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ACI 435.3R-68

(Reapproved 1989)

# Allowable Deflections

Reported by Subcommittee 1, ACI Committee 435

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Discusses the factors affecting the deflection of reinforced concrete members and emphasizes the importance of taking them all into consideration for an accurate estimate of deflection. Includes a table with an extensive list of situations requiring deflection limitations. These are based on  $L/\Delta$  ratios and absolute values applied to the total or incremental deflections. Discusses the most significant parameters affecting the  $L/D$  ratios as an indirect limit on deflections. Presents formulas and graphs for  $L/D$  and gives examples for their use.

The report is divided into five chapters: Introduction, Computation of Deflections, Allowable Deflections, Allowable Span/Depth Ratios, and Correlation with Actual Building Structures.

**Keywords:** creep (materials); damping; deflection; modulus of elasticity; reinforced concrete; serviceability; shrinkage; span depth ratio; structural analysis; structural design; temperature; vibration.

## CHAPTER 1—INTRODUCTION

The purpose of this report is to: (1) discuss some practical considerations in the computation of deflections of reinforced concrete building structures, (2) suggest limits on the movements to avoid undesirable deflection or dynamic responses, and (3) suggest limits on the ratio of span to depth which will result in structural members having satisfactory stiffness in most cases.

Most of the factors affecting deflection computations and allowable limits are discussed. No attempt has been made to condense the recommendations into a form suitable for design tables or code limitations.

The committee sent questionnaires to about 300 practicing structural engineers in the United States and received over 40 replies. On the basis

of these replies it appears that the design for deflection of reinforced concrete members has not kept pace with design for strength. Many engineers apparently have vague ideas on how to compute deflection and on the significance of the computations. Deflection limitations as commonly specified are rarely more sophisticated than 180 to 480 or more for span/deflection ratios and 10 to 40 for span/depth ratios. Many engineers apparently make no distinction between simple and continuous spans in setting span/depth limits.

However, there seems to be a growing awareness of the problems created by excessive deflections. The majority of the respondents indicated first hand knowledge of such problems.

It is hoped that this report will assist structural engineers to make more intelligent estimates of

**ACI Committee 435**, Deflection of Concrete Building Structures, was organized in 1957 to study research on deflection of concrete flexural members in building structures under rapid and long-term loads. Dan E. Branson was chairman from 1962 to 1968 during which time this report was prepared. This is the committee's third published report. Subcommittee 1, Allowable Deflections, consists of seven members with Russell S. Fling as chairman.

the actual deflections and to place more realistic limits on the magnitude of these deflections.

## CHAPTER 2—COMPUTATION OF DEFLECTIONS

Strength computations are usually based on the assumption that the member will never (or on a probability basis, almost never) have less strength than demanded by the superimposed loads. If the same philosophy is used in stiffness computations, structural members will result that are unduly conservative and sometimes unsatisfactory.

The engineer's natural tendency to overestimate loads and use conservative design assumptions should be resisted since an overestimate of deflections could be as troublesome as an underestimate, especially if the members are to be cambered. Stiffness computations should predict the true deflections as accurately as possible with a unit "factor of safety." The maximum expected error due to fallacious assumptions or inaccurate data on material properties or loads can be estimated and a range of deflection values established. The probable effect of deflection at the high or low end of this range can then be assessed.

Although methods for computing deflections of reinforced concrete members have been available for many years,<sup>1,2</sup> they have not yielded uniformly consistent results. The principal reason for this is that many factors affecting the true magnitude of the deflection have been inadvertently ignored. This has led to an unjustified lack of confidence in the available computational methods. Some of these factors are discussed in the following list.

1. For strength computations, the concrete is assumed to carry no tension; however, this assumption is unduly conservative for deflection computations. In many cases (particularly solid slabs), the concrete remains essentially uncracked and behaves as a gross transformed concrete section. Even a shallow highly stressed beam may remain uncracked over a substantial portion of its depth and length. Consequently it is somewhat stiffer than a fully cracked beam. In the fully cracked zone, the tensile strength of the concrete between cracks and near the neutral axis increases the effective stiffness.

2. Permanent and transient loads that are actually likely to be applied to the structure should be used instead of those assumed in strength computations, especially for long-term

deflections. The actual live load is often substantially less than the maximum specified in building codes. Similarly, the assumed dead loads are frequently on the heavy side to be "safe" in strength computations.

