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ACI Code Requirements for Deflection Control: A Critical Review

by A. Scanlon, D. R. Cagley Orsak, and D. R. Buettner

Synopsis: ACI Building Code requirements for deflection control are critically reviewed. Provisions for minimum thickness, deflection computations, and permissible computed deflections are reviewed. Differences in the approaches to deflection control for one-way and two-way construction are identified. Limitations in the application of the prescribed deflection calculation method are discussed. Results of a survey of consulting firms concerning deflection control in design offices are presented. The paper concludes by suggesting possible directions for future changes in building code requirements for deflection control.

Keywords: beams; building code; cracking; deflection; minimum thickness; slabs

Andrew Scanlon, an ACI Fellow, is a Professor of Civil Engineering at the Pennsylvania State University, University Park, PA. He is Chair of ACI Committee 435 (Deflections), a member of Committees 224 (Cracking), 342 (Evaluation of Concrete Bridges) and a member and former Chair of Committee 348 (Safety).

Debrethann R. Cagley Orsak is a Principal and Vice President of Cagley & Associates, a structural engineering consulting firm in Rockville, Maryland. She is a member of the ACI Board of Direction, Secretary of ACI Committee 435 (Deflections), Chairman of the ACI 100th Year Anniversary Task Group, and a member of the following ACI Committees; Educational Activities Committee, Convention Committee, Scholarship Council, E-702 (Designing Concrete Structures), and E-801 (Student Activities Committee).

Donald R. Buettner, an ACI Fellow, is President of Computerized Structural Design of Milwaukee, Wisconsin and Denver, Colorado. He is a member and past chair of ACI Committees 435 (Deflections) and 550 (Precast Structural Concrete).

INTRODUCTION

Deflection control is an important serviceability consideration in the structural design of concrete buildings. While provision of an adequate level of safety against collapse is the primary design consideration, the structural engineer must take into account possible adverse effects of excessive deflections on the performance of the structure at service load levels. Potential problems associated with excessive deflections are well known and include damage to nonstructural elements including partitions and windows, jamming of doors and windows, gaps between partitions and floors, and between columns and floors, improper operation of equipment, visual perception of sagging floors and ceilings, and the need to provide expensive floor leveling materials.

Some guidance is provided in Section 9.5 of the ACI Code (ACI 318-99) on design for deflection control of one-way and two-way nonprestressed construction, prestressed concrete construction, and composite construction. The general approach to deflection control in the code has remained essentially unchanged since 1971. This paper presents a review of the current provisions with some suggestions for improvement of these provisions.

DEFLECTION CONTROL AND THE BULDING CODE

The introduction to the 1999 ACI Code contains the statement:
"A building code states only the minimum requirements necessary to provide for public health and safety. The code is based on this principle."

Because deflection control is an issue which for the most part has no impact on public health and safety the question is sometimes raised as to why deflection control should be part of the building code. Some engineers have expressed the opinion that deflection control is an issue between the design engineer and client and should not be dealt with in the building code. A structure may have unacceptably large deflections and yet have an adequate margin of safety against collapse. Deflection control is an economic issue involving a balance between first cost and potential costs associated with maintenance, repair and other costs that might be incurred as a result of a problem related to deflection. There is also the question of the engineer's professional reputation and potential professional liability issues. Deflection control has traditionally been mentioned in the code even though it is not a safety issue. Engineers will continue to look to the code both for guidance and criteria for some measure of acceptability in deflection levels.

Because serviceability criteria are not as clearly defined as safety criteria and vary much more depending on requirements of particular projects, the question of establishing minimum requirements becomes quite difficult. The engineer may well have to exceed the minimum requirements given in the code to meet the requirements of the client. In many cases, the client will rely on the professional judgment of the engineer as to the needs for a particular project.

ACI 318 REQUIREMENTS

The ACI Code provides a two-tier approach to deflection control. Under certain circumstances deflection control requirements will be deemed to have been satisfied if the flexural member depth is greater than a minimum value expressed as a fraction of the span length. Otherwise the code requires that deflections be computed and compared with specified permissible values. Details of these provisions are outlined in the following sections.

Minimum Thickness Requirements

Minimum thicknesses for one-way slabs and beams are given in Table 9.5(a) of ACI 318-99. In this table span length is defined as clear span plus depth of member but need not exceed distance between centers of supports. The table is reproduced in Appendix A.

