Construction Tolerances for Concrete in Highway Structures

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Construction tolerances for concrete now generally specified or recommended in various design standards are discussed. The need for new tolerance criteria is stated, and a basic approach to tolerancing as a function of design is proposed, taking into account service requirements, structural integrity, and appearance of concrete construction.

•TOLERANCES IN CONCRETE work involve both qualitative and quantitative factors. Although concrete is a "manufactured" material, the application of scientific tolerancing in concrete construction has not been considered to any extent in engineering and design procedures. Unfortunately, the lack of tolerance information in contract documents has led to misunderstanding and controversy among architects, engineers, inspectors and contractors regarding acceptance of concrete construction. Specifications such as "Surfaces cast to true planes" or "Contractor to verify all dimensions in the field" leave much to the imagination of the resident engineer, inspector and contractor.

In the past, most concrete structures have been cast in place, usually designed with conservative working stresses and adequate margins of safety. The dimensions have been made to fit by a process of adjustment to previously built parts. The recent trend in the direction of ultimate strength design with higher working stresses and lighter concrete sections reinforced with high-strength steels will demand greater precision of concrete manufacturing and workmanship. Qualitative and quantitative tolerancing will become a part of the engineering and design procedure.

NEED FOR RECOGNITION OF TOLERANCES

In concrete construction tolerances are necessary in relation to three important aspects: (a) integrity and safety of the structure, (b) aesthetics or appearance of the finished work, and (c) economics, involving cost to owner, designer, or contractor.

Integrity and Safety of Structure

Quality of concrete is influenced by manufacturing tolerance measured by a coefficient of variation. The American Concrete Institute (ACI) Standard 214-57, Recommended Practice for Evaluation of Compressive Strength of Field Concrete, discusses the relationship between concrete mix design strength and specified strength as a function of the variation in cylinder strength obtained on the job. This relationship is illustrated in Figure 1. By maintaining a tight tolerance in the manufacture of concrete, the ratio of required strength of concrete mix to specified strength can be kept to a minimum. Thus, the specified concrete strength should recognize a tolerance in cylinder test strengths (1).

Quantitative tolerances related to integrity and safety of structure are dimensional or geometric. The concrete section, effective depth of reinforcement and cover over reinforcing steel affect integrity and strength. In precast concrete construction, dimensional accuracy may affect the stresses at connections between members.

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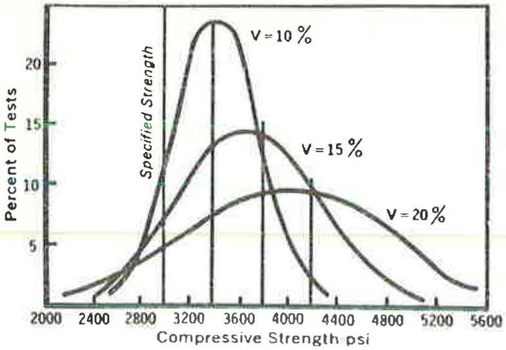

Figure 1. Relationship between coefficient of variation and required average cylinder strength to satisfy specified strength of concrete.

Aesthetics—Appearance of Finished Work

The satisfactory composition of a concrete structure usually depends on conformity with design dimensions within certain tolerances. The designer visualizes the columns or piers plumb, the girders level or set to an established camber or grade. He expects the final structure to correspond to the appearance shown on his drawings. Since no concrete structure is ever built exactly true to every plan dimension, tolerances should be specified, informing the contractor within what limits he must adhere to the theoretical dimensions. Allowances for shrinkage and creep of concrete should be anticipated in setting the tolerances. If no tolerances are specified, who is to judge how much variation from plan dimensions constitutes satisfactory compliance with the contract?

The finish of concrete surfaces exposed to view should be specified within reasonable tolerances. Uniformity of color and texture of surface should be defined, either by illustrations or standard samples for the benefit of contractors and inspectors, showing a range of acceptability for a given project.

Economic Aspects

John R. Nichols stated (2):

> Tolerances must be related on the one hand to their reasonableness, to the cost of building within them; and on the other hand to the need for, and the value of, close adherence to the indicated line and grade. In judging any proposed tolerance, therefore, one must inquire first, is it necessary and is it sufficient to build within this tolerance in order that the structure may have suitable appearance, may satisfy the purpose for which it is erected, and may be structurally safe; and second, can such accuracy be obtained reasonably, that is, without unjustified cost?

In 1940, Nichols was thinking of cast-in-place concrete construction. Today, concrete construction is moving toward prefabrication of structural members and becoming an industrialized process in which mass production of factory-manufactured structural elements will prevail. Already highway structures are being assembled from precast and prestressed concrete parts which are factory produced and delivered many miles to the construction site. The economy of prefabricated concrete structures is becoming more obvious as savings in labor and material are achieved through better designs and the exploitation of very high-strength concrete (6,000 to 10,000 psi) and prestressing steel (250,000 to 300,000 psi). As Abdun-Nur pointed out (1), average field-produced concrete may be assumed to have a compression strength coefficient of variation between 20 and 25 percent. Factory-produced concrete, scientifically controlled, may have a coefficient of variation of 10 percent, with important economic implications. Thus, the designing engineer should be concerned with qualitative tolerances related to concrete strength.

