Title: **Interconnectivity of Design and Construction for Complex Towers in Relation to Movement Issues**

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Interconnectivity of Design and Construction for Complex Towers in Relation to Movement Issues

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Abstract

As the trend for complex architectural forms continues, the relationship between design and construction has become ever more interdependent.

Where this interdependency was once limited to distinct elements, such as outriggers, and vertical differential strain issues, the advent of complex, irregular structural systems, has led to ever more significant vertical and lateral movement and related strain issues.

The nature and magnitude of these movements now poses significant challenges to façades and vertical transportation, as well as to the detailing, fabrication and installation of the buildings themselves. It generally requires significant allowances to be built into the frame during or prior to construction, with different requirements depending on construction material and movement to be accommodated.

This paper examines the challenges to both consultant and contractor through two case studies, briefly looks at theoretical material models and material testing, and discusses the role of sensitivity studies and the issue of building tolerance.

Keywords: Complex Structural Systems, Construction, Eccentric Structural Systems, Movements, Non-linear material behaviour, Tall Buildings

Introduction

Tall buildings have historically adopted conventional, regular, uncomplicated steel framing systems with the structure. They are typically following the pattern of a centrally positioned core housing stairs, elevators and MEP service risers, often forming part or all of the lateral stability system, with vertical columns situated at the, typically rectilinear, floor plate perimeter. Such formulaic engineering was often driven by the building developer, wanting both to maximize the use of space within the building and on the plot, and to build as quickly as possible to gain maximum return on investment.

As building materials became stronger, and construction and elevator technology advanced, the height of buildings grew and new systems, including perimeter frames and outrigger braced cores, evolved to resist the greater lateral forces. With the advent of these systems, where vertical elements with different axial stresses started to become more interconnected, the differential strain in these elements began to cause secondary issues. If the stress in such elements could not be readily equalized, the resultant parasitic forces needed to be designed for in any linking elements and the levelness of the slab between the elements needed to be corrected during construction. These issues were generally not difficult to resolve using simple, published mathematical methods (Khan & Fintel, 1966) so avoiding a requirement for complex analyses. Levels could also be simply pre-set on site to resolve the difference in level.

As different materials, such as all concrete and mixed composite framing, began to become more widely used in tower construction, the differential strains became more pronounced and the non-linear effects of creep and shrinkage began to have a more significant impact, complicating the analysis further.

The current trend for tall buildings is taking us still further from these formulaic solutions of the past, where the designer and contractor were able to work almost entirely in isolation, and more and more complicated structural systems and forms are created with inherent complicated differential strain and movement issues that need to be considered by both the designer and contractor due to the effects on both the structural design and the building position relative to tolerance.

Figure 1. National Bank of Kuwait Tower (Source: Foster+Partners)

The following sections look at two such towers and discuss the key aspects of interest to designer and contractor.

National Bank of Kuwait

National Bank of Kuwait Tower (figure 1) is a 320m tall commercial headquarters building in Kuwait City. Designed by Foster+Partners, the tower has a unique, iconic form with a structural system consisting of a concrete core, sitting eccentrically to the floor plate, with a system of radial, inclined composite concrete filled steel columns around the perimeter supporting gravity loads.

Due to the eccentric floor plate (figure 2) and the non-vertical nature of the columns, the tower has a tendency to lean over under gravity load and in order to arrest this lean, and as a means to additionally resist the high wind forces, the central concrete core connects to a pair of composite framed "outrigger staircases" via two levels of steel outrigger trusses at plant levels. These outriggers and composite frames act as a pair of stabilizers, to prop the core against lateral forces and the horizontal gravity lean.

The front of the core is subject to significant gravity load, much higher than the lightly loaded rear wall causing the core to rotate under the resultant high strain differential. The combination of the rotation of the core and the stiff axial nature of the composite frame propping it up, leads to a double curvature of the building under gravity loading, with the top outrigger inducing a reverse rotation of the building as can be seen in Figure 3. This is all the more pronounced as the composite columns are subject to significantly lower creep and shrinkage strain than the core due to the large comparative steel content and the confinement of the concrete in the composite elements.

