Structural Design

design issues for structural engineers

Accommodation to Reinforced Concrete High-Rise Building Deformations and Movements

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During their service life, high-rise buildings and the associated nonstructural components endure various movements and deformations. Although the deformations and movements are not life threatening, inappropriate design of buildings and associated nonstructural components could induce expensive economic consequences in the long-run and, in order to ensure proper building behavior of the superstructures and the attached nonstructural elements, should not be ignored. In this article the possible deformations and movements of reinforced concrete high-rise buildings and the accommodation of the affected components are discussed.

Common Deformations and Movements

Common, inevitable building movements and deformations include: differential column shortening, lateral story drift, building racking, slab and beam deflection, thermal deformation and building dynamic vibration, etc.

Differential Column Shortening under Gravity Loads

When subjected to gravity loads, vertical reinforced concrete structural members, such as columns and shear walls, experience short-term and long-term shortening that is zero at the base and accumulates to be the maximum at the roof level. Magnitudes are dependent on concrete mix, gravity stress levels, construction sequences, loading histories, volume-to-surface ratios and ambient relative humidity, etc.

Short-term column shortening is primarily a result of elastic deformation, while long-term shortening is the resultant of concrete creep and shrinkage. For reinforced concrete high-rise buildings, the long-term column shortening can be as high as ⅛ inch per floor (for a 10-foot story height building), and the cumulative differential column shortening causes floors to tilt. In order to reduce differential column shortening, it is a good practice during the design stage to ensure that the layout of vertical members is balanced so that the vertical members experience gravity-induced axial stresses as equal as possible. For example, in order to minimize the differential shortening between shear walls and columns, it is desirable to locate columns away from shear walls so that more gravity loads will be distributed to shear walls – thus resulting in smaller gravity-induced axial stress differences between columns and shear walls.

Differential column shortening should be estimated by considering the effects of actual concrete mix, environment, construction sequence, etc. Although accurately evaluating column shortening is a very challenging task due to uncertainties of material parameters, environment, and gravity load redistribution, the method presented in the America Concrete Institute's *Guide for Modeling and Calculating Shrinkage and Creep in Hardened Concrete* (ACI 209) can reasonably estimate column shortening if reliable material parameters are given. According to ASCE 7-2010, the load combination for long-term column shortening estimation can be used as $D+0.5L$, in which D is service dead load and L is service live load.

Slab and Beam Deflections Due to Gravity Loads

Well-established procedure, including maximum permissible criteria for reinforced concrete slab and beam deflection computation, is specified in ACI 318 (*Building Code Requirements for Structural Concrete*, 2011). The load combination for short-term effect deflection check is $D+L$, and for long-term effect is $D+0.5L$ (*Minimum Design Loads for Buildings and Other Structures*, ASCE-7, 2010). It is also a general practice to use Finite-Element Analysis software to check floor deflections (especially for two-way flat slabs) based on actual reinforcing layout and reasonably assumed material parameters.

When one checks floor system deflections, it is necessary to estimate floor slab edge deflections for cladding system installation, especially for large prefabricated concrete/stone panel facade system. For interior partitions, allowance is needed for differential deflection between two adjacent floors after the installation of interior partitions. There have been numerous examples where these joints have not been appropriately installed, particularly on tall slender buildings, which results in "creaking" complained by tenants because of rubbing joints as the buildings move under wind loading. The long-term deflections of girders, which pick up floors above, are particularly important and the deflection acceptance criteria should be more stringent than code-allowed values. Absolute long-term deflection limit values for the girders are recommended to control associated deflection of floors above, instead of satisfying the code-allowable deflection-over-span ratio alone.

In many cases, cambers are specified in construction documents to ensure level slabs and minimum slab infill. Since there are many uncertainties in long-term deflection estimation, a camber may be set as one-half of the computed total long-term deflections including the immediate deflections, as building owners and contractors prefer that the cambers are sized to accommodate only immediate deflection and a portion of the long-term deflection. It is also worth noting that cambers less than ¼ inch tend to be ignored by concrete contractors because the value is within construction tolerance and error range.

Building Drift and Associated Racking Due to Lateral Loads

Transient lateral loads acting on buildings induce not only horizontal story drifts but also temporary shortening and elongation of vertical members. As a result, transient dynamic racking of the building is to be expected during the service life of buildings. Allowances for building cladding systems and interior partitions should be provided to accommodate the transient story drift and dynamic racking motions under both wind loads and seismic loads.