With prefabricated concrete construction, dimensional tolerancing takes on new importance. As in other manufacturing industries, such as the automotive and aircraft, mass production and assembly of parts involve tolerances for dimension, form, and position. Over the past 40 or 50 years, the automotive and machine tool industries have evolved an advanced concept of tolerancing. Today, national and international

CHARACTERISTIC	PRESENT	NEW	ISO
STRAIGHTNESS	⌒	—	—
FLATNESS	⌒	—	▱
ANGULARITY	∠	∠	∠
SQUARENESS	⊥	⊥	⊥
PARALLELISM	∥	∥	//
CONCENTRICITY	◉	◉	◎
TRUE POSITION	⌖	⌖	⌖
ROUNDNESS	○	○	○
SYMMETRY	⌯	⌯	⌯
ACCURACY OF LINE OR PROFILE		⌓	⌒
ACCURACY OF SURFACE		⌓	⌓
RUN OUT		↗	↗
CYLINDRICITY		⌭	⌭
DATUM	[-A-]	[-A-]	▲
MMC	Ⓜ	Ⓜ	Ⓜ
RFS	Ⓢ	Ⓢ	

Figure 2. Symbols for geometric and positional tolerancing.

societies are working on standards for tolerancing and means of communicating design tolerances on drawings and specifications. Belitsos (3) traced the evolution of the technology of graphics from its very simple beginnings to a highly sophisticated language of communication between engineering, manufacturing and inspection. Figure 2, taken from this article, shows tolerance symbols for geometric and positional tolerancing.

CURRENT STATUS OF TOLERANCING FOR CONCRETE CONSTRUCTION

Tolerancing in concrete construction today is comparable to the situation in the automobile industry 60 years ago. Each part was made to fit to its neighbor by selective assembly. An overrun in dimension of one section was deducted from the dimension of an adjacent section so that the overall total would add up to the desired sum.

In current practice of highway design, the only widely used tolerance for concrete structures relates to the surface of the roadway, namely, a maximum deviation from the design surface of $\pm 1/8$ in./10 ft of distance.

The American Concrete Institute Standard 347-63, Recommended Practice for Concrete Formwork, contains suggested tolerances for concrete bridge structures. These tolerances give plus or minus limits of permitted departure or variation from the design dimensions, summarized as follows:

1. Departure from established alignment, 1 in.
2. Departure from established grades, 1 in.
3. Variation from plumb or specified batter in the lines and surfaces of columns, piers, walls, and arrises—exposed, in 10 ft, 1/2 in.; backfilled, in 10 ft, 1 in.
4. Variation from level or grades indicated on drawings in slabs, beams, horizontal grooves, and railing offsets--exposed, in 10 ft, 1/2 in.; backfilled, in 10 ft, 1 in.
5. Variation in cross-sectional dimensions of columns, piers, slabs, walls, beams, and similar parts, -1/4 in., +1/2 in.
6. Variation in thickness of bridge slabs, -1/8 in., +1/4 in.
7. Footings—variation in dimensions in plan, -1/2 in., +2 in.; misplacement or eccentricity, 2 percent of footing width in direction of misplacement but not more than 2 in.; reduction in thickness, -5 percent of specified thickness.

The contractor is expected to set and maintain concrete forms to insure completed work within the tolerance limits.

Suggested tolerances for precast concrete construction are also included in ACI 347-63, as follows:

1. Overall dimensions of members per 10 ft of length, ±1/16 in.
2. Cross-sectional dimensions of sections less than 3 in., ±1/16 in.; of sections over 3 in. and less than 18 in., ±1/8 in.
3. Deviations from straight line in long sections, not more than 1/8 in./10 ft.
4. Deviation from specified camber per 10 ft of span, ±1/16 in.; maximum differential between adjacent units in erected position, 1/4 in.

These tolerances are considered too restrictive by most precast concrete manufacturers, and counterproposals with liberalized tolerances have been suggested, such as the Michigan Precasters Recommendation:

1. Cross-sectional dimensions—less than 6 in., ±1/8 in.; 6 to 18 in., ±3/16 in.; 18 to 36 in., ±1/4 in.; over 36 in., ±3/8 in.
2. Length, ±1/8 in./10 ft; maximum deviation, ±3/4 in.
3. Deviation from line (sweep), 1/8 in./10 ft.
4. Deviation from specified camber (as installed), ±1/8 in./10 ft.
5. Differential camber in adjacent units (as installed), one-half total allowance.
6. Vertical deviation in squareness of ends[1]—less than 12 in., 1/32 in./in.; over 12 in., 3/16 + 1/64 in./in.; maximum deviation, 3/4 in.
7. Horizontal deviation in squareness of ends[1]—less than 12 in., 1/64 in./in.; over 12 in., 3/32 + 1/128 in./in.; maximum deviation, 3/4 in.

