Title:	**A Software Tool for the Analysis of Time-Dependent Effects in High-Rise Buildings**
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Subject:	IT/Computer Science/Software
Publication Date:	2016
Original Publication:	CTBUH Journal, 2016 Issue III
Paper Type:	1. Book chapter/Part chapter 2. **Journal paper** 3. Conference proceeding 4. Unpublished conference paper 5. Magazine article 6. Unpublished

A Software Tool for the Analysis of Time-Dependent Effects in High-Rise Buildings

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Increased use of concrete in high-rise buildings has made these structures especially sensitive to delayed deformations due to concrete's natural tendency to creep and shrink. This is exacerbated in particularly tall buildings of hybrid construction, due to the different behavior of concrete and steel elements. In this paper, the authors present a software tool specifically developed to predict time-dependent behavior of high-rise buildings in both the construction and service stages. The specific features of the software are illustrated, and the results of a review and validation study are presented. Finally, the approach is applied to a real high-rise building currently under construction in Malaysia.

Concrete Properties' Effect on Tall Buildings

In recent decades, the use of reinforced concrete as the main construction material for high-rise buildings has significantly increased (Safarik et al. 2014). As a consequence, these structures have become sensitive to the effects of time-dependent concrete properties such as creep and shrinkage (*fib* 2014). The problem becomes particularly relevant in supertall buildings (Gardner & Chiorino 2007).

While the construction of the building proceeds, vertical supporting members, such as columns and cores, are subjected to successive incremental loads and axial strains due to the construction of the overlying floors. In concrete elements, these initial strains increase due to creep and shrinkage, shortening the overall building and causing shortening differences among columns; between cores and columns; or between concrete cores and steel or concrete/steel composite columns. The differences in the initial and time-dependent strains among concrete vertical members are normally due to differences in the stress levels and/or in the creep and shrinkage properties, due to members' volume-to-surface ratio (effective thickness) and/or longitudinal reinforcement ratio. Such differences in strains are intrinsic to hybrid concrete/steel structures, due to the different initial deformability of the two materials and the absence of creep and shrinkage in steel elements. The problem is further complicated by the continuous changes of the structural configuration inherent to construction sequences.

Redistribution of stresses and internal actions as vertical loads in the supporting members, and shear stresses and bending moments in horizontal members, are normally associated with all these effects in rigid connections between floor structures and vertical elements, especially when a stiff horizontal brace or transfer structure is present. In an asymmetrical building structure or in the construction sequence, lateral displacements and vertical deviations can develop as well, affecting the load distribution in vertical elements.

If all these phenomena are not adequately understood and analyzed in the design and construction phases, several serviceability concerns may arise (Gardner & Chiorino 2007; *fib* 2014; Chiorino et al. 2011; Fintel et al. 1986; Lagos et al. 2012). This affects structural members as well as non-structural components, such as the sloping and cracking of floors, cracking of horizontal structures and interior partitions, buckling of elevator guides and piping, misaligned elevator stops relative to floors, and damage to curtain walls and column cladding. In the case of incremental loads in vertical elements, their influence on the ultimate strength cannot be neglected. Special attention must be paid in the case of hybrid structures (which typically feature significant shifts of axial loads from concrete to steel vertical elements), especially when the

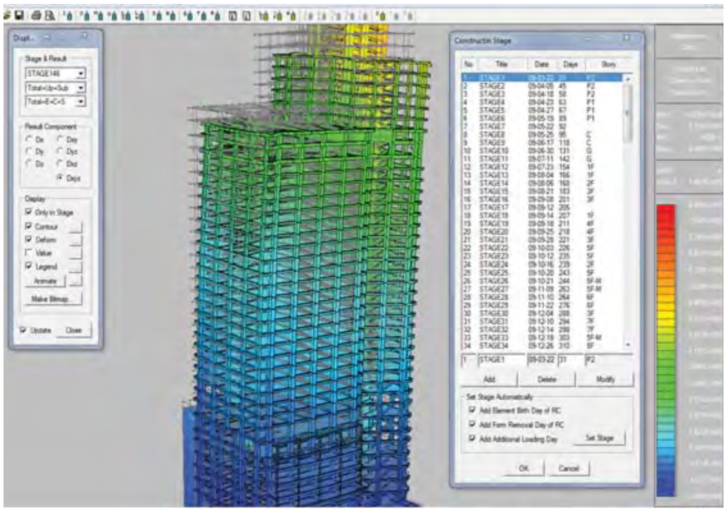


Figure 1. User interface of ASAP for post-processing of results.

