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MASTER'S THESIS

# MODULAR CONSTRUCTION IN MULTI-STOREY BUILDINGS

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### ABSTRACT

Modular multi-storey buildings are one of the new developing building strategies that have become relevant these past 20 years. Several technologies in the manufacture, building and design have made new opportunities arise. CNC for automated manufacturing of building elements, or the Building Information Modelling (BIM) for the overall construction process and life cycle are among the most important ones.

However, due to the recentness and small numbers of buildings constructed with this method to the date, there is an absence of detailed scientific research or case studies that investigate the different aspects of modular buildings and weighs them against traditional stick-up built constructions.

This thesis will develop a study of modular buildings overviewing past researches in different fields of the building construction such as the design process, the structure or the sustainability aspect. On the structural regard a study using Strand7 computational software will be carried out, modifying an initial multi-storey model of a fully modular construction system. The results of these analysis are critically evaluated in order to present a better understanding of the behaviour of multi-storey modular buildings.

This research provides a preliminary knowledge-base for the construction of modular multi-storey buildings and understands how the whole building process is developed and the decision-making throughout it, from the design and manufacturing to the performance and disassembling.

Los edificios de varios pisos construidos con unidades modulares son una de las nuevas estrategias de construcción que más se han desarrollado en los últimos 20 años. Se han dado evoluciones en tecnologías de fabricación, construcción, y diseño, como el automatizado CNC para la fabricación o el Building Information Modelling (BIM) para el proceso constructivo y ciclo de vida útil del edificio. Estas tecnologías han permitido que ideas previamente teorizadas se lleven a la realidad.

A pesar de ello, debido a los pocos años que se llevan desarrollando estos proyectos y el pequeño número de ellos hasta el momento, hay una ausencia de investigación en este campo de los edificios modulares. Los datos de investigaciones que los comparen analíticamente con edificios tradicionales son pocos y con eventuales contradicciones.

Mediante este Trabajo de Fin de Máster se pretende hacer un estudio de la construcción modular y en concreto de los edificios de varios pisos, debido a las grandes diferencias que pueden tener en el proceso constructivo y en su diseño. Para ello se revisarán estudios previamente completados en campos como el proceso constructivo, la sostenibilidad o el sistema estructural. Respecto al sistema estructural se hará un análisis de un modelo de seis plantas con estructura completamente modular mediante el software Strand7. Los resultados serán analizados posteriormente para comprender el comportamiento de las estructuras modulares ante distintas cargas.

Esta investigación sirve para obtener un conocimiento base en la construcción modular de varios pisos durante todo el proceso constructivo, desde el diseño hasta su vida útil y desmontaje.

Ale modularren bitartez eraikitako solairu ugariko eraikinak azken urteetan gehien garatu diren estrategietako bat da. Teknologia ugari garatu dira azken urte hauetan bai fabrikazio bai erikuntza eta diseinuan, adibidez CNC fabrikazio automatizatua, edo Building Information Modelling (BIM). Azken honek eraikuntza prozesu osoan zehar, diseinutik azken desmuntairarte, balio handikoa da. Teknologia hauen bitartez eraikuntza modularrari buruzko ideien garapena lortu da.

Hala ere, denbora gutxi igaro da sistema berri hauen bilakaeratik, eta ez dira ohikoak oraindik. Hori dela eta momenturarte egin den ikerketa eskasa da, eta analitikoki eraikuntza konbentzionalekin konparatzen dituen datuak falta dira eraikuntza industriak sistema berri hau berea egiteko.

Master amaierako lan honen bitartez eraikuntza modularraren ikerketa bat egingo da, solairu ugariko eraikuntzetan zehazki. Azken hauek erronka handiak aurkezten dituzte batez ere albo-indarren aurkako mekanismoetan, baina baita ustiatzeko prest dauden abantaila handiak. Horretarako lehendik arlo ugaritan egin diren ikerketen errebisio bat gauzatuko da, hala nola, diseinuan, eraikuntza prozesuan, egitura eta ingurumen jasangarritasunean. Egiturari dagokionez sei solairuko adibide baten analisi zehatza egingo da Strand7 software-aren bitartez, ondoren emaitzak aztertzeko asmoz.

Ikerketa honen bidez solairu ugariko eraikuntza modularraren oinarrizko ezagutza bat lor daiteke, diseinu prozesutik hasiz bizitza ziklo osoan zehar eukiko duen portaera ulertzeko.

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## 1. INTRODUCTION

### 1.1. CONTEXT

Modular building is a construction technique whereby buildings are highly prefabricated off-site by the manufacturing of volumetric modular units. These room-size units are fabricated with great precision and then transported on-site to be assembled in a short time.

Modular construction refers to the application of a variety of structural systems and building materials, rather than a single type of structure. Prefabrication by off-site manufacturing can lead to a reduced overall construction schedule, improved quality, and reduced resource wastage. The disadvantages include the lack of design codes and restraints on the structural spans due to module transport limits.



