Summary

- **Commendable effort by ACI 117**
- **Should not be a standard**
- **Some tolerances not clearly stated**
- **Some tolerances too tight**
- **Little data to support the tolerances**

Committee closure

- Engineers specifying ACI 117-81 should accept the specific tolerance values but realize the need for engineering judgment.
- An in-depth review of each tolerance will begin following publication of ACI 117-81.
- Subcommittees have been set up to review each section of the proposed document and comments relating to changing a tolerance.
- ACI 117 can request backup data to support proposed changes.

Tolerances in ACI 117-10 for which no data are cited

- **Vertical alignment control**
- **Elevation control**
- **Cross-sectional dimension control**
- **Relative alignment control**

Other Tolerance Problems

- **Specified values based on expectations rather than reality**
- **Tolerance incompatibility for adjoining building systems**
- **Contractor responsibility for design**
- **Specifications written so they *could* be misunderstood**

The first tolerance trap...

**Tolerances not based on
as-built data (experience)
may not be reasonably
achievable.**

**Some tolerances in ACI 117-06
for which no as-built data are cited**

Controls for:

- **Cross-sectional dimensions**
- **Vertical alignment**
- **Elevation**
- **Relative alignment**

Cross-sectional dimensions for slabs on ground

ACI 117-10 Tolerances

Section 4.5.4 *Thickness of slabs-on-ground*

Average of all samples..... **-3/8 in.**

Individual sample **-3/4 in.**

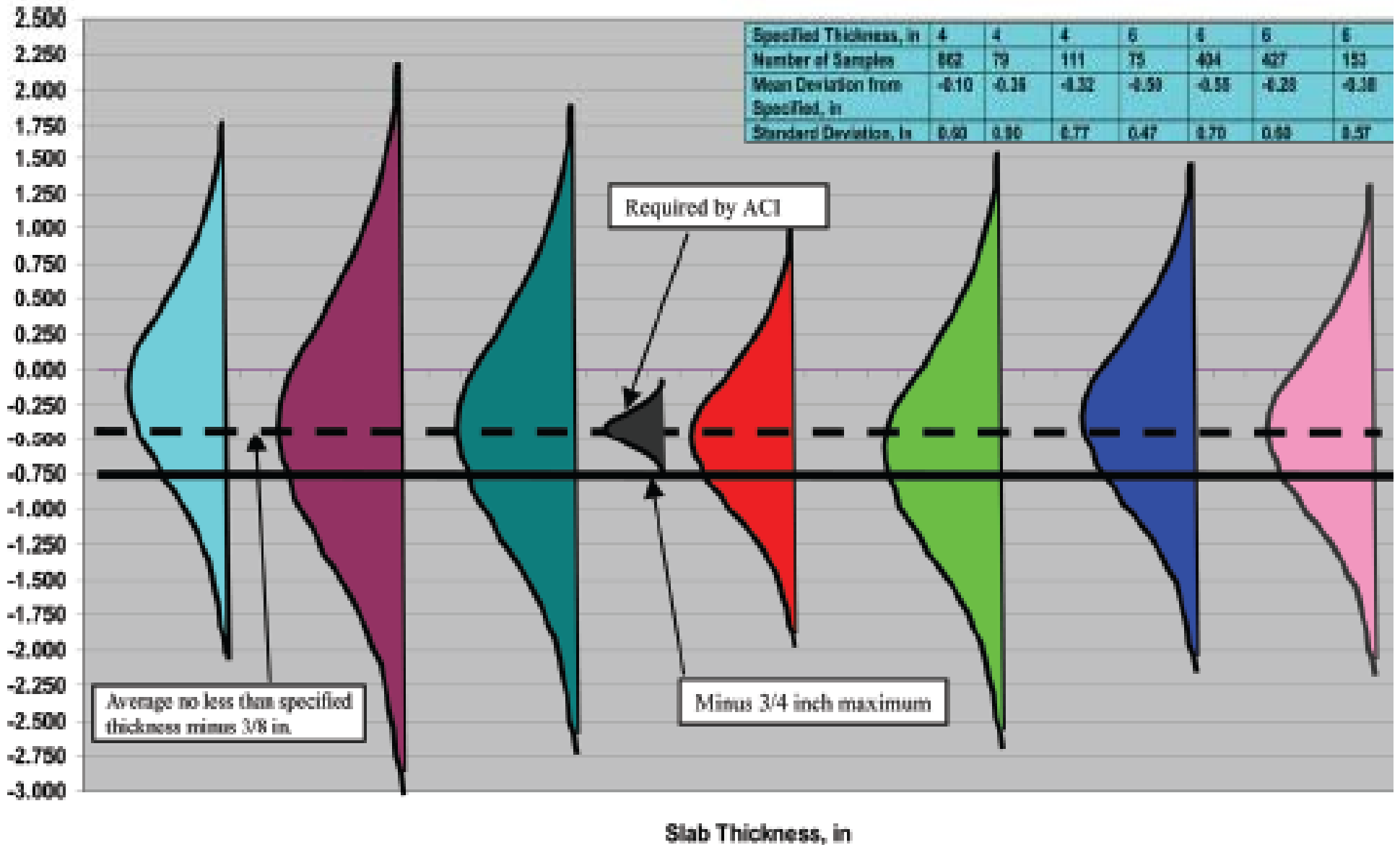
What it means

- For a specified 6-in. floor thickness, the average length of all cores must be 5-5/8 in.
- For a specified 6-in. floor thickness, the length of any individual core must be no less than 5-1/4 in.