These minimum thicknesses can be used for members NOT supporting or attached to partitions or other construction likely to be damaged by large deflections. Members that do support or are attached to partitions or other construction likely to be damaged by large deflections are not covered by Table 9.5 (a) and consequently, deflections should be computed for these members and compared to specified permissible values.

Minimum thicknesses for two-way slab systems are presented in Table 9.5 (c) and Eqs. 9-11 and 9-12 of ACI 318-99. In this case the span length to be used is defined as length of the clear span in long direction, measured face-to-face of supports. In contrast to one-way construction, no restrictions are placed on use of these minimum thickness values for members supporting partitions. However the commentary does note that "The minimum thicknesses in Table 9.5 (c) are those that have been developed through the years." and "These limits apply to only the domain of previous experience in loads, environment, materials, boundary conditions, and spans." This cautionary note in the commentary suggests that care should be taken in selecting the slab thickness for arrangements that fall outside the realm of previous experience.

The minimum thickness requirements for one-way and two-way construction appear to have developed independently and as a result a number of inconsistencies can be identified in comparing the two sets of requirements:

a) Different definitions of span length: There appears to be no reason to use different definitions of span length. For members built integrally with supports, whether one-way or two-way, clear span seems to be the logical choice while for members not built integrally with supports, distance between edge of bearing seems to be a reasonable definition. The question also comes up in determining permissible computed deflections as discussed later.

b) Different levels of conservatism for one-way and two-way slabs: If a two-way flat plate is designed based on minimum thickness and subsequently changed to a one-way system by addition of stiff beams or walls along column lines in the short span direction, an increase in minimum thickness or deflection calculations would be required. It is not logical to increase the slab thickness when stiffening elements have been added. Scanlon and Choi (1999) showed that the one-way slab minimum thickness values are generally conservative for typical building spans and recommended an alternative approach to minimum thickness. Proposals for revising minimum thickness of one-way or two-way construction have also been presented by Rangan (1982), Grossman (1981), Thompson and Scanlon (1988), and Gardner and Zhang (1995) among others.

(c) Different treatment of partition damage: The minimum thickness for two-way construction is applicable even if the slab is supporting partitions, which is not the case for one-way slabs.

Computed and Permissible Deflections

The code prescribes a simplified methodology for computing deflections although more comprehensive methods are permitted as long as effects of cracking and reinforcement on member stiffness are considered for immediate application of load, and creep and shrinkage are taken into account when considering long-term deflection. The effective moment of inertia concept is used to allow for a gradual transition from uncracked to fully cracked stiffness as loading increases. Effective moment of inertia is given by,

$$I_e = \left(\frac{M_{cr}}{M_a}\right)^3 I_g + \left[1 - \left(\frac{M_{cr}}{M_a}\right)^3\right] I_{cr}$$

(1)

Where,

$$M_{cr} = \frac{f_r I_g}{y_t}$$

(2)

and

$$f_r = 7.5\sqrt{f_c'}$$

(3)

A simple long-term multiplier is provided for the computing of long-term deflections. The multiplier is applied to the computed immediate deflection corresponding to the sustained load level considered. The multiplier is given by,

$$\lambda = \frac{\varsigma}{1+50\rho}$$
(4)

Where ζ takes the following values

5 years or more................ 2.0
12 months........................ 1.4
6 months.......................... 1.2
3 months.......................... 1.0

The compressive reinforcement ratio is included in Eq. 4 to account for the effect of reinforcement in the compressive zone which resists creep deformation. The commentary points out that long-term deflections are affected by many factors including temperature, humidity, curing, and age at time of loading. Many references are available for computing creep and shrinkage effects separately including those listed in the commentary and the ACI 435 report on Control of Deflection in Concrete Structures (ACI 435-95R). The simple multiplier is considered by ACI 318 to be satisfactory for use with the code procedures and the limits specified in Table 9.5 (b).

If minimum thickness cannot be used to satisfy deflection control requirements, deflections must be computed and compared to specified permissible deflections listed in Table 9.5 (b) of ACI 318-99 (See Appendix). The code requires two separate deflection calculations, one for immediate deflection due to live load, and one for that part of the total deflection occurring after attachment of non-structural elements (sum of the long-term deflection due to all sustained loads and the immediate deflection due to any additional live load). The latter will be referred to as the "incremental long-term deflection".

The calculation of live load deflection depends on whether the live load is assumed to occur during first-cycle loading or subsequent loading. If first cycle loading is assumed and cracking occurs during loading, the live load deflection is taken as the difference between the total load deflection and the dead load deflection. Since the stiffness gradually decreases as loading increases due to progressive cracking, the stiffness under dead load is greater than the stiffness under total load. On the other hand, if it is assumed that the member has already experienced an application of live load, it should be recognized that the member cannot become uncracked after removal of the live load. In this case the stiffness for both dead load and total load is that corresponding to application of total load. This is illustrated in Figure 1. The definition of M_a in ACI 318-99 implies that first cycle loading should be considered since M_a is defined as the maximum moment in the member at stage deflection is computed. Dead load deflection would then be calculated based on the dead load moment. In many concrete structures the highest loading is experienced during construction as a result of shoring, reshoring, and other construction loads. In such cases, the stiffness for all service load checks should be that associated with dead plus live load. This has the effect of decreasing the computed live load deflection but increasing the computed dead load deflection and consequently the incremental long-term deflection. In the event that restraint built into the structural system would produce shrinkage cracking then that should be taken into account in the design.

The effective moment of inertia procedure has now been a part of the code for almost 30 years and has generally been found to provide satisfactory results for members with medium to high reinforcement ratios. However some difficulties have been experienced in applying the method to members with low reinforcement ratios, particularly lightly reinforced slabs for which flexural stiffness is sensitive to cracking. The following factors contribute to poor correlation between computed and measured deflections in these cases.

1. The modulus of rupture specified as $7.5\sqrt{f'c}$ represents a low estimate of the material property as determined from laboratory tests on small samples. ACI 209 reports that the typical range is about 6 to $12\sqrt{f'c}$. On the surface it appears that a conservatively low estimate of the cracking moment is being used to compute deflections. However, cracking is affected not only by applied loads used to compute M_a, but also by restraint of shrinkage and temperature deformations. In some cases cracking can be detected before forms are removed and the member is subjected to dead load. The effect of restraint cracking should therefore be considered in deflection computations.

2. If incremental long-term deflection due to sustained load is computed based on first cycle loading, the stiffness will often be based on an uncracked section because the dead load moments may be less than the computed cracking moment. Recognizing that loads approaching the specified live load may be experienced at early age, the sustained load deflection should be computed based on the stiffness associated with dead plus live load. The problem may be exacerbated by the tendency for unanticipated overloading of slabs due to shoring and reshoring.

3. A further complicating factor comes into play for flat plates and flat slabs supported on columns. The elastic distributions of moments adjacent to columns produce locally high intensities that invariably initiate cracking in the negative moment regions around columns.

The cracking allows redistribution of these high moments but the stiffness has been reduced.

4. For members with low reinforcement ratios the rate at which the effective moment of inertia approaches the fully cracked moment of inertia is too low.

To account for the factors mentioned above, Scanlon and Murray (1982) recommended that a reduced effective modulus of rupture be used in computing deflections of two-way slab systems. A value of $4\sqrt{f'_c}$ has been found to produce satisfactory results in several case studies involving field measured deflections. A similar approach has recently been suggested by Gilbert (1999). Because of the many uncertainties and variabilities associated with estimating the factors that affect deflections a more precise estimate may not be worthwhile.

The historical development of deflection limits has been reported by Warwaruk (1979). It appears that deflection limits in use today have developed over the years based on experience with rules of thumb dating back at least to the 19th century. In the past thirty years or so a great deal of effort has been put into developing more refined algorithms for computing deflections. At the same time relatively little effort has gone into defining appropriate criteria for deflection limits (Scanlon and Pinheiro, 1992). Four deflection limits are specified in Table 9.5 (b), two for live load deflection, and two for incremental long-term deflection, depending on whether or not the deflection is likely to cause damage. These limits are specified as fractions of span length, $l/180$ and $l/360$ for live load deflection, $l/240$ and $l/480$ for incremental long-term deflection. The limit for incremental long-term deflection, $l/480$, which applies when damage to non-structural elements is likely, can be exceeded if special precautions are taken to prevent damage. The ACI code does not place a limit on total deflection as some codes do, however the other limits indirectly limit the permissible total deflection, immediate and long-term. While these deflection limits appear to cover a broad spectrum of design situations quite satisfactorily, it is recognized that there may be situations requiring more stringent limits. For example a limit of l/1000 has been suggested for members supporting brittle partitions such as unreinforced masonry. ACI Committee 435 (1963) provides suggested limits to cover some applications requiring more stringent limits than given in the code.