*Figure 1.1.1 Craning of a modular unit during the final assembly of the building .*

The modular system has been used before for in low-rise or temporary housing, but in recent years, modular steel buildings has gained engineers' attention for their application to mid- or high-rise structures in different building types. Furthermore, research interest in new modularity techniques has also increased, developing new systems and helping to widen the use of modular construction.

Generally speaking, there are two main types of modular unit, each with its different varieties and combinations of them. Load bearing wall-supported units have been the most used ones but are not usable on medium and high-rise construction, where lateral forces gain relevance. Then, corner supported modules are the only viable option, with combinations of more traditional reinforced concrete and steel cores or load bearing walls. Applications can be seen in skyscrapers as the 461 Dean building in New York or the Student Housing Building in Wolverhampton.

This thesis is the consequence of a four month research developed in the department of civil engineering in the university of Padova, Italy. This abroad stay happens during the second year of the Master's degree in industrial engineering with a specialization in structures and construction.

Related to both the traditional factory manufacturing industry and to the Architectural Engineering and Construction (AEC) industry, the main points of the thesis are carried out: an overview and benefits of modular construction, process breakdown, its benefits to sustainability across the life cycle of the building, structural analysis and the modelling of a case study. It is focused on the multi-storey angle of modular construction. In the modelling section, with the purpose of learning how to analyse a buildings structure, the computational software Strand7 has been used to identify the critical points and elements that a modular construction can have.

### 1.2. AIMS AND OBJECTIVES

This research is part of the two-year industrial engineering Master's degree specialized in structures and construction and takes a look not only at the modular construction design aspect from an architectural and the process engineering point of view, but also produces a model that is later analysed. With this research the following objectives are set out:

- Understanding the prefabrication aspect of modular construction as a part of the natural evolution that the Architectural Engineering and Construction (AEC) industry is developing, and study the key differences from conventional construction.
- Identifying the general structural behaviour and load transfer mechanisms of the different modular systems.

- Evaluating the behaviour of a modular building by constructing a six-storey model using the advanced corner supported modular system. For the construction of this model the Strand7 computational software is going to be used, as a training for the building of more complex computational models in the future.
- Learning to read the results that a computational model offers, that helps identify failure criteria of modular buildings.
- Identifying the opportunities that this kind of construction method offers by the analysis of already constructed buildings with a critical view.