Note Section 4.5.4.1: Minimum number of core samples is four per 5,000 sq ft of floor surface, and core length is determined per ASTM C174.

Is this a reasonable requirement?

**Let's look at as-built
data to see if it's
achievable.**



Conclusion:

- **The average slab thickness tolerance is attainable**
- **The minimum slab thickness (core length) tolerance is not.**
- **We have lots of as-built slabs on ground with thin spots.**

**ACI 117-10 states this in R4.5.4
of the Commentary**

**“Specifiers should anticipate
localized occurrences of reduced
thickness for slabs-on-ground.”**

If we know the thin sections are present, why do most floors perform satisfactorily?

- **Conservative k -values in soils reports**
- **Conservative concrete flexural strength assumptions**
- **Some design charts are conservative**
- **Safety factor of 2 used to account for fatigue effects**

But designers must be cautious

- FEM design methods may be less conservative
- Using lower safety factors (e.g. 1.2) permits more competitive slab alternatives, but at the expense of possibly poor performance.
- **Actual** slab thickness values should be assumed in design if lower safety factors are used.
- **Don't** specify minimum thickness unless you want a slab much thicker than the design value, and can pay for it.

Another achievability trap...

Beams have to connect to columns, but column plumb tolerances and beam location tolerances in ACI 117-10 are mismatched.

Horizontal alignment

ACI 117-10 horizontal alignment tolerances

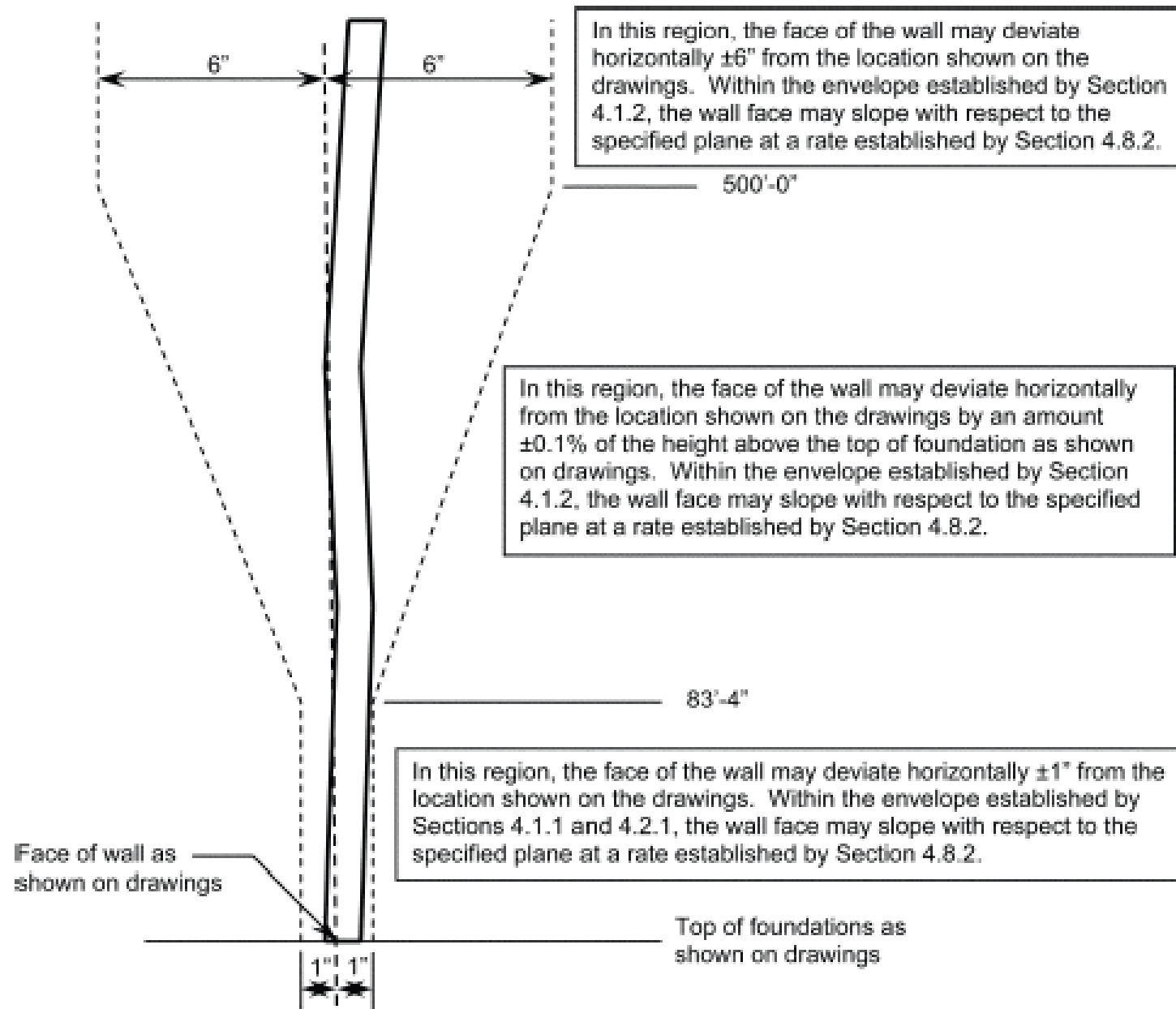
4.2.1 Horizontal deviation from location

