Tall Buildings — Lateral Load Resisting Systems

Afonso Morais Sarmento
Instituto Superior Técnico, University of Lisbon, Lisbon, Portugal (2021)

Abstract: Lateral load resisting systems are extremely important in tall buildings, because the lateral loads represent a major concern in tall and slender structures. There are several different systems to resist the lateral loads in tall buildings, each of them with their specific characteristics. Some systems are very intrusive in the façade of the building, imposing an architectural expression, and some are more discreet but either interfere with space or have low efficiency. An outrigger frame structural system is a lateral load resisting system that transforms the bending moment present in the core of the building into axial load in the perimeter columns. It is an interior system that synergizes with the external elements of the structure. In this way, outrigger systems can interfere with rentable space of floors but are also very efficiency, allowing for taller buildings and with more architectural freedom when comparing with the other systems. This thesis intends to compare the efficiency of the different types of outrigger frame systems. For this purpose, a comparative study of different solutions was applied to the original outrigger system presented in the Montreal Stock Exchange Tower, in Montreal, Canada, and the most important factors are highlighted.

Keywords: outriggers; belts; structural stiffness; tall buildings; lateral loads

1 Introduction

As cities became more populated, the need for space has been a major priority of city planners and promoters. Since, the horizontal space is limited, the only way to increase space was to go higher and to make structures taller. Together with the increase in height of buildings, the forces increase as well, both the vertical and lateral, but specially the lateral forces. These lateral loads become a priority. If in small structures they are so small that sometimes can be disregarded, in tall buildings they are a major concern and present a few problems and challenges for structural engineers.

There are several different lateral force resisting systems, developed along the years, to be employed in tall buildings. Some systems are simple and cannot reach a considerate height and others can but present other challenges like onerous and arduous building processes and architectural restraints.

Outrigger systems provide strong and stiff structures without interfering much with the facade of the building, subjecting it to more architectural freedom. Some structures are very efficient in resisting the lateral loads but compromise, either by approximating the vertical elements and reducing the views or by interfering with the architecture and aesthetics of the facade, thus outrigger systems present a valuable solution comparing to the other systems.

2 Types of lateral load resisting systems

There are several types of structural systems that are designed to resist horizontal loads. There are also several ways to classify these systems and divide them. For example, according to Mir M. Ali and Kyoung Sun Moon, they can be divided into two broad categories, the interior structures and the exterior structures, and each of the categories can be subdivided into smaller groups as well. This distinction refers to the location and distribution of the components of the primary lateral load-resisting system over the building [1]. The classification of the structural systems and especially their efficient height is only a guideline. It differs with the buildings aspect ratio, shape, load conditions, site constraints, buildings stability, etc., but since the rigidity of each system is different and some are stronger and stiffer than others, as the height of the building increases, the choice of the structural system decreases. For a high-rise building, the choice of a structural system strong enough is limited and it is frequently combined of a few systems whereas for a low-rise building, there can be many choices available. For a high-rise building, since the alternatives are limited, the structural design and the architectural design should go together and be considered together. Also, the structural system of a building tends to be connected to the form and function of it, and this becomes more important in taller building in order that sometimes the structural design must define the architecture.

2.1 Rigid Frames

Also known as moment resisting frames, rigid frames are one of the two basic interior structural systems to resist lateral loads [1]. It consists of vertical elements — the columns, connected to each other by thick beams — the girders, in each floor creating a planar grid frame, offering a certain rigidity to the structure. Moment resisting frames rely on the premise that the nodes are rigid. For this reason, reinforced concrete is the preferable material for this type of structures because of its naturally monolithic behavior, whereas for steel structures rigid framing is achieved by the strengthening of beam-column connections. These frames resist the lateral loads through the combination of the flexure resistance of its elements [2] and it is as rigid as the elements composing it.

2.2 Shear Trusses and Shear Walls

Shear trusses and shear walls are the second basic interior structural system to resist lateral loads. It consists of a vertical truss/wall capable of resisting the vertical and horizontal loads, sometimes eliminating the need for columns, and approximating the behavior of the building to a vertical cantilever rigidly fixed at the base of the building. Due to the cantilever behavior, the inter-story drift between adjacent floors is greater in the upper floors than the others. Therefore, in very tall buildings, it is difficult to control the lateral sway of the top of the building. This system can be used in steel, reinforced concrete, or composite structures.

