Concrete Tall Buildings

Guidance on the design and construction of building tall in concrete

Contents

About this publication

Urban density is causing a need for more homes, and building tall has therefore become a necessity. This publication seeks to provide information for structural engineers who are designing tall buildings in concrete. It will also provide information for clients, architects, constructors and cost consultants about the benefits of designing tall buildings in concrete.

Some of the information in this brochure is given in more detail in The Concrete Centre's technical guide *Tall Buildings*, produced and published in partnership with Fédération Internationale du Béton (*fib*).

The publication intends to help designers gain an insight into the factors involved in the design of tall buildings in concrete but is limited in its scope in that it deals only with the structural frame, and not with ancillary parts, including cladding.

Cover image: The Shard, London, is the tallest building in western Europe, at 87 storeys and 306m. See page 18 for a full case study of the project. © Alamy

At a total height of 829.8m, Burj Khalifa, Dubai, is currently the tallest building in the world. With a primary structure of high performance reinforced concrete, the concrete guarantees low permeability and higher durability, as well as acoustic and fire resistant benefits. © Alamy

Introduction

The drive to build tall buildings comes, most fundamentally, from a need to maximise returns from the increased efficiency of land use. By building additional storeys on any given footprint, the number of people accommodated either at work or in a residential setting can be greatly increased.

The pressure to maximise the efficiency of land use is driven by many factors, including:

- Location
- Land value
- Limiting urban expansion
- Accessibility to travel hubs
- Cost
- Sustainability
- Co-locating workers
- Accessibility to existing public services.

In addition to these economic and technical factors, there are social and aspirational factors that influence individuals' and/or organisations' drive for living or building tall, such as:

- Status
- Views from high level
- The feeling of modernity
- Catalyst for investment
- Technological advancement
- Creating an iconic symbol
- Urban townscape design.

Around the world there is a trend for the demolition of low-rise buildings to make way for taller buildings as the pressure to build taller is ever present.

Critical factors in tall buildings

To realise its full potential, a tall building must simultaneously satisfy many varying objectives, including:

- Efficient layout
- Minimal circulation space and structural footprint
- Density of use
- Efficient services provision
- Speed of construction
- Cost
- Appearance
- Safety.

The above list is greatly simplified and each item could be broken down into many constituent parts. Furthermore, the items and their constituent parts are interdependent in many varied and complex ways which need to be addressed with the wider project team and with consideration of occupants and the long-term sustainability and resilience of our built environment.

The Lexicon Tower, London is a 36 storey residential tower which is parallelogram-shaped with an angled top to allow for open terraces. It has a concrete core, concrete floorplates and a series of rectangular concrete columns that ring the perimeter of the floorplates. © Alamy

Concrete and tall buildings

The unique benefits inherent to concrete mean that it is firmly established as the leading tall building construction material.

Concrete offers:

- Flexibility in form
- Consistent availability around the world
- Ease of delivery
- Low cost
- Adaptability to local conditions
- Inherent fire resistance
- Excellent wind and seismic damping characteristics
- Inherent acoustic properties
- Excellent strength-to-weight ratio
- Local, long-life, low-risk solutions
- Responsibly sourced certified materials to BES 6001
- Material efficiency
- Thermal efficiency
- Whole-life benefits.

Flexibility in form

Concrete is unique as a building material as it can be delivered in a fluid form and thus can be moulded into any shape on site. It can also be delivered to site as precast elements, which equally can take any shape. When combined with steel reinforcement it becomes an extremely strong, durable and efficient material, the properties of which can be exploited by designers to produce extremely efficient structures.

This flexibility in form allows buildings to take any shape in both footprint and elevation. Irregular structural grid arrangements can be easily accommodated, as can cantilevering of the slab edge, openings through the structure, changes in structural cross-section and late changes in design.

Installation of precast panels at One Coleman Street, London. The project used recycled secondary aggregates in the main structural concrete.

Slipforming is a method of vertically extruding a reinforced concrete section and is suitable for construction of core walls in high-rise structures. Courtesy of Careys.

Ease of delivery

A key factor in constructing a tall building is the need to lift/hoist the building materials to a high level. The lifting of materials is key to the overall construction period, and the 'hook-time', the time the material is being lifted by the crane, is a key metric that influences both cost and programme. Not only can concrete be delivered to site in a fluid state, but it can also be pumped through dedicated pipework and delivered directly to the working face without the need for any cranage, and thus with zero hook-time. Precast elements can be delivered to site and placed in position from the lorry, so little or no storage area is required.

Significant developments have been made in the design of concrete mixes to allow concrete to be pumped to very high levels (up to 600m) while maintaining workability and strength. Concrete mixes have also been developed that allow rapid placement, reduce the need for vibration and provide rapid early strength gain. Such characteristics are essential for efficient construction of tall buildings as they offer reductions in the cycle time from floor to floor.

Damping

Unlike low-rise structures, the loadings on tall buildings are dominated by cyclic loads from wind and, where relevant, seismic events. The response of the structure to these loadings is critical to its structural design and is directly affected by the degree of natural damping within the structure. Concrete structures have significantly higher degrees of natural damping than steel structures and this is often a key consideration in selecting concrete as the primary structural material.

Fire resistance and durability

Concrete has inherent fire-resistance characteristics. The layer of concrete provided outside the reinforcement (the cover) provides fire resistance and also creates an environment that protects the reinforcement from corrosion. Fire-resistance periods of up to two hours and a design life in excess of 50 years can be easily achieved, both of which are typical requirements for tall buildings.

This 'in-built' resistance is a major advantage over steel structures where post-applied finishes are required to achieve both fire resistance and long-term durability.

The Grenfell Tower tragedy in June 2017 is under investigation (as this guide is published). The 24 storey tower was a reinforced concrete frame, and it appears that the retrofitted external cladding spread the fire to the whole of the building in a very short time, resulting in the loss of life. The concrete frame itself has survived the fire, having been subjected to a fire duration of many hours, rather the two hours required by Building Regulations.

It is widely expected that the Building Regulations for England are to be revisited following the tragedy and the requirements for fire resistance may be changed. Concrete and masonry are inherently fire resistant and provide fire protection. As a non-combustible structural material, concrete does not burn and can be used to meet and exceed more stringent requirements for the fire safety of people and property.

Acoustic performance

Concrete structures benefit from their inherent acoustic performance properties. Where concrete floors are used in tall buildings, the floor will normally provide the required level of acoustic separation between residential floors for airborne noise. Typically, only an absorption layer will be required to cater for impact noise. This can be particularly important in residential buildings where the use of a concrete frame can contribute to a significant saving in overall building height, or enable additional floors to be accommodated.

Strength-to-weight ratio

Concrete provides an excellent material for use within tall structures, due to its strength-to-weight ratio. For vertical elements, concrete strength can be varied throughout the building's height, using higher strengths at lower levels where the loads are greater. This in turn allows the vertical elements to be standardised in cross-section, which can assist with the reinforcement detailing and fixings and thus the speed of construction. Although concrete has a relatively high weight, concrete floors are typically found to offer the optimum solution when considering weight, overall depth and speed of construction. Post-tensioned concrete flat slabs are often specified for tall buildings as they can be constructed more quickly and with less concrete that normally reinforced slabs. This reduces the overall depth further and also reduces the weight on the columns and foundations. Refer to The Concrete Centre guide, *Post-tensioned Concrete Floors*, for further information.

Although the use of lightweight concrete is not yet widespread in concrete framed buildings, advances in its design, batching and delivery have led to its use in a number of recent tall structures. The savings in weight to the columns, walls and foundations can be significant.