As a result of the outrigger connectivity and relative stiffness, the outriggers take up this load and act to prop the core rotation and thus reduce the building lean.

Because the strain and hence movement is time dependent, the sequence of construction becomes a key issue for design as well as for the initial setting out and final constructed position of the tower. The movement, and hence design forces, are dependent on many factors which the contractor typically controls: final material properties, specifically the final concrete mix design; final construction sequence, including time of application of façade and finishes etc., and overall construction speed. As a result, the initial design used upper bound and lower bound estimates of all the variables to size the principal elements and determine the range of expected movement. This initial analysis demonstrated however that the expected range of movement would mean that the building would be out of vertical tolerance from the end of construction and thus needed to be corrected for in construction.

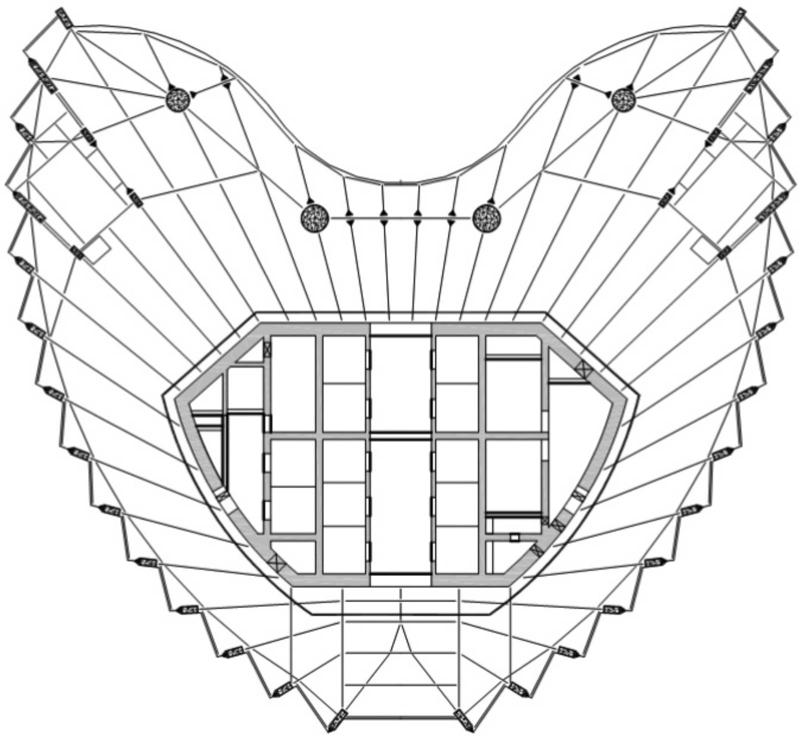

Figure 2. Floorplate Layout (Source: BuroHappold Engineering)

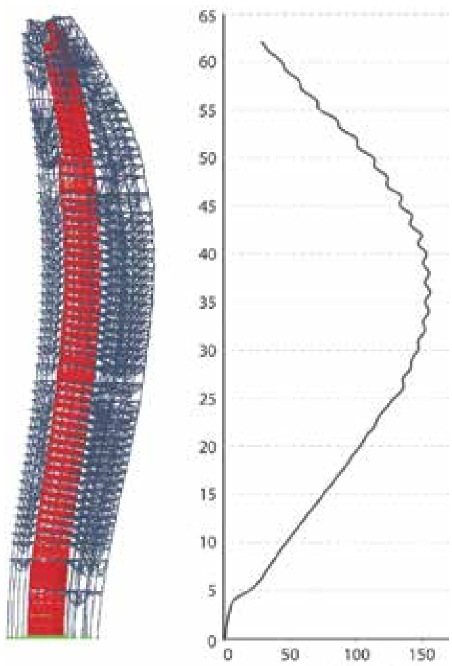

Figure 3. Gravity Displacement of the Tower (Source: BuroHappold Engineering)