> “Current commercial software is functionally limited in solving problems typical of high-rise buildings and their complex construction-stage sequences, which consist of a large number of multifaceted steps spread across an extended time.”

buckling of slender steel elements must be considered. In concrete structures between 50 and 100 meters in height, the effects of the delayed deformations are often disregarded without serious consequences. In taller structures, as well as in hybrid structures, ignoring the effects of creep and shrinkage can lead to undesirable service conditions, and in some cases, to concerns for the structural safety of the building.

Axial shortening of a tall building can be predicted relatively easily during the preliminary design stage as the sum of elastic, creep and shrinkage deformations in the single vertical elements, taking into account the construction sequence (Fintel et al. 1986). This prediction method is usually referred to as “one-column shortening analysis.” The most significant limit of this approach is the fact that the restraining effects against differential shortening of the beams or slabs connected to the column or wall are not considered or are considered in an approximate way. The method has been widely used for decades, but recently there has been a move towards sequential construction stage analyses and time-history analyses of 3D models of entire building structures.

Advanced Stage Analysis Program (ASAP)

For assessing building movements, construction-stage and time-history analysis using a 3D finite element (3DFE) model that incorporates the time-dependent effects in concrete gives more accurate and comprehensive results than a one-column shortening analysis. The 3DFE analysis considers the effects of sequences of gravity loading and consecutive changes in the structural system as construction progresses. It also concurrently evaluates the effects of the various time-dependent properties of the concrete elements of the structure on the building structural response. Movements of the building are calculated through time in the construction stage and in service mode, as well as redistributions of internal actions in vertical and horizontal members.

Although there are several types of analysis software that can simulate sequential construction, they were mostly designed for the construction-stage analysis of bridges. As a result, current commercial software is functionally limited in solving problems typical of high-rise buildings and their complex construction-stage sequences, which consist of a large number of multifaceted steps spread across an extended time. Such software has limited capacity to analyze intrinsic aspects of high-rises like axial shortening, deviation from verticality, and redistribution of internal actions.

The Advanced Stage Analysis Program (ASAP) is a 3DFE analysis software specifically developed to analyze time-dependent behavior of high-rise buildings during the construction stage and throughout their service lives (see Figure 1).

The program predicts building movements in the vertical and horizontal directions at any stage of construction and at any desired target time. Redistribution of internal actions and stressed – as a consequence of the delayed concrete strains and the related differential shortenings and deviations from verticality as well as the progressive changes in the structural system – can also be evaluated at any time. In particular, the program calculates the variations over time of internal actions and stresses in rigidly connected floor structures and in stiff horizontal structural members such as transfer beams, outriggers, and belt walls/trusses, as well as the concurrent load variations in vertical elements.

Once the loading dates and duration of column forms and slab supports are defined, the software automatically generates the construction stages. Users can also create specific construction sequences for their own needs.

It is possible to import FE models from software such as SAP2000, ETABS and MIDAS/GEN. Beam and plane FE elements (such as shell, plate, plane stress, etc.) are implemented in the software. For the time-dependent behavior of concrete, creep and shrinkage prediction models can be used in the analysis. Interaction between