For steel structures, shear trusses are used. It consists of braced frames creating a vertical truss that resists the horizontal loads through axial deformation of the diagonals on the braces. These braces can have several formats and according to its structural behavior they can be categorized as concentric braced frames or eccentric braced frames (Figure 1).

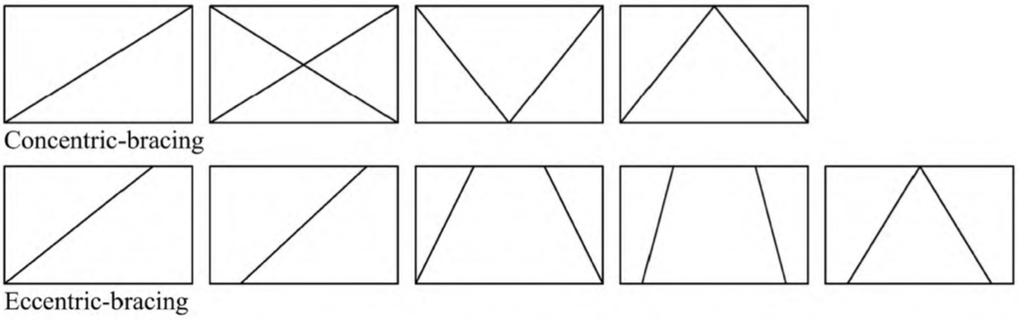

Figure 1: Types of Concentric Braced Frames and Eccentric Braced Frames

For reinforced concrete or composite buildings, shear walls are generally used. They consist of reinforced concrete walls uninterrupted from bottom to top that can be perforated or solid. It is one of the most used forms for tall buildings to create lateral stiffness. There can be, combined in the same plane, two or more shear walls connected to each other by beam, and this is called a coupled shear wall. Usually, the shear walls and coupled shear walls are located in the core of the building. When the shear wall or shear trusses are solely located in the core of the building this system can be called a core system.

2.3 Shear-Frame systems

Shear-frame is the name given to the interaction of both rigid frames and shear trusses or shear walls. This combination results in a significant increase of the lateral stiffness of the structure which can lead to higher structures. A rigid frame resists lateral loads through the ductility of the beams and columns and the inter-story drift is higher at the base of the structure because it is where the shear force is higher. On the other hand, shear wall structures are less ductile, but they resist lateral loads within elastic limits because they have a greater area subjected to the shear force, thus they have a great stiffness. As they behave as a vertical cantilever, naturally the higher inter-story drift is at the top of the building while at the bottom is where the structure is more rigid. The weakness of each system is compensated by the other and that both make a stronger and stiffer structure. While at the bottom rigid frames tend to have bigger displacements, shear walls are more rigid, thus restraining the frame, and at the top the displacements induced by the behavior of the shear walls are compensated by the stiffness of the nodes, beams, and columns of the frame, that in its turn restrain the shear wall. The functioning of these two systems acting together is represented in Figure 2.

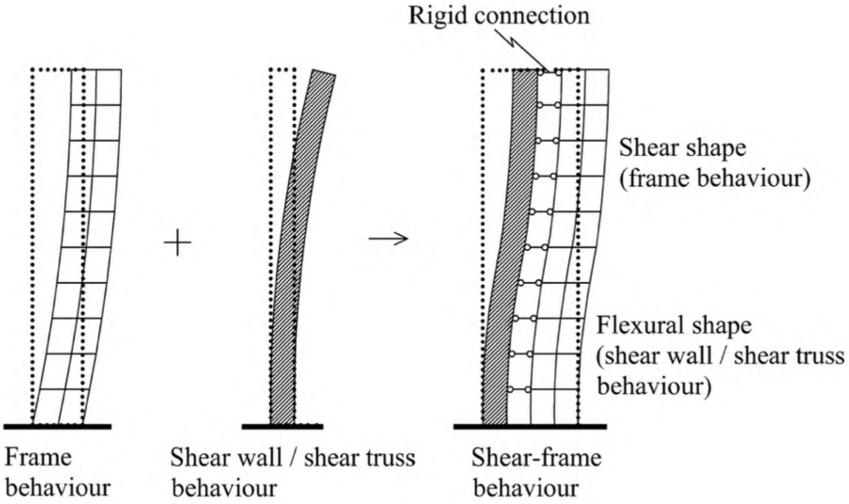

Figure 2: Behavior of the rigid frames and shear walls/trusses acting alone and together