Other elements ± 1 in.

The other elements can be:

- Beams or girders that frame into columns, walls, or other vertical elements**
- Beams and joists that frame into other beams or girders**
- Slab edges at the building perimeter**

ACI 117 vertical alignment envelope

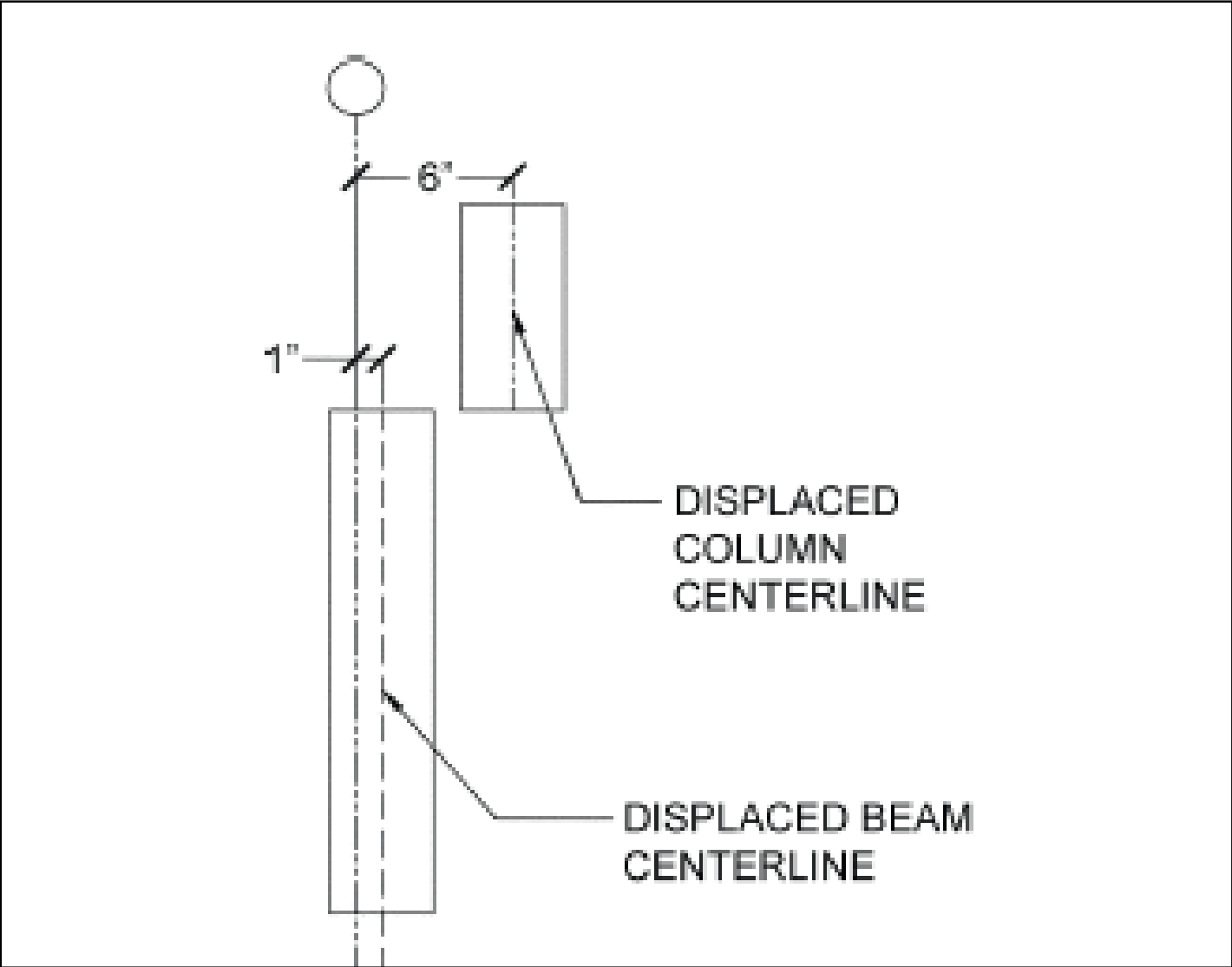


The problem with beams framing into columns or walls:

Section 4.1.2 allows an out-of-plumb tolerance up to ± 6 in. for columns

But Section 4.2.1 allows a tolerance of only ± 1 in. for the vertical edge of a beam.