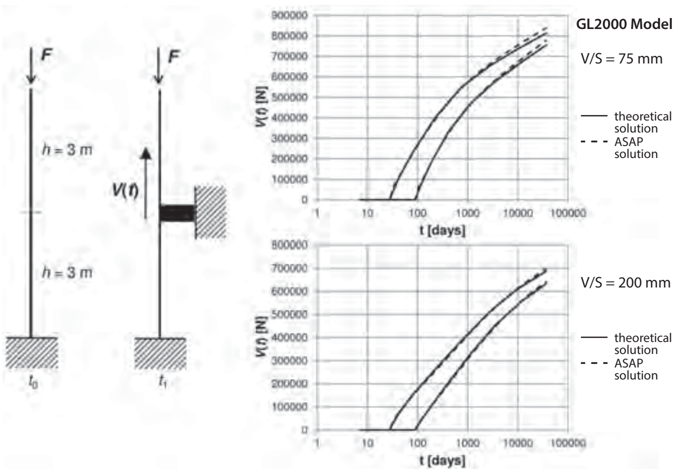


Figure 2. ASAP software validation – case study of a column loaded at time $t_0 = 7$ days subjected to the application of an additional delayed restraint at mid-height, at time $t_1 = 28$ or $t_1 = 90$ days. The graph show the development of the vertical reaction of the delayed restraint for different sets of influencing parameters.

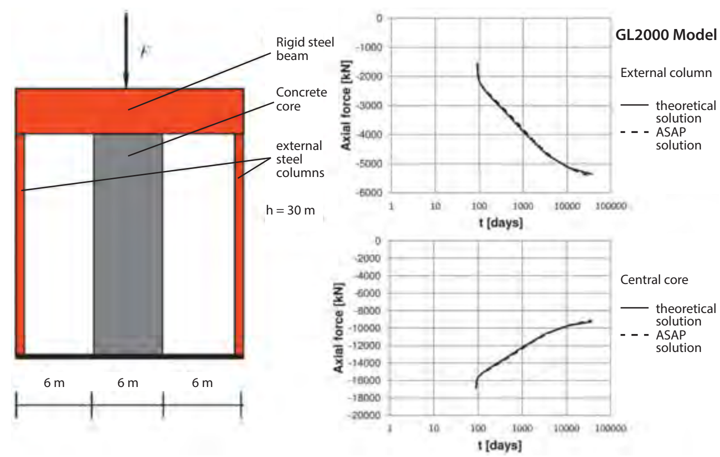


Figure 3. ASAP software validation – case study relative to a non-homogeneous hybrid structure with concrete core and steel columns loaded at time $t_0 = 90$ days (the horizontal bracing element is considered as a rigid body). The graph show evolution over time of the axial force in columns and core.

foundation and superstructure can also be simulated by iteration during the staged analysis.

The software's algorithm facilitates programming and control of compensation procedures by classifying vertical components of movement, allowing the insertion of diverse compensation (preset) options, identifying progressive horizontal movements, and allowing the adoption of the related suitable corrections. The cumulative effects of all these geometrical counteractions are considered in the analysis.

The software structure also allows the incorporation of test results on time-dependent concrete properties. This permits updating of the implemented creep and shrinkage prediction models and the incorporation of structural behavior in terms of strains and stresses, deformations, movements, and forces resulting from on-site survey and monitoring campaigns during the construction stage and during service life. This also allows verification of program outputs and appropriate program updating procedures. The unique features of this software make it favorable for construction-stage analysis.

Software Validation

The review process is intended to ensure that the computational algorithm of ASAP is able to:

- Evaluate the structural effects of delayed concrete deformations.
- Consider the intrinsic sequential character of high-rise buildings in the construction phase, and address the effects of progressive sequential actions, as well as changes in the structural system as construction proceeds.

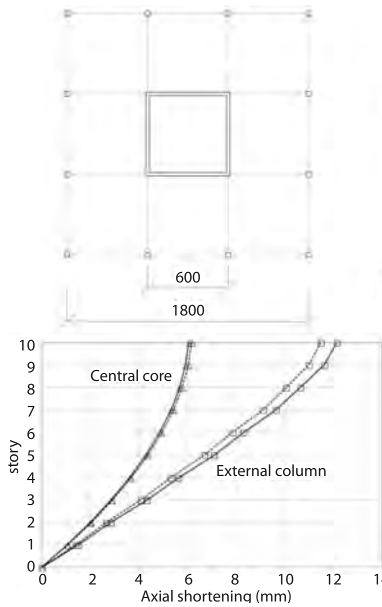
Concerning the initial and time-dependent properties of concrete, the review considers the ability of ASAP to correctly incorporate different prediction models. In particular, the program must be able to evaluate the specific shrinkage and creep properties of each individual structural element as influenced by inherent properties, time of casting and age. For this study, the correct incorporation of the Eurocode 2, B3, and GL2000 prediction models was checked.