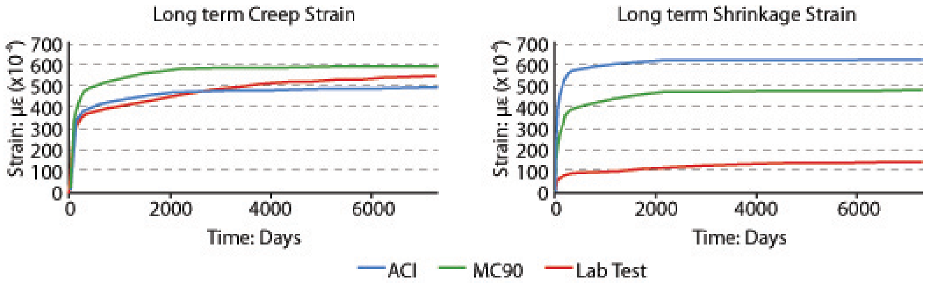

Figure 4. Comparison of Model Behaviour and Test Behaviour (FIB, 2010) (Source: BuroHappold Engineering)

To ensure that the final building position was within tolerance at the end of construction and beyond, an additional detailed analysis was undertaken after the contractor was appointed and once the final concrete mix design, construction sequence and program were determined. As part of the analysis, concrete material testing was carried out to determine creep and shrinkage characteristics of the concrete mixes being used.

Concrete material testing was carried out over a 16 month period in total, with available results up to 8 months used to assess the material properties for initial analysis due to construction time constraints; the values determined from testing were then compared against two international codes: ACI 209R and MC90-90.

As can be seen for one of the concrete mixes in figure 4, creep and shrinkage strain of the tested material was lower than the material model predictions. This was more marked in the shrinkage results than the creep results and the difference increased significantly with the higher strength mixes for the ACI code. It should be noted that the higher strength mixes had significantly higher plasticizer content and correspondingly lower water to cement ratio which would explain the difference for the ACI code which uses wet slump values as a key input parameter which become irrelevant with the use of the plasticizers. Following comparison of all the test results, it was determined that the MC90-90 code was a better overall fit with the test results, and the MC90-90 code parameters were used to determine an upper bound to the building movement, with extrapolated values from the test data used for a lower bound parameter set. Use of the higher code values was deemed a prudent approach considering the extrapolation required from very early age test results to long term behavior.

Following initial analysis, which confirmed that the building would be out of tolerance if merely built back to datum position at each level, an iterative process using a series of construction sequence analyses began to determine the ideal initial position for the built structure such that the final position was as near to vertical as practicable within construction tolerances. The initial assumption was to build the analysis model pre-set to a perfectly inverted shape of the anticipated movement and then to refine the pre-set through a series of iterations. Once this was determined, the foundation movement was included to demonstrate that the building would still sit within construction tolerance.

Once the initial pre-set position (figure 5) was determined, a sensitivity study along with further analysis iterations was carried out to examine the impact of variability in several of the key factors:

- Material behavior: difference between material test values versus code model values
- Variability of foundation movement
- Variation in applied load
- Change in construction speed and delays to load application

Including for the "worst credible" foundation movement was the most significant of all the sensitivity studies. As can be seen in figure 6, the final building position would be outside the specified tolerances, but it was agreed that such movement would

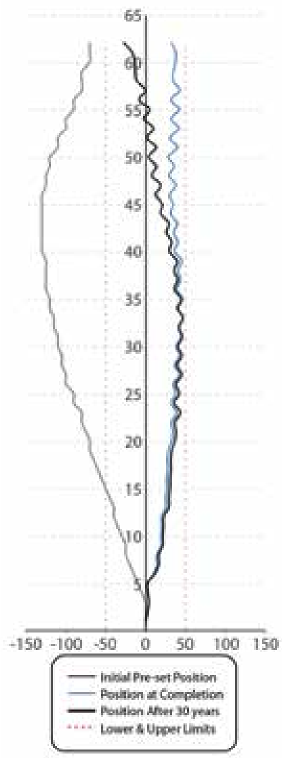

Figure 5. Basic Pre-set Position and Final Stages of Movement (including foundation movement)
(Source: BuroHappold Engineering)