### 1.3. RESEARCH SCOPE AND METHODOLOGY

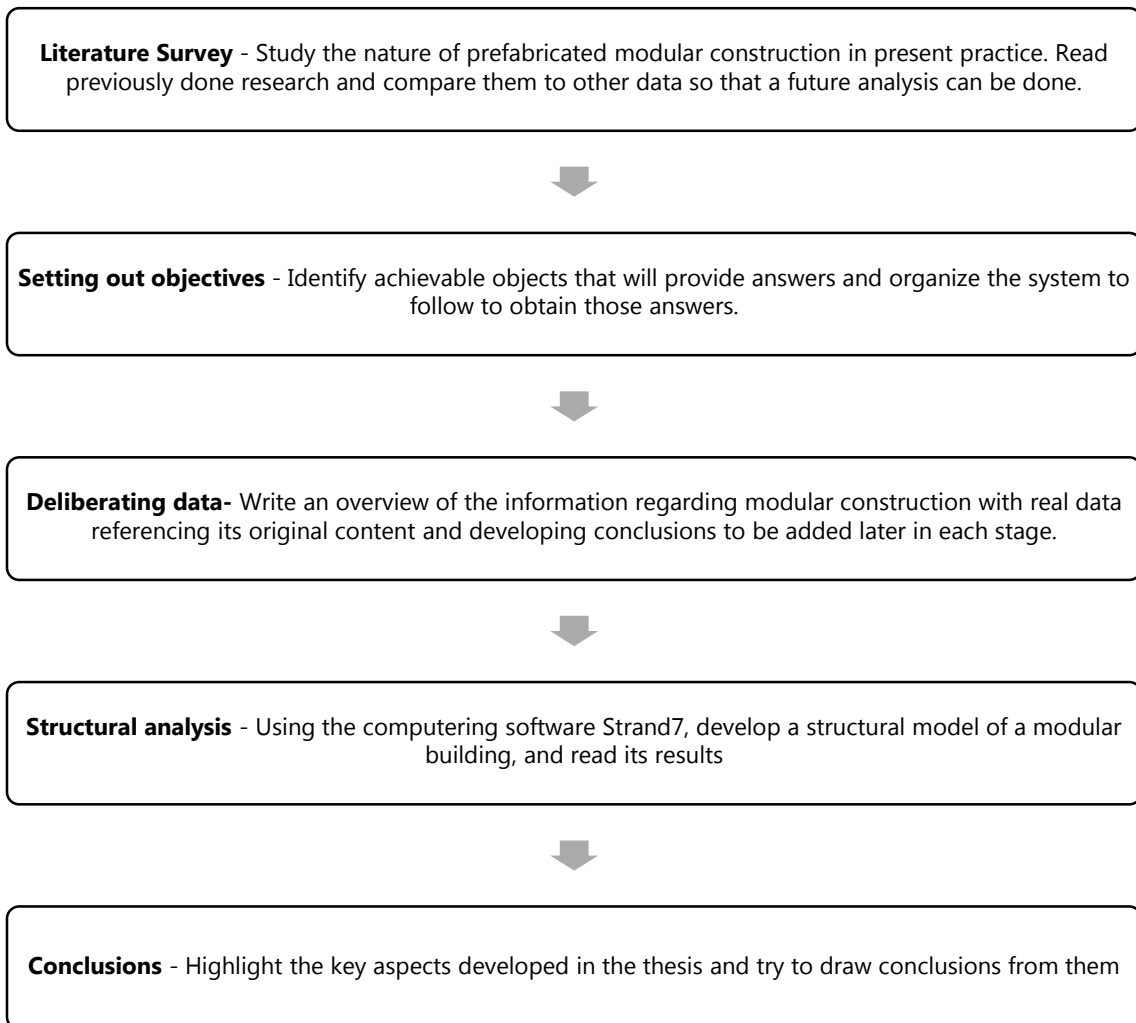


Figure 1.3.1 Flow chart of the thesis' work.

### 1.4. THESIS LAYOUT

The thesis is divided in eight main parts

- *Part I- Introduction.* Illustrates the context in which this work is developed, and briefly explains the purposes and the layout of the thesis.
  - Chapter 1 introduces the main points of the thesis and puts into perspective the construction industry revolving prefabrication and modular construction.
  - Chapter 2 tries to specify the aims and objectives this thesis hopes to achieve with its development.

- Chapter 3 focuses on how these previously mentioned aims and objectives are going to be achieved.
- Chapter 4 takes a quick look at the layout of the thesis, with its different parts and the chapters they contain.
- *Part II- A review of modular construction* explains the principles and the outputs that define and characterize modular fabrication.
  - Chapter 1 defines the concept of modular construction and looks the evolution that construction has suffered to reach modular construction.
  - Chapter 2 focuses on the process in the making of a modular building, from the planning and design to the final assembly of the units on site.
  - Chapter 3 shows the main materials used in construction and what possibilities they have in modular construction.
  - Chapter 4 evaluates the opportunities and/or advantages that modular construction offers and how the industry is taking advantage of them.
  - Chapter 5 analyses the principle barriers and/or disadvantages that the implementation of modular construction can face in the current construction industry.
- *Part III- Structural system of modular buildings.* This section provides structural design information, including a brief explanation of the different structural systems that modular units and modular based buildings have.
  - Chapter 1 introduces the three main designs that the modular units can have, and in which cases each of them is used.
  - Chapter 2 explains how the modular systems act as a whole, coupling with other on-site construction methods if needed be. The lateral force aspect is addressed.
  - Chapter 3 briefly explains the foundation types used in modular construction.
  - Chapter 4 mentions some structural issues that these types of constructions tend to suffer.
  - Chapter 5 shows the types of connections and their use.

- *Part IV- Case study. Structure analysis of a 6 storey modular building.*
  - Chapter 1 gives an idea of how the model is going to be developed based on a previous model of a modular building.
  - Chapter 2 explains the design chosen for the six-storey model developed in Strand7.
  - Chapter 3 explains the loads chosen for the linear static analysis and studies the critical points with Strand7
  - Chapter 4 makes the natural frequencies analysis and takes a look at the modes of vibration with Strand7.
- *Part V- Construction process and BIM* explains how the recent technology developments open the door to an acceptance from the building construction industry. With these technologies like the Building Information Modelling challenges are able to be overcome and opportunities rise in the AEC industry.
- *Part VI- Sustainability in Modular construction*
  - Chapter 1 addresses the environmental aspect of sustainability in modular construction and the benefits it can offer in this field.
  - Chapter 2 takes on the social aspect of sustainability as the second pillar of a sustainable process of modular construction and points out the benefits for the different stakeholders.
  - Chapter 3 briefly explains the economic aspect of sustainability, previously explained in the Chapter 4 of Part I.
- *Part VII- Applications. Case studies.*
  - Chapter 1 takes a look at the "The Stack", a seven storey building in the centre of New York (USA), and its effective method of construction.
  - Chapter 2 examines a Student Housing Building in Wolverhampton (UK), which became the highest building at the time of its construction.
  - Chapter 3 studies the One 9 Condominiums in Melbourne (Australia), a 9 storey building with a prefabricated core that was erected only in 5 days.
  - Chapter 4 analyses 461 Dean (Atlantic Yards B2) in New York (USA), currently the tallest modular construction based building and the benefits and problems that offered modular construction during the building process.

- *Part VIII- Conclusions* makes an overview of the main points that this thesis has explained and summarizes the results that can be derived from this study of modular constructions in multi-storey buildings.



## 2. REVIEW OF MODULAR CONSTRUCTION

### 2.1. CONCEPT AND EVOLUTION

Modular, in its definition, means a “made up of separate modules that can be rearranged, replaced or interchanged easily, and that is constructed with standardized units or dimensions for flexibility and variety in use”. In an engineering environment it is tightly coupled with the concept of prefabrication, which consists in “the practice of assembling components of a building out of the construction site (factory or other) before the final assembly in the construction”. [1]

In the AEC (Architecