Tolerances in concrete construction

We need greater clarity and realism in specifications and also agreement on how tolerances are to be measured and what to do in specific instances of noncompliance

By the Editorial Staff of Concrete Construction

When a contractor finds that something won't fit, or when the architect or owner thinks that the walls aren't vertical or straight or that the floors aren't flat or level enough, someone is unhappy with the degree of tolerance achieved. Maybe the construction operations weren't precise enough. Maybe the specifications weren't tight enough or clear enough. Maybe the structure as designed couldn't actually be built to the requirements specified. In any case, some accommodation must be made—by repair, adjustment or just plain acceptance of a bad situation. And, someone most likely will be disappointed.

Part of our present situation in construction is that we are not entirely sure what degree of precision is needed in each individual circumstance, or what degree of precision can be achieved at reasonable cost. There is a need for all members of the construction industry to compare notes on what we want, what we really need, what practical considerations affect any particular degree of precision in building, and the relation of all this to cost.

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The need to specify tolerances

From among the possible definitions of tolerance the one we have chosen to use in this article is given in *Cement and Concrete Terminology*, by American Concrete Institute (ACI) Committee 116: "the permitted variation from a given dimension or quantity." This variation can usually be in either of two directions and so can be regarded as positive or negative. Thus a tolerance in level of a ceiling amounting to ¼ inch in 10 feet[(1)*] of length could represent concrete that is up to ¼ inch[(2)] above the target level or as much as ¼ inch below.

The immediate reason for specifying tolerances is to establish the ease of construction without the necessity of later modifying parts to fit together. A more long-range reason is to ensure that the structure will perform as needed, particularly with respect to safety. The parts of the structure should have adequate strength and be of such shape and dimensions that there is no danger of structural failure through movement of the parts. Joints should be sufficiently close to the design to perform properly and, where necessary, be capable of being sealed against intrusion of water, wind, dirt and debris. Tolerances on the location of reinforcing steel should be adequate to ensure the placeability of concrete all around the reinforcing cage.

The tolerance required for appearance depends to a large extent upon the distance from which the structure will be viewed. The tolerance for an architectural concrete wall may be small compared with the surface of a dam to be viewed from a considerable distance. Within a hydraulic structure tolerances must be specified to ensure that friction losses are not high enough to significantly reduce hydraulic capacity or efficiency. Tolerances in hydraulic conduit must also ensure sufficiently smooth surfaces to prevent serious damage from erosion.

Considerations that should determine tolerances

It is common for a specifier to pick tolerances out of specifications previously used in the design office or from ACI or other published standards. This practice can lead to excessive costs by specifying closer tolerances than needed. Some specifiers and designers have profitably found ways to confer with constructors during the design process so that constructors can point out any unforeseen construction difficulties imposed by the tolerances. Constructors can ask questions about the reasons for the degree of precision specified and both parties can confer about the possibility of alternative, more economic designs and methods of construction.

The tolerances achievable with precast concrete and cast-in-place concrete are likely to be quite different. Similarly the tolerances achievable with fixed forms, sliding forms and other types of forming systems can differ. If the specifier arbitrarily establishes a tolerance, he may be unknowingly prescribing the construction method to be used and possibly thereby increasing the cost.

Sometimes it is difficult to predict the tolerance achievable. For example, the foreshortening of jobsite precast concrete beams during prestressing may not conform to the designer's predictions. Also, the amount of camber in prestressed concrete beams is difficult to predict. In some cases it might be possible to design a prestressed concrete structure to accommodate relatively large tolerances in foreshortening or camber. A more usual way of handling the problem is to make a minor adjustment in the form after job experience with casting of beams has begun to show what dimensions are actually being achieved.