Other benefits

Thermal efficiency

If designed appropriately, the benefits of concrete's thermal mass can add to the energy efficiency of the building in reducing both heating and cooling loads and therefore running costs. For more information, download *Thermal Mass Explained*, from www.concretecentre.com.

Material efficiency

Concrete can provide both structure and finish, thus eliminating additional finishes and reducing waste. For more information, download *Material Efficiency*, from www.concretecentre.com.

Responsible sourcing

The concrete industry adopted independent certification to the responsible sourcing standard, BES 6001, from its launch in 2008. The latest published data shows that 90% of all concrete produced in the UK is certified to BES 6001.

Whole-life benefits

When considered over the whole life of the building, concrete structures provide a carbon-efficient solution that can be further enhanced by reuse and ultimately provides materials that are fully recyclable at end-of-life. For more information, download *Whole-Life Carbon*, from www.concretecentre.com.

Post-tensioned concrete floor during construction. This solution can achieve long-spans and is the most efficient in delivering the maximum number of storeys to total building height.

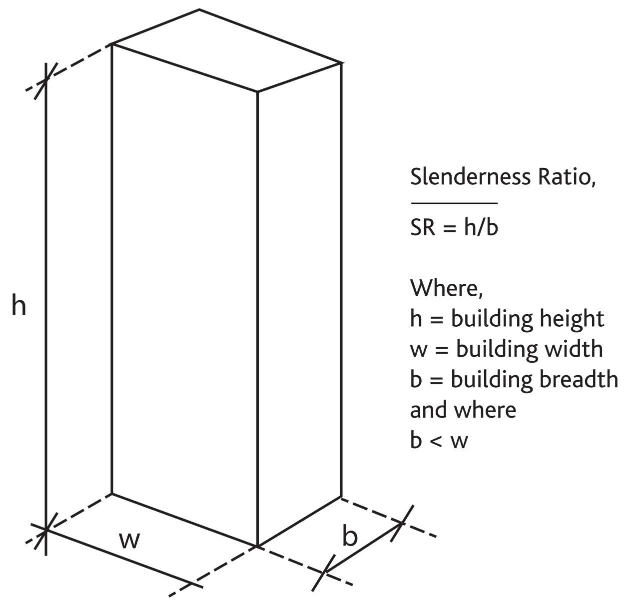
Design considerations for tall buildings

Tall buildings involve all of the design interfaces present in low-rise construction but there are also a number of key additional criteria that designers must consider.

In developing the design solution, the design team will need input from other specialists in areas such as:

- Facade design
- Wind
- Geotechnics
- Seismicity
- Fire
- Vertical transportation
- Construction methodologies.

For a design to be effective and economic, it is essential that all disciplines work holistically and gain a good understanding of the critical factors that have an impact on the associated disciplines.



Slenderness ratio diagram. The slenderness ratio can give a good indication of the influence the lateral loading will have on the design.

Stability and dynamics

The choice of structural system is fundamental to planning a tall building and must be considered at the outset. One of the main factors in the design of tall buildings, and the key difference from the design of low-rise buildings, is the influence of lateral loading.

The dynamic performance of tall buildings must be considered in detail. Loading from wind and seismic actions occurs across a broad spectrum of frequencies and the response of the building will be influenced by its natural frequency and the degree of inherent damping. Where the natural frequencies of the building are close to the frequencies of applied loadings, there is a risk that the response is amplified, resulting in increased loadings and movement. This mechanism requires detailed consideration by the structural engineer to investigate the performance of the structure across the full frequency spectrum of the applied loadings. If accelerations associated with any movement are excessive, building users could potentially experience motion sickness.

In regions of the world at risk of earthquakes, the response and performance of buildings during such events is also a critical design consideration.

The slenderness ratio

At the initial planning stage, it is advisable to consider the basic proportions of the structure. The slenderness ratio can give a good initial indication of how hard the structural system will need to work. The slenderness ratio is obtained by dividing total building height (h) by the smaller base width (b). At a slenderness ratio of 5 or less, the structural system can usually easily accommodate the lateral loads, whereas for 8 or above the structural system will be working harder and the dynamic behaviour is likely to be dominant in the structural solution.

Structural arrangement

At the outset of a tall building design the structural engineer must consider how the main structural components will be arranged. The vertical elements are generally arranged to give clear floor spans in the range of 8-10m, or perhaps longer for commercial use. A key consideration is the mechanism by which the lateral loads will be resisted and transferred to the ground. The structural options are discussed further in the section on stability systems on page 8. The structural core of the building, the zone that houses the lifts, normally provides most or all of the building's lateral strength and stiffness. The layout and design of the core is often the most crucial element in the overall design and the ultimate efficiency and success of the building. The layout of the core is influenced primarily by the number of lifts required, which is in turn influenced by the use of the building and the vertical transportation strategy. Residential uses typically have a much reduced need for lifts compared with more densely occupied buildings such as offices.

Lift strategy

Technology in lift design and specification has progressed significantly through the years and the vertical transportation strategy is critical to the design of the structural core of the building. Factors such as lift size and speed, lift call arrangements, lift lobby position and firefighting requirements will influence the number and arrangement of the lift shafts. As the structural core of the building is frequently arranged around the lift shafts, the structural engineer must understand these factors to allow the core to be optimised in arrangement and overall size.

Designing for movement

Movements in tall buildings require specific consideration. Movement occurs in both the vertical direction and the horizontal direction due to cumulative loading, time-dependent material properties (such as creep and shrinkage) and the construction sequence.

Tall buildings will move laterally by significant amounts, typically in excess of half a metre. This lateral displacement or 'drift' must be calculated and may need to be limited. Excessive lateral displacement could potentially affect finishes, internal partitions and external cladding, particularly if the inter-storey drift (lateral displacement over one storey) is too high.

Due to the differing stress levels between walls and columns, these elements will shorten by differing amounts. This differential movement imposes stresses on the structure which must be considered in the design. Building movements should be addressed in the design stage, based on the results of a staged construction analysis.

Construction

Speed of construction is often paramount to the viability of tall buildings. Designers should work closely with the contractors to ensure that the building can be constructed efficiently.

Effective collaborations should result in designs that have:

- A good degree of repetition between floors
- Regular and repeating column and wall cross-sections
- Slab systems that can be made offsite or cast and struck quickly and that can take the weight of subsequent floors
- Core arrangements that are suitable for slip- or jump-forming
- Facade systems that can be installed from the inside
- Mechanical engineering systems that are modularised and can be sub-assembled off site.

In considering the structural design of a tall building, the engineer must also consider how the basement and foundations of the building will be constructed. Options such as top-down construction should be evaluated and, where possible, the design should allow for a range of construction approaches.

From a contractor's point of view, the main drivers are:

- Safety of site operatives and the public
- Crane use
- Incoming logistics, laydown and storage areas
- Vertical movement of operatives and materials
- Standardisation of structural elements and components, which leads to repeatability of forming.

A 13-storey concrete frame under construction at Queen Elizabeth University Hospital, Glasgow. Courtesy of Dunne Group.

Stability systems

The structural options available fall into four main categories: moment frames, shear wall systems, tube systems and outrigger-braced systems.

Selection of the most appropriate structural system for tall buildings is influenced by factors including, but not limited to, geographical location, building height, plan dimensions and intended use, as well as preferred visual appearance and architectural requirements. Not all of these parameters are in the direct control of structural engineers.

Tall concrete-framed buildings will almost always rely on the lift and stair core for a large proportion of their lateral stability and overturning lateral load capacity. Structural engineers need to pay particular attention to the position, size and arrangement of the core. Centrally located cores are preferred but are not an absolute requirement. Positioning the core too far from the centre of a building plan may necessitate the use of other lateral stability systems to resist building twist.

