Shortening of High-Strength Concrete Members

by H. G. Russell

Synopsis: When high-strength concretes are used in high-rise buildings, long-span bridges, and offshore structures, special attention must be given to the dimensional changes that occur in the concrete members. For design purposes, the length changes are usually considered to consist of instantaneous shortening, shrinkage, and creep. Instantaneous shortening depends on stress level, cross-sectional dimensions of the member, and modulus of elasticity of steel and concrete at the age when the load is applied. Shrinkage deformations generally depend on type and proportions of concrete materials, quantity of water in the mix, size of member, amount of reinforcement and environmental conditions. Creep deformations depend on concrete stress, size of member, amount of reinforcement, creep properties of concrete at different ages and environmental conditions. In recent years, questions have been raised about the validity of methods for calculating deformations in high-strength concrete members and about the in-place properties of high-strength concrete members. These properties include compressive strength, modulus of elasticity, shrinkage, and creep. This paper reviews existing state-of-the-art concerning instantaneous shortening, shrinkage, and creep of high-strength concrete members.

Keywords: beams (supports); columns (supports); compressive strength; creep properties; deformation; high-strength concretes; modulus of elasticity; shrinkage; strains

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INTRODUCTION

All concrete members change in length due to the effects of load and shrinkage. When differential shortening of members occurs, such as in high-rise buildings, the serviceability of the structure can be impaired. For structures built in the 1950's and designed by the working stress method, the effects of movements due to creep and shrinkage were secondary and could generally be neglected in design. However, with the utilization of higher strength concretes, the designer now has to consider how the length changes will affect the performance of the building. When appropriate, the effects have to be taken into account in design.

Column length changes within a single story height of a building may only be a fraction of an inch. However, over the height of a high-rise building, the length changes can amount to several inches. For example, a concrete building designed to be 1,000 ft (305 m) tall could shorten by 1 ft (0.3 m) due to gravity loads and shrinkage. The shortening of columns must be taken into account when detailing adjacent elements of the building that do not shorten that much. These elements include exterior partitions, interior partitions, elevator rails, and steel pipes. Differential movements between columns and walls within the building can result in sloping floor slabs unless the formwork for the floor slabs is set to accommodate future differential movements. In both cases, it is necessary to calculate the amount of differential shortening that is likely to occur. Differential vertical shortening can also result in serviceability problems where a high-rise building is connected to a low-rise building and adequate provisions have not been made for differential movements.

For calculation purposes, time-dependent deformations may be considered to consist of instantaneous deformations, creep deformations, and shrinkage deformations. In general, these deformations are assumed to occur independently, and the method of superposition is applied to determine the total length change. This assumption is not completely correct in that shrinkage and creep deformations generally result in a reduction of stress in the concrete and an increase of stress in the reinforcing steel. However, with the current state of the art, consideration of this refinement from a design viewpoint is probably not warranted. Consequently, consideration of the effects separately is generally the approach taken by designers.

In recent years, questions have been raised about the validity of the method currently being used for the calculation of deformations in high-strength concrete members. Many of the factors taken into account when determining length changes have been determined for lower strength concretes but not for higher strength concretes. Consequently, it is only natural that the applicability of these procedures and properties to higher strength concretes should be questioned. The purpose of this paper is to review the existing state-of-the-art concerning instantaneous shortening, shrinkage, and creep of high-strength concrete members relative to North American design procedures and known material properties.

INSTANTANEOUS SHORTENING

Instantaneous deformations occur whenever load is applied to a concrete member. The deformation for any load increment may be calculated using the appropriate member stiffness for the concrete at the age when the load is applied. The total instantaneous deformation at any age is then the sum of the incremental deformations up to that age. The number of increments used in the calculations will vary depending on the number of stages of construction and the age of the concrete.

For example, a small load will generally come onto the columns within a few days of casting. This load can vary from the self weight of the next column to the weight of a full bay of dead load plus construction loads. The amount and timing of these loads will vary depending on the type of falsework used. The maximum load will not come onto the column until the building is completed and occupied. For lower columns in a high-rise building, this will be many months after the column is cast. For most stories of a high-rise building, the largest proportion of instantaneous deformation is caused by dead load of the columns, walls, and floors. Very little instantaneous deformation is caused by live load.

