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Deflections of Horizontal Structural Members

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W.G. Plewes and G.K. Garden

Please note

Many of the difficulties that develop in buildings are the result of deflections of spanning members in excess of those allowed for by the designer. Roof membranes are subjected to accelerated deterioration when drainage of roof slabs fails due to deflection, and may also crack at the intersection of roof panels from excessive rotation of the panels. Deflection of spandrel beams causes cracks in exterior walls that provide an entry for waters which accelerates the breakdown of the wall materials. Even the joints between prefabricated components of curtain walls frequently fail to perform their required functions when sufficient allowance is not made for deflections. In the interior, excessive deflection can cause cracking of partition walls and ceilings or concrete floor slabs. In some cases the gradient in mechanical lines may be reversed. These are but a few of the difficulties arising out of excessive deflections of structural members, but they indicate the importance of this subject for all building designers.

Deflection or sag in a member is the expression of a differential change in length between its upper and lower portions. It is generally understood that in a spanning member under bending load the portion in compression shortens, whereas the tension section elongates and the member assumes a curvature or deflection. There are several other mechanisms, however that cause deflections, and in most cases they must be added to those resulting from the design loads.

Design of durable, problem-free buildings requires the recognition that deflections always occur and that the total allowable is directly related to the associated construction. Where allowance for deflection by size and frequency of joints that permit differential movements is not practical, stiffening of the spacing member is required.

Factors Affecting Deflection

Deflections of spanning members in floors or roofs may be caused or significantly affected by many factors. Most prominent among these are:

Elastic strains,
Creep strains,
Shrinkage and moisture changes.

Temperature differentials,
Load characteristics,
Form of structure.

Elastic Strains

The determination of the deflection in simple structures of homogeneous elastic materials uniformly loaded presents no problem for the designer. Even for complicated and statically indeterminate structures under complex loading, reliable means of estimating deflections are available. There are, of course, problems in determining the degree of fixity at partially fixed edges and ends; and reinforced concrete presents special difficulties, because even under short-term loads of less than the working loads (when concrete is considered essentially elastic) cracks exist in spanning members. The selection of an appropriate moment of inertia for concrete is not straight forward, but satisfactory means for sound approximations are generally available (Refs. 1 and 2).

Creep Strains

When subjected to long-term loading all building materials experience "plastic flow" (or creep) strains that increase the total deflection when added to elastic strain.

Too often creep is neglected in design and this results in excessive deflection. Weep inevitably occurs in concrete, with the total deflection of members under long-term load being several times that occurring elastically at the time the load is applied. The amount of creep in concrete depends on many factors of which age at loading, duration of loading, relative humidity of environment, and type and proportioning of materials are of major significance. A precise prediction of the amount of creep to be expected requires a detailed study of all the influencing factors. Where this is not warranted or practicable, average values are generally assumed. (Creep strains are found by laboratory tests to be 2½ to 7 times the elastic strains, with the actual value dependent upon the above-mentioned factors. Multiples of 2½ to 3 are normally assumed because larger extremes occur only rarely in actual practice. As increased strains also lower the neutral axis this is approximately equivalent to the assumption in the normal elastic formulae that the effective modulus of elasticity is reduced to Ec/3 or Ec/4, depending on the steel ratio (that is, that the total elastic plus creep deflections may equal the instantaneous elastic deflection multiplied by 3 or 4).

Wood under a sustained load will also creep, but there is little available information on the amount to be expected with different species. In view of this, any generalizations regarding creep in wood cannot be made.

At normal stress levels and temperatures creep strains in structural steel cannot be detected by ordinary means and can be disregarded for steel building structures.

Shrinkage

Maximum shrinkages of different concretes from the time the forms are stripped to the dry condition vary widely, depending upon materials, proportioning, size of member, curing, and the relative humidity of the environment. From laboratory tests values of 0.02 to 0.08 per cent are obtained. A shrinkage value of 0.030 to 0.035 per cent is commonly assumed and may be acceptable for members of ordinary size in normal environments. For very dry conditions or where an accurate value of the total defection is essential, a closer study, possibly with tests, should be made to determine an appropriate value for shrinkage.