Moment frames

This is a relatively simple structural system, in which beams and columns are rigidly connected to form moment-resisting frames in two orthogonal directions, resisting lateral and gravity loads.

Each frame resists a proportion of the lateral load, determined on the basis of its relative stiffness compared to the total stiffness of the frames. For increasing structural height, there is an associated direct increase in the size of the frame elements to satisfy lateral drift and deflection limits.

The most economical arrangement is the flat-slab rigid-frame structure, although the frame stiffness is limited by the stiffness of the column/slab connection. The most economical flat-slab span is in the range of 8-9m, but this will also depend on the building and floor heights and whether post-tensioned slabs are used. An advantage of the reinforced-concrete moment-resisting frame system, particularly in in-situ construction, is the continuity of the concrete and consistently determinable stiffness of the structural members and joints.

This structural system is applicable for buildings of up to approximately 75m in height; however, it is most economic for buildings below 50m.

Shear wall systems

This system consists of shear walls designed to resist lateral forces in two orthogonal directions. Figure 2 shows a typical arrangement, with shear walls arranged near the centre of the structure to house lifts, fire-escape stairs and other building servicing, thus providing a stiff structural spine to resist horizontal loads in two directions. This is often termed a 'core system', with the core designed to act as a single vertical cantilever with sufficient lateral, torsional and bending stiffness to resist the worst-case combinations of service and ultimate conditions. A variation on this system involves the dispersal of additional shear walls evenly throughout the plan area of the building. If this layout is adopted, it is beneficial to attain a level of symmetry in the wall dimensions and positions across the plan to mitigate building twist.

For this framing typology, the very large lateral stiffness of the walls, compared to the remaining vertical elements (columns), ensures lateral loads are resisted entirely by the main shear walls. The columns are then designed to resist gravity loads only, simplifying the design process and slab construction.

Often the architectural arrangement will result in separate banks or groups of shear walls being separated by some distance, such as in a lift lobby. In such cases, it is common to connect these walls with stiff slabs and link

Figure 1: Moment frame

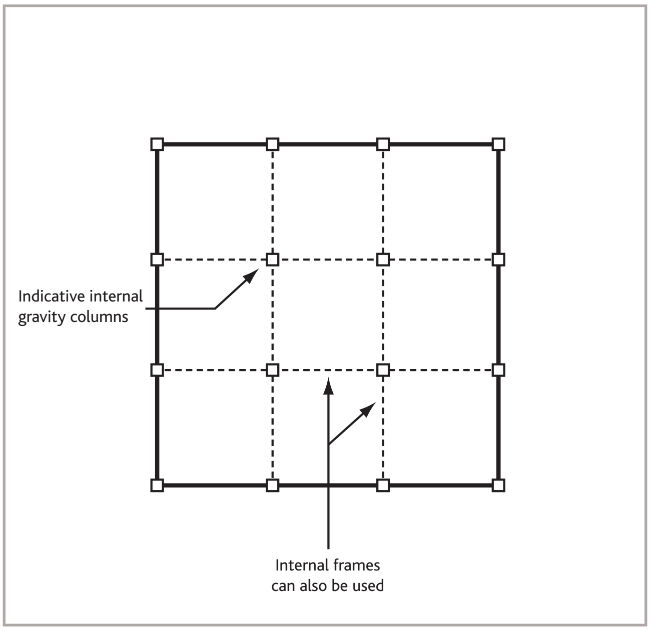
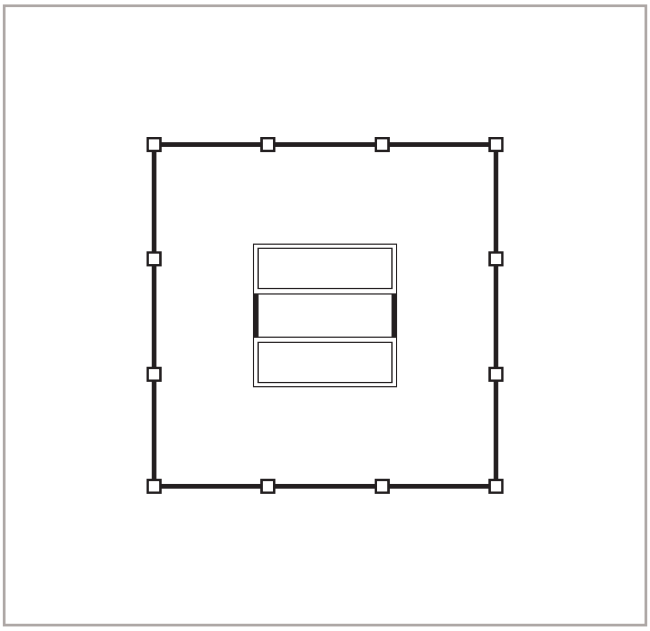


