THE GAP - BETWEEN STRUCTURAL DESIGN AND CONSTRUCTION METHODS

Girish Dravid

Director, Sterling Engineering Consultancy Services Pvt. Ltd., Mumbai, Maharashtra, India

Abstract

A structural designer is given a brief in the beginning of his design process in the form of a set of architectural drawings, soil investigation report, and at the most, an indication about the number of additional floors over and above the sanctioned height of the building. Based on this information, the structural designer embarks on an arduous course involving load calculations, element sizing, gravity and lateral load resisting framing ensuring a proper load path, selecting appropriate grades of materials, making computer models, multiple analysis runs, complying with innumerable code requirements, satisfying peer reviewers and sanctioning authorities, preparing complicated reinforcement details and producing a huge pile of drawings to be issued to contractors for execution. In this entire process, he is solving a given problem with a fixed set of assumptions and parameters. The design is valid only if the contractor builds the building exactly as is shown on the drawing and in the details. On the other hand, the contractor prepares his own methodology of construction, most often at the tender stage itself, not having adequately detailed drawings and to satisfy time and milestone targets pre-decided by the project management. The methodology is based on the skills and resources he has - for example, the number of formwork sets, formwork system he is comfortable with or sometimes imposed by the project management, his understanding of the site situation and his perception or mis-perception of the structural configuration. It has been observed that there is often a gap between the parameters assumed for design calculations and how the building is constructed in reality. When the construction of the building is complete, one cannot see a geometrical deviation from the intended structural framework. However, the way it has been constructed, there could be a significant variance between intended behaviour and the actual one. The expected long life of the building can be compromised due to this disconnect. For a high rise building performance, such a situation can prove to be alarming. This paper aims at moving the already known facts into the realm of discussion and beginning a focused movement to bridge the gap.

Keywords : *Design, Construction, Gap, co-ordination,*

--***--

Disclaimer : *This article is not about wrong designs on part of designer or poor quality of construction by contractors. It is strictly about the need of mutual understanding of design assumptions and implications of construction methodology, that may influence each other.*

The author does not claim that interactions between contractor and the designers do not take place. However, this is a compilation of experiences which may help the concerned project participants during the process of planning, designing and construction of a high rise project.

1. INTRODUCTION

High Rise Buildings are special structures that need careful attention during design as well as construction. The magnitude of loads and forces to be resisted by the structural framework and foundations in a tall building is very large. With sophisticated software products and the ease with which high grade construction materials are now available, it is possible for the structural designer to match his designs to conform to the market averages of cost and material consumption, at the same time, satisfying aesthetic, spatial and services requirements.

With advances in construction techniques, availability of modern construction equipment and machinery, a high rise contractor is in a position to promise speedier and relatively economical and quality construction to the developer. Ease of procuring high performance materials has resulted in pushing the slab cycles to bare minimum periods to attain early returns on investment.

With such higher levels of sophistication in respective disciplines, it is found that a small push is still needed to bring about a closer co-ordination between the design office and the construction site.

A structure is analyzed and designed to be stable and strong to resist the forces likely to be imposed in its completed form. It is taken for granted that the stability during construction is part of the contractor's scope. While, this is generally accepted by all the parties, including contractors, there are some important areas which demand a more intimate interaction between the contractor and the designer. It is also imperative that both - the contractor and the designer - must have sufficient knowledge about design process and method of construction respectively, to ensure what is designed is constructed and in turn, what is constructed is designed.

With the pressures from the developers to economize the designs, a critical balance needs to be maintained between the design margins and the construction tolerances. It is a fact, that RCC civil / structural construction cannot be precise with millimetre accuracy as in structural steel construction. Apart from the tolerance levels, the construction techniques and the modern construction equipment used by the contractor to carry out speedier construction, have their own implications on the way the structure will perform through its lifetime. These methods could be either fulfilling the design assumptions or sometimes, could be completely contrary, resulting in a suspect behaviour of the structure.

2. EXAMPLES

Following are some examples that the author has commonly found during high rise building construction in recent times after the advent of modern construction technology.

2.1 Missing Dowels or Couplers and Unplanned Construction Joints

A technique commonly used by contractors to defer the construction of connected RCC members by leaving bent dowel bars within the formwork or embedding doweled couplers to facilitate splicing the bars of the left out structural member in future, fires back many times on account of lost, disoriented couplers or distorted, broken or lost dowel bars. Recourse is then taken to what is usually termed as "re-barring". The fundamental action at such a junction needs to be verified by the designer. In the first place, whether deferring the construction of the connected member is violating the design assumption of a monolithic joint, and secondly, whether the re-barring can adequately develop the lost monolithic action.

Fig - 1 Missing Dowels (1)

Fig - 2 Missing Dowels (2)

Unplanned construction joints may prove to be quite disastrous. There has to be process of pre-defining the locations of construction joints. The criteria from contractor's side could be maximum concrete pouring capacity in one session, his readiness with formwork and reinforcement and the sequence of construction he has planned. Designer should make himself aware of such requirements of construction and carry out local or sequential analysis of the structure to study the effects by simulating cold joints at construction joint locations. The action should be understood of such joints and the joint detailing should be appropriately carried out.

Fig 3 - Unplanned Construction Joints

To some extent, problems at cold joints could be eliminated if long time retardation of concrete is achieved through proper mix design. Concretes are available with up to 12 to 16 hours retardation. If the topmost recent layer of a raft or a transfer girder is retarded by sufficient time, so that the adjacent layer of the next pour can be vibrated along with the last one, assumption of monolithic section as desired in the design calculations can be easily achieved. Alternately, clamping reinforcement or post-tensioned clamping can be resorted to, to achieve adequate shear friction. (ACI 318 - 14 : Clause 22.9)

2.2 Climbing formwork - Cold Joint

Fig 4 - Climbing Formwork

With the introduction of climbing or jumpform system for advancement of the shear / lift core ahead of the slabs, substantial time saving has been achieved in the high rise construction. The tedious and time consuming work of reinforcement binding and formwork erection within tolerances, has been taken out of the slab cycle calculations. This work is now happening three, four or sometimes seven to eight floors above the current slab casting level, with much dimensional accuracy, with near verticality and using minimum labour. If one is using reinforcement meshes, the work is further faster and better. However, with the use of climbing formwork, comes the inevitable cold joint between the core and the floor diaphragm. Needless to say, a floor diaphragm plays extremely important part in the utilization of the combined action of the core and the peripheral frames in lateral load resistance. The reinforcement in the floor slabs and beams is generally designed considering a monolithic joint between the floor diaphragm and the core walls. It is quite a big debate if this assumption is properly realized in actual construction. While the advantages of using climbing and jumping formwork for the core are undisputed, it is up to the designer to review the consequences of the construction method and incorporate in his analysis and design any relevant parameters to simulate the situation.

2.3 Climbing formwork - Maximum limit on advance construction

Climbing, jumping or slipping formwork needs another important design check as it climbs ahead of the floor construction. The contractor often desires to build sufficient lead by advancing the core as high as possible. The ease of raising the formwork systems along with its working platforms and the mounted crane encourages the contractor to complete the otherwise difficult work of core construction earlier, book the turnover and carry on with the relatively simpler work of floor construction at a regular smaller interval. Since the rate of climbing the core is very fast, the concrete in the core is still raw and weak, both in strength and in its elastic stiffness. The lateral loads due to crane movement and wind load act on the bare core. It has been observed that with lower strength and the low E value of concrete corresponding to various time intervals for its pours, the deflections in the bare core could be as high as 12 to 15 mm. In raw concrete, such deformations can result in yielding of concrete as the stress levels hover around and above elastic limits. Thus, if the contractor does not refer his core climbing requirements to the structural designer, permanent deformations may set in, which will not be noticeable in the overall picture when the building is complete. Such deformations will be treated as construction allowances. On the other hand, if the contractor diligently approaches the designer for approval of his proposal of climbing the core to a certain height and if the designer casually approves the proposal without going through a small analysis, the results would be equally detrimental. If there is a proper interaction, there could be solutions to this problem -such as coming to a conclusion regarding the number for floors for which the core can be advanced above the last concreted floor, or ensuring that the strength of concrete reaches a certain threshold for a desired height of the core. Other measures such as installing temporary steel braces on the faces of the core to bring in additional stiffness to the core can also be adopted.