2.4 Mega Column, Mega Frame, Space Truss, Mega Core

These systems are made of columns and shear walls with cross sections much larger than the usual. They are reinforced concrete or composite buildings that can resist to vertical and lateral loads solely by their big columns and walls which can alone ensure the lateral stiffness of the building.

One of the biggest concerns in this type of structure is to ensure the connection between vertical elements as to in this system, the floor slabs alone are probably not rigid enough to act as floor diaphragms. In this way, to restrain the columns or walls laterally for them to act and deform as one, belts and Vierendeel frames are normally used. These elements are horizontal shear trusses or shear walls of at least one floor deep that connect the several vertical elements in its floor. Belts are usually located around the perimeter of the building while Vierendeel frames can go through the building and act also as a transfer structure, since the columns are usually discontinued in the frame. In some cases, to ensure the lateral connections of the mega column buildings, mega braces are used instead of belts or Vierendeel frames. Even though these braces have the same purpose, they act in a different way: they also restrain the vertical elements laterally for them to act as one, but they don't do it in a single floor but throughout the building's height, At the same time, they contribute to the building's lateral stiffness with their axial strength and diagonal nature

For buildings with mega columns and belts or Vierendeel frames connecting them, the structure can act as a big frame and the belts or Vierendeel frames as girders. This type of structural systems can be called Mega Frame systems. For systems with mega columns and mega braces connecting them, they can be called Space Truss systems since they resemble a vertical tridimensional truss.

2.5 Outrigger Frame systems

Outriggers were historically used in naval construction (Figure 3). They were the spreaders that connected the sailing ship to the outer stays to stabilize the sailing ship and to help resist wind forces in the sail. There is an analogy between sailing ships and tall building where the tall and slender mast is the core of the building, the stays that help stabilize the ship are the external columns and the outriggers have the same function in ships as they have in the buildings where on one side, they help stabilize the ship connecting it to the stays, on the other they help transferring the acting moment on the core as an axial force in the external columns.

Figure 3: Outrigger Canoe

Outriggers are widely used in design and construction of supertall buildings nowadays [1]. They are usually utilized in buildings with a shear-frame system with shear walls concentrated in the core (core-frame systems). In these systems, the cantilever behavior is assured by the core and assisted in the upper stories by the rigid frame and the outrigger acts as a knee helping the structure by stiffening it and significantly minimizing the movement at the top. Outriggers in steel structures are commonly represented by a horizontal steel truss and in reinforced concrete structures by a horizontal sheer wall. They have a depth of at least one floor to ensure sufficient flexure and shear stiffness for its purpose and can be in the shape of a shear truss, shear wall or deep beam. These elements are normally connected rigidly to the core and by hinges to the external columns for the moment to be transferred from the core to the outriggers but not to the columns [2]. This way, the columns have mostly axial tension or compression.

2.6 Tube systems

Tube systems are tridimensional systems that use the entire perimeter of the building to resist the lateral loads. They were invented by the famous engineer and architect Fazlur Rahman Khan who is considered “the father of tubular designs”. Khan invented the tube systems and all its variations that were very revolutionary for its new way of conceiving the structural design. Tube systems are a tridimensional rigid frames around the perimeter of the entire building that are capable to resist the lateral loads just with their façade. This system frees the internal space of buildings, but it can also be placed in the interior of buildings a core or even another tube to increase the structural stiffness of the building, redistributing the lateral loads through both systems. Tubular systems can have several types depending on the connection of the elements which can lead to different structural efficiencies. The main types in which tube systems can be divided are: Framed-tube systems; Trussed-tube (Braced-tube) systems; Bundled-tube systems; and Tube-in-tube systems.