Figure 2: Shear wall system



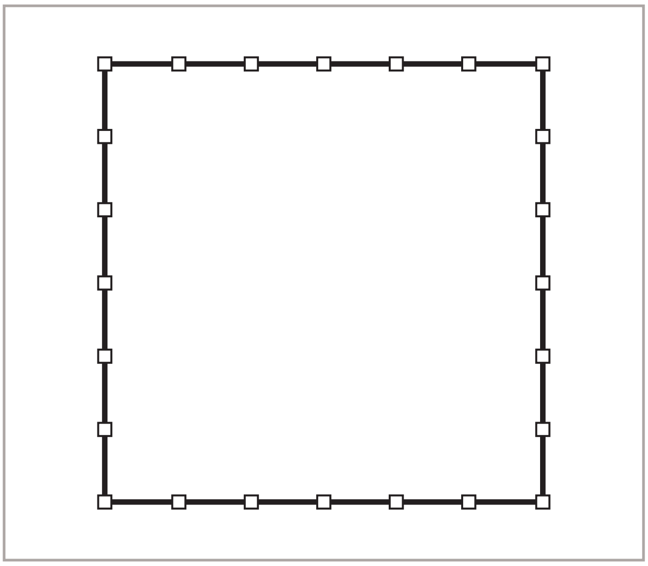


Figure 3: Tube system

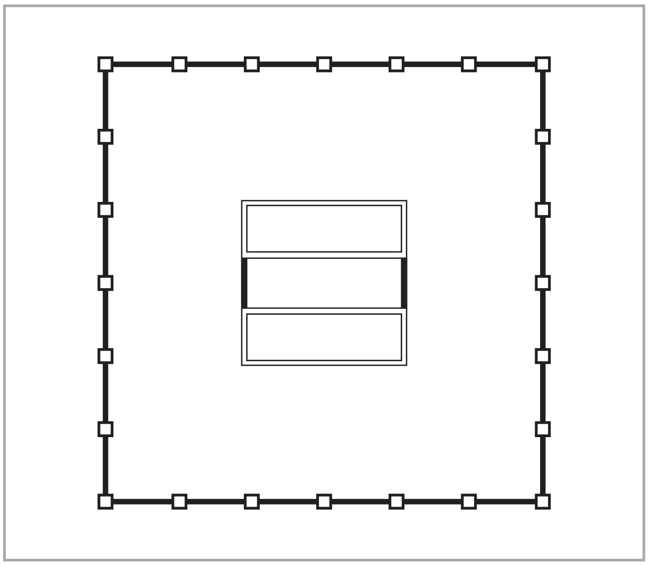


Figure 4: Tube in Tube

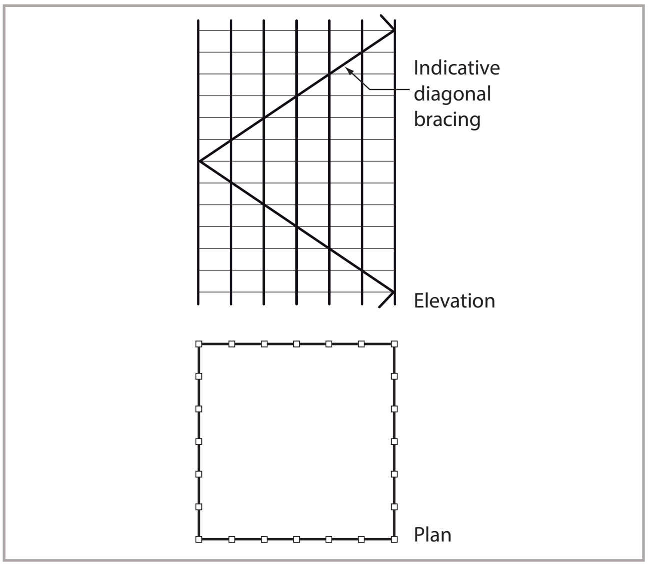


Figure 5: Braced Tube

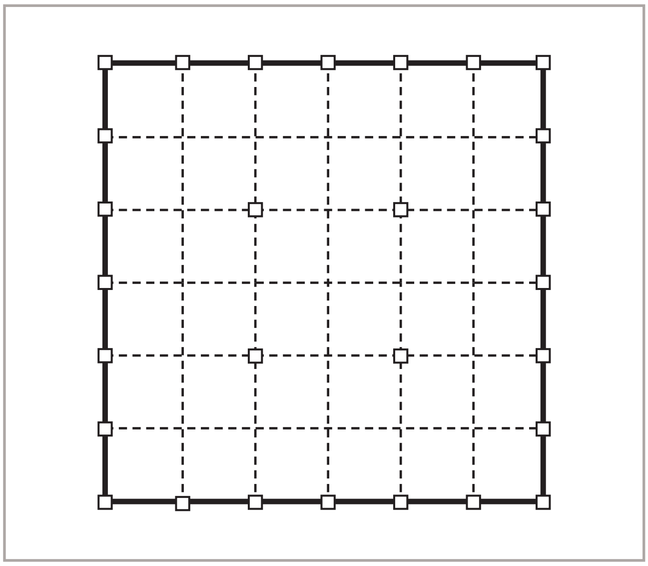


Figure 6: Bundled Tube

beams. Such linking structures greatly increase the efficiency of the shear wall system; however, they attract large forces and therefore their design and detailing must be considered in depth.

This system is generally sufficient for buildings up to 120m tall – although making shear walls larger and longer within the limits of the floor plan may achieve significantly greater heights.

Tube systems

This system allows the full width of the building footprint to be used to resist the lateral loads on the building. This produces a very stiff structure but requires a certain arrangement for the structural elements. Typically, columns will be placed at relatively close centres of 2-4m, connected by beams to create rigid frames around the perimeter. The resulting form is a closed tube acting as a hollow vertical cantilever, with internal columns positioned as necessary to support the gravity loads from the floor framing.

The framed tube system is suitable for buildings up to approximately 150-170m in height.

Variants of the tube system include: tube in tube; bundled tubes; and braced tubes, where diagonal braces are provided in the outer faces. These variants typically offer increased flexural stiffness and allow the spacing of the perimeter columns to be increased. By adopting such structural systems buildings up to approximately 300m in height can be realised.

Outrigger-braced systems

To achieve the greatest flexural stiffness, it is beneficial to use the full width of the building footprint and mobilise the perimeter columns as a fundamental part of the structural system. This can also be done through the introduction of horizontal outrigger elements (often trusses) of one or two floors deep, connecting the core with the outer columns at regular height intervals up the building. At the same level as the outriggers there will be exterior solid walls or trusses – often termed 'belt trusses' – up to two storeys deep, that connect the perimeter columns to the outriggers and also serve to distribute vertical loads.

This system is used for the design of structures up to 350m tall, or super-tall. The braced system concept of using outriggers can, however, be applied to much shorter buildings.

For most tall buildings, system combinations may be applicable and engineers should allow reasonable time to determine the most appropriate structural system for each case.

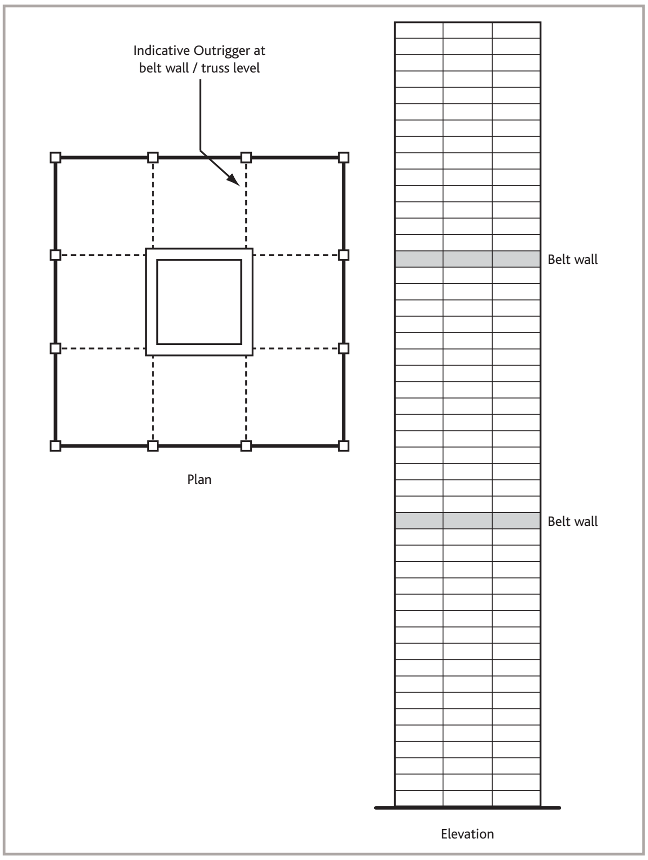
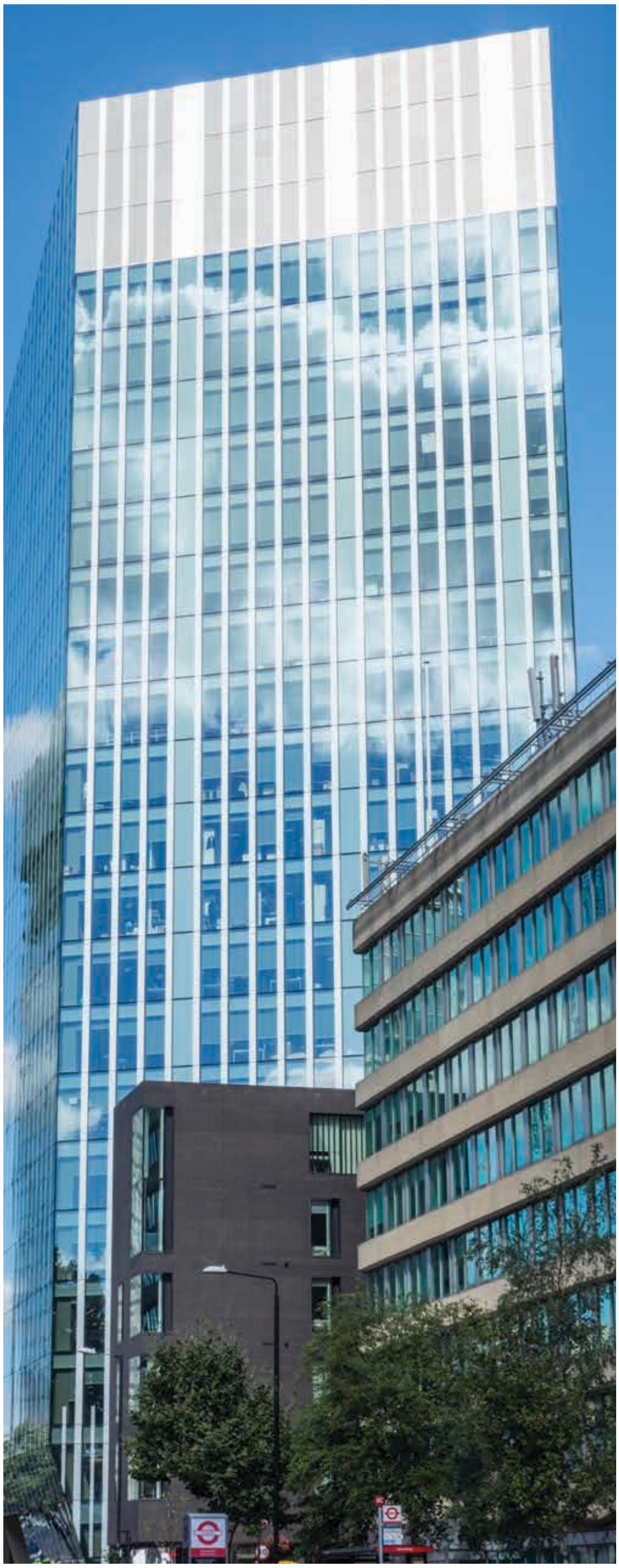