Realistic, practical tolerances

Phillip Birkeland, a consulting engineer, and Leonard Westhoff, a construction superintendent, report that they had "asked around" to find out how the tolerance tables in ACI 301 (Specifications for Structural Concrete for Buildings), ACI 347 (Recommended Practice for Concrete Formwork) and other standards had been arrived at. They came to the conclusion that the data had "been compiled in the equivalent of smoke-filled rooms with no direct relationship to reality. In the absence of hard data, these committees have had to rely on their judgment" (Reference 1). These tolerance tables appear to be the best the industry has but there seems to be a considerable lack of understanding of how closely they match either the tolerances being obtained in the field or the tolerances it is possible to get.

For that reason Birkeland and Westhoff made extensive measurements on a building in which they were involved. Since the building seemed to be satisfactory to the owners and similar in quality to other acceptable buildings the investigators felt that the deviations measured represented acceptable tolerances. They found that the slopes and surface curvatures of the floors were generally greater than the ACI standards in effect at the time. ACI 347 permitted a tolerance of 1/16 inch per foot[3] in the slope of a floor but the investigators concluded that a more realistic tolerance might be

TOLERANCES SUGGESTED BY ACI FOR REINFORCED CONCRETE BUILDINGS*†

Variations from the plumb.

In the lines and surfaces of columns, piers, walls and in arrises
- In any 10 feet of length . . . . 1/4 inch[1]
- Maximum for entire length. . . . . 1 inch[7]

For exposed corner columns, control-joint grooves and other conspicuous lines
- In any 20 feet of length . . . . 1/4 inch[8]
- Maximum for entire length. . . . . 1/2 inch[9]

Variation from the level or from the grades indicated on the drawings.

In slab soffits, ‡ ceilings, beam soffits and in arrises
- In any 10 feet of length . . . . 1/4 inch[1]
- In any bay or in any 20 feet of length . . . . 3/8 inch[10]
- Maximum for entire length . . . . 3/4 inch[11]

In exposed lintels, sills, parapets, horizontal grooves and other conspicuous lines
- In any bay or in any 20 feet of length . . . . 1/4 inch[12]
- Maximum for entire length. . . . . 1/2 inch[9]

Variations of distance between walls, columns, partitions and beams.

1/4 inch per 10 feet[1] of distance but not more than 1/2 inch[9] in any one bay and not more than 1 inch[7] total variation

Variation of linear building lines from established position in plan . . . . 1 inch[13]

Variation in the sizes and locations of sleeves, floor openings and wall openings.
- Minus . . . . 1/4 inch[14]
- Plus . . . . 1/2 inch[15]

Variation in cross-sectional dimensions of columns and beams and in the thickness of slabs and walls.
- Minus . . . . 1/4 inch[14]
- Plus . . . . 1/2 inch[15]

Footings.

Variation in dimensions in plan
- Minus . . . . 1/2 inch[16]
- Plus . . . . 2 inches[17]§ when formed or plus 3 inches[18] when placed against unformed excavation

Misplacement or eccentricity
- 2 percent of the footing width in the direction of misplacement but not more than . . . . 2 inches[19]§

Reductions in thickness
- Minus . . . . 5 percent of specified thickness

Variations in steps.

In a flight of stairs
- Rise . . . . 1/8 inch[20]
- Tread . . . . 1/4 inch[2]

In consecutive steps
- Rise . . . . 1/16 inch[21]
- Tread. . . . . 1/8 inch[20]

* From Section 3.3.1 of ACI 347-78, *Recommended Practice for Concrete Formwork.* The Standard also suggests other tolerances not published here for precast and precast-prestressed members, mass concrete structures, tunnel linings and cast-in-place conduits, slipformed structures, canal linings, siphons, culverts, bridges and similar structures.

† Variations from plumb and linear building lines on upper stories of high-rise structures (above 100 feet[22] high) are special cases which may require special tolerances.

‡ Variations in slab soffits are to be measured before removal of supporting shores; the contractor is not responsible for variations due to deflection except when the latter are corroboratory evidence of inferior concrete quality or curing, in which case only the net variation due to deflection can be considered.