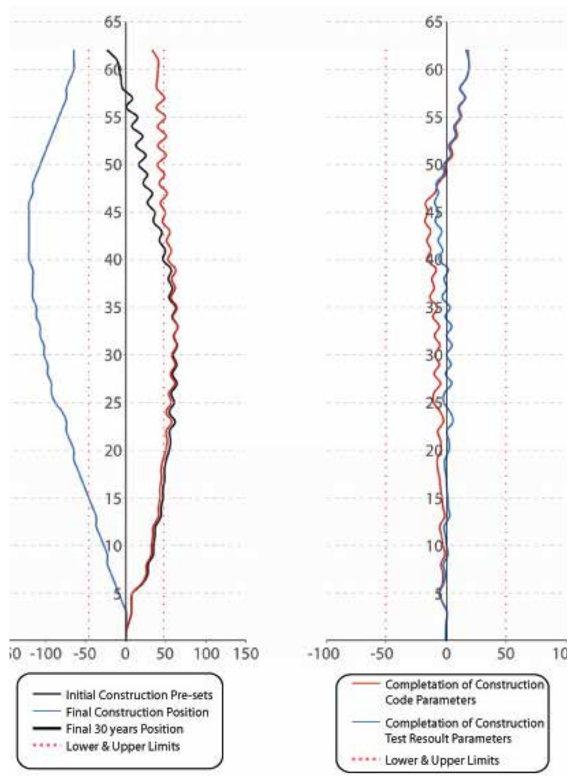

Figure 6. Final Positions Including "Worst Credible" Foundation Movement (L) and Reduced Superimposed Load (R)
(Source: BuroHappold Engineering)