Figure 7: Outrigger Braced System



At 240 Blackfriars, London, the parallelogram-shaped floor plates are supported on an in-situ concrete structural frame. This comprises a concrete core, positioned at the eastern edge of the floor plates, and a series of columns rising up through the building and around the rest of the perimeter. © Alamy

Concrete flooring systems

The floor elements of building structures carry the gravity loads from the floor's self-weight and applied loads to the supporting walls and columns. Table 1 (overleaf) shows some of the options for the concrete floor slab in a tall building.

Depending on the structural framing system adopted, the floor structure may also contribute to the lateral load carrying system, either via diaphragm action or in more complex ways. For certain stability systems, the floors may contribute directly and form the horizontal elements of moment-resisting stability frames. In some cases, integral beams are added to the floor construction to provide increased stiffness and load capacity. When the floor does contribute in some way to the lateral load carrying system, load reversal may be possible and strength assessments should be used to ensure all load cases are addressed.

The primary considerations in selecting the flooring system for a tall building are:

Floor depth

As the floors within tall concrete buildings repeat many times, even a small saving on floor depth can become significant. In some cases, making savings on the floor depth could allow an extra floor to be accommodated within a given overall height. Concrete floors always offer the minimum overall structural depth, with post-tensioned flat slabs (see box-out) offering the minimum depths available for any given span.

Overall weight

There are a range of concrete solutions that can help to reduce weight, although weight shouldn't be considered in isolation. Any weight saving from the choice of floor solution are multiplied across repeating storeys, thus any saving can have a significant effect on the sizing of vertical elements and the foundations. Weight and material savings can also speed up the construction through reduced cranage requirements. Although in-situ concrete floors may not always be the lightest form of construction, they have the benefit of being formed using a pumped concrete supply, which does not require cranage. Precast floor systems can also be used which do require cranage. These tend to have a reduced weight due to hollow cores or formed voids and can be prestressed to further reduce weight. Lightweight concrete has been used successfully on some tall buildings and can be used on all types of floor construction. Lightweight concrete can significantly reduce the loads to the columns/walls and the foundations, although its use is still not that common.

Speed of construction

Speed of construction plays a vital role in the viability of a tall building. The floor construction can be the key factor influencing the contractor's ability to construct the building quickly. In comparing flooring systems, one of the key criteria should be the cycle time from floor to floor. For most tall buildings, the contractor will aim to achieve a cycle time of somewhere between four and seven days. This can be achieved with many of the structural floor options available. For example, post-tensioned concrete flat slabs offer a very quick floor cycle as they can be stressed and are thus self-supporting at an early stage.

Post-tensioned floors

Post-tensioning of the flooring elements is a popular choice for tall buildings due to the reductions it brings to overall thickness and weight, while speeding up construction.

Where post-tensioning is proposed, it is important to consider the following points:

- Restraint to the prestress shortening due to stiff core walls and columns
- Access to undertake the stressing of the post-tensioned strands
- The method of providing the tie into the core walls when they are progressed ahead of the floor slabs
- Post-tensioning will generally only be designed to resist gravity loadings, and traditional reinforcement may be required to cater for any load reversals caused by lateral loading. This can be particularly relevant in seismic zones.

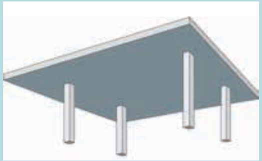
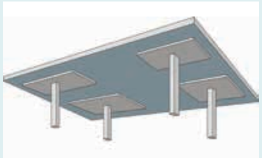
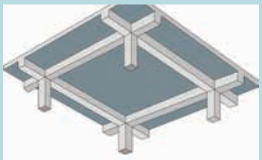
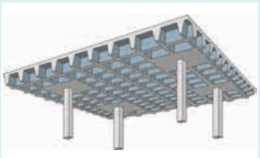
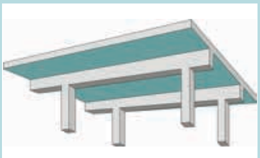
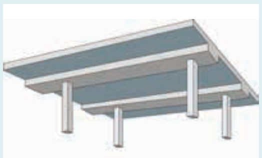
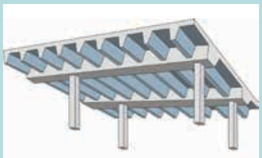
For more information, download *Post-tensioned Concrete Floors*, from www.concretecentre.com/publications

In selecting the floor type, the normal serviceability criteria will need to be considered, including cracking, deflection, fire resistance, acoustic performance and vibration response. Careful consideration must be given to construction tolerances and floor deflections, particularly at the slab perimeter, where cladding systems are attached.

The use of precast concrete floor systems can offer some advantages in terms of speed of construction and can also offer large-span floors, which are attractive for office and retail uses. Precast solutions also have benefits relating to concrete supply at high level, back propping and initial strength gain. Where precast floors are used, it is essential that the engineer fully considers the robustness of the structure and provides the requisite ties between the individual precast elements to ensure that the structure as a whole can perform adequately in the event of accidental loading. It is also essential that the cranage and lifting strategy to be used for the construction is fully considered, ideally in conjunction with the constructor.

All the flooring options shown in Table 1 can be normally reinforced concrete or post-tensioned concrete. The flat slab option and the slab on beam option also can be precast or hybrid concrete solutions, partially in precast and partially in in-situ concrete. For further information on floor slab options, see The Concrete Centre publication, *Concrete Framed Buildings*.

Table 1: Typical flooring solutions

Slab Type	Floor Depth	Overall Weight	Speed of Construction	Overall Rating	Comments
 Flat Slab	✓✓✓	✓✓	✓✓✓	✓✓✓	Easy to form and quick to construct. Offers a thin floor plate, which is good for coordination with building services.
 Flat Slab with drops	✓✓	✓✓✓	✓✓	✓✓	Structurally efficient but slower to form and construct. Overall depth can be efficient if building services and dropped panels can be coordinated.
 Solid two-way slab with beams	✓✓	✓✓✓	✓✓	✓✓	Structurally efficient but slower to form and construct. Beams can be useful where flooring system is used to contribute to lateral stability system.
 Waffle slab	✓	✓✓✓	✓	✓	Structurally efficient in terms of material weight but considerably slower to form and construct. Also produces a large overall depth and hence is rarely economic for tall buildings.
 Solid one slab with beams	✓✓	✓✓	✓✓	✓✓	Structurally efficient but can be slower to form and construct. Beams can be useful where flooring system is utilised to contribute to lateral stability system in the direction of the beams. Overall depth can be efficient if building services and beams can be coordinated. This arrangement is suitable for use with precast components.
 Solid flat slab with band beams	✓✓	✓✓	✓✓	✓✓	Structurally efficient but can be slower to form and construct. Beams can be useful where flooring system is used to contribute to lateral stability system in the direction of the beams.
 Ribbed slab with beams	✓	✓✓✓	✓	✓	Structurally efficient in terms of material weight but slow to form and construct. Also produces a large overall depth and hence is rarely economic for tall buildings.