The instantaneous strain ε_I in a member caused by an incremental axial load P is given by:

$$\epsilon_I = \frac{P}{A_c E_c + A_s E_s} \qquad (1)$$

where

A_c and A_s = area of concrete and steel, respectively.

E_c and E_s = modulus of elasticity of concrete and steel, respectively, at age when load P is applied.

For a given member, the areas of concrete and steel are defined and modulus of elasticity of the steel is known. The only variable with time is the modulus of elasticity of the concrete. Traditionally, the modulus of elasticity of the concrete has been calculated using the following equation from the ACI 318 Building Code(1) modified to use compressive strength of concrete at age of loading:

$$E_c = w_c^{1.5} 33 \sqrt{f'_{ca}} \qquad (2)$$

where

w_c = unit weight of concrete

f'_{ca} = compressive strength of concrete at age of loading

Using the assumptions that stress is proportional to strain, plane sections remain plane, and strain in the steel is equal to strain in the adjacent concrete, Equation 1 has a sound theoretical basis. It has been shown to be valid experimentally for lower concrete strengths.(2) Experimental verification of the applicability of the equation for reinforced concrete members with concrete compressive strengths above 10,000 psi (69 MPa) needs to be verified. However, it is the author's opinion that the equation can still be used because of its theoretical derivation.

Considerable controversy surrounds the use of Equation 2 from two aspects. Equation 2 was developed by Pauw(3) on the basis of concrete with compressive strengths up to about 5500 psi (38 MPa). As additional data have become available on higher strength concretes, various investigators have made comparisons between the equation and the data for higher strength concretes. Figure 1 represents a compilation of data published by Nilson.(4) Based on these data, a modified equation was recommended for the calculation of the modulus of elasticity. This revised equation predicted a lower modulus of elasticity for higher strength concretes than the values obtained using Equation 2. However, more recent data published by Cook(5) and shown in Fig. 2 indicate that Equation 2 underestimates the modulus of elasticity for the higher strength concretes. It should be noted that the higher strength concretes reported by Nilson were obtained using a smaller aggregate size. However, Cook was able to produce higher strength concretes using larger size aggregates.

It should be recognized that Equation 2 was based on a statistical analysis of the available data. As such, there is considerable scatter in the relationship between modulus of elasticity and concrete compressive strength. Consequently, it is recommended that, when accurate calculations are required for high-strength concretes, the modulus of elasticity should be measured as part of the concrete mix design preparation. Alternatively, the engineer must assume that there is going to be some deviation from the values predicted by Equation 2 or any other selected equation.

The second controversial item surrounding the calculation of instantaneous deformations is a question as to whether the modulus of elasticity as measured on a 6x12-in. (152x305 mm) concrete cylinder or other plain concrete specimen is applicable to large size structural members. Currently, there are no published data on this topic related to high-strength concrete. However, Hester and Cook have extracted cores from large concrete members and measured their modulus of elasticity. For the strength levels used in his program, Cook showed that the modulus of elasticity as measured on cores varied as the measured compressive strength varied. If the core strength was low, the modulus of elasticity was also low. Hester also observed the same phenomena. However, both strengths and modulus of elasticity of cores were lower than corresponding values measured on cylinders. This implies that actual deformations in full size structures may be larger than calculated.

CREEP

Creep deformations in a member depend on creep properties of concrete at age of loading, stress level in the concrete, size of member, amount of reinforcement and environmental conditions. The creep properties of unreinforced 6x12-in. (152x305 mm) concrete cylinders obtained from various concretes used in Water Tower Place,(6) Chicago, are illustrated in Fig. 3. In addition, Fig. 3 includes the creep properties of 14,000 psi (97 MPa) concrete used in some experimental columns at Chicago

Mercantile Exchange. The data are presented in terms of creep per unit stress. As can be seen from Fig. 3, the creep deformation of plain concrete varies depending on the age when the load is applied. It is also evident that the creep per unit stress of higher strength concretes is less than the creep per unit stress of lower strength concretes. Fintel, et al(7) have suggested that creep per unit stress varies from $0.003/f'_c$ to $0.005/f'_c$ where f'_c is the compressive strength of concrete at 28 days.