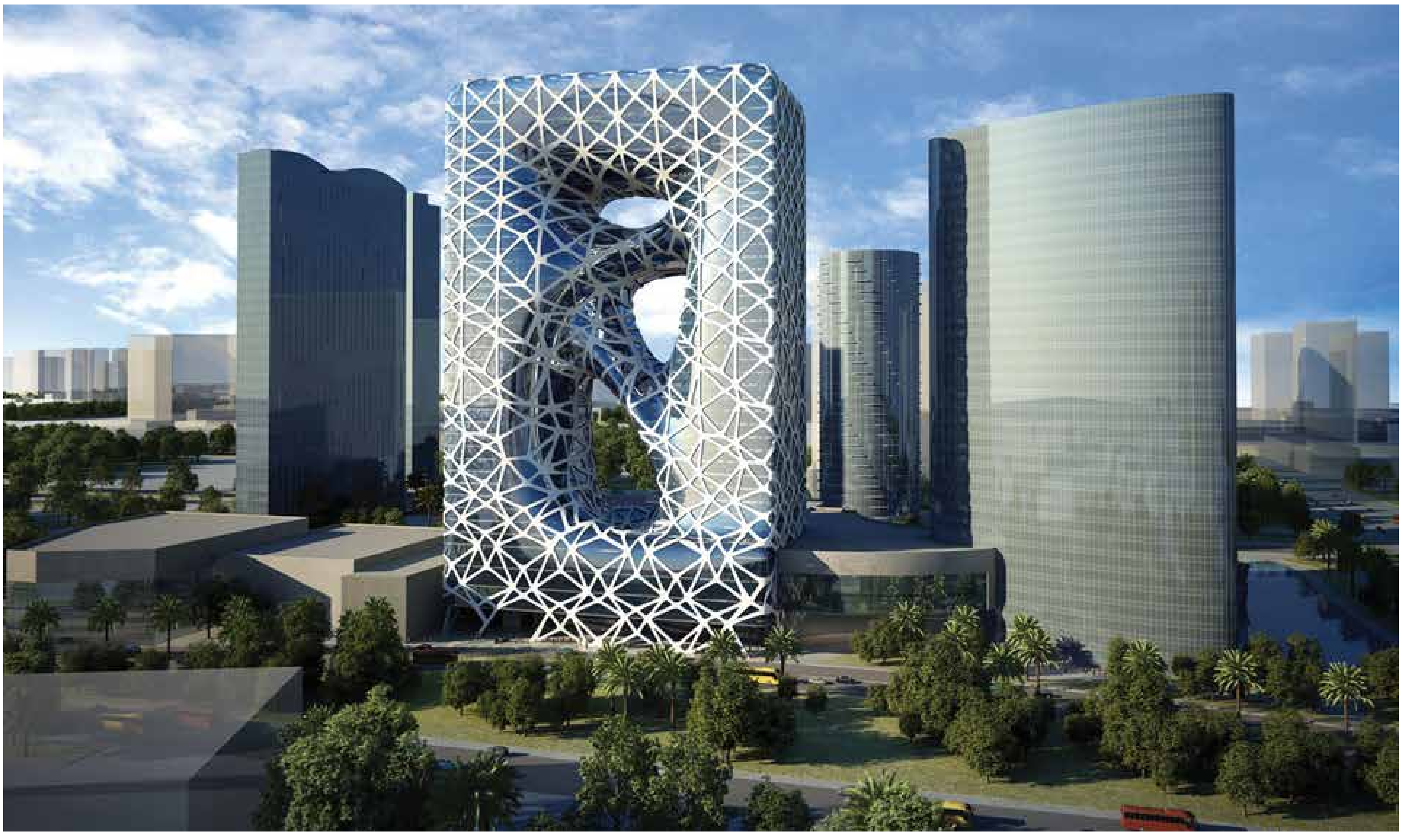

Figure 7. City of Dreams Hotel, Macau (Source: Zaha Hadid Architects)

still be considered acceptable as a worst case, being within the acceptable values from international codes. Other sensitivity studies, including a reduced superimposed load case, all demonstrated less overall movement, but showed that the initial pre-set was still valid and was not excessive if movement occurred was less than predicted. Additional studies, including contractor setting-out tolerances were studied, but all showed no significant impact on the final overall position.

Once the studies were completed and final pre-set position agreed, the impact on design and façade and vertical transportation installations were examined. The initial structural design, which used both upper bound and lower bound movement estimates, was found to remain valid and not overly conservative, and the façade system was designed and detailed to accommodate the expected movement. The most significant concern was for the installation of the vertical transportation system; the total movement being such that installation needed to be delayed to a time when the remaining movement was within tolerance of the installation.

Figure 8. Superstructure and Temporary Works Analysis (Source: BuroHappold Engineering)

The final output for construction included a series of lateral pre-set values for the core comparative to datum, and a series of vertical offsets for the composite columns, limited to the uppermost levels of the tower. The form of construction and connection detailing was such that no amendments were required to the fabricated steel, and any offsets required to build to level and lateral offset (other than the top levels discussed above which needed minimal pre-set built into the fabrication) could be made during construction of the joints at each level.

Surveying will be carried out during construction to assess the actual movement of the frame against the predictions made to ensure that any significant variations are accounted for in re-adjustments in the required pre-sets. Initial survey results to date show reasonable agreement with prediction.

City of Dreams Hotel

City of Dreams Hotel (figure 7) is a new luxury hotel and casino being constructed in Macau. Designed by Zaha Hadid, the 160m tower features a unique expressed structural exoskeleton, with complex freeform areas