2.4 Action of Incomplete Structure - Transfer Girders, Virendeels, Hangars, Propped Retaining walls

High rise buildings often have requirements of transfer of columns on account of the necessity of accommodating multiple uses of occupancy across their height. There have been instances when a single building has three to four different uses one above the other - for example, a multi level car park at the lower zone, a couple of shopping / retail levels, some levels of office floors, and then a few levels of hotel, residential floors making up the top zone of the building is one of the probable configurations in a multistorey mixed use skyscraper. The column locations in such buildings cannot remain identical on all floors. Transfer systems have to be provided in such buildings to bring about the change in column alignments. If it is convenient, these transfer levels and the transfer elements can be converted into outrigger system as well, relieving the individual function floors of the bulky lateral load resisting system.

However, these transfer elements are difficult to design and construct. Being voluminous, they require special staging and formwork, there is high probability that there is congestion of various embedments - reinforcement, diagonal struts and ties, post-tensioning cables, insert plates, clamping reinforcement, steel coupling beams, shear studs and high level of shear reinforcement. First, the designer must make detailed dimensional drawings to accommodate all such elements in the given geometrical volume, taking into account construction tolerances as well, and by ensuring flow of concrete.

Fig 5 - Transfer Girder Embedments

Contractor has a genuine difficulty in erecting formwork and staging for these heavy transfer elements. His problems are twofold. First, the investment in the non-repetitive heavy duty formwork and staging and its erection cost at intermittent levels throws his cashflow and timeflow out of cycle. He has to design this formwork and staging for huge self weight of the transfer system, and transfer the load to the lower floors, which might not have been designed to carry all this construction stage load. This entails propping the lower slabs for multiple levels and maintaining the locked propping material for a considerable time until the transfer system is completely cast and achieves the desired strength for continuing with the construction of the upper levels. It is to be noted that a structural designer designs the structure for its completed configuration, and is not willing to take the responsibility of action of the incomplete structure.

It is at this point, that one realizes the importance of the interaction between the contractor and the designer to know each other's assumptions and parameters before even commencing the construction activity. There have been instances in this author's career, when a bridging multi-storey virendeel connection between two towers, properly detailed for its construction using intermediate temporary supports with foundations and columns upto podium designed to take the load of the bridge structure, was stalled due to ignorance of the newly appointed contractor's project manager of the tender stage negotiations and discussions with contractor's tendering team, which unfortunately had been dismembered in the course of time. The project manager wanted an elaborate staging system to be installed from the third basement level right up to the fifteenth floor and maintain it until the terrace was cast. Obviously, he also wanted the client to approve his claim for out of turn work, running into lakhs of rupees. The matter was resolved only when the project manager was shown the set of tender drawings and the horde of minutes of meetings how there was a perfect dialogue about the construction methodology of the bridging structure and that there was a very simple design solution already built in the structural scheme of the building at no extra cost.

Deep transfer girders can be designed as multiple shallow beams capable of sustaining the load of upper self weight of the girder and the immediate floor slab supported on the girder. Information regarding the concrete pouring capability of the contractor in one pour and the strength of the staging he is intending to erect, will be of good help to the designer. This will allow the contractor to design the staging in a normal way, without throwing the burden on the lower floors and also permitting early removal of staging, since the lower strip of the girder can now sustain all upper loads during construction of the girder. The designer however, shall keep in mind while designing the deep girders, the necessity to provide adequate clamping reinforcement across the horizontal construction joints, in accordance with ACI 318 - R : Clause 22.9

Similarly, although not exactly restricted to high rise construction, the retaining walls are commonly designed for propped conditions. This means that they are capable of resisting the lateral soil loads only if they are laterally supported by the basement slabs. This puts restriction on the contractor to defer the backfilling of the retaining walls until the slabs of the basement are cast. A dialogue in this respect and a value engineering exercise to determine whether it is optimal to design the retaining wall as cantilevers, allowing the contractor to backfill without props, or backfill only after constructing the slabs, is called for. In certain cases, it was observed that designing the retaining walls as cantilevers resulted in achieving faster progress, resulting in substantial savings in time, and effectively in cost, due to the particular nature of contract.

In case of hangers, it may be prudent to provide a propping temporary column below the hanger point temporarily, throwing the entire load through this temporary compression member to the foundations, until the hanger is installed for all the upper floors. This way, the huge cost towards staging being maintained throughout can be substantially saved.