It should be recognized that for a given concrete strength, the creep will be different for different materials. The data shown in Fig. 3 are plotted in terms of creep per unit stress. For concrete stress levels less than 40% of the concrete compressive strength, it is generally considered that the total creep deformation is proportional to the stress level. This has been established experimentally for lower strength concretes but not for high-strength concretes. However, the short-term stress-strain curve for high-strength concrete is more linear than the stress-strain curve for lower strength concretes. Consequently, it is likely that the linear relationship between creep deformation and stress is still valid for higher strength concretes and could even be valid above the 40% stress level.

Since the creep deformations of concrete vary with age of loading, calculations for creep deformations require an incremental analysis. The analysis must take into account that the load will not be applied to some members until many months after the columns are cast. This has the impact of significantly reducing the calculated and actual creep deformations.(8-10) To perform these calculations accurately, a knowledge of how much the creep decreases with age of loading is needed.

The total amount of creep and the rate of creep are influenced by the size of the member. Large members have less creep and will creep at a slower rate than smaller members. This factor has to be taken into account when extrapolating data measured from the creep on standard 6x12-in. (152x305 mm) cylinders.(11) For column sizes used in high-rise buildings, the creep of unreinforced columns could be approximately 60% of that occurring on 6x12-in. (152x305 mm) cylinders. It should be noted that most of the correction factors that are used to take into account size effect are based on the work by Hansen and Mattock.(11) The highest strength concrete used in their investigation had a compressive strength of about 6000 psi (41 MPa). Data by Ngab(12) obtained for higher compressive strength concretes suggest a different relationship.

Creep is also reduced by the presence of reinforcement. A column with 8% reinforcement will have considerably less creep than the same size column with 1% reinforcement but carrying the same stress level in the concrete. This has a big impact on the creep deformations in the lowest columns of a high-rise building. The lowest columns may have the maximum amount of reinforcement permitted by the building code. Correction procedures to take into account the effects of reinforcement have been developed by Dischinger(13-15) and used by Fintel(7,16), Pfiefer,(9) and Russell.(8,17) These procedures rely on the input of certain empirical data. The applicability of Dischinger equations to columns in buildings was demonstrated by Pfeifer.(2) Reasonably good agreement was obtained between measured and calculated deformations.

In calculating creep deformations in columns, it has been accepted that deformations may be calculated in a series of increments. The creep deformations from each increment are added using the theory of superposition. The validity of the superposition for higher strength concretes has not been verified.

Most available data on creep have been obtained from specimens stored and tested under standard laboratory conditions of temperature and humidity. Data on lower strength concretes indicate that creep is influenced by both temperature and humidity. It is likely that the same effect will apply to high-strength concretes. However, data are not available to illustrate the magnitude of the effect. The situation is further complicated when consideration is given to the fluctuations of outdoor environment and that a column may undergo a large change in temperature before it is enclosed in the building.

SHRINKAGE

Shrinkage of concrete is generally determined on the basis of measurements of the length changes of 6x12-in. (152x305 mm) cylinders or similar specimens. In a structural member, the amount of shrinkage is influenced by the size of the member and the amount of reinforcement. Data obtained for different strength concretes used in Water Tower Place(17) are shown in Fig. 4. Generally, the shrinkage of 6x12-in. (152x305 mm) cylinders tends to be in the range of 600 to 900 millionths for most concretes.

When calculating the shrinkage deformation in structural members, the size of the member and the effects of reinforcement must be taken into account.

A large member will shrink at a slower rate than a small column(11) and for practical purposes will undergo less shrinkage. The size correction factors used for shrinkage are generally based on the work of Hansen and Mattock.(11) As mentioned above, their highest strength concrete had a compressive strength of about 6000 psi (41 MPa). The variation in calculated shrinkage due to size effects is much larger than the variation likely to occur as a result of changes in concrete constituents.

The effects of reinforcement on shrinkage have been demonstrated by Pfeifer.(2) Analytical procedures have been developed by Dischinger(13-15) and used by Fintel,(7,16) Pfeifer,(9) and Russell(8,17) for concretes with compressive strengths up to 9,000 psi.

Environmental conditions influence shrinkage in a similar manner to their effect on creep. It is well known that higher relative humidity results in less shrinkage of small specimens. However, the effect of relative humidity on the shrinkage of large members is unknown. It could even be assumed that large high-strength concrete members experience very little effect from changes in relative humidity due to the dense matrix.