2.6.1 Framed Tubes

Also known as the Vierendeel tube system or the Perforated tube system, it is a basic tubular system form. It can be described as an evolution of the rigid frame systems and an alternative to the shear-frame systems. It consists of closely spaced perimeter columns, about 1,5m to 4,5m apart, connected by thick beams [1]. As the column space increases, the cross-section of both the beams and the columns themselves increase as well.

2.6.2 Trussed Tubes

It is a variation of the framed-tube system that consists of stiffening the perimeter rigid frames of the framed-tube with braces. For this reason, trussed-tube systems can also be called the braced-tube systems. The diagonals on the braces can help resisting both the lateral loads — through their axial deformation, and the vertical loads — by supporting and distributing them, allowing the cross-section of the columns and beams of the frames to be smaller and being located more apart from each other creating more spacious windows. Column spacing in framed-tube systems usually is, as said before, between 1,5m and 4,5m and the column spacing on a trussed-tube system can be higher than 10m.

2.6.3 Bundled Tubes

Bundled-tubes are a set of several framed-tubes or trussed-tubes connected to each other working together as a single tube. The system provides great architecture freedom not only by not restraining internal space but also allowing for each tube to have its own geometrical shape and end at different height. The fact that the height of each tube is independent from the others is a great advantage that the other tube systems do not have allowing not only the creation of distinct buildings but also, structurally speaking, it enhances the control of the buildings slenderness ratio.

2.6.4 Tube in Tubes

The tube-in-tube system is an external tube stiffened by an internal tube or a core. The connection of the tubes is assured by the floor diaphragms which ensure that the lateral loads are distributed to both the external and internal tubes. This system can be considered a variation of the bundled tube in the way that it is the method of stiffening a tube with internal structures.

2.7 Diagrids

Diagrid systems are a special kind of exterior structure, very close to a tube system, but it has a stronger architectural expression that defines it and it has been frequently used in this era of pluralistic styles for this reason. Diagrid systems are somehow similar to tube systems and can be considered somewhere between the framed-tube systems and the trussed-tube systems. As framed-tubes have tubular shapes with closely spaced linear elements in two directions crossing and creating a grid-like frame, so do diagrids, but only with the exception that instead of vertical and horizontal directions they have up right and up left diagonals. Diagrids are very similar to trussed-tube systems as well by having both tubular shapes formed with diagonals but trussed-tubes are made of frames reinforced with braces and diagrids are already a diagonal frame and so they do not have vertical elements.

2.8 Concluding Remarks

To conclude and gather all the different systems presented, the following chart in Figure 4 represents them and their efficient heights in a comparatively mean. It is noted that the chart is represented as a guideline and that each structural system has a wide range of height applications depending upon other criteria like the building shape and stability, aspect ratio, load conditions, site constraints or architectural function.