Differential strains producing curvature or deflection will occur in concrete flexural members reinforced at one face only, because shrinkage will be resisted by the steel but not at the other face. Assuming 0.03 per cent shrinkage of the concrete, a 4-inch simply-supported slab spanning 10 feet would deflect 1/8 inch, and larger values have been know to occur under some conditions. Deflections from this mechanism can be prevented by provision of symmetrical reinforcement at both faces of the slab. Shrinkage deflections are more severe in simply-supported elements than in continuous elements and more acute with simply supported precast elements having non-symmetrical reinforcement than with monolithic construction.

Wood species commonly used for floor and roof systems shrink 5 to 7 per cent across the grain when dried from green to oven-dry. Similar expansions result from a corresponding rise in moisture content. The shrinkage and expansion across the grain caused by changes in moisture content normally experienced in the wood in buildings is about 3 per cent. Shrinkage of wood parallel to the grain is about 1/30 of the transverse shrinkage and 0.10 per cent is an average value for design of wooden members in heated buildings. The properties of different wood species vary widely and more detailed information should be obtained where differential movements of structural elements are critical (Ref. 3).

Most building materials other than metals are affected dimensionally by changes in moisture content, which varies with relative humidity. A temperature gradient across a concrete or wood member can produce a moisture content gradient, and this will cause differential shrinkage, resulting in warpage or deflections. As a drop in temperature causes a rise in relative humidity and moisture content, and produces an expansion that may partially compensate for a temperature gradient warpage, the direction of warpage should be observed.

Temperature

A temperature differential across a member causes a thermal expansion differential that produces warpage or deflection. Again, direction of warpage must be observed. Owing to this mechanism, 20-foot precast concrete members in a roof system were observed to rise and fall at the centre of span about ¼ inch on a daily cycle corresponding to the hours of sunshine. In this particular case the plaster ceiling was applied directly to the structural slabs, and the cracks could not be patched because they opened and closed almost daily. Deflections resulting from temperature differentials occur with all materials in proportion to their coefficients of expansion.

Load Considerations

As steel is essentially elastic at working stresses, there is no significant creep and it is normal to consider deflections due to live load only. This is an acceptable practice since finishing materials are applied after most of the dead load deflection has taken place and cracking can only occur under the live load.

With concrete members, on the other hand, deflections resulting from permanent load do not cease when the building is finished, but continue to increase for several years owing to shrinkage and creep. These permanent load deflections must therefore be included in the calculation of total deflection. Hence, for concrete members the maximum expected deflection is the sum of the creep deflection from permanent loads, the "elastic" deflection from transient loads, and the deflection effects of shrinkage and temperature change. For precise determinations these should be evaluated separately, but in various approximate methods they are sometimes lumped together. In Reference 1, for example, factors are given by which the calculated elastic deflections resulting from the permanent loads can be multiplied to account for shrinkage and creep combined. For loads of three years or more the given factor for a beam with no compression reinforcement is close to three. At best such methods are only approximate.

The lack of information regarding creep in wood prevents an accurate determination of long-term deflections. Some authorities recommend doubling the long-term load and adding the other loads to arrive at an exaggerated total load for elastic deflection calculations so that a rough but reasonable approximation of the creep will be included in the value gained.

Form of Construction

The physical form of a structure has considerable influence on the total deflection to be expected. Deflections in rectangular, fully fixed-ended spanning members are 1/3 to 1/5 those of simply-supported members for the same uniform loads, stresses and spans. Deflections in cantilevered members can be 1 to 9 times those occurring in simply-supported members under similar conditions.

Beam shape and depth have considerable effect on deflection, as do decking and finishing materials when attached so as to provide some stiffening to the member. Unfortunately, in most cases the benefit of this stiffening is unpredictable and cannot be considered in design. Where deflection is of particular importance decks can be fastened to supporting beams by special methods and the value of the composite action determined.