ACCURACY OF PREDICTIONS

Total shortening of an individual concrete member may be determined by adding instantaneous, creep, and shrinkage deformations. In buildings, the total shortening may be used to determine required clearances between exterior wall panels, elevator rails, and rigid interior partitions. In long-span post-tensioned bridges, the deformations affect both prestress losses and camber changes.

Effects of column or bridge shortening are cumulative throughout the height or length of the structure. Shortening over 60 to 70 stories of a building can amount to many inches. Whereas total shortening in itself may not be a problem, differential shortening between different members requires particular attention. In a building, some of the differential is accommodated each time a new floor is cast. It is, therefore, only the differential movement that occurs after a particular level is constructed that is important for that level. Net differential movements may be determined by summing the vertical shortening at each level from the foundation to the level under consideration. Appropriate ways to accommodate the calculated differential movements can then be considered by the designer.

Deformation can be calculated to as many significant figures as the designer cares to specify. However, the accuracy of the numbers is only as good as the accuracy of material data used for the input and the proven accuracy of the prediction method. The objective of this section is to review the accuracy of predictions.

Variation of Material Properties

The previous sections on instantaneous shortening, creep, and shrinkage have recognized that concrete is a material whose properties are variable. Even when identical concretes are produced with no intended variations in the materials, the resultant properties will show some variation. The property that is likely to vary the least is the concrete compressive strength, yet it is not unusual to have variations of plus or minus two standard deviations. This in turn will result in variations in the modulus of elasticity of plus or minus one standard deviation on the assumption that Equation 2 provides perfect correlation. With this in mind, it is not unreasonable to expect that the modulus of elasticity would vary plus or minus 10% from a mean value. Also, the mean value may be different from that assumed in design.

It should also be recognized that concrete compressive strength is often specified as a minimum value. Consequently, actual strengths are higher than the minimum value. Calculations of instantaneous shortening should take into account whether the modulus of elasticity corresponds to the minimum compressive strength that is being used or one corresponding to the actual compressive strength. In the calculation of relative deformations, an underestimate of shortening can be as critical as an overestimate of shortening. Calculations should be made as a best estimate with recognition given to possible variations. It is, therefore, important that material properties be known as accurately as possible.

Accuracy of Prediction Methods

Within North America, two general methods are most frequently used to calculate shortening of concrete members. The methods are those of the European Concrete Committee(18) and the American Concrete Institute Committee 209(19). Both of these methods allow the designer to make a complete prediction of the time-dependent deformations with very limited information about the actual material properties.

The accuracy of these prediction methods can be considerably improved when material properties of the specific concretes to be used in a structure are known. For example, a measured modulus of elasticity would improve the accuracy compared to a value calculated using Equation 2. Similarly, creep and shrinkage data measured on standard specimens(20) provide a better starting point than creep and shrinkage calculated from the assumed concrete materials. In recent years, construction specifications for several long-span bridges have required the contractor to measure the creep and shrinkage properties of the concrete for comparison with the design assumptions. Although these were not high-strength concrete bridges, the importance of this approach with high-strength concrete members cannot be overstressed.

It must also be recognized that the prediction methods represent some average of the available data. As such, they cannot be expected to allow for the precise prediction with all different types of concrete.

Comparisons with Actual Shortening

Despite the inherent sources of inaccuracy described in the previous sections, comparisons of field measurements with actual shortening have shown a remarkable degree of accuracy.(7-9,17) One example of calculated shortening versus measured shortening for different levels in a building is shown in Fig. 5.(17) The curves marked "I" indicate the instantaneous shortening. The curves marked "I+S" represent the instantaneous shortening plus shrinkage. The curves marked "T" are the total shortening caused by instantaneous shortening, shrinkage, and creep. The contribution from instantaneous shortening, shrinkage, and creep varies for different levels. For the lower columns, instantaneous shortening provides the larger contribution to the total during construction. Thereafter, instantaneous deformations remain constant but shrinkage and creep continue to increase. At the higher levels in the structure, shrinkage and creep contribute a larger proportion. For example, at the top story of a building, shrinkage is the predominant effect causing shortening. This occurs because the columns at this level are only lightly loaded and contain minimum reinforcement. It should be noted that the highest strength concrete used in the building had a specified compressive strength of 9000 psi (62 MPa).