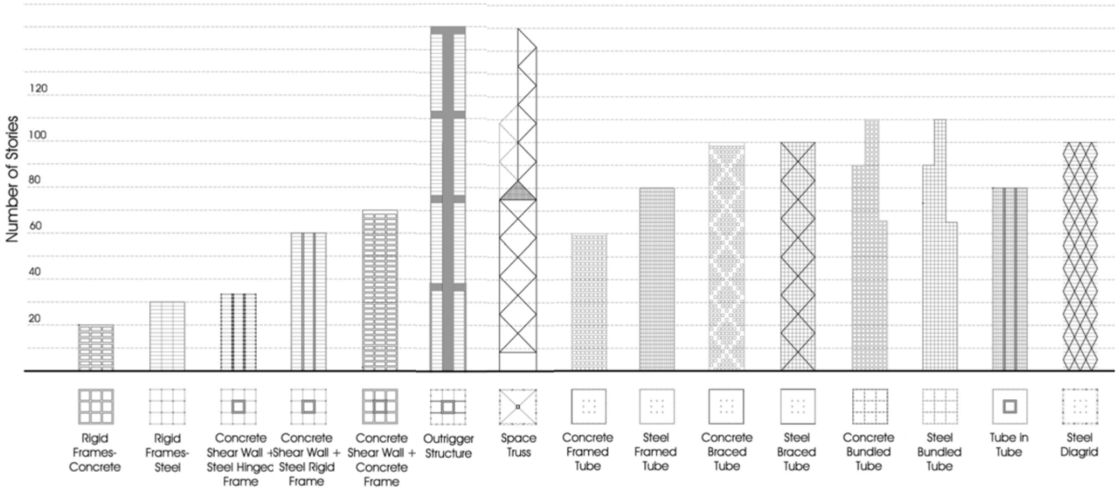

Figure 4: Lateral load resisting structural systems

These systems are represented alone but they can be combined and strengthened by each other creating stiffer, and consequentially, higher structures. One example of a building with a combination of structural systems to resist lateral loads is the 492m high Shanghai World Financial Center completed in Shanghai in 2008.

3 Outriggers: Concept and types

The widespread popularity of outrigger systems can be seen as a response to fundamental disadvantages of the tube frame systems. Tube systems have relatively dense exterior frames that resist the lateral loads alone with little or no help from the building core and the lateral resistance of any structural system increases if the perimeter couples with the core and the deeper the beams that connect the exterior to the interior structures, the stiffer the system. While structurally efficient, the tube systems also have a strong presence on the building exterior with limitations for architectural aesthetic freedom and the core-and-outrigger system offers far more perimeter flexibility and openness. Spandrel beams in outriggers are sized for gravity loads alone thus can be relatively shallow and column spacing can be adjusted to meet architectural requirements. Also, compared to tube buildings, outrigger buildings tend to reveal very little of their underlying structural logic from the exterior.

3.1 Concept

The main idea is to couple the perimeter and the internal structure as a whole. If uncoupled, they both work as a pure cantilever [3] and the lateral stiffness of the system is about the same as the stiffer structure, either interior or exterior. The main behavior of outriggers is simple: they are rigidly attached to the core, engaging the outer columns, and when the lateral load induced moments acting on the core forces it to rotate, the outrigger tips at the end move upwards and downwards following the rotation of the core and at this point, as the outriggers are connected to the perimeter columns, these columns restrain this movement creating an opposing force that will be then transferred to the core to help resist the overturning moment.

Outrigger systems are very popular due to some benefits they present, but they are not a solution that fits all cases. There are some situations favorable for the application and some that are less suitable. The most obvious benefit, and probably the most important of them all, is the reduction of deformation, which can go up to 60%. Other benefits of the outrigger frames and belts include: the efficiency of the use of material towards the increase of stiffness.

- Effective distribution of overturning loads on foundations.
- Reduction of differential axial shortening of vertical elements by gravity force transfers.
- Creation of alternative load paths in case of a sudden loss of member capacity or connection (for example a column failure).
- Improvement of torsional stiffness of the system.
- Greater architectural freedom due to adjustable spacing of external columns to satisfy aesthetical goals and specific functional requirements.

The less suitable conditions, and reasons, can be:

- Structural systems with considerable story shear, since the outriggers are efficient at reducing the overturning moment but do not contribute much to increase shear stiffness.
- Eccentrically located cores because they generate torsional forces under lateral loads, and outrigger structures without belts do not offer sufficient torsional stiffness, and because they generate lateral displacements under vertical loads due to the differential shortening.
- Different materials of vertical elements that can have considerable different long-term shortening which can create locked-in forces in the outrigger elements.
- Tight mechanical floors because the outrigger elements require considerable space.

3.4 Conventional Outrigger systems

The two main types of outriggers are the direct or conventional outriggers and the indirect or virtual outriggers. Direct or conventional outriggers are stiff trusses or walls oriented in a vertical plane that connect the shear core to the columns at the perimeter of the building. Lateral loads causing overturning moment and rotation of the core at outrigger levels will try to move outrigger truss tips up and down and at this point the columns will restrain this movement generating opposing forces. The main purpose of an outrigger system is to reduce the moment of the core walls. The opposing forces generated by the columns create an opposing moment that is then transferred to the core by the outriggers (Figure 5).