§ Applies to concrete only, not to reinforcing bars or dowels.

3/16 inch per foot[4]. ACI 301 allowed a floor surface curvature of 1/8-inch offset from a 10-foot[5] straightedge. The investigators concluded that curvatures up to ½-inch offset from a 10-foot[6] straightedge might be acceptable. Other measurements on the building indicated that the ACI 347 tolerance on intended floor slab elevation was about the same as they were measuring in the building. Tolerances on distances between columns required by ACI 301 and 347 agreed fairly well with what they measured.

Although designers often specify unrealistic tolerances without questioning the lack of realism in the data they have access to, they also often accept the finished structure with all its deviations from the specified tolerances. It is likely that neither designers nor constructors know what tolerances are realistically obtainable; both think that the public is getting structures that are more accurately built than they really are.

In Europe, realistic tolerances have been established by statistical analysis of deviations. But in Europe considerable precasting is done, which makes it relatively easy to make dimensional measurements of elements and study them statistically. Another important factor is the involvement of the design engineer in the selection of construction methods, a practice associated with industrialization of the European building industry.

In the normal course of construction the deviations of any set of measurements from the intended value will fit the statistical normal distribution curve. By calculating the standard deviation from a large body of measurements it can be determined how many measurements are statistically expected to fall within given limits. If tolerances were established in statistical terms, thus acknowledging that a small number of measurements will fall outside an acceptable range, our tolerances might be more realistic.

* Numbers in parentheses refer to metric equivalents listed with this article.

It appears that no matter what system is used for specifying tolerances there will always be some parts of a structure that are unacceptable. The number of these instances can be decreased but frequently at considerable cost. It is simpler to plan to accommodate these by repair.

Guidance for those who specify tolerances

It should be possible for those directly concerned with construction to clearly interpret the tolerance requirements in the construction specifications. Tolerances should be sufficiently clear and specific not to give trouble to:

- the contractor who prepares the bid
- the job superintendent who determines materials requirements and types of craftsmen needed
- the shift foreman who is responsible for setting lines and grades for formwork and embedments
- the inspector who checks formwork for accuracy and strength before concrete is placed

Several general guidelines can be stated for specifying tolerances.

- Be certain that the design does not demand tolerances that are unrealistic or unattainable.
- Provide places where the inevitable variations can be absorbed.
- Choose construction concepts that will ensure that critical dimensions are controlled directly and check these out with builders to be sure they are free of bugs.
- Dimension the drawing in such a way that the inspector can measure critical dimensions directly.
- Emphasize or highlight critical dimensions in drawing so that they are forcefully called to the attention of the constructor.

The use of double dimensioning on drawings inevitably leads to trouble and should be avoided. This is the practice of showing both the individual dimensions and the total dimension. It leads to uncertainty about which dimension can best be allowed to float to meet all of the tolerance requirements. This subject is well explained in Reference 1.

PROPOSED TOLERANCES FOR PLANENESS OF FLOORS AND OTHER FLATWORK

ACI Committee 302 is preparing a new "Guide for Concrete Floor and Slab Construction." This has not yet been either published or adopted, SO the proposed tolerances given here have no current authority and are still subject to change. The new tolerances being suggested by the committee are for the maximum depressions between high spots in a floor or slab for four classes of finish:

Class A finish
1/8 inch below a 10-foot[23] straightedge*

Class A-2 finish
3/16 inch below a 10-foot[24] straightedge

Class B finish
1/4 inch below a 10-foot[25] straightedge

Class C finish
1/4 inch below a 2-foot[26] straightedge

* The Committee states that the tolerance for a Class A finish is "extremely difficult and expensive to achieve on large areas. [It] should be specified only for critical areas where such [a tolerance is] vital for the operations that will take place in the area."

Ambiguity is also caused by the practice of center-to-center dimensioning. The exact location of the center line of a column may be a matter of opinion. The best practice is to give dimensions to the face of the concrete.