Vertical elements

The location and size of the vertical elements, i.e. columns and walls, becomes more important to the design of the building the taller it is. Reinforced concrete is very strong in compression and that strength can be varied, over the building's height, to produce a very economical structure.

Columns

Columns are generally spaced at regular intervals along the perimeter of the structure but, for larger floor plates, interior columns are frequently needed to reduce the span of the floors. The column spacing along the perimeter of the slab can be influenced by the stability system chosen but is more frequently set to limit the slab-edge deflections to suit the tolerances of the selected facade system.

The design of the core benefits from supporting a larger share of the vertical loading, as this assists with resisting overturning from lateral loads. Spacing of columns from the core should, therefore, ideally be maximised. The central core may typically support about 60 per cent of the vertical loading, with the columns supporting the remaining 40 per cent.

Columns may be arranged to form part of the stability system, as discussed in the section on stability systems, and this will make further demands on the performance of the columns.

Important considerations include:

- Reducing the columns' geometric footprint
- Ease of detailing and connection to floors
- Speed of construction
- Robustness of the element and its resistance to fire.

Concrete is well suited to economically resist high levels of compression stress and in-situ concrete can be pumped over long distances, both vertically and horizontally. High-strength concretes can be used if the type of construction allows it; the gain in usable floor area, resulting from the reduced column cross-section, can compensate for any additional cost.

Due to the size of the columns in tall buildings, it is not normally possible to conceal them within walls, as is common practice in low-rise construction. Adjustment of column layout should be kept to a minimum, as each change in plan position requires some form of transfer structure, which can be expensive, slow the construction rate and occupy more depth than a typical floor plate.

Precasting of columns is possible for tall buildings but requires careful consideration of the cranage implications and the detailing to ensure load transfer and robustness at connections to the surrounding structure.

Walls

When structural walls are provided within tall buildings, they frequently have two primary functions. The inherent in-plane stiffness of the walls will normally contribute to the lateral load carrying system in the building. They also support vertical loadings and, wherever possible, the vertical loading in a wall should be maximised to counter lateral loadings by helping to resist associated overturning. The core walls of tall buildings may resist most, if not all, of the lateral loadings and typically may support around 60 per cent of the total vertical loading on the building.

Walls are mainly subjected to in-plane shear forces and axial compression. When selecting the wall arrangement, engineers should consider the following factors:

- Reducing the walls' geometric footprint
- Ease of detailing and connection to the floor structure
- Speed of construction, particularly the ease with which walls can be slip-or jump-formed.

Concrete is well suited for use in the walls of tall buildings, as it can most easily accommodate in-plane shear forces and associated compression. As wall sizes are most often established from requirements for stiffness rather than strength, high-strength concrete is not commonly used in the construction of walls, except for the tallest of structures. Wall thicknesses ranging from 350-800mm are not uncommon in tall buildings.

Ideally, walls should be placed symmetrically around the global centroid of the building in each principal horizontal axis, to reduce the torsional response of the building to lateral loadings. Positioning walls to intersect at right angles can greatly increase their overall stiffness and stability, allowing them to work compositely to resist lateral loading.

It should be remembered that the analysis of the full building will only look at the completed structure as a whole and may therefore miss loading conditions during the construction process. Temporary conditions may produce more onerous load cases, particularly if core walls are advanced ahead of the remainder of the structure with techniques such as slip- or jump-forming.

Axial shortening effects

For tall buildings, the effects of differential axial shortening must be considered in structural design. Differential axial shortening arises due to the different levels of axial stress in the columns of the building compared to the walls/core.

Core walls are generally quite large, with their size influenced by both axial stress requirements and stiffness requirements to resist lateral loads. Columns, by contrast, are usually kept as small as possible and are generally more heavily stressed. As construction progresses, columns and core walls undergo elastic and creep shortening at differing rates. The effect on the floor slab is like having a spring support at the column locations thus altering the distribution of moments and shear forces around the floor plate, and requiring reinforcement rates to be adjusted accordingly in floor design. The differential relative settlement of supports can also affect the levelness of floors, if not carefully considered and compensated for in design and construction.

The Concrete Centre has produced a design spreadsheet to assist with axial shortening. For more details on this software package see www.concretecentre.com/rcdesign

Foundations

Tall buildings exert huge forces on the supporting ground and it is essential therefore that the prevailing ground conditions are thoroughly investigated.

The influence of a tall building can extend to great depths and affect the ground outside the immediate footprint. Investigations should therefore extend to a depth and plan that will capture the full impact. Investigation of the foundations to any adjacent buildings and the impact on adjacent infrastructure, both above and below ground, must be undertaken. The site investigation should be designed by a geotechnical specialist.

Basements

The majority of tall buildings have deep basements which frequently extend well beyond the footprint of the main building. Basements need to be designed to suit the prevailing ground conditions, which may include ground-water pressure and uplift pressures. The construction programme can drive the design solutions adopted for the basement construction as there is often a wish to commence the construction of the tower as early as possible. This tends to lead to the adoption of 'top-down' construction techniques.

In designing the basement structure, consideration must be given to the large differences in vertical load between the tower columns and the outer basement columns. This can lead to differential settlements and induce loadings within the basement slabs. Additionally, the large lateral and overturning forces to be transferred from the tower structure must be considered. Tall buildings are comparable to a cantilever embedded at its base; any lack of stiffness at the base can be detrimental to the performance of the structure overall.

For more information on basements, refer to The Concrete Centre guide, *Concrete Basements*.

Foundation options

Depending on the nature of the foundation soil, tall buildings may either rest directly on the ground via a raft foundation or be embedded on deep pile-type foundations. The interaction between the structure and the supporting ground must be considered by engineers when designing the structure of tall buildings and should be included in detailed construction studies.

The soil-structure interaction influences the distribution of vertical loads on the ground and stresses in the structures, design of foundations, soil settlement study and the dynamic behaviour of the building under the effects of horizontal (wind and seismic) forces.

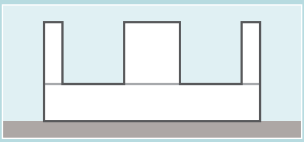
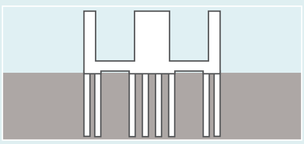
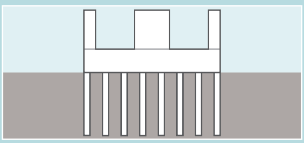
As buildings have become taller, raft foundations have become complex feats of engineering in their own right. Rafts can be several metres thick to accommodate the punching-shear effect of heavily loaded columns, while ensuring adequate load spread onto the underlying strata. The construction of the raft foundation should consider the reliability of the concrete supply and will normally involve monitoring and limiting the temperature differentials within the concrete.

While many foundations are either simple rafts or end up as large pile groups, the benefits of both forms can be realised in a pile-assisted raft. This can be envisaged as a raft with piles strategically placed beneath highly loaded columns. The approach affords considerable efficiencies over the adoption of a fully piled system, while the use of a raft avoids excessive settlement.