Uniformly loaded plate-like elements supported on two opposite sides behave structurally in much the same way as do rectangular beams. Support and continuity on three or four edges stiffens them considerably, but because they are generally designed to be as thin as possible there may still be significantly large deflections. Solutions for calculation of the deflection of homogeneous elastic plates can be found in standard texts, but there is greater uncertainty in such calculations for two-way or flat concrete slabs because the influence of cracking is difficult to evaluate (Ref. 2).

Precambering of spanning members is commonly done to compensate for elastic deflections due to dead load. The same practice may be used to advantage for part of the deflection resulting from long-term loading by providing sufficient allowance in joints between the spanning member and any construction beneath.

Allowable Deflection

Having determined the maximum deflection by precise or approximate methods, the critical question is how much deflection can be allowed. There is a good deal of excellent literature on the prediction of deflection, but statements on allowable values are usually limited to a brief note that limits such as 1/360 of the span (L) are "customary" and have "worked well in the past". The reason for this is that there is little information available on which to judge the rationality of such rules. In those buildings in which significant defections develop, the actual values and their effects ale seldom measured and recorded, except where they are flagrantly in excess of tolerable values.

The above-mentioned ratio L/36O has been a traditional limit for deflections, although its origin is not widely known. The principle of limiting deflection in proportion to the span appears to have begun with Tredgold, a famous engineer born in 1788, who was one of the first to establish and publish criteria for the design of flexural members (Ref. 4). He recognized that permissible deflections should be proportional to the length of the member and recommended a limit of L 480. Later in the 19th century American engineers increased the allowable deflection to L 390 for houses.

Bearing in mind that materials and construction methods today are quite different from those used in 1850, there is little in the way of factual information to indicate whether L/360 is still an appropriate limit. Examination of the small amount of relevant literature describing laboratory tests and studies of building movements (Refs. 4, 5 and 6) indicates that with regard to plaster and masonry cracking, visibility of sags and springiness of floors, the traditional deflection of L/360 is an adequate limit for normal cases, but just barely so. It offers no guarantee that plaster will not crack, and part of its success has been due to the fact that buildings seldom receive their full design loads that there is load sharing among members (not taken into account in the design) and that although cracks do occur, sometimes they cause no further trouble when patched. Where greater assurance is wanted that cracks will not occur, the total deflection limit might profitably be reduced to L/480 or even L/720. Similar remarks regarding materials other than plaster and masonry cannot be made at this time, except that the susceptibility to cracking of other materials can perhaps be judged by these standards. In general, the more rigidly finishing materials are attached to the structure the more probable is the chance of damage. Where plaster ceilings are rigidly attached to structural members, cracking can occur at actual deflections of L/1000 or less. Larger deflections of the order of L/180 are often allowed for roofs having no finishing materials on their underside. This may, however, cause damage to the roofing, interfere with proper drainage and be clearly visible.

The allowable deflection for any situation should be established from consideration of the material used and the associated construction. For steel members an allowable elastic deflection of L/360 is normally satisfactory because dead-load deflections seldom contribute to deflection problems and design loads are seldom realized. The greatest portion of the total deflection in concrete members, however, is due to the permanent portion of the total load. An allowable design deflection of L/360 for concrete members is only satisfactory when longterm deflections resulting from creep, shrinkage and temperature effects have been included. The fact that the design live load is seldom attained in service is of little significance in this case. The validity of L/360 in timber construction is related to the ratio of permanent to total load since long-term loads do influence the total deflection.

Conclusion

Deflections in horizontal flexural members do occur and are influenced by several mechanisms, some of which have cumulative effect. With the contemporary practice of using higher working stresses and more slender members, deflections are greater than those that occurred with past construction methods. With finishing and cladding materials being installed to close tolerances, excessive deflections cannot be tolerated unless they are adequately predicted and allowed for. In many cases it may be necessary to redesign structural spanning members to reduce the total ultimate deflection to suit associated finishes, partitions and walls. These points all indicate. that deflections due to elastic strain, creep, shrinkage, temperature and moisture changes, load characteristics and form of structure must be considered, especially when the design deviates from practices that have proved satisfactory.

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