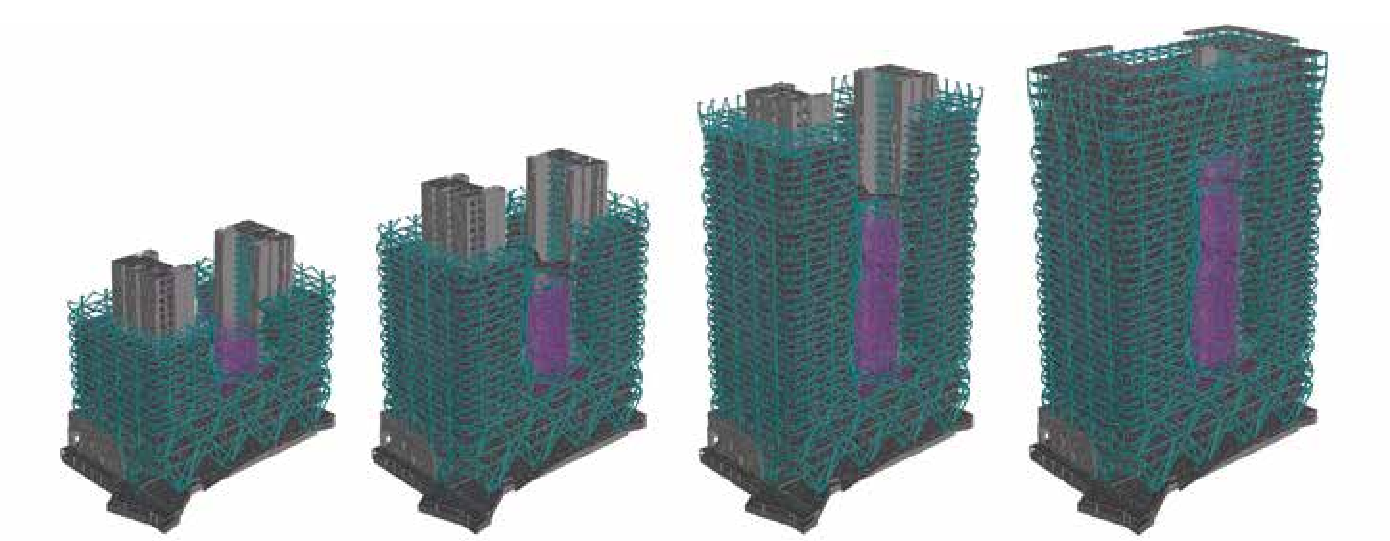

Figure 9. Selection of Construction Stages (Source: BuroHappold Engineering)

where openings through the building are formed. The exoskeleton sits proud of the façade through the vertical areas, with the exoskeleton supporting the freeform façade areas directly.

Internally, a composite floor plate spans between the exoskeleton and internal columns adjacent to the two concrete cores, one at each end of the building.

With such a structural arrangement, the issue of movement is threefold: elastic exoskeleton strain shortening and spreading; elastic axial strain of internal columns; and elastic, creep and shrinkage strain of the concrete cores. As well as general differential axial shortening issues in the frame, the principal challenge for the project was the construction method statement and sequence. Because of the freeform areas of the exoskeleton, detailed contractor input was required to determine how the final structure would be built so that any shortening analysis and structural design forces could be informed by the specific sequence. Unlike for more regular structures, upper bound and lower bound forces are more difficult to define due to the large number of potential sequences and construction methods, all of which would load the frame differently. As a result, an initial design was carried out in accordance with a set of designer's assumptions, and a later stage by stage analysis was developed to determine the locked-in stresses to be used for design.

The final construction method involved erection of a system of temporary works through the freeform area for the full height of the building, designed by a contractor; this enabled the complex nodes to be temporarily positioned and stabilized for the in-situ connections that were required. The system of temporary works was a significant structure in itself and required careful coordination to ensure that it did not clash with the permanent structure and that all joints were adequately supported. A final, detailed analysis was carried out on a combined 3D model of the permanent and temporary works to ensure that the interim movement of the exoskeleton was considered by the temporary works and vice-versa that the staged propping and later de-propping from the temporary works was considered in the design of the exoskeleton (see Figure 8).

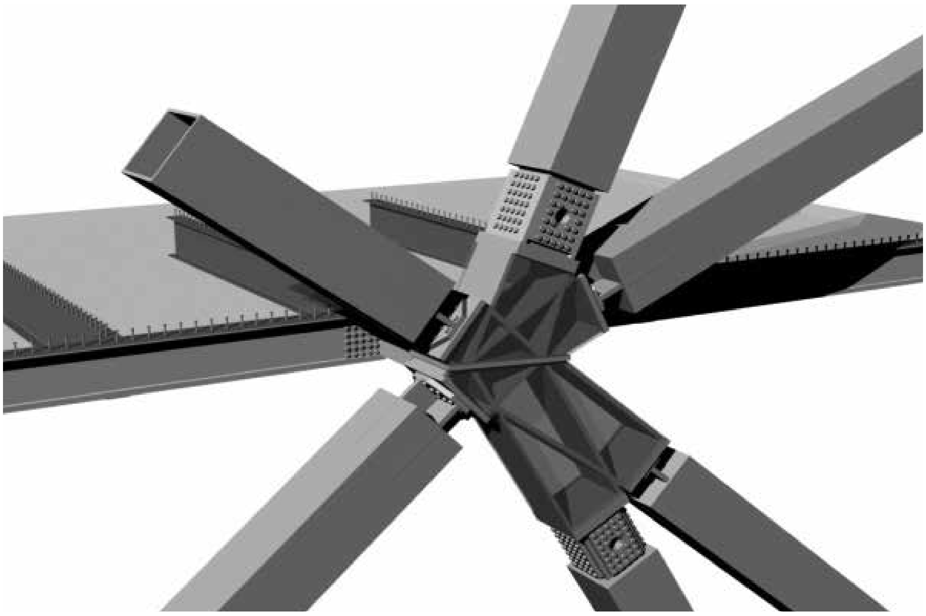

Figure 10. Exoskeleton Node (Source: BuroHappold Engineering)

Because the design of the permanent and temporary works is interrelated (due to differing stiffnesses of the two interacting systems) analysis iterations were required to determine the final propping and de-propping sequences (Figure 9).

Following agreement of the final arrangement and de-propping sequence for the tower, further iterations were carried out to determine vertical pre-sets of the nodes in the exoskeleton and the internal structure. As concrete is generally built to datum level at each lift, this was used as the benchmark for the steel frame and the setting-out of the nodes of the exoskeleton were pre-set to ensure that, after loading, the floor plates were level, within specified tolerance. Once the final sequence and pre-set construction setting out was agreed, the resultant "locked-in" stresses were extracted and included in the final design of the exoskeleton members and connections. These "locked-in" stresses increased the original design forces by up to 20% in some areas.

As a final output, pre-set construction setting out of the entire exoskeleton was provided for the contractor to determine the final fabrication geometry of the frame. Additionally, surveying will be required on site to ensure that the differential movement matches the anticipated movement so that minor adjustments can be made to the frame connections as necessary (Figure 10).

Practical Challenges

As seen in the two examples provided, the issue of movement is complex and has different implications on design and construction dependent on many factors including: geometry and form; structural systems and materials used; and construction timing and sequence. What is clear is that design and construction considerations are becoming ever more connected and the previously isolated approach to tall buildings is no longer appropriate in some cases, particularly if practical, efficient and economic designs are to result, and designers and contractors need to cooperate.

Even with cooperation and coordination between designer and contractor, challenges remain. Materials, and concrete in particular, are variable in nature and the parameters used to assess movement can vary considerably. For concrete, there are several theoretical material models available, with varying degrees of input parameters required, most of which are empirically benchmarked against specific regional materials and practice.

Two of the simpler theoretical concrete models for application frequently used in construction movement studies are ACI 209R and MC90-90. These models use readily available and simple input data in order to assess the elastic, creep and shrinkage behavior of the concrete. One notable issue with the ACI code specifically is the use of wet slump as one of the input parameters; for the types of concrete generally used in tall building construction, plasticizers are used with reduced water-cement ratios which have collapse type slumps. Use of such values would give significant errors particularly in creep behavior. One "fix" proposed (Brooks, 1999) is to use wet slump values for the same concrete with the exact mix minus plasticizer, and then increase the creep values by 20%. For the National Bank of Kuwait project however, this method still showed excessive creep values compared to the test results and MC90-90 model was preferred as it compared better in both magnitude and time development of the strain.