Allowable seismic story drift criteria are given in ASCE 7 and vary with seismic risk category and the seismic force resisting structural system types (ASCE 7-2010). The building seismic design story drift is computed first by using the prescribed seismic design load through elastic analysis, and then adjusted with deflection multiplication factor C_d and seismic importance factor I_e. This nonlinear seismic story drift is compared with the relative seismic glass fallout limit ($\Delta_{fallout}$), which is determined with the dynamic test method recommended by the American Architectural Manufacturers Association (AAMA).

Different from the seismic story drift requirements, the building story drift ratio limit for wind design is not explicitly specified in building codes and is usually taken as 1/600 ~ 1/400 based on decades of design practice. Depending on the sensitivity of nonstructural elements to building lateral story drift, the lateral design loads for wind story drift check can be chosen as 10-year, 50-year and 100-year return periods respectively. The choice of return period should be governed by local code requirements and design engineer's judgment. If 10-year return period design loads are used, the story drift ratio limit should be more stringent than the conventional drift criteria when the cladding systems are same. It is a typical design practice that 50-year return period wind design loads are used for story drift check, along with the commonly used inter-story drift ratio limit 1/400 for high-rise buildings.

Temperature-induced Deformation

Expansion/contraction of building members and facade systems due to temperature variation can induce large internal forces if they are constrained. Brittle façade systems, which are sensitive to thermal movements, tend to experience larger temperature oscillation and expansion joints (soft joints) should be provided. For roof parapets, relief joints are recommended to control the location of cracks because the parapets are usually exposed to weather and experience extreme temperature variation during the building's service life cycle.

In large scale cast-in-place reinforced concrete podium areas or mat foundation slabs, where the concrete floor expansion and contraction are restrained by structural elements such as foundation walls, control strips should be provided for cracking control.

Building Dynamic Vibrations

There are two main types of dynamic vibration issues in building service life: wind-induced building acceleration and floor vibration. Both may cause resident discomfort depending on tenants' sensitivity to the motions, and can be reduced to a reasonable limit through well-planned structural design by adjusting building stiffness, mass and damping (for instance, introducing supplementary damping systems).

Although floor vibration usually needs to be checked for light structures such as steel framed floor systems, long span cast-in-place reinforced concrete floor systems could vibrate uncomfortably as well when subjected to gymnastic exercise or mechanical equipments vibration. A simple guideline was suggested to identify potential vibration problem by checking natural frequency of floor systems. However, controlling the floor fundamental frequency alone may result in uneconomic design of long-span reinforced concrete floor systems. To limit the long span reinforced concrete floor vibrations, structural stiffness, mass and damping should all be considered, and floor Finite Element dynamic analysis is recommended with realistic boundary conditions and reasonably assumed damping ratio at the design stage.

Peak accelerations and peak torsional velocities at the topmost occupied floor of a high-rise building under wind loading should be checked to avoid excessive resident discomfort. Approximate estimation formula was given in *National Building Code of Canada* (NBCC); however, in many cases wind tunnel testing companies are hired to estimate the peak accelerations based on wind tunnel test results from scaled building models. In addition to building stiffness, mass distribution, damping and building geometry can be adjusted to reduce the peak accelerations and peak torsional velocities.

Affected Components and Measures to Accommodate Building Movements

Because of inevitable building deformations and movements, the structure itself and the associated nonstructural components must be appropriately designed in order to ensure proper serviceability performance.

Floor Elevation Correction

Building floor elevation "loss" and floor tilting are expected due to the differential column shortening and should be addressed. During the construction process, the concrete subcontractor should adjust formworks to the prescribed slab elevations in construction documents to level out the to-be-constructed floor, and compensate for the immediate shortening and a portion of long-term shortening of vertical members. The concrete sub-contractor should monitor floor elevations from a fixed base to make sure that reinforced concrete vertical structural members are shortening in an orderly fashion. In the long run, the magnitude of column shortening for a 10-foot story height residential building can be as high as ⅛ inch per floor, which accumulate to be largest at building's roof level. Usually, the long-term absolute floor elevation "loss" is ignored as long as appropriate soft joints or connections are provided for other nonstructural components. When the long-term absolute floor elevations must be maintained, it is suggested to specify lumped elevation corrections every several floors. In this case, façade fabrication and installation should also be adjusted accordingly.