3. True moments should be used rather than those computed in the design for strength, especially when empirical moment factors have been used. For example, moments based on factors given in Section 904 of ACI 318-63<sup>3</sup> will generally be too high (the sum of the positive and negative moments equal up to 123 percent of the static moment), while those derived from Section 2104 of ACI 318-63<sup>3</sup> will generally be too low (the sum of the positive and negative moments equal as little as 72 percent of the static moment). Another source of error is the redistribution of moment due to creep. This redistribution usually decreases the moment causing high stresses and increases the moment causing low stresses. At the present state of the art, computational methods for estimating this error are not available.

4. Almost all flexural members have some end restraint even though many are designed for strength as simple spans. A small end moment will materially reduce the deflection, therefore full credit should be given the restraint afforded by masonry bearing walls, columns, and minor structural elements. When satisfactory analytical techniques are not available, logical estimates of this restraint should be made.

5. Where possible, the modulus of elasticity and modulus of rupture should be based on measured values from concrete similar to that used in the structure. However, tests to determine the modulus of elasticity must be conducted in such a way as to obtain values which are consistent with the theoretical assumptions on which the deflection computations are based. When they are computed from the cylinder compressive strength using empirical formulas, the average cylinder strength at the time load is applied should be used rather than the strength assumed in the design. The average modulus of rupture of a series of identical test specimens should be used rather than the lowest value as this will more nearly represent the true line of demarcation between a cracked and an uncracked section.

6. The conditions of loading during construction (for example, the reshoring sequence) can drastically alter the subsequent deflection. Concrete loaded at an early age will have a greater initial deflection than concrete loaded at a later age. In addition, the modulus of rupture will also be lower. Consequently, cracking is more likely with a resultant increase in deflection. Conversely, concrete that is properly cured and is protected from early stresses until high moduli of elasticity

and rupture have been gained, will ultimately prove to be much stiffer.

7. The ambient weather conditions during and after construction will affect the drying shrinkage and hence the magnitude of shrinkage warping. Concrete members cast and maintained in a damp, cool atmosphere can be expected to have less deflection than those in a hot, arid atmosphere.

8. Since the amount of drying shrinkage and creep is affected by the volume/surface ratio, large concrete beams will have a lower ultimate deflection than thin slabs. The difference can be as high as 40 or 50 percent.<sup>4</sup>

9. Nonstructural elements of the structure frequently reduce calculated deflections quite substantially. For example, partitions may span from end to end and carry almost their entire weight when the "supporting" member deflects. Deflecting members may come to rest on walls or window mullions below. For many years it has been known that high rise buildings may not deflect laterally as much as the theoretical frame computations indicate because of the stiffness contributed by walls and partitions.

10. Full allowance should be made for the flanges in tee beams even when they are on the tension side of the beam. Flanges may increase the stiffness of an uncracked section to as much as 234 percent and the stiffness of a cracked section to as much as 185 percent\* of that of rectangular sections with the same over-all depths and with widths equal to the stem widths of the flanged sections. Consideration should be given to using a greater flange width than permitted by ACI 318-63<sup>3</sup> for strength computations. For example, the effective stiffness of a beam with pan slab joists parallel to it might include the stiffness of several adjacent joists.

11. The transformed area of reinforcing steel in uncracked sections should not always be ignored as it may increase the moment of inertia of the plain concrete as much as 30 percent.\* Similarly, compression steel in cracked sections may increase the moment of inertia as much as 15 percent.

12. Concrete that is subjected to high temperatures in service [over about 100 F (37 C)] may have deflections increased significantly.<sup>5</sup>

13. Compression reinforcing steel will substantially reduce the long term creep deflection. In some circumstances, the long-term increase in deflection may be reduced to 20 or 30 percent of the short-term deflection.<sup>6</sup>

14. In continuous beams, where the flexural rigidity varies from negative moment regions to positive moment regions, the deflection must be computed by a method which takes into account the contribution of each section of the beam to the total beam deflection. For example, if the rela-

tive flexural rigidity in the positive moment region is equal to 1.0 and the relative flexural rigidity in the negative moment region of the same beam is equal to 2.0, the average flexural rigidity would be 1.5. However, the deflection of a beam with small or no end moments would be proportional to a flexural rigidity close to 1.0.

### CHAPTER 3—ALLOWABLE DEFLECTIONS

Before World War II, allowable bending stresses were lower than those permitted at the present time. As a result, reinforced concrete structures were often uncracked in service. The lack of cracks as well as the lower stresses resulted in small deflections. In addition, many construction materials were softer and more pliable than those used today. For example, soft brick and lime mortar versus hard brick and portland cement mortar, wood stud versus exposed concrete block partitions, wood versus steel window sash, wood versus steel doors and frames, and wood plank versus plywood paneling. Walls and partitions were more massive and helped carry structural loads, even though they were not designed to do so. Modern construction uses harder, more brittle materials, and more slender structural members. Thus, more sophisticated limits on deflection are required now instead of formerly used rules of thumb.