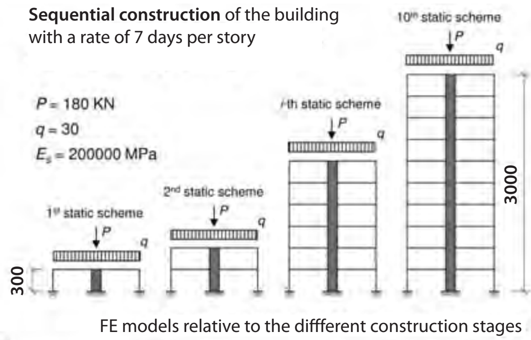
To evaluate delayed deformation effects, particularly creep, ASAP's outputs are reviewed for consistency with results derived from current advanced creep prediction models. These are based on the theory of aging linear viscoelasticity, with due account taken of the aging properties of concrete and its behavior over time. For complex sequential structures, histories of application of external actions, and progressive changes of structural systems, this involves solving linear integral equations or the adoption of equivalent-rate-type approaches. On this basis, the validity of ASAP has been tested through a few select case studies.

In each case study, numerical values obtained from ASAP are compared to those obtained from the integral-type general computational approach analyzing time-dependent structural effects in concrete developed at the Politecnico di Torino (Casalegno et al. 2010; Chiorino et al. 2007 & 2011; Chiorino & Casalegno 2012; Gardner & Chiorino 2007; Sassone & Casalegno, 2012). The latter program anticipates heterogeneity due to the presence of materials with different elastic and viscoelastic characteristics. Successive changes in the structural system can be considered as well, due to changes in the restraint conditions or to the variation of structural elements. Note, only beam and truss elements are implemented in the program, and the analysis is limited to 2D models.

In particular, the following simple scholastic case studies – representing (1) extreme one-time-step problems and (2) staged construction of a multistory structure – have been analyzed in order to check the validity of the tested software:

a. An unloaded concrete column, in order to check the shrinkage prediction models.
b. A concrete column (without considering shrinkage), subjected to a constant-unit axial stress, in order to check the creep prediction models.
c. A concrete column (without considering shrinkage), subjected to a constant imposed axial deformation, in order to check the accuracy of the software regarding the stress response to imposed deformations (a relaxation-type problem).
d. A concrete column (without considering shrinkage), in which a rigid restraint is introduced at mid-height at time t_1 after the application of an axial force at the top of the column at time t_0. This "creep-induced redistribution of internal stresses and actions" is a consequence of a change in the structural system due to the introduction of a delayed rigid restraint after the application of constant external loads. In Figure 2 the model considered for this case study is represented, together with the results of the comparison in terms of development of the vertical reaction of the delayed restraint for different sets of influencing parameters.
e. A frame structure with a concrete core and steel columns (the horizontal steel bracing element is considered as a rigid body), analyzed to check the software's solution for a case of a non-homogeneous hybrid structure, in which the stress migrates over time from the viscoelastic to the elastic part of the structure. For this case study, the evaluation of the effects of shrinkage and of the interaction between creep and shrinkage has been checked, also considering the shrinkage deformations of the central core. In Figure 3 the structure considered for this case study is represented, together with the results of the comparison, in terms of evolution over time of column and core axial forces.
f. A simple demonstrative case of a multi-story building realized through a sequential construction procedure. Two options have been considered: (1) the whole structure is made of reinforced concrete and (2) the external columns are made of steel, horizontal floor structures are in concrete, and shrinkage deformations are not considered. In Figure 4 the structure considered is represented, together with the analysis models and the characteristics of the structural members adopted for the concrete and composite buildings, while the diagram represents the long-term shortening (at 100 years) of the different floors for the concrete building.