Such foundation solutions are complex and impact on the overall design solution for the tall building. Specialist geotechnical input should be sought to arrive at an appropriate solution.

More information on this topic can be found in the full *Tall Buildings* technical guide, available at www.concretecentre.com/publications.

Table 2: Concrete foundation options

	Foundation Type	Use	Comments
	Raft	Stiff grounds Shorter to medium-height buildings, depending on the ground conditions	Displacements can be higher than piled solutions
	Piles with pile caps	Shorter to medium-height buildings Wide range of soil types	Differential settlements between pile caps should be considered
	Piled raft	Taller buildings Wide range of soil types	Soil structure interaction is complicated

Loading

As with all structures, the vertical elements need to accommodate the worst-case combination of gravity and lateral loads. Although the gravity loads will be large – particularly in very tall buildings – wind and seismic loads, acting on what is essentially a large vertical cantilever, dominate the assessment of structural sizes for the preferred lateral framing system and will necessarily inform the architectural layout and spatial arrangement.

Gravity loads

The gravity loads applied to tall buildings are essentially the same as those for low-rise structures. However, given that such loads are summed over a number of floors, a benefit can be obtained by a statistical approach based on the likelihood of loads being applied simultaneously to all floors. Care must be taken to avoid overestimating the dead and live loadings on the stability structures where such loads provide a restoring moment to resist the overturning from the lateral loads.

Lateral loads

The dominant loads on tall buildings are lateral (horizontal) wind and seismic loads; the magnitude and predominance of which are determined in accordance with the appropriate loading code. Accurate determination of these forces and their effects is critical to the development of framing systems and evaluation of the size of the main structural members.

Wind loads

The primary wind loads for tall buildings can often be determined from the appropriate code of practice. However, for a more detailed building analysis, particularly if a building is very slender or has complex geometries, wind tunnel testing should be considered. Tall buildings are likely to be wind-sensitive where:

- The slenderness ratio (h/b) > 5, or
- The first cantilevering bending mode of the structure is at a frequency lower than 46/h[m], or
- The first modes of vibration of the structure appear to be very three-dimensional, or
- The building is in relatively close proximity to other tall structures of comparable massing and scale.

Three main options are available for wind tunnel testing:

- High-frequency force balance (HFFB)
- Simultaneous pressure integration (SPI)
- Aeroelastic.

Advice should be sought from a wind specialist to establish the most appropriate method of testing for any particular building. It should be noted that different types of test are usually used at different design stages throughout the development of the architectural and structural solution. Such advice can impact on the orientation and plan shape of the building as well as providing design data for the structural and facade design.

Seismic loads

The consideration of seismic loads is not normally necessary for structures in the UK. However, when designing buildings in seismically active regions, engineers should seek specialist advice to determine the associated loadings. Seismic loads act in a horizontal and vertical direction, although horizontal loads are typically more significant for tall buildings. Seismic loads can usually be idealised as equivalent static lateral shear forces or, for taller or more slender structures or where the ground conditions dictate, as a load or response spectrum.

Seismic loading is likely to affect the way the tall building is detailed, with the objective being to increase the ductility of the structure and prevent brittle failure. The detailing of shear links in walls and columns is often adjusted and additional reinforcement provided in slabs and beams in areas of load reversal.

Construction loads

Consideration of construction loads in the early stage of the design process is of great importance. In some cases, construction loads are greater than loads applied to the building over its entire life, particularly at the podium and basement levels but also on the upper suspended tower floors where laydown and material-storage areas are provided.

Where the chosen construction sequence requires the core to be advanced well beyond the floor slabs, the designer will be required to consider the associated temporary load case. This is particularly relevant where the core is tied in the permanent condition with link beams, but not tied in the temporary condition. Depending on the arrangement, the movements and forces generated may require alterations to the design of some elements, or detailed consideration of the proposed erection sequence to mitigate adverse effects.

Highpoint, London, is a 45-storey residential building which used a lean, material-efficient, robust design that was repetitive and fast to construct. © Alamy

Dynamics

Tall buildings are, in effect, vertical cantilever beams, and will naturally respond to lateral forces by moving in the direction the force is applied. Since wind (and seismic) forces are not static, the structure will tend to sway back and forth.

Serviceability limit-state (SLS) design checks, such as movements and the dynamic response to lateral loads, are a key aspect in the total design of tall buildings, and careful studies should be considered as routine during the early stages of any project. With the continual advancement of design and construction practice, tending towards more flexible structures as materials are used more efficiently, it is not uncommon for serviceability limit states to govern the structural design of tall reinforced-concrete buildings. Wind (and seismic) loads are the primary lateral loads that must be resisted by tall buildings. Wind forces, being more frequent, may govern the design of tall buildings at both serviceability and ultimate limit states. Engineers must understand how tall buildings respond during loading events to avoid adverse behaviour.

Tall buildings formed of in-situ reinforced concrete have a relatively high degree of natural damping – the measure of a structure's ability to dissipate energy. Natural damping can have a significant effect on the performance and response of buildings, and should be considered at an early stage in the design.

In concrete structures the damping is produced, in part, as the concrete cracks and thus absorbs energy. Damping is, therefore, dependent on the amplitude of the movement. Engineers will typically use different damping values for the serviceability design, such as estimates of accelerations, as opposed to ultimate limit state design where more cracking in the structure can be expected and tolerated.

There remains much debate in the engineering community, even among experienced engineers, regarding what damping values are appropriate for any given structure. The selection of the damping value used in the design can be critical, as the impact on the design lateral forces can be significant. It is often prudent, therefore, to undertake a sensitivity analysis on the damping values used.

Damping is also influenced by the structural framing system, building configuration, foundation system and ground conditions; evidence also suggests that damping reduces with increased building height. Therefore, particular care and experience is required in selecting the damping value used in the design.

Engineers undertaking designs of dynamically sensitive tall or super-tall buildings (higher than 350m) should make every effort to update their knowledge of the most recent research and debate surrounding this very complex topic.

Auxiliary damping

Auxiliary damping devices may be used to significantly increase the level of overall damping in a structure and reduce the peak lateral accelerations. Although auxiliary damping can offer savings in the stability system and the structure generally, such systems can be expensive to install and maintain and are normally only adopted on taller or more slender buildings.

New Street Square, London provides outdoor courtyard spaces for its occupants.

Occupant comfort criteria

Tall buildings present a unique serviceability limit state related to the occupants' perception of the building's lateral motion. Reinforced-concrete structures inherently have relatively high stiffness, mass and material damping characteristics, all of which are beneficial in limiting the magnitude of building motion under the action of wind.

The perception and sensitivity of humans to building movement and vibrations vary significantly and are dependent upon a large range of complex and unique physiological and psychological characteristics. Over the past few decades, various organisations (including the Council for Tall Buildings and Urban Habitat) have developed limiting criteria for building motion. Lateral acceleration and torsional velocity limits, used in the dynamic study of buildings, should limit the risk of occupants perceiving the building motion as uncomfortable.

For more information on this topic, refer to The Concrete Centre publication, *Tall Buildings*.

If early predictions indicate that lateral building accelerations are beyond acceptable limits, there are a number of options for reducing the accelerations. These include:

- Increasing the overall lateral stiffness e.g. longer, thicker core walls
- Increasing the mass of the structure
- Changing the cross-sectional shape of the building
- Changing the exterior surface of the building
- Providing auxiliary damping systems, such as tuned mass dampers.

Core construction

Slipform and jumpform techniques are fast and efficient systems for constructing cores and shafts in high-rise structures.