Excessive deflection and tendency to vibrate in structural members can be undesirable for a variety of reasons. These can be classified in four broad categories: (1) sensory acceptability, (2) serviceability of the structure, (3) effect on nonstructural elements, and (4) effect on structural elements.

Sensory acceptability tends to be a matter of personal opinion. Therefore, limits will vary considerably with the social culture and use of the structure. Deflection limits for serviceability of the structure are more easily defined since they can be related to the intended use of the structure. Movements affecting the nonstructural elements of construction, such as walls and ceilings, must be limited to prevent cracking or other damage. In some cases excessive deflection can prevent doors, folding partitions, and other movable elements from operating properly. Similarly, movements may affect the structural element itself. In this case, the movement must be limited to prevent structural behavior from being different than that assumed in the design. If this is not possible then the deflection must be considered as part of the design for strength.

Structural deflections are usually thought of as linear movements or a vertical movement of a member at midspan. In cantilever beams at the

\*See Appendix.

TABLE 3.1—DEFLECTION LIMITATIONS FOR VARIOUS EXAMPLES

| Reasons for limiting deflections                          | Examples                                                                                 | Deflection limitation <sup>a</sup>                                                                 | Portion of total deflection on which the deflection limitation is based               |
|-----------------------------------------------------------|------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| <b>1. Sensory acceptability</b>                           |                                                                                          |                                                                                                    |                                                                                       |
| 1.1 Visual                                                | Droopy cantilevers and sag in long span beams                                            | By personal preference <sup>b</sup>                                                                | Total deflection <sup>c</sup>                                                         |
| 1.2 Tactile                                               | Vibrations of floors that can be felt                                                    | $L/360^d$                                                                                          | Full live load                                                                        |
|                                                           | Lateral building vibrations                                                              | No recommendation <sup>e</sup>                                                                     | Gust portion of wind                                                                  |
| 1.3 Auditory                                              | Vibrations producing audible noise                                                       | Not permitted                                                                                      |                                                                                       |
| <b>2. Serviceability of structure</b>                     |                                                                                          |                                                                                                    |                                                                                       |
| 2.1 Surfaces which should drain water                     | Roofs, outdoor decks                                                                     | $L/240^f$                                                                                          | Total deflection                                                                      |
| 2.2 Floors which should remain plane                      | Gymnasias and bowling alleys                                                             | $L/360 + \text{camber}^{g,h}$ or $L/600^h$                                                         | Total deflection<br>Incremental deflections after floor is installed <sup>j</sup>     |
| 2.3 Members Supporting sensitive equipment                | Printing presses and certain building mechanical equipment                               | Manufacturer's recommendations                                                                     | Incremental deflections after equipment is leveled <sup>j</sup>                       |
| <b>3. Effect on nonstructural elements</b>                |                                                                                          |                                                                                                    |                                                                                       |
| 3.1 Walls                                                 | 3.1.1 masonry and plaster                                                                | $L/600$ or 0.30 in. (7.6 mm) max <sup>k,h</sup> or $\phi = 0.00167 \text{ rad.}^i$ See Reference 7 | Incremental deflections after walls are constructed <sup>j</sup>                      |
|                                                           | 3.1.2 metal movable partitions and other temporary partitions                            | $L/240$ or 1 in. (25.4 mm) max <sup>h</sup>                                                        | Incremental deflections after walls are constructed <sup>j</sup>                      |
|                                                           | 3.1.3 lateral building movement                                                          | 0.15 in. (3.8 mm) offset <sup>m</sup> per story $0.002 \times (\text{height})$ See Fig. 3.1        | Five min sustained wind load                                                          |
|                                                           | 3.1.4 vertical thermal movements                                                         | $L/300$ or 0.60 (15.2 mm) max. <sup>n</sup> See Reference 8 and Fig. 3.2                           | Full temperature differential movement                                                |
| 3.2 Ceilings                                              | 3.2.1 plaster                                                                            | $L/360^{h,p}$                                                                                      | Incremental deflections after ceiling is built <sup>j</sup>                           |
|                                                           | 3.2.2 unit ceilings such as acoustic tile                                                | $L/180^{h,p}$                                                                                      |                                                                                       |
| 3.3 Adjacent building elements supported by other members | Windows, walls and folding partitions on unyielding supports below the deflecting member | Absolute deflection limited by tolerances built into the element in question                       | Incremental deflection after building element in question is constructed <sup>j</sup> |