Floors	Concrete columns size [cm]	Steel columns section	Beams dimensions (b x h) [cm]	Central core thickness [cm]
1-2	45x45	HEA 400	30x60	25
3-4	40x40	HEA 340	30x60	25
5-6	35x35	HEA 300	30x60	25
7-8	30x30	HEA 240	30x60	25
9-10	25x25	HEA 200	30x60	25

Figure 4. ASAP software validation – case study relative to a multistory building with concrete core and concrete or steel columns (sequential construction). Layout plan, analysis models relative to the different construction stages. Axial shortening is shown, corresponding to different floors at 100 years (concrete structure) and to the characteristics of the structural members adopted in the comparison.

The analyses have been carried out for different sets of influencing parameters (loading age, volume-to-surface ratio, etc.). Cases a) and b) only require the computation of shrinkage and concrete strains and consequent deformations according to the implemented shrinkage and creep models. The software results are correct for all the case studies considered. Small differences between the software's results and the numerical solutions of the inherent hereditary integral equations are obtained only for the case study f) relative to the multistory building (see Figure 4). For this study, only the GL 2000 prediction model was considered in all checks; for other prediction models, checks were limited to the model implementations by analyzing only the first two simple case studies.

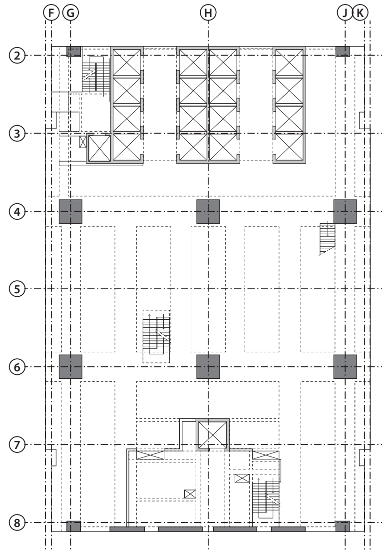
Application to a Real Case Study

After the thorough review and validation of ASAP code as a result of previous steps, the code has been applied to the case of a real high-rise building, the Public Mutual Tower, currently under construction in Kuala Lumpur, Malaysia (see Figure 5).

The tower block is 179 meters high (42 stories with 6 levels of basement). The structure is made of reinforced concrete megacolumns, in combination with post-tensioned floor beams. The tower block comprises two zones: the low-rise office floors from level 6 to 22, and the high-rise office floors from evel 23 to level 38. The high-rise office floors have larger usable office space due to the low-rise lift core terminating at level 22.

In brief, the structural framing consists of the following:

- Post-tensioned beams with span lengths of 14 to 16 meters; the beam depths for main and secondary beams are 750 millimeters and 650 millimeters, respectively.
- Reinforced concrete beams at shorter span areas with beam depths of 600 millimeters.
- Reinforced concrete beams are also provided at levels 5, 22, 39, and 40 due to



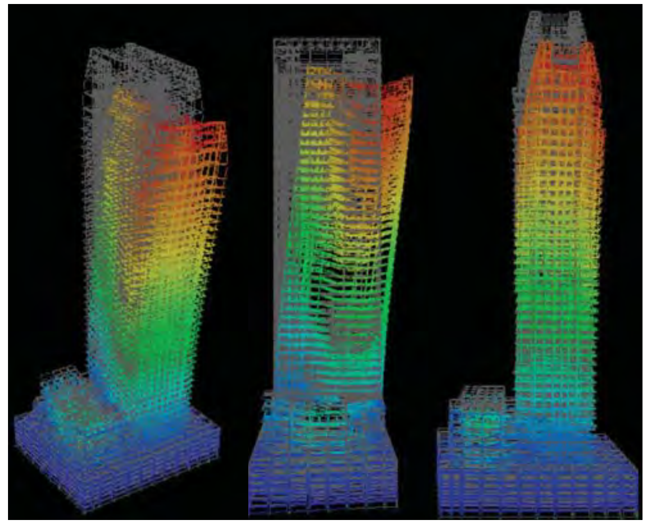


Figure 5. Public Mutual Tower, Kuala Lumpur. © Daewoo Engineering & Construction

Figure 6. Public Mutual Tower – typical plan. © Daewoo Engineering & Construction