In computing the incremental long-term deflection the engineer needs to make an assumption regarding the time of installation of non-structural elements. In most cases this will be unknown at the design stage. It is probably not unreasonable to make the conservative assumption that installation will take place immediately in which case the full value of the multiplier would be applied. It is also necessary to make an assumption regarding the portion of live load to be considered as sustained. Live load surveys for office and similar buildings have shown that the actual live load at any time is typically quite low compared to the design live load.

The span length to be used in applying Table 9.5 (b) to calculate the permissible deflection limit for two-way slab systems is not clearly defined. If the mid-panel deflection is computed it appears to be most logical to take the span length measured along the diagonal whereas if the column strip deflection is being calculated, the span length should be measured between the two columns on the column strip. It would also seem logical to use clear span for calculating permissible deflection limits.

In addition to the detailed treatment of deflection of one-way and two-way nonprestressed construction given in the code some general guidance is provided for deflection of prestressed and composite construction.

Construction Requirements

Deflection control is not simply a design issue. At least as important is the proper attention to construction procedures. Section 6.2 of ACI 318-99 addresses the question of removal of forms, shores, and reshoring, and includes the general statement: "Forms shall be removed in such a manner as not to impair safety and serviceability of the structure."

DEFLECTION CALCULATION PRACTICES IN THE U.S.

Consulting engineers typically design structures (and particularly concrete structures) using purchased software. There are a number of relatively inexpensive and readily available software packages for design of concrete beams, slabs and two-way systems. One can argue that the design practice for deflections is whatever procedures are built into commonly used commercial software.

ACI Committee 435 conducted a survey of consulting firms in 1999. The results of that survey are most interesting. All respondents use one or more commercial software packages. That software in turn incorporates the basic code prescribed procedures for deflections. Essentially the $I_{effective}$ concept is used along with all code prescribed procedures for long term deflection calculation. The deflection is compared with permissible limits (e.g. L/360) and member sizes are increased until the deflection criteria is satisfied.

The software does not include options to enable the designer to account for restraint (and the effect this would produce on cracking and, in turn, on stiffness). Software incorporates $7.5\sqrt{f'c}$ as the modulus of rupture and designer input on this parameter is not available.

According to the survey, engineers are generally comfortable with purchased software and feel it adequately predicts deflections. If any calculation problems are perceived to exist, engineers feel that the deflection predictions for two-way systems (flat slabs and flat plates) are the most unreliable and that the limited deflection related problems that have been experienced in structures have occurred in two-way systems.

FUTURE CODE DEVELOPMENTS

The deflection control provisions given in the ACI code appear to have resulted in satisfactory performance of concrete structures over the years. While deflection at service load levels is understood to have no impact on structural safety, it is expected that deflection control will continue to be an integral part of the code, to provide guidance to engineers in design for serviceability. This paper has pointed out a number of areas where improvement and clarification of the code provisions are possible. These include a more unified treatment of one-way and two-way construction, and additional guidance on deflection calculations for two-way systems. Computers are becoming increasingly used in structural design practice and future developments of the code provisions should keep this in mind.

As new developments are made through research involving different reinforcing materials, the calculations for deflection of members using these materials will have to be reviewed. The new materials have different properties than the Grade 60 reinforcement on which the current deflection calculations have been based.

The code should continue to provide guidance to designers on deflection limits, but perhaps some of the limiting conditions could be better defined.

REFERENCES

ACI Committee 318 (1999). Building Code Requirements for Structural Concrete (ACI 318-99) and Commentary (ACI 318R-99). American Concrete Institute, Detroit, 391 pp.

ACI Committee 435 (1995). Control of Deflection in Concrete Structures (ACI 435-95R). American Concrete Institute, Detroit, 77 pp.

ACI Committee 435 (1968). Allowable Deflections (ACI 435.3R-68), American Concrete Institute, Detroit, 12 pp.