Jumpform

Generally, jumpform systems comprise the formwork and working platforms for cleaning/fixing of the formwork, steel fixing and concreting. The formwork supports itself on the concrete cast earlier so does not rely on support or access from other parts of the building or permanent works.

Jumpform, here taken to include systems often described as climbing form, is suitable for construction of multi-storey vertical concrete elements in high-rise structures.

Construction is in a staged process. Jumpform is a highly-productive system designed to increase speed and efficiency while minimising labour and crane time. Systems are normally modular and can be joined to form long lengths to suit varying construction geometries. Three types of jump forms are in general use:

- Normal jump/climbing form: units are individually lifted off the structure and relocated at the next construction level using a crane. Crane availability is crucial.
- Guided-climbing jumpform: also uses a crane but offers greater safety and control during lifting as units remain anchored/guided by the structure.
- Self-climbing jumpform: does not require a crane as it climbs on rails up the building by means of hydraulic jacks.

Slipform

Slipform is similar in nature and application to jumpform, but the formwork is raised vertically in a continuous process. It is a method of vertically extruding a reinforced concrete section and is suitable for construction of core walls in high-rise structures – lift shafts, stair shafts, towers, etc. It is a self-contained formwork system and can require little crane-time during construction.

It is a formwork system which can be used to form any regular shape or core. The formwork rises continuously, at a rate of about 300mm per hour, supporting itself on the core and not relying on support or access from other parts of the building or permanent works. It can affect the reinforcement in the walls as the formwork is supported on the reinforcement.

Commonly, the formwork has three platforms. The upper platform acts as a storage and distribution area while the middle platform, which is the main working platform, is at the top of the poured concrete level. The lower platform provides access for concrete finishing.

Cranage

Tower cranes will be jumped and tied into the structure as it progresses. A specialist tower crane supplier with experience in tall buildings should be consulted at an early stage to ensure that temporary tie loads, which can be significant, are fully coordinated with the permanent works. Coordination will need to extend to the facade design to ensure the ties allow the cladding to commence and the building to become watertight at the earliest available opportunity.

Hoists

Hoists can provide a useful alternative to tower cranes for the movement of materials and are essential for the movement of site personnel for most tall buildings. Hoists can be internal to the core or external to the building. Internal hoists are not weather-dependent and users are less likely to be nervous compared to travelling in an external hoist. The location of hoists needs to be carefully considered to avoid overloading slabs and to avoid clashes with formwork systems and the external cladding.

Tolerances

Local codes of practice and standards may not always provide relevant guidance on tolerances (the acceptable variation in the position of which elements of the structure are cast) for high-rise construction. For general guidance purposes, core tolerances of ±25mm in overall position and ±15mm in verticality per storey and pre-strike slab level tolerances of ±10mm are likely to be achievable. The achievable tolerances should be discussed with local contractors prior to finalising the project movement and tolerances report.

Construction tolerances should be carefully considered in relation to the predicted building movement caused by shrinkage and creep. Realistic expectations should be set, particularly when coordinating with secondary installations such as cladding, sliding doors and flooring systems.

Owen Street, Manchester. Slipform was utilised tp construct the core of this 64-storey residential tower. © Alamy

Case study: Shard, London

Project summary

- **Structural System:** RC core with hat truss
- **Type/ occupancy:** Office/Residential/Hotel
- **Storeys/height:** 87 storeys – 306m
- **Floor area:** 120,700m^2
- **Completion date:** 2013

This iconic, mixed-use development is located on the south bank of the Thames near to London Bridge. It provides 55,000m^2 of office space on 25 floors, three floors of restaurants, a 17-storey hotel, 13 floors of apartments and a triple-height viewing gallery, as well as an open-air viewing floor on level 72.

The stability system is a reinforced concrete core with a high level 'hat truss' to engage the external columns so as to control acceleration. The columns are a mixture of concrete and steel with high-strength C65/80 concrete used at the bottom. The walls are 250mm – 800mm thick and also use high-strength C65/80 concrete at the bottom.

IT PROVIDES 55,000 M^2 OF OFFICE SPACE ON 25 FLOORS, THREE FLOORS OF RESTAURANTS, A 17-STOREY HOTEL, 13 FLOORS OF APARTMENTS AND A TRIPLE-HEIGHT VIEWING GALLERY, AS WELL AS AN OPEN-AIR VIEWING FLOOR ON LEVEL 72

There are three basement levels and the foundations consist of a secant piled perimeter wall and piled raft. Top down construction was used to construct the core and the foundations.

The floors are composite floor on steel beams up to level 40 and then 200 -250mm thick post-tensioned slabs from levels 41 to 69. The top spire levels are formed by a steel frame. The concrete for the horizontal elements is C32/40.

At the time of publishing it is the tallest building in Western Europe.

PROJECT TEAM

Client: Sellar Property Group in partnership with the State of Qatar

Architect: Renzo Piano Building Workshop with Adamsons Associates

Structural Engineer: WSP

M&E: Arup

Main Contractor: Mace

Concrete Frame Contractor: Byrne Bros.

Case study: One Blackfriars, London

Project summary

- **Structural System:** Raft slab/ PT/inclined in situ columns including the central core
- **Type/ occupancy:** Public buildings/Residential/Hotel
- **Storeys/height:** 50 storeys - 170m
- **Floor area:** 74,925m^2
- **Completion date:** 2018

One Blackfriars – one of a string of towers planned for Blackfriars Road, south of the Thames – used a self-compacting concrete mix specified at C80/95, designed with specialist high-performance admixtures.

At 3,200m^3, the building required the largest concrete pour ever completed in one sitting by contractor Laing O'Rourke, as the team took delivery of approximately 400 trucks of concrete to the site from concrete plants in Kings Cross and Silvertown.

The stability system used has staggered outrigger elements strategically placed to control the tower's movement, with minimum impact on apartment layouts. This was particularly complex, as was determining a suitable arrangement of raking and walking columns which best fits the building geometry.

The design team used RAM Concept to model and design 225mm thick post-tensioned concrete floors. Post-tensioned concrete was considered the most cost-effective solution based on minimum structural zone and reduced self-weight of floors, which allowed for maximum slab spans.

POST-TENSIONED CONCRETE WAS CONSIDERED THE MOST COST-EFFECTIVE SOLUTION BASED ON MINIMUM STRUCTURAL ZONE AND REDUCED SELF-WEIGHT OF FLOORS

The design for this soaring asymmetrical tower features a dynamic double envelope façade with two distinct layers. This double-skin helps fresh air to circulate the building, reducing the need for further cooling systems and giving the building an unusual curved form, adding an impressive new silhouette to the London skyline.

The tower will be mixed-use, incorporating public, residential and hotel space. The 170m-high residential tower is due for completion in 2018.

PROJECT TEAM

Client: St George South London Ltd

Architect: Simpson Haugh

Structural Engineer: WSP

M&E: Hoare Lea

PT Contractor: Byrne Bros.

The Concrete Centre provides material, design and construction guidance. Our aim is to enable all those involved in the design, use and performance of concrete to realise the potential of the material.

The Concrete Centre provides design guidance, seminars, courses, online resources and industry research to the design community.

The Concrete Centre is part of the Mineral Products Association, the trade association for the aggregates, asphalt, cement, concrete, dimension stone, lime, mortar and silica sand industries.
www.mineralproducts.org

For more information and downloads, visit:
www.concretecentre.com/publications
www.concretecentre.com/events
www.concretecentre.com/cq

Subscribe to our email updates:
www.concretecentre.com/register

Follow us on Twitter:
@concretecentre
@thisisconcrete

www.concretecentre.com

The Concrete Centre, Gillingham House, 38-44 Gillingham Street, London SW1V 1HU

Ref: TCC/03/060
ISBN: 978-1-908257-20-8
First published 2018