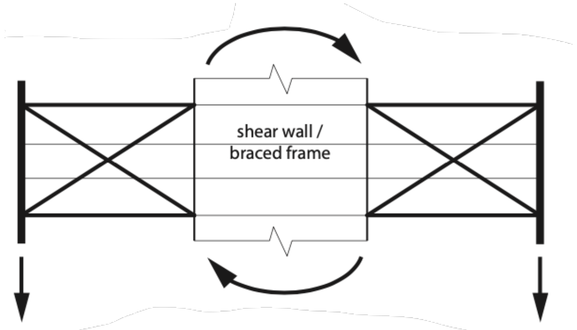

Figure 5: Force transfers in conventional outrigger systems

The importance of an efficient topology of outriggers arises, for its magnitude to be as high as possible and because of the limitations of where to place it. In practice, it is more important the form and efficiency of the outrigger rather than the placement of it because this one is limited to the program of the building or the codes of the country. One key concern of the design of outrigger connections is the locked-in forces. As the stiffness of outriggers is very high, a small deflection will induce large forces, which are the locked-in forces in the outrigger element. This small deflection is the result of differential shortening which occurs due to elastic deformation, shrinkage, and creep.

3.5 Virtual Outrigger systems

Another alternative that is quite advantageous and frequently used is the indirect or virtual outriggers. They are belt trusses that completely ring the building's perimeter engaging all the exterior columns. The virtual outrigger system provides a similar behavior to the conventional outrigger system but without the outrigger element connecting the core to the perimeter columns. Instead, they count on the floor diaphragms to insure such connection. These diaphragms placed at the top and bottom of the outrigger levels transfer the overturning moment of the core as horizontal forces to the belt truss (Figure 6a). The latter structure, in turn, acts as a virtual outrigger and transforms that horizontal force into vertical forces (Figure 6b). These vertical forces are then resisted by all exterior columns engaged by the belt truss. The elimination of a direct connection between the core and the columns or belts avoids many of the problems associated with the use of conventional outriggers. Virtual outriggers can be seen in two forms: belts and basements. Belts can be concentrated, which is usually the case, creating a truss or wall that completely rings the building in a certain height, but the concept of the virtual outrigger effect can be extended further by distributing individual belt walls along the height of the building.

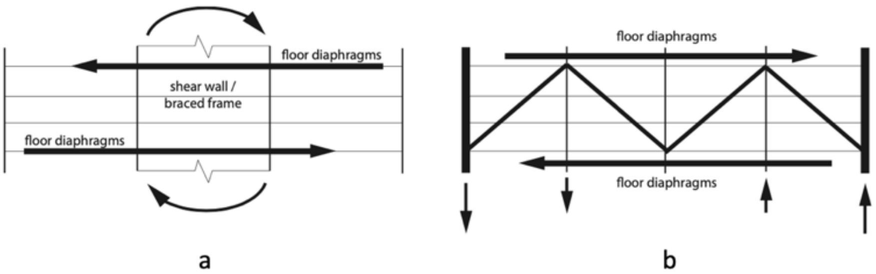

Figure 6: Force transfers in Virtual Outrigger Systems: a) from core to the floor diaphragms; b) from floor diaphragms to the columns (through the effect of the belt)

3.6 Comparison of systems

The whole process of outriggers relies on the relative stiffness between the core and the outrigger-and-column system. The load path is more direct for conventional outriggers and so it provides a better restraint efficiency that the virtual outriggers. Nevertheless, virtual outriggers are in some cases sufficient to meet the needs of the tall building and they stand out in other important issues comparing with the conventional outriggers, making them preferable for certain situations. For example, some disadvantages of conventional outriggers include: the space occupied, which is not the case with virtual outriggers; the complex connections of outriggers to core, that don't exist for virtual outriggers; the need to place large outrigger columns on the perimeter to be engaged by the outriggers when these do not count with belts; and the differential shortening effect of the core and perimeter columns that create locked-in forces in conventional outriggers but are disregarded for the virtual outriggers.