How's that working out for you?



Beams can't connect to columns within tolerance if column plumb and beam location tolerances are mismatched.

The simple solution

The horizontal alignment envelope must be in sync with the vertical alignment envelope if the beams are to connect to the columns .

Suggested specification language:

Horizontal alignment

Formed concrete surfaces shall not fall outside the limits set by the vertical alignment envelope

[Beams must connect to columns]

Yet another achievability trap

For a 20-ft high column, plumb tolerance is $\pm \frac{3}{4}$ in. (0.3% of ht.)

But for the outside corner of an exposed 20-ft high corner column exposed to view the plumb tolerance is $\pm \frac{1}{2}$ in. (0.2% of ht.)

[Both requirements in Section 4.1.1]

**How do we check
plumb for a
column?**

Modified carpenter's level



Plumbing forms



With typical forms and column clamps in place, how can the outside corner be held to a different tolerance than the rest of the column corners and four faces?

The Solution

- **Eliminate separate plumb requirement (0.2% vs 0.3% x height) for the outside corner of corner columns**
- ***Specifier* to define and select tolerances for important conspicuous lines**

A high-tech solution



Embedded permanent plumb position Indicator.



A second tolerance trap...

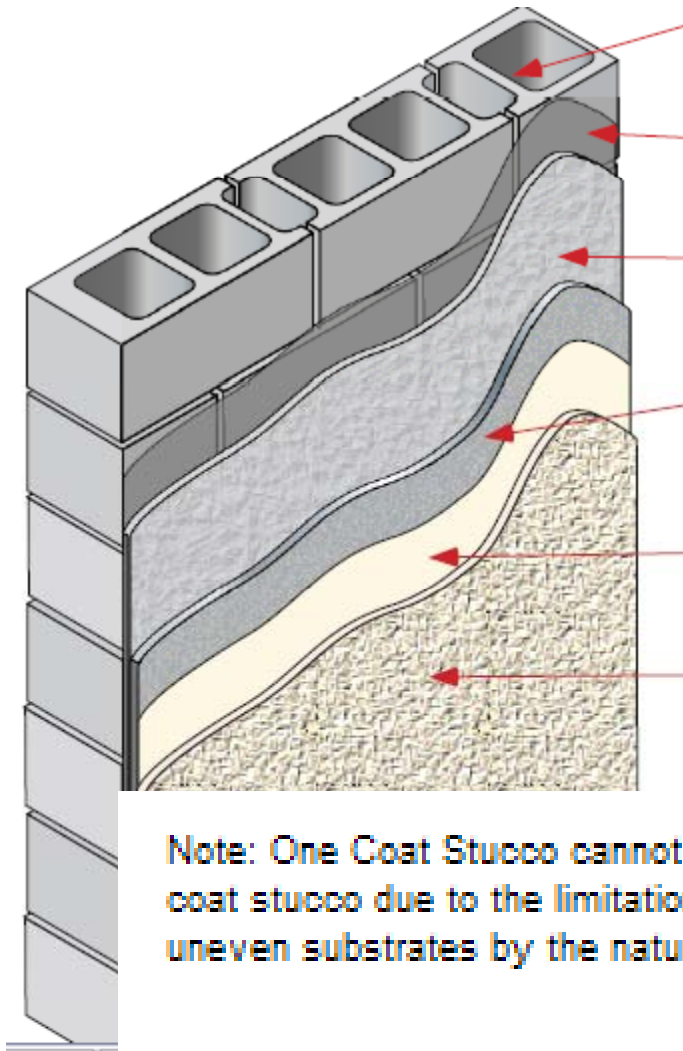
Tolerance incompatibility

Applying the ± 1 in. horizontal tolerance for edges of slabs often results in construction disputes between the concrete contractor and the building envelope contractor. Here's one illustration.

Concrete frame
Post-tensioned slabs
Masonry infill walls
Stucco finish

ASTM C 926, “Standard Specification for Application of Portland Cement-Based Plaster,” requires the concrete surface to be straight and true within 1/4 in. in 10 ft. But edge of slab can be out of location by plus-or-minus 1 in. per ACI 117-10.

Three-course stucco
Nominal thickness 7/8 in.



Scratch coat

Brown coat

Finish coat

Two-course (one coat) stucco combines the scratch and brown coats plus the finish coat
Nominal thickness:

1/2 in. for masonry base

3/8 in. for concrete base

Thus it's less expensive.

Note: One Coat Stucco cannot achieve the finish tolerances achieved with traditional three-coat stucco due to the limitations on rodding the basecoat and the inability to straighten uneven substrates by the nature of its 3/8"-1/2" thickness.









11 10:40AM

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The solution

- **Check for conflicting tolerances that appear in different parts of the specifications:**
 - **Division 3 vs. cladding, curtain walls**
 - **Division 3 vs. floor finishes**
 - **Division 3 vs. doors and windows**
 - **Division 3 vs. ceilings and partitions**
- **Ensure that different subcontractors are aware of tolerance conflicts**

A third tolerance trap...

Contractors are sometimes held accountable for meeting tolerances on performance related to design decisions.

Elevation envelope

Components of ACI 117-10 elevation tolerances

- 4.4.1 Deviation from elevation for top surface of formed suspended slabs, before removal of shores..... $\pm \frac{3}{4}$ in.
- 4.4.2 Deviation from elevation for formed surfaces before removal of shores $\pm \frac{3}{4}$ in.
- 4.8.5 Flatness/levelness requirements to control elevation changes of top surface within the $\pm \frac{3}{4}$ -in. envelope.

The trap...

- **Interior partitions in a multistory building don't fit.**
- **Elevation measurements of slab top and bottom surfaces are made when the fit problem is first noticed.**
- **The measurements are outside the elevation tolerance envelope.**
- **The contractor is required to patch the floor(s) so partitions will fit.**

This may not be a contractor issue

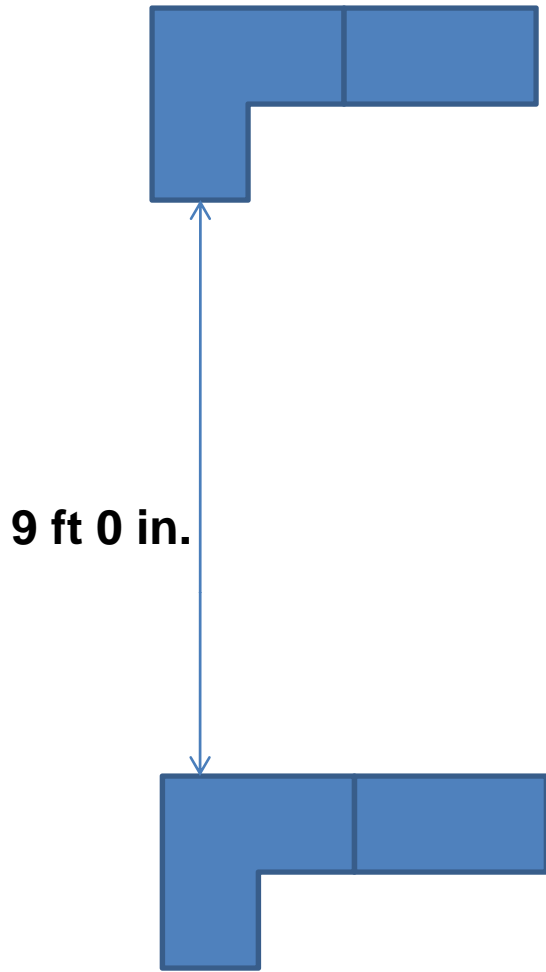
- **Elevation measurements for compliance with tolerances must be taken before shore removal.**
- **Partitions are usually installed after shore removal.**
- **The measured elevations reflect initial elevation but also deflection after shore removal.**
- **Deflection is not the contractor's responsibility unless the structure was loaded with construction materials before slabs were reshored.**

Sorting out responsibility

- **Contractor can take elevation readings on the slabs while the shoring is still in place.**
- **Deflection measurements can then be related to the as-built initial slab elevation—not to the design elevation.**
- **If no measurements of the initial slab elevation were made (most likely), elevation readings of the slab surface at the columns should be taken as the baseline for additional slab surface measurements.**

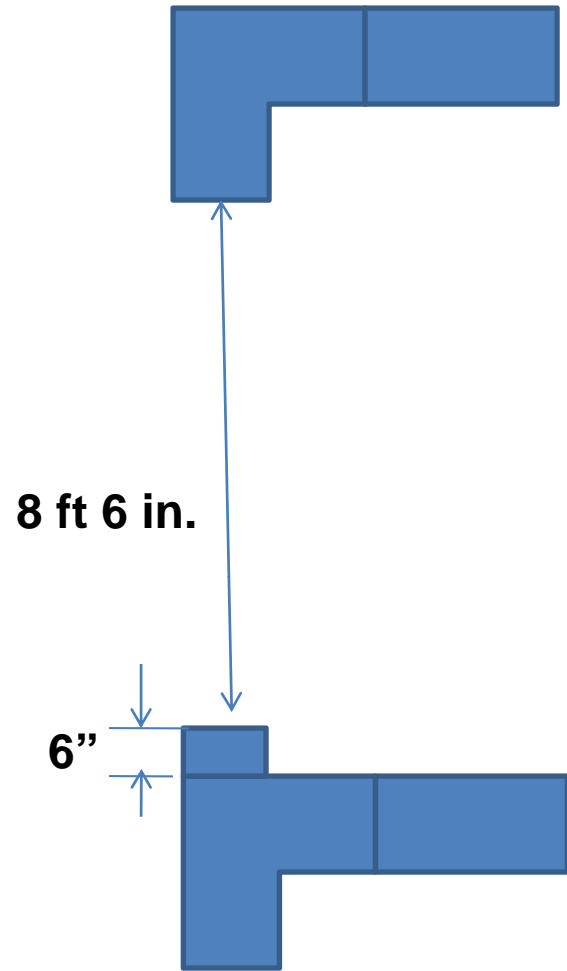
A fourth tolerance trap...

**The definition of an opening
can be misunderstood.**



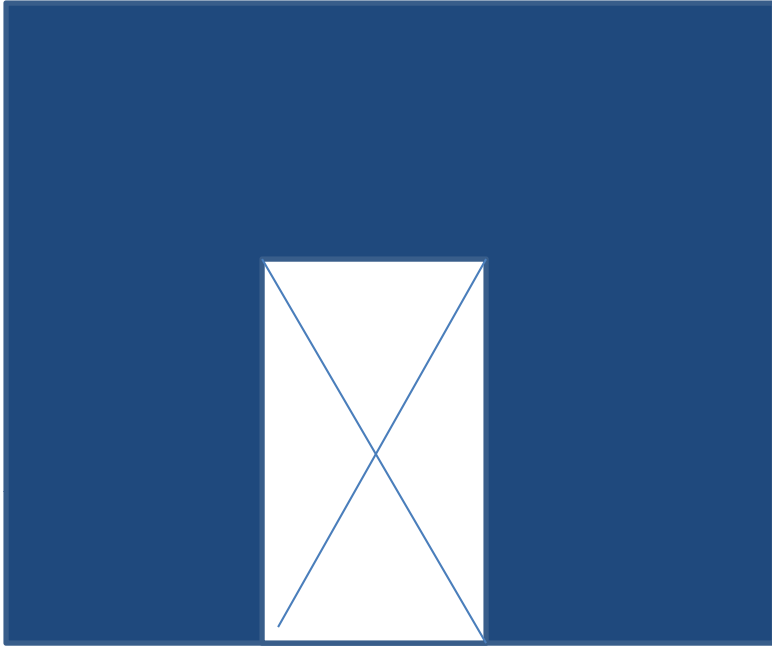
A

Is the space between the beam soffit and floor surface (A) an opening?



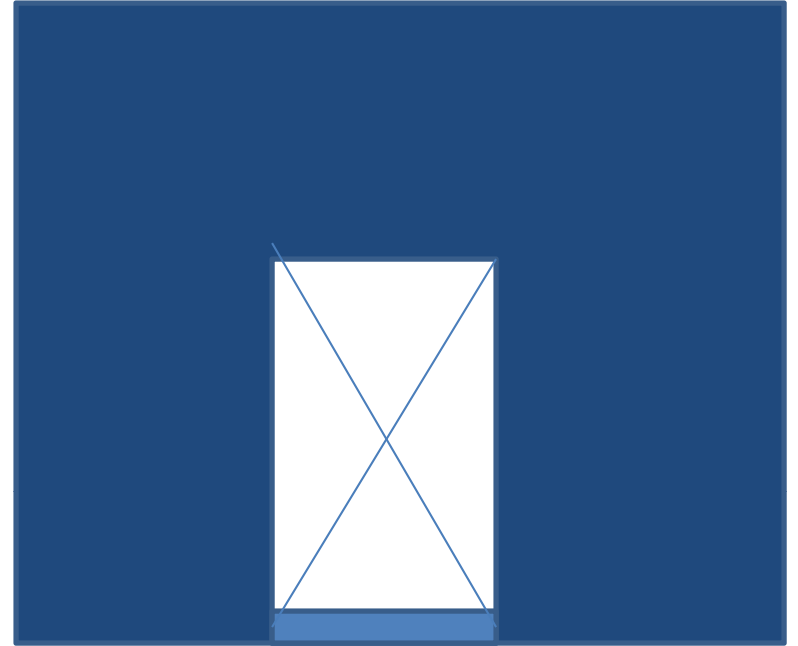
B

Is the space between the beam soffit and curb (B) an opening?



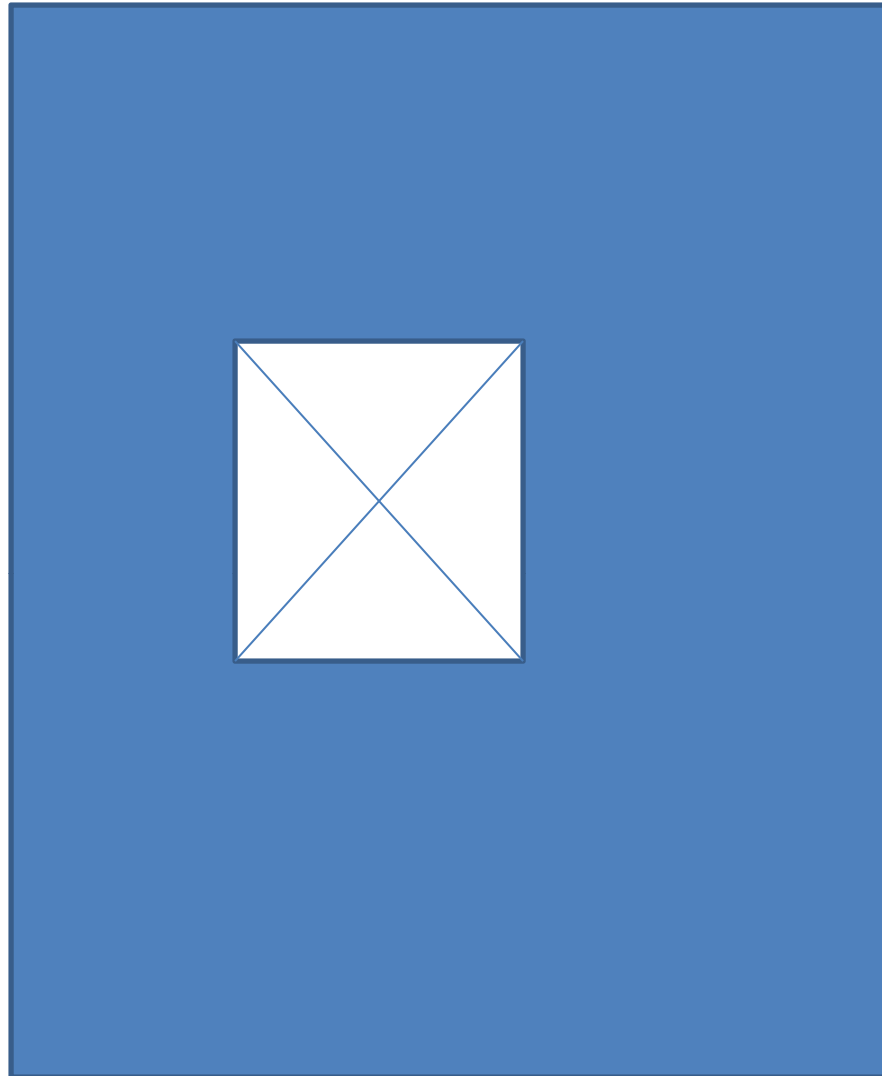
C

Is the space between the floor and the top of the doorway an opening?



D

Is the space between the curb and the top of the doorway an opening?



E

Is this an opening?

Why an opening definition matters

- In A, the tolerance on both the beam soffit and floor elevation is $\pm \frac{3}{4}$ in. Thus the distance between the soffit and floor surface can vary from 8 ft 10½ in. to 9 ft 1½ in.
- But if A is an opening, the Section 4.6.1 tolerance of minus ½ in. and plus 1 in. applies. Thus, the distance between the soffit and floor surface can only vary from 8 ft 11 ½ in. to 9 ft 1 in. The tolerance is cut in half.

Some clues

- **Section R4.2.2 of ACI 117-10.**

“The tolerance for vertical deviation would also apply to items such as the horizontal edges of openings **in** walls, beams, or columns.”

So neither A nor B represents an opening in a wall.

- **Section 4.6—Deviation from ...formed opening width or height**

In C and D, only the top and sides of the door opening are formed surfaces. So they're not openings.

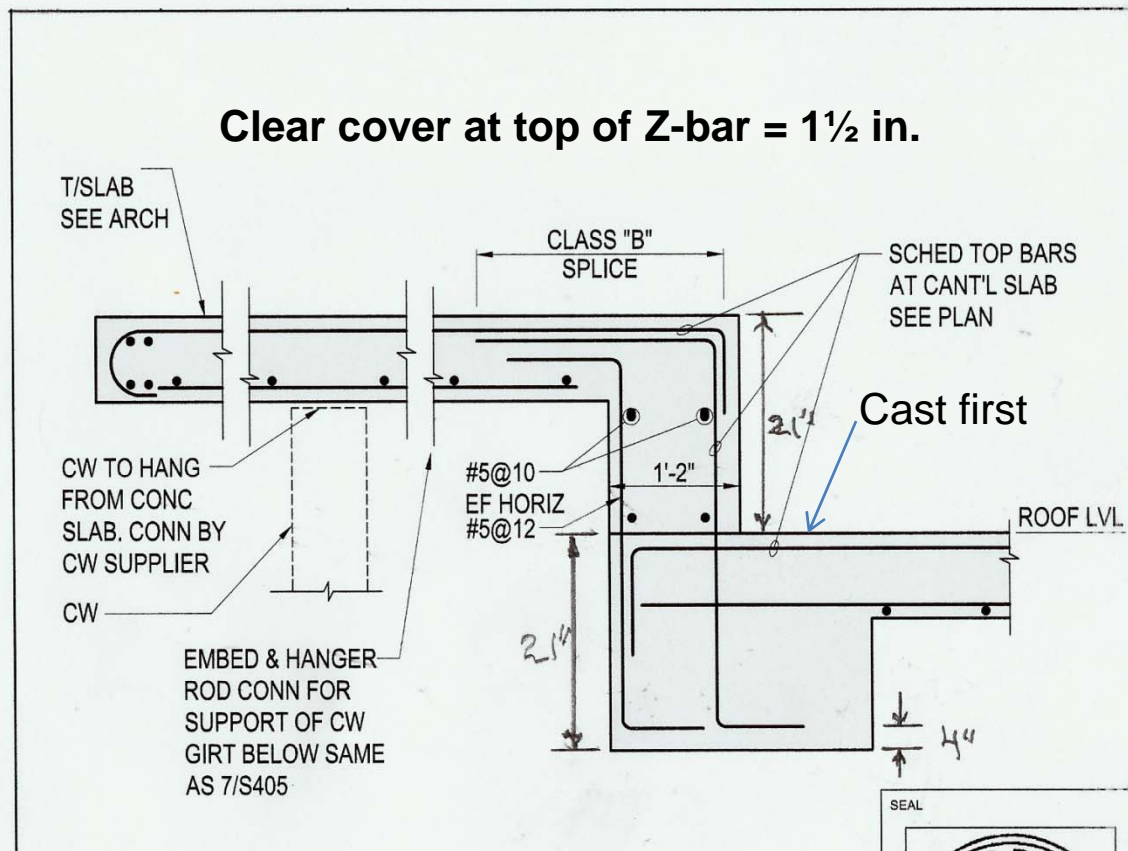
Only the wall shown in sketch E has an opening to which the minus ½ in. and plus 1 in. tolerance applies.

As an added note, the minus ½ in. and plus 1 in. tolerance seems to be in line with as-built data we collected.

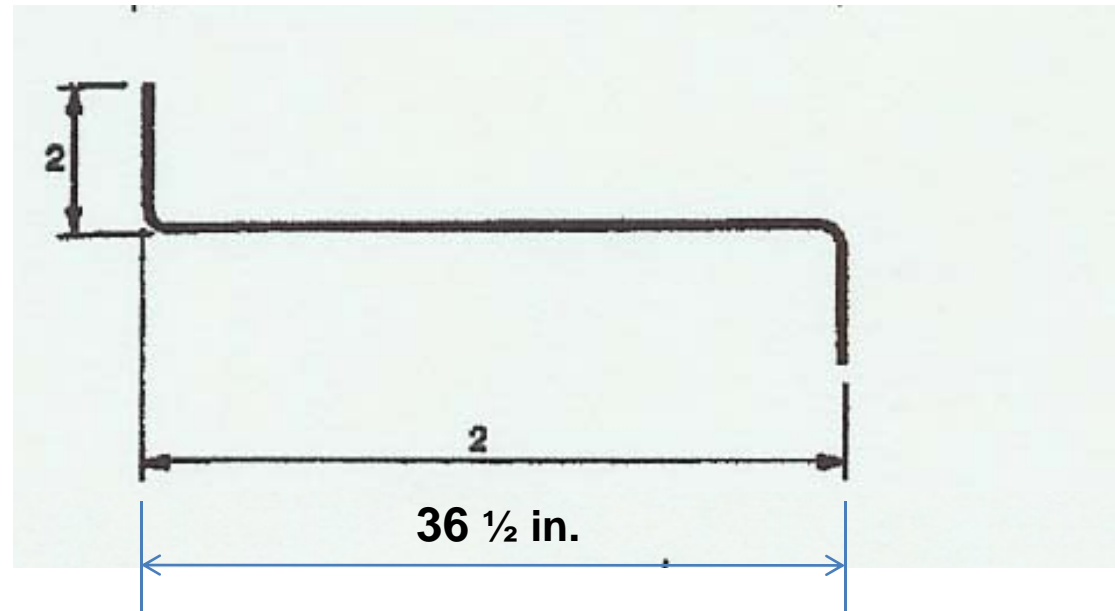
A useful hint for designers

When using a curb cast later to ensure a good fit with doors, windows, and elements installed by others, don't specify the curb height. Place concrete to an *elevation* consistent with the tolerance for the element.

Internal tolerance problems



Z-bar length



Bar fabrication tolerance 2 = ± 1 in.

Here's the problem

- The bar fabricator can fabricate a Z-bar with a tolerance of ± 1 in.
- The ironworker has a position tolerance of $\pm \frac{1}{2}$ in. on each tail of the Z-bar.
- Fabricating the bar either 1 in. short or long forces the ironworker to place the bar perfectly by using the $+\frac{1}{2}$ in. tolerance at one end of the bar and the $-\frac{1}{2}$ in. tolerance at the other end of the bar.
- The ironworker also has a clear cover tolerance of $-\frac{1}{2}$ in. If the Z-bar is fabricated 1 in. too long, the ironworker must place the bar exactly on each face.

In summary

- Many of our current tolerances are unachievable.
- Some of our tolerances are not understandable.
- Some of the concrete tolerances are incompatible with tolerances for interfacing materials.
- More as-built data are needed to use as a basis for realistic tolerances.
- Too much time and money is wasted in fighting claims that there are dire consequences of not meeting current tolerances.

The End

Questions?