2.5 Sequential analysis

Nothing to do with contractor much, once he defines the sequence of construction, it is now upto the designer to use the information to assess the impact and determine the transient stresses the structure - or the partially completed structure - is going to undergo through the construction process. The effects could be observed on behaviour of transfer girders, virendeels, floor diaphragms, coupling beams, long and slender columns and other structural elements in the form of differential settlements, higher deflections and induced moments, axial deformations etc. If any structural element is observed to be overstressed beyond what it is designed for in the model of completed structure, adequate measures have to be provided in the form of temporary strutting or propping, additional reinforcement or coming to a mutually agreed construction methodology that could eliminate the condition.

2.6 Faster slab cycle - floor loading - Sagging of slabs

One of the prime objectives of highrise construction for any contractor is to achieve maximum possible frequency of slab concreting. In general, if the floors are typical one above the other, it is very much possible to bring down the slab cycle to five or six days, once the rhythm of repetitive work is attained. One fall out of faster slab cycle, however, is the requirement of supporting the loads of construction on the lower slab, which are probably designed for much less imposed loads other than self weight. The following table shows the loads for which the slabs are designed in their final action.

Table 1 - Residential Floor Loads

Residential Slabs	
Load component	**Load**
Floor Finish	1.0 kN/sq.m
Live Load	2.0 kN/sq.m
Total	**3.0 kN/sq.m**

Table 2 - Commercial Floor loads

Commercial Slabs	
Load Component	**Load**
Floor Finish	1.5 kN/sq.m
Wall Load	2.0 kN/sq.m
Suspended services	0.5 kN/sq.m
Live Load	4.0 kn/sq.m
Total	**8.0 kN/sq.m**

Table 3 - Load During construction

Construction Loads	
Self Weight of wet slab	3.75 to 6.25 kN/sq.m
Staging and Formwork	2.0 kN/sq.m
Construction Live Load	1.0 kN/sq.m
Self Weight of slab	3.75 to 6.25 kN/sq.m
Ponding Water	1.0 kN/sq.m
Total	**11.5 to 16.5 kN/sq.m**

One can imagine that in either of the cases, the design load on the slab is much less than the weight of the wet concrete of the upper slab to be cast, the formwork, staging, construction live load on the slab to be cast, and most probably the water load arising out of ponding the slab supporting the staging.

It is certainly not advisable to design the slab directly under the proposed slab to carry the transient construction loads described above, for its premature strength at say 7th day to 10th day as per the proposed slab cycle. There are three precautions to be taken to support the above loads, while the concrete of the last constructed slab has not yet achieved full strength.

a. The weight of the slab to be cast should be adequately supported by a well designed multiple level propping system.
b. Deflection due to the construction load and the self weight of the slab to be cast in the lower slab should be avoided to make sure the deflection is not permanently set in the still fresh concrete.
c. Appropriate camber to be provided to the slab to be cast, so that even if the formwork and staging undergoes certain deflection during casting, the resultant profile of the slab is reasonably flat.

Common precautionary measure is to prop the slabs at multiple levels, so that the construction loads and the weight of the wet concrete is distributed among slabs which have attained progressively higher concrete strengths. This system must also incorporate the cambers that have been mentioned above to account for the deflection of the lower slabs, which is inevitable.

2.7 Transfer of column load through floor

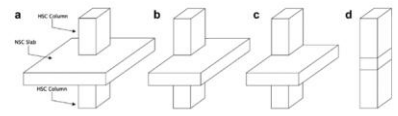
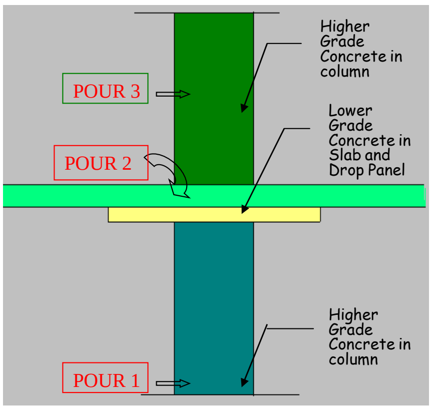


Figure 1 Schematic views of slab-columns connection: (a) interior column (b) edge column (c) corner column (d) sandwich column (following [13]).



15.3—Transfer of column axial force through the loor system

15.3.1 If f_c' of a column is greater than 1.4 times that of the loor system, transmission of axial force through the floor ystem shall be in accordance with (a), (b), or (c):

(a) Concrete of compressive strength specified for the column shall be placed in the floor at the column location. Column concrete shall extend outward at least 2 ft into the floor slab from face of column for the full depth of the slab and be integrated with floor concrete.
(b) Design strength of a column through a floor system shall be calculated using the lower value of concrete strength with vertical dowels and spirals as required to achieve adequate strength.
(c) For beam-column and slab-column joints that are restrained in accordance with 15.2.4 or 15.2.5, respectively, it shall be permitted to calculate the design strength of the column on an assumed concrete strength in the column joint equal to 75 percent of column concrete strength plus 35 percent of floor concrete strength, where the value of column concrete strength shall not exceed 2.5 times the floor concrete strength.

SLAB	COLUMN
M:30	M:40
M:35	M:50
M:45	M:60

Permissible variation In Concrete Grades

Fig 6 - Different Concrete Grades

Using different grades for columns and floors is a very common practice in high rise buildings. While the concrete grade in floors can be maintained almost the same throughout in most of the cases, the concrete grade in columns needs to be varied. Cases in which the lower column grade of M:80, reducing stagewise to M:40 or 30 are observed. Such optimization is certainly desired in megastructures such as high rises. However, with it, come certain restrictions. The load flow through columns necessitates that the concrete grade in the junction of column and floor be the same as that of the column concrete. However, this imposes serious construction difficulties and loss of rhythm in the floor construction activity. Concreting the column first in a higher grade and then allowing the concrete to disperse in the floor concrete around, many times results into poor workmanship as well. Designer must take recourse of the well known and well established clause of transfer of column load through floor by maintaining a maximum grade difference between floor concrete and the column concrete. (ACI 318 - 14 : Clause 15.3 c).

Pre-empting such design decisions will help construction become faster as well as with desired quality.

2.8 Axial Shortening of columns

As every analysis and design engineer of a tall building must have noticed, the induced flexure and shear forces in columns, floor beams and floor diaphragms vary considerably along the height of the building due to unequal axial shortening between adjoining columns or between peripheral columns and shear walls. A designer many times, accounts for this variation and provides reinforcement in the RCC elements differentially at various floors. However, the problem of physical deformations may still exist, and also, there could be instances when the mitigation of this problem only by varying the reinforcement may not be feasible.

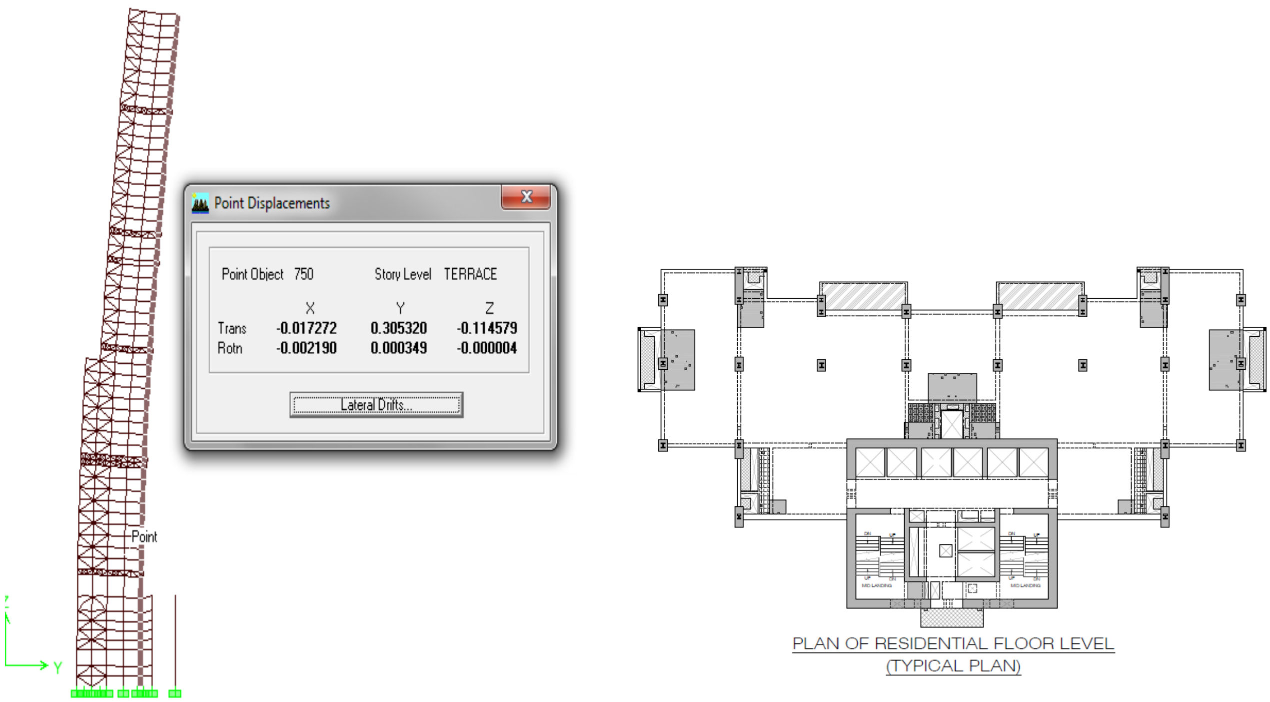


Fig 7 - Eccentricity of load and geometry

A common solution to address this aspect is to pre-camber the floors, by specifying that the columns which are found to be shortening in analysis significantly, be cast taller by a few millimetres. Such instructions must be clearly mentioned on the drawings at tender stage itself. The contractor must be made aware of the implications of differential axial shortening. A designer, by actually carrying out sequential analysis, find out the consequences of progressive loading on columns during construction stage, which comprises of at least 60% of the overall design gravity load.

There has been an instance of adjusting a difference in theoretical elastic shortenings of columns and the adjoining core wall of almost 80 mm in a 50 storey building, the column carrying about 33000 kN axial load, through a compensation of about 55 mm towards dead loads. This was done in 11 stages of 5 mm each.

In one of the unique structural schemes that the author has provided, the shear core has been post-tensioned on the permanent tension side to limit the axial shortening of columns on one side due to the gravity loads, which occurred due to load eccentricity.

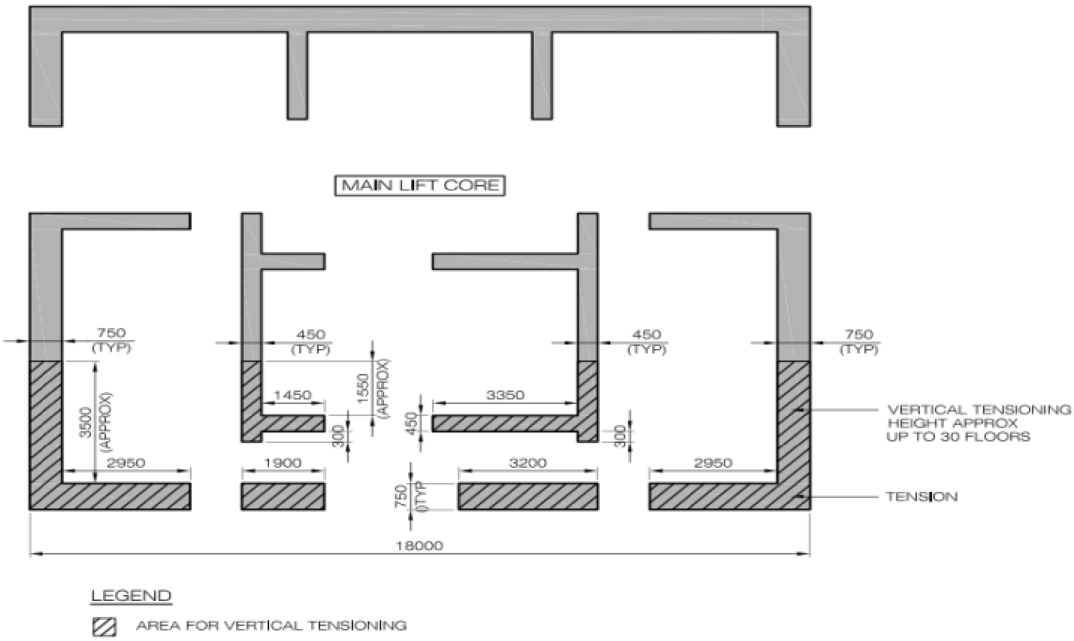


Fig 8 - Differential Post Tensioning of Core

Fig 9 - Site Photo of Vertical Post Tensioning

2.9 Differential Settlement of foundations - Different loads / different foundation system / Different strata

High rise buildings quite often have large footprints at foundation level. The tower block and the surrounding basement / podium structure have widely separated load ranges. Considering uncertainty of the foundation strata in spite of careful extensive soil investigation, there is high probability of differential foundation settlements between tower and podium foundations. While the designer can appropriate the foundation sizes to maintain approximately the same base pressure levels under the two sets of foundations, the actual behaviour of the soil cannot be accurately predicted. Sometimes, the superimposed dead loads on the tower and the podium structure are imposed at different times. The designer has to identify all the loading and uncertainty conditions, and analyse the connected blocks to assess the envelope condition of combination of settlements.

On the other hand, the contractor may have a fixed sequence of construction of podium and the tower block. He may choose to advance the tower block without concentrating of the podium structure. Or he may construct the tower block and the podium slabs together in the beginning. In both the conditions, the settlement graph against time is different. If the designer has not accounted for the sequence of construction as planned by the contractor, there could be induced flexural and shear forces in the raft, slabs and beam connecting the two structures of different geometrical characters.

One simple solution is to independently construct the tower block and the podium by leaving what can be termed as a "settlement strip" around the tower block. This strip can be filled up when major settlements of the two structures takes place under their dead loads, thus reducing the level of induced stresses, confining their source mainly to the live loads.

2.10 Coupling Beam

Coupled wall system is quite common in high rise buildings to resist lateral loads. Most important element in a high rise building with shear walls could be the detailing of coupling beams. Coupling beams are inevitable where openings one above the other are required for two or multiple levels. By coupling individual flexural walls, the lateral load resisting system is modified into partially converting the overturning moments into a compression-tension couple across the walls rather than by the individual flexural action of the walls. In order for the coupled wall system to perform as intended, the coupling beams must be designed and detailed so that they are strong and stiff, at the same time, must also yield before the wall piers. They must be ductile and should have significant energy absorbing characteristics. Sometimes, the anchorage and confinement requirements make the diagonal reinforcing extremely difficult to construct due to congestion at the centre and the face of the wall. There is always a concentrated reinforcement zone at the interface due to presence of boundary elements of the shear wall as well. Structural beam or plate embedment may provide a viable alternative to reinforced concrete coupling beams.

Fig 10 - Coupling Beam Reinforcement

Fig 11 - Steel Coupling Beam

In both cases, it is important for the designer to anticipate the construction difficulties in implementing what is a mandatory detail for resisting high sway shears and provide accurate dimensional details, keeping in mind the construction tolerances as well. On the other hand, a contractor must be aware of requirement of coupling beams in a tall building, and even if such elements are not adequately presented in the tender drawings, he must raise the questions and obtain clarifications before even providing the quotations. Particularly, the structural drawings must be read for at least three floors together and not separately for column details and floor beam details, since the coupling beam details may span across three floors at a time.

3. CONCLUSION

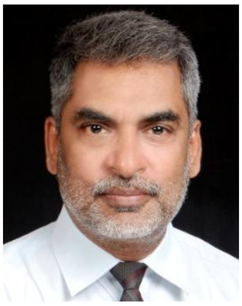
High rise buildings require special treatment, both in structural design as well as during construction. High rise building performance is predominantly assessed not only by its ability to carry huge vertical loads, but more significantly, its response to lateral loads - mainly the wind loads and the earthquake loads.

It is a discipline of building science, which has its own specific requirements of design, detailing and construction practices. Sufficient reserves of energy absorption are necessary to be built into the building, which is possible by implementing the intent of the structural designer into actual construction. The construction itself is carried out with the help of modern construction equipment that allows fast and accurate construction.

If the high rise building has to perform well, it is necessary to ensure that the demands of design and the repercussions of adopting a particular construction method do not bring about conflicts and contradictions between intention and implementation. Hence, it becomes important for the designer and the contractor to put together their proposals in the beginning of the project planning and allow a unified approach for the success of the project.

An important role has to be played in this respect by the owner, developer or the project manager in ensuring the synchronization of the designer's and constructor's ideas about realizing the high rise dream.

BIOGRAPHY



GIRISH DRAVID
B.Tech.(Civil) 1981, IIT Bombay
M.Tech.(Struct) 1983, IIT Bombay

Director :
Sterling Engineering Consultancy Services Pvt. Ltd., Mumbai, India.

India Representative :
Council on Tall Buildings and Urban Habitat