Unfortunately it is all too easy for a designer to assume that a building can be built to zero tolerance and for him to design accordingly. The construction of such a building may easily lead to trouble, cost everyone more money than necessary and may wind up in a lawsuit. The fact that such a design may have been constructed successfully in the past can provide a false sense of security.

Constructing within the tolerances

Everything possible should be done to avoid ambiguity. Much time is wasted on the job over differences about how to interpret tolerance requirements.

The constructor could wish that the specifications would supply all the required tolerances. In practice, however, he must make his own decision concerning most of them. This involves study, to determine which tolerances are important; it calls for both experience and intuition. The constructor ultimately prices his job with his own particular concept of the tolerance requirements in mind. If he has underestimated the precision needed in any part of the job it is likely to cause trouble during construction or later and cost him money.

A constructor would do well to think out ahead of time the methods to be used in controlling tolerances. For example, in a situation where the clear distance between columns is particularly important, he might decide to form the opening between columns instead of the columns themselves. This would lead to deviations in the column width rather than in the space between columns and the tolerance would be taken up in the amount of concrete cover over the column ties.

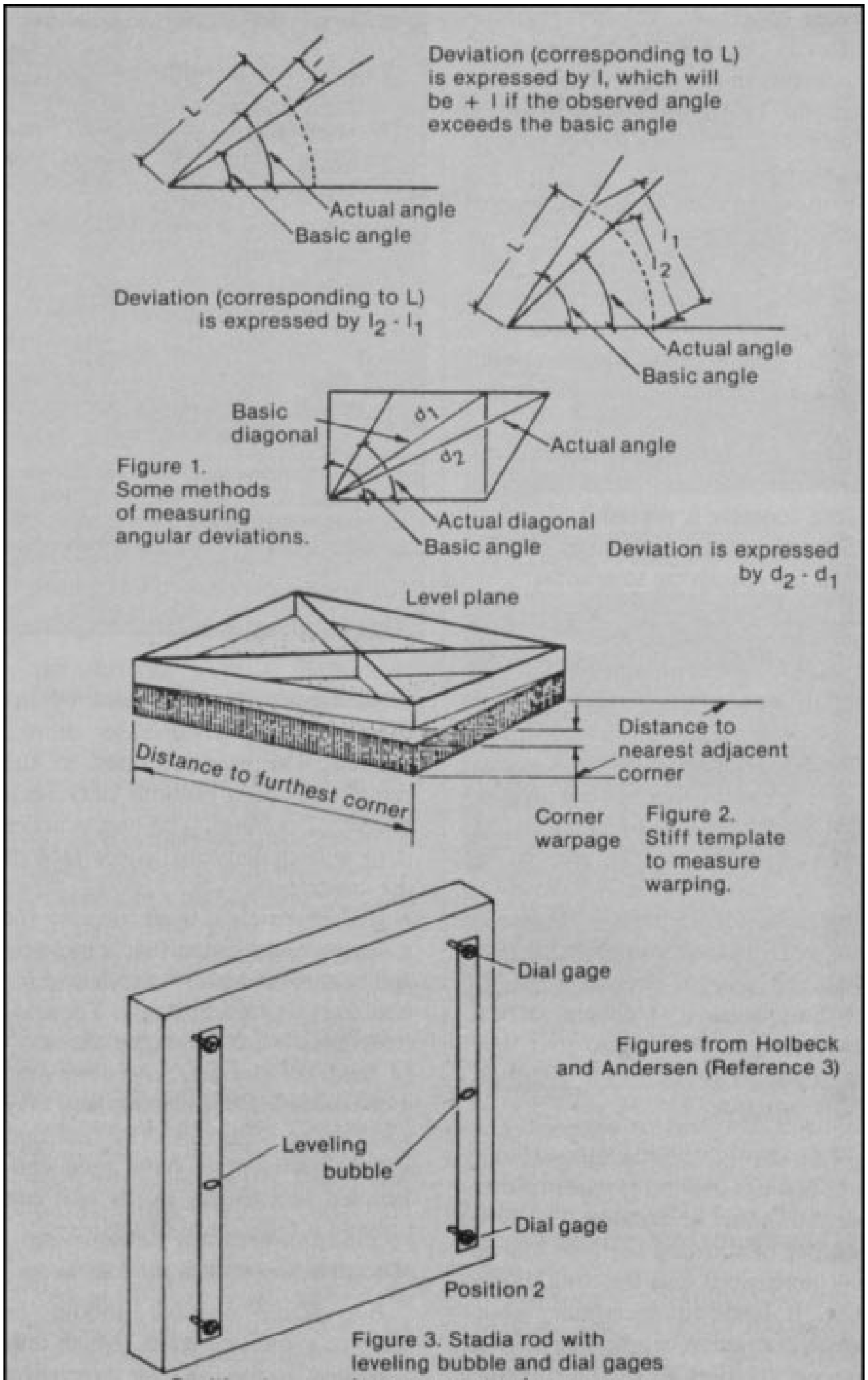

Figure 1. Some methods of measuring angular deviations.

Figure 2. Stiff template to measure warping.

Figure 3. Stadia rod with leveling bubble and dial gages to measure warping.

Tolerances cannot be achieved unless they are controlled. The work begins at the time of surveying and setting out the site and includes all subsequent construction.

One recent advancement in the control of dimensions, elevations, plumbness, planeness and alignment has been the introduction of lasers. Their use in construction measurement is discussed in the 7-page article "Laser Construction Tools," Concrete Construction, September 1978, page 516.