These tolerances are considered standard in the Michigan area for the various precast concrete items including columns, beams, single and double tees, hollow core and solid slabs. Allowances should be made in the design to accommodate these standards wherever possible. If closer tolerances are necessary, they should be clearly noted on the drawings and in the specifications.

Tolerances for surface finishes have been published by the U. S. Bureau of Reclamation in "Concrete Manual", 1963 Edition. Five classes of finishes for concrete surfaces cast against forms are designated as F1 through F5. Four classes of finishes for unformed surfaces are designated as U1 through U4. Surface irregularities permitted for these finishes are termed either "abrupt" or "gradual." Offsets and fins caused by displaced or misplaced form sheathing, lining or form sections, by loose knots in forms, or by otherwise defective form lumber are considered as abrupt irregularities. All others, classed as gradual irregularities, are measured with a template consisting of a straightedge for plane surfaces or its equivalent for curved surfaces.

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[1] This not to be in addition to overall length tolerance.

TABLE 1
MAXIMUM ALLOWANCES OF IRREGULARITIES IN CONCRETE SURFACES

Type of Irregularities	Formed Surfaces[a]					Unformed Surfaces[b]			
	F1	F2	F3	F4	F5	U1	U2	U3	U4
Depressions	1	-	-	-	-	-	-	-	-
Gradual	-	1/2	1/4	1/4	1/4	-	-	-	-
Abrupt	-	1/4	1/8	1/4[c] 1/8[d]	1/4	-	-	-	-
All surfaces	-	-	-	-	-	3/8	1/4	1/4	-
Canal surfaces, bottom slabs	-	-	-	-	-	-	-	-	1/4
Canal surfaces, side slopes	-	-	-	-	-	-	-	-	1/2

[a]Measured from 5-ft template.
[b]Measured from 10-ft template.
[c]Of irregularity or offset extending parallel to flow.
[d]Of irregularity or offset not parallel to flow.

The various classes of finishes and the categories of construction where applicable are described. The allowable irregularities in concrete surfaces for the various classes of finishes are given in Table 1.

Tolerances for the fabrication and placing of reinforcing steel, although very important, have not received much notice in technical publications. Nichols (2) did propose the following allowable variation from plan dimension in the fabrication and placing of reinforcing steel:

1. Variation from dimension in the fabrication of stirrups, column ties and spirals, 1/4 in.; of other bars, 1/2 in.
2. Placement of reinforcement affecting protective covering or effective depth in bending, in slabs and members not over 1 ft in transverse dimension (in the direction of the tolerance), 1/4 in.; in other members, 1/2 in.
3. Spacing of bars indicated to be evenly spaced in a group—variation from even spacing, 2 in.; variation in average spacing affecting the number of bars in the group, 5 percent; minimum clearance between parallel bars, 1/4 in.

The ACI Detailing Manual for Reinforced Concrete includes information on tolerances for fabrication of reinforcing steel, shown in Figure 3. These tolerances reflect standard practice in the cutting and bending of steel by reinforcing bar fabricators.

Obviously, available published tolerance data on reinforced concrete construction reflect consideration for safety, appearance and economy of concrete construction. Unfortunately these data are not generally incorporated into construction contract documents. Provision for enforcement of tolerances in construction creates problems for resident engineers and inspectors and this area needs more attention.

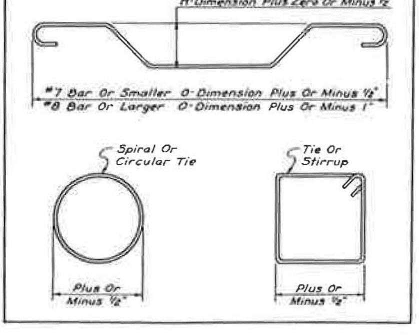

Figure 3. Tolerances for cutting and bending reinforcing steel, from ACI detailing manual.

A review of tolerances for reinforced concrete construction gathered from published sources indicates that values seem reasonable for average practice. However, no basic formula has been proposed for tolerancing in function of total dimension of members. Nothing reflects percentage variation of lever arm ratios in reinforcing steel or eccentricity of forces in compression members. Thin-wall hollow cylinder piles are not distinguished from large diameter cast-in-place reinforced concrete columns. Tolerance figures of 1/8, 1/4, and 1 in. seem to be popular values put into tables.

CONCLUSIONS

A need exists for a logical system of tolerancing concrete structures from the standpoint of safety, aesthetics and economics of concrete structures. Lack of adequate concrete tolerance communication in contract documents has led to misunderstandings and disputes between engineers and contractors, often resulting in litigation.

Construction trends are shifting to prefabrication, with mass-produced components requiring accurate fitting into final assembly. Tolerancing must become an engineering and design procedure. Much can be learned from those in other fields of engineering who have developed tolerancing to a highly logical and scientific procedure in design. Concrete engineering and construction needs a language of tolerancing for communication between the designers and the builders.

REFERENCES

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