Further complications exist when concrete filled steel columns are used, where long-term behavior of the concrete fill is altered by the steel outer column, typically leading to slower shrinkage and lower ultimate creep. In particular, the outer steel tube acts to seal the concrete fill from moisture migration, so almost eliminating drying shrinkage (the largest component of total shrinkage) and drying creep (the smaller component of total creep). The confinement effect of the tube also constrains the concrete from spreading, thus reducing the total creep. A further significant consideration in composite columns, whether filled or encased, is the stress transfer from concrete to steel over time as the concrete strain is restrained by the high steel percentage. This is often considered, but its impact is far more marked in composite columns, often leading to significant reductions in total strain. Models to account for this behavior are available (Khan & Fintel, 1966).

One of the key issues to consider then in relation to construction movement is the use of expected as opposed to conservative material values for analysis; any design implications in variability are taken into account by the standard load combinations applicable. The best way of assessing the actual material behavior is by carrying out material testing on the specific material to be used. Steel batches are generally tested frequently and this information is available early on after award of the construction contract, but concrete properties are more difficult to obtain in a timely manner. Material tests should preferably be commenced ahead of the construction contract and the standard minimum period for testing is 12 months, but this is often not possible and testing will typically commence a short time before construction which puts significant time pressures on the analyses and potential inaccuracies due to parameters based on extrapolation of short-term results for long-term values. In these cases, it is important that the parameters used are constantly reviewed against continuing test results to ensure that no significant differences arise, invalidating the initial results. Carrying out sensitivity analyses and using a degree of conservatism in the upper bound set of parameters can ensure that no problems arise if future results demonstrate higher ultimate strain values.

A further practice on site is monitoring of movement and verifying against expected movement at specified stages. The challenge with this is that early age movement is often only a very small portion of the total; for example, movement measured at a quarter height of a tower, once construction is 50% complete, could be as little as 10% of the total movement, and depending on the value of the measured figure, tolerances in surveying could greatly diminish the accuracy so that assessment of theoretical versus actual movement is very difficult to assess. Even if reliably accurate measurements are taken, given the small percentage of total, still make this measurement unreliable and difficult to provide enough information to determine whether adjustments should be made to the movement compensation strategy.

As well as survey of actual movement on site, progress of construction also needs to be carefully monitored. As discussed earlier, total movement and potentially distribution of forces is greatly related to the progress and sequence of construction. Some considerations to be made in relation to changes to the construction progress include:

- Slower construction will generally lead to smaller movement as concrete will have longer to cure prior to load application. Conversely, faster construction will generally lead to greater movement.
- Delayed application of secondary and tertiary loads (i.e. delayed fit-out and façade installation) will lead to greater overall movement as elastic component of movement becomes more significant as it is not built out as construction proceeds.
- Concrete cast at a higher temperature will cure faster and typically will exhibit less movement.

Changes to construction sequence could potentially have an impact on load paths and as such needs to be monitored on site to ensure it matches agreed methods.

Tolerances

Tolerances are rarely of concern and generally easily achievable through simple construction adjustments when considering slab level etc., but when the movement includes a lateral component, the issue becomes more challenging. Tolerance specifications, such as ACI 117 (ACI, 2010) are typically written for as-built tolerances and do not consider post-construction or creep and shrinkage movement.

The governing factor for such movement is more appropriately related to practical considerations and the movement that the building can sustain considering the design of other key building components, most notably the façade and vertical transportation installations, which are typically the key restricting factors.

The designer must always account for the expected movement in the design, including any second order effects of the movement as appropriate.

Concluding Remarks

As demonstrated above, the design and construction of tall buildings are becoming ever more intertwined as architectural forms becomes more complex and gravity movement issues become more pronounced.

There are many factors to consider in the final design and determination of appropriate construction pre-sets, and it is often not sufficient to rely on a single set of parameters, program or construction sequence to ensure that all the key factors are known and understood and accounted for appropriately.

Engineering judgment is a key factor, and practical considerations taken in consultation with all stakeholders are vital to a successful outcome.

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