Other methods of controlling tolerances are illustrated in the figures. Figure 1 shows three simple methods of checking deviations of angles. A template like that shown in Figure 2 can be used to measure warping. Warping of a vertical surface can be measured with a stadia rod equipped with leveling bubbles and dial gages as shown in Figure 3. The rod is set in Position 1 near one vertical edge with the leveling bubble in a fixed position and the dial gages are adjusted to give a reading of the distance between the rod and the surface. The rod is then moved to Position 2 and held with the leveling bubble in an identical position. The distance that one dial gage has to be moved in or out indicates the amount of warping.

Bowing in a simple curve can be measured by stretching wires tightly over spacer blocks and measuring down to the surface. Another method is to measure from the curve to a straightedge.

Accepting out-of-tolerance work

Work rarely is rejected or tom out simply because it is out of tolerance. This may be evidence that specified tolerances are likely to be more stringent than actually needed. The type of out-of-tolerance work that might require replacement are slabs on grade that are intended to drain but don't, or concrete that is intended to accommodate installation of machinery but does not provide sufficient room.

In precast work it is generally more economical to cast building elements with a degree of precision that anticipates some out-of-tolerance elements. Then these elements are modified later for use in the structure. This is simply a way of recognizing the fact that there is some economical limit to the degree of precision obtainable in concrete work.

Such a practice leads to an idea that is now being considered in the construction industry: describe tolerances in statistical terms, giving both the mean and the standard deviation as descriptions of the characteristic deviations allowable. Based on European experience tolerances amounting to plus or minus 1.5 to 2.5 times the standard deviation might be realistic. In the meantime everyone must do what they can to make tolerances realistic and to plan for efficient methods of meeting tolerances during construction.

References

This article is based almost entirely on information from the following sources:

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(4) Stephan, Dean E., Jr., and Murk, Alan, "Establishing Tolerances in Concrete Construction," *Journal of the American Concrete Institute,* May 1977, pages 208-211.
(5) Graham, J.R., and Lindholm, E.A., "Concrete Tolerances—Importance and Achievement in the Bureau of Reclamation Construction," *Journal of the American Concrete Institute,* February 1978, pages 49-54.
(6) *Recommended Practice for Concrete Formwork (ACI 347-78),* American Concrete Institute, Detroit, Michigan 48219.

Metric Equivalents

(1) 6 millimeters in 3 meters
(2) 6 millimeters
(3) 0.5 percent
(4) 1.5 percent
(5) 3-millimeter from 3-meter
(6) 12-millimeter from 3-meter
(7) 25 millimeters maximum
(8) 6 millimeters in any 6 meters
(9) 13 millimeters maximum
(10) 9 millimeters in any bay or in any 6 meters
(11) 19 millimeters maximum
(12) 6 millimeters in any bay or in any 6 meters
(13) 25 millimeters
(14) minus 6 millimeters
(15) plus 12 millimeters
(16) minus 12 millimeters
(17) plus 50 millimeters
(18) plus 75 millimeters
(19) 50 millimeters
(20) 3 millimeters
(21) 1.5 millimeters
(22) 30 meters
(23) 3 millimeters below a 3-meter
(24) 5 millimeters below a 3-meter
(25) 6 millimeters below a 3-meter
(26) 6 millimeters below a 0.6 meter

SOME BRITISH MEASUREMENTS OF TOLERANCES ACHIEVED

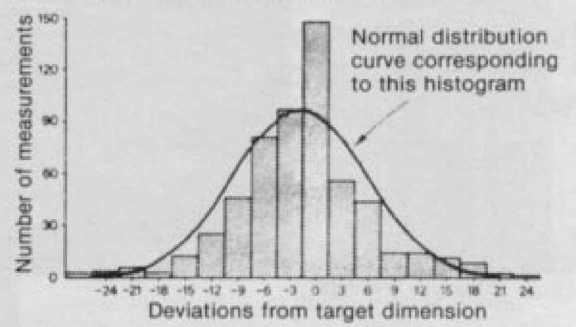
The British Research Establishment (BRE) measured tolerances achieved on 200 sites representing the work of many large and small contractors. The study included measurements of horizontal and vertical distances, internal and external dimensions, levelness, verticality, straightness and squareness. Their findings of how much the actual distances between concrete columns (measured at floor level) varied from target values are of interest. A total of 611 measurements were made on 20 sites of the distance between cast-in-place columns up to 7 meters (23 feet) apart.

The deviations are shown in the histogram. Since measurements were made in both metric units and imperial units it was convenient to show the deviations in 3-millimeter (1/8 inch) increments. BRE reports:

"The greater number of negative deviations suggests that the average space between [cast-in-place] concrete columns may be characteristically less than the designed space. Only 20 percent of all the measurements matched the target dimension, while 3 percent were outside the range represented by the target dimension ±20 millimeters.

"Again taking the example of 'distance between [cast-in-place] concrete columns,' the distribution of deviations measured at floor level has a mean of -2 millimeters and a standard deviation of 7.5 millimeters. The negative mean value indicates that the average space between columns was less than the design space by 2 millimeters. Approximately 1 percent of the measured deviations were outside the limits of -2 ±23 millimeters corresponding to ±3 standard deviations about the mean."

Thus for distances up to 23 feet the mean distance was about 5/64 inch (2 millimeters) short and 68 percent of the measurements (one standard deviation) varied from this mean value by 19/64 inch (7.5 millimeters). These would easily meet the requirement of ACI 347-78 of a tolerance of 1/4 inch in 10 feet, but obviously a significant number of the measurements would not. The 1 percent that were outside the limits of ±3 standard deviations, represented individual deviations greater than minus 1 inch (25 millimeters) and plus 53/64 inch (21 millimeters) in distances up to 23 feet.



Deviations from target dimensions of distances between columns up to 23 feet apart based on 611 measurements.

Some other conclusions of the BRE study were:

- The degree of variation in floor level seemed to bear no relationship to floor length.
- The measured standard deviations in depth of beams were smaller for beams up to 12 inches deep than for those up to 60 inches deep.
- Where greater than usual precision had been specified for distances between cast-in-place columns the actual, measured deviation in the structure did not appear to be any smaller than usual.