Façade System

Façade systems are inherently sensitive to building movements; therefore, great care and good communication between the structural engineer and the façade designer is needed to avoid unexpected façade damage in the building's service life (e.g. connection failure, non-uniformities and irregularities of joints, misalignment of faces and panel fallout), especially when the façade system is composed of large prefabricated concrete/stone panels, or includes panels of dissimilar materials. Prior to cladding installation, a new survey should be taken from a fixed base at the ground floor to establish new benchmarks to divide the available soft joints equally between the existing typical floor levels.

Additional long-term building deformations and transient movements will continue to occur after the façade installation. Because long-term deformation and deflection are time-dependent, it is important for the designer to be informed as to when and how the façade system will be installed, in order to prescribe recommended joint sizes. To reduce the façade joint size, the installation of the façade system may need to be arranged to a later construction stage so that a larger portion of the long-term deflection and deformation can occur before installation.

After installation of the façade system, the soft joint or adjusting device for prefabricated cladding system should accommodate the following items for both vertical and horizontal joints:

Vertical joint:

- Story drift due to wind design loads (50-year return period)
- Thermal expansion/contraction of the façade system between expansion joints

Horizontal joint:

- Future additional long-term column shortening of exterior columns
- Immediate deflection due to live load and long-term deflections due to sustained loads at the exterior edges of floor slabs
- Thermal expansion/contraction of the façade system between expansion joints
- Elastic column elongation and shortening due to wind design loads (50-year return period)

Nominal joint size for a façade system should be equal to (or greater than) the sum of the calculated relative movements and the maximum tolerance permitted for abutting façade elements:

Width of joint = total movement + total tolerance

When wind loading acts on façades, the panels may tend to bow in (or out) and could touch supporting backup members. Large size glass panels could collide with the adjacent supporting structures; therefore, enough separation distance should be provided between the façade and the adjacent supporting members as well.

Besides interstory drift due to wind design loads, the structural engineer should provide seismic inter-story drifts (with nonlinear effect) for the cladding design engineer to check the glass fallout limit ($\Delta_{fallout}$) which is dependent on glass types and glazing details (AAMA).

Vertical Transportation

Due to the long-term shortening of vertical structural members and possible thermal movements, special attention is required to ensure proper behavior of the vertical transportation system and associated electrical vertical pipes. For example, elevator guide rails are tied back to the reinforced concrete superstructure and tend to move downward as the long-term shortening builds up over time. Allowance should be provided between elevator guide rails to accommodate the long-term movements (as mentioned before, about ⅛ inch each floor on average). The elevator stop locations may need to be adjusted as the building undergoes long-term creep and shrinkage.

Vertical Piping

Vertical piping should be supported vertically in between their expansion joints at one level only, and guided laterally at other levels as necessary. Expansion details and clearance above and below the piping to accommodate long-term shortening must be provided: the expansion joint should allow for long-term shortening of ⅛ inch per floor on average. Additional clearance will be required if the piping is located adjacent to the periphery of buildings, where building racking and temperature variation will induce extra movements for the piping.

Horizontal pipe branches which are off vertical piping support, and distant from that support, such as sprinkler piping and gas lines, must be allowed to move freely up and down with respect to the adjacent floors. The allowance should be increased accordingly if long-term relative floor deflection will affect the horizontal pipes. Extra sloping of horizontal drain pipelines is required in order to accommodate the future reduction in slope due to differential shortening among building vertical members.

Interior Partitions

For interior partitions or nonstructural walls, allowance should also be provided for differential deflection between two adjacent floors after the installation of interior partitions. If allowance is not large enough to compensate the floor deflection occurring after installation, "creaking" resulting from rubbing partitions will be heard. To make it worse, non-load bearing partitions could inadvertently become load bearing walls causing the partition walls to fail or develop a change of load path. As mentioned earlier, floor deflection is time-dependent so allowance can be relaxed if the installation of partitions is arranged to a later construction stage. Usually, the permissible allowance is generally not less than the clear span between supports divided by 360.

Summary

During their service life, reinforced concrete buildings constantly experience deformations and movements. The common deformations and movements in reinforced concrete high-rise buildings include differential column shortening, lateral story drift, building racking, slab and beam deflection, thermal deformation and building dynamic vibration, etc. As long as the inevitable movements and deformation and the effects on associated structural and nonstructural elements are not ignored by engineers, impaired serviceability performance can be avoided by applying precautionary accommodation measures during both design and construction stages.▪

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