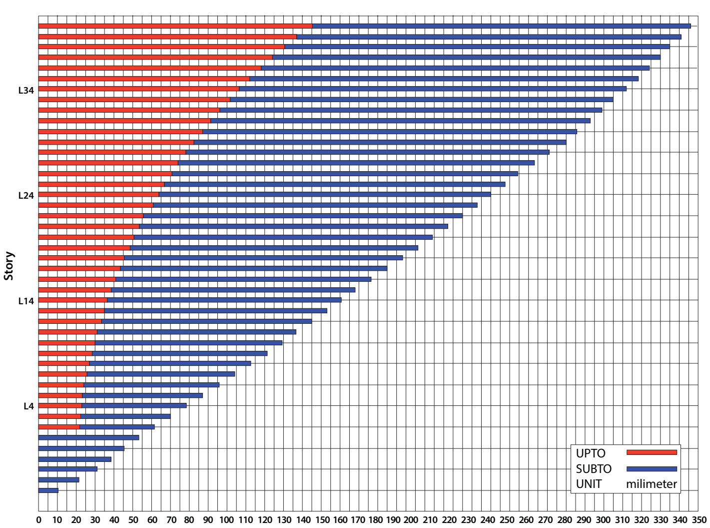
Figure 7. Deformed shape of the Public Mutual Tower at target time of 100 years.

the heavier loadings on these floors; here the beam depths adopted are 1.0 meter (level 5), 1.1 meters (level 22), and 1.5 meters (levels 39 and 40).

- The biggest columns are located along grid lines 4 and 6 (see Figure 6), with sizes varying from 2.4 by 2.4 meters to 2.6 by 2.4 meters; these columns reduce in size to 1.7 by 1.7 meters from level 22 to 31 and 1.35 by 1.35 meters from level 31 upwards.
- The size of four corner columns varies from 1.8 by 1.8 meters to 1.4 by 1.8 meters and subsequently reduces to 1.1 by 1.8 meters and 1.1 by 1.4 meters from level 6 upwards.
- Core wall thickness varies from 450 millimeters to 250 millimeters, depending on structural requirements.

An FE model of the building was built in ASAP. All 86 construction stages were modeled. Construction-stage and time-history analyses were carried out for a final target time of 100 years. In order to evaluate the influence of time-dependent deformations of concrete on the long-term behavior of the building, compensation of displacements was excluded from analysis.

The deformed shape obtained at the final target time of 100 years (see Figure 7) shows, besides the shortening of columns and walls, a significant deviation from verticality. The total shortening results – up to the completion of the floor (UPTO) + subsequent to the completion (SUBTO) – are visible at different levels after 100 years. Figure 8 shows that the maximum values at the top of the building are around 350 millimeters. The larger part of the shortening occurs after the completion of the floors (blue part of the diagram). This is also true for the higher floors, without adding significant loads after the completion, meaning that the long-term shortening is due in large part to creep- and shrinkage-delayed deformations. The horizontal displacements at the top of the building are a maximum of about 250



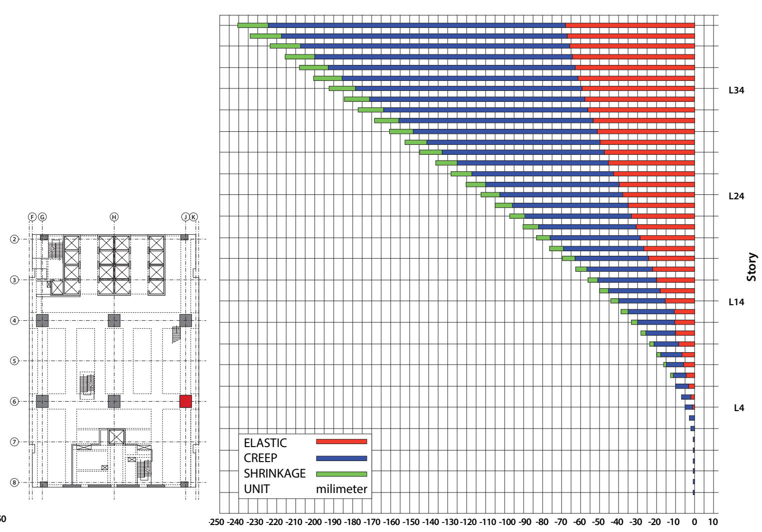


Figure 8. Shortening at the different levels of Public Mutual Tower at column J6 over 100 years.

Figure 9. Horizontal displacements at the different levels of Public Mutual Tower at column J6 over 100 years. Total (UPTO + SUBTO) displacements.

millimeters (see Figure 9). The diagram shows that these displacements are mainly due to elastic (red) and creep (blue) deformations, while the shrinkage (green) contribution results are much lower. Finally, the differential shortening between adjacent vertical members is about 50 to 60 millimeters at the top of the building (see Figure 10). The shortening differences are mainly due to displacements that occur after the completion of the floors (blue part of the diagram). Although these displacement values are very significant, it must be noted that the shortening that occurs up to the completion of the floors is usually not very important, at least for cast-in-place concrete structures, since the slabs are leveled at the time of casting. Nevertheless, the shortening that occurs after the completion of the floors also appears to be significant. The absolute maximum values are approximately 200 millimeters and the relative values between adjacent vertical members are between 20 and 30 millimeters (see Figures 8 and 10).

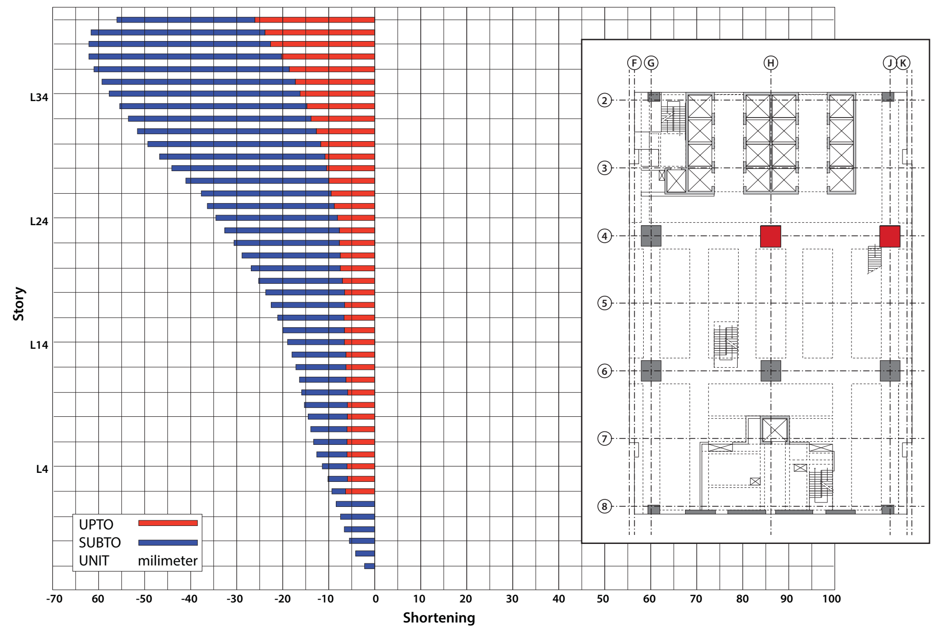


Figure 10. Differential shortening between column H4 and wall J4 of Public Mutual Tower at 100 years.

Conclusions and Future Developments

The time-dependent deformations of concrete play a significant role in the performance of high-rise buildings and need to be properly considered in the design stage in order to avoid serviceability and structural concerns. The presented software allows structural engineers to evaluate these effects by combining 3DFE and time-dependent analysis of structures. The validation process presented here evidenced the reliability of the software for the case studies and the prediction model considered. The analysis of the case study building evidenced a very significant influence of time-dependent concrete deformations on the long-term behavior of the building, highlighting the need to take into account these phenomena and to adopt proper countermeasures, such as compensation for displacements (via presets). The software allows consideration of the effects of adopting different compensation measures.

In this preliminary review, only the GL2000 prediction model was considered. The next steps will concern the check of the correct implementation in the software of all other referenced prediction models. Finally, an effort will be made to set up long-term monitoring programs in high-rise buildings, thus generating a positive feedback loop for the calibration of predictive models. ■

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