4 Design considerations

4.1 General considerations

In tall buildings, the core is usually located to the center of the floor plan. This is not only to free the exterior walls for occupants, since views are a significant part of the intrinsic value in tall buildings, but also because the core represents an important role in the lateral stiffness of the building and in this way it locates the center of lateral stiffness close to the center of lateral wind load and center of mass for lateral seismic loads, minimizing torsional forces. The core may be combined with other elements to provide additional torsional stiffness, such as a core and frame or a tube in tube, but the core alone supposably resists the overturning and stiffness against drift. For an aspect ratio of the core higher than 8, the structural premium to control drift and resist overturning is large enough to consider introducing outriggers. This height is usually smaller for residential buildings than for office buildings since the cores are tendency smaller, as explained before. This is because the drift from flexural behavior will increase approximately as the cube of the building's height (Lame, 2008), thus, to maintain the drift/height ratio below an acceptable amount, as the heigh doubles, core stiffness would have to quadruple. For this reason, and because in some cases thickening core walls would be unpractical, introducing outriggers can alleviate the dependence on the core system and maximize useful space between the core and exterior columns.

There are ideal locations for outriggers, but the realities of space planning make such considerations purely academic, and the outrigger locations are typically limited to mechanical or refuge floors. Nevertheless, locations and effectiveness are driven by 4 issues: number of outrigger sets; outrigger column and truss stiffness; spacing to equalize distances from outriggers to core inflection points and space availability [4].

Diaphragm properties are also very important for outrigger design: they are important for conventional outriggers because incorrect modeling of them can report incorrect force values in outrigger chords and incorrect building deformation; and are particularly important for virtual outriggers because they are key elements in the load paths that make the system work. Improperly modeled diaphragms will result in misleading behaviors and load paths, and incorrect member design forces for both indirect and direct outrigger systems. Overly optimistic diaphragm stiffness will overestimate outrigger participation and underestimate building drift and core overturning forces. Too-low diaphragm stiffness assumptions will underestimate the forces experienced by the diaphragms, belt trusses, and perimeter columns. Designs should envelope reasonable ranges for diaphragm stiffness.

4.2 Construction considerations

Construction of a core-and-outrigger building has two key aspects: mitigation of differential shortening and effect on overall construction schedule [4]. For the first aspect, it is an important issue in all tall buildings and in this case, it is of special attention as differential shortening can create locked-in forces in conventional outriggers.

There are three causes that can generate differential shortening:

- The first cause is gravity shortening which is elements shortening with the increase of compression stress due to the increment of weight.
- Another cause is the thermal effect that are less common and relatively smaller but are still significant for conventional outriggers connecting members with different thermal exposure like the perimeter columns and the internal core.
- The last cause for differential shortening isn't actual shortening but instead the settlement of the sub-grade. Although this is a different phenomenon than differential shortening of the vertical elements, the result is the same as it induces locked-in forces in conventional outriggers.

The time at which the outrigger is connected to the structure also has a big relevance to the force transfers locked into the outrigger because this can establish how much of the total differential shortening has already occurred, and how much has yet to occur. During construction, the gradual application of loads affects the elastic shortening of the vertical elements and delaying the final connections of the outriggers to the columns can provide a further reduction in the locked-in forces create but even though delaying the connections may eliminate most of the elastic shortening, post-top-out differential axial shortening of core and columns will still occur. Some methods and connections of outriggers to columns were developed that allow for later adjustment and release of the locked-in forces. Some examples of these methods and connections are the Shim Plate Correction Method, the Oil Jack Outrigger Joint System, and the Cross Connected Jack System.

5 Case Study: Montreal Stock Exchange Tower

The Montreal Stock Exchange Tower, in Montreal, Canada, was designed by engineer Pier Luigi Nervi and architect Luigi Moretti and when completed, on May 1st, 1965, it was the tallest reinforced concrete building in the world, which at that time clearly distinguishes from the original model of the American steel frame skyscraper [5]. The building is entirely made of concrete and with a floor plan bi-symmetric to the center. The main structural system is composed of four corner columns at the corner of the building, a central core with crossed walls, hollowed slabs and for levels of outriggers with four outrigger beams connecting the central core to each corner column. Along with this main structural system there are two columns at each facade of the building, between the corner columns, as a secondary structural system to help support the vertical loads [6].

It was proposed five more alternative cases as variations of the solution applied to this original model. One first alternative is the main structure of the building with both the main and the secondary vertical load support systems but without any lateral load support system besides the main core. So, the only change to the model was to delete the 16 direct outriggers that connected the core to the corner columns, leaving the core by itself to resist the loads and bending moments. The other four alternatives were developed by two criteria. The first criterion is that they are solutions presented in point 2, previously in the text, and applied to other structures. The first three solutions are variants of the outrigger system — Virtual Outrigger Systems, materialized by one simple Belt or by two different sets of a Distributed Belts. The last solution was to check the efficiency of a tube system — Braced Tube, when compared to the outrigger system. The other criterion was the preservation of the quantity of material used, reflected by the volume of the elements and by the self-weight of the structure. The differences to the original model were all below 1,25% (Table 1), which was enough to consider all the models as equals and valid.

Table 1: Self-weight of models and errors

	Original	Simple	Belt	Dist.1	Dist.2	Braced
Self-Weight	806653,1	776306,3	806546,3	806411,9	806210,3	806447,7
ETABS [kN]	813213,5	773008,2	803248,2	803113,8	803046,6	803076,8
Error [%]	0,81%	0,42%	0,41%	0,41%	0,39%	0,42%
Difference to Original [%]	-	-4,94%	-1,23%	-1,24%	-1,25%	-1,25%

From the analysis, the values that were collected were: the reaction at the base and the bending moment at the pier, for detecting the percentage of moments at the pier and at the perimeter of the building; the modal participation mass ratios, to ensure that the model was symmetric; and the displacements of the center of mass of each floor. One of the main concerns and goals of the analysis was the distribution of the base forces from the core to the other vertical elements at the perimeter of the building such as the corner columns. The first thing that was verified was that the solutions with the lower period value and the higher fundamental frequency were the ones with the lower percentage of moment in the core and highest in the perimeter columns. In the same way, the building with the expected worst performance, which was the simple model, had the highest period and the lowest fundamental frequency which corresponded also to the highest percentage of moment in the pier element.

- Seismic analysis

It was made mainly two analyses of each solution corresponding to a seismic analysis and a wind comfort analysis. For the first analysis, the seismic analysis, it was verified the consideration of the 2nd degree effects and it was verified the damage due to relative displacement of the floors. The intent of this last verification is to assure that the displacement between floors isn't enough to damage the structural elements and the analysis showed that every solution verified this except the simple solution.

The verification of the 2nd degree effects is intended to verify if the relative displacement of a building, considering the weight and the shear forces, expressed by a factor of θ, is enough to justify an adjustment to the forces and bending moments of the building in order to define the reinforcement of the cross section of elements but, since in this analysis it wasn't made any definition of cross sections, the purpose of this verification is mainly comparative as it is used to check if the solutions were comparable, since one could be so unparalleled that it couldn't be compared in the same terms as the others, and to have another comparison criterion between the solutions to better classify them. The results showed that all the solutions had relatively low values of θ except of course the simple solutions. The values of the braced tube solution is lower than 0,1 in every floor, which not only can be assured that the 2nd degree effects can be disregarded and the forces and bending moments are already accurate but also defines the braced tube as the best system to resist the lateral loads.

- Wind Comfort analysis

For the wind analysis, three verifications were made which were the maximum displacement at the top of the building, the vibration modes for the direction transversal to the wind due to the vortex shedding effect, and the vibration of the building in the direction of the wind due to the wind force. All the models checked these three verifications and again the braced tube solution showed to have the lower values of amplitude of movement, referring to the displacement at the top, and the lower values of the wind characteristic acceleration which refers to the comfort of the vibration of the building in the direction of the wind.

6 Conclusions

The increase in material, from the simple core structural system to the original outrigger frame structural system, was less than 5% and the period decreased more than 40% of the original value. As for the decrease of the displacements at the top of the building due to the same seismic action or the same wind loads, it was more than one third of the total value in each case.

The other alternatives presented for the original conventional outrigger system were developed with approximately the same amount of material. Since the study does not focus on the definition of the reinforcement of any solution, it can be assumed that the cost of the material used in each solution can be about the same. It was also verified that all the solutions could be employed with some adjustments. Since some alternatives have more clearance with the safety and comfort verifications, their cross sections could be reduced and therefore their quantities of material and final cost could be lower than the other solutions. This applies mainly to the braced tube solution which can be assumed to be the most efficient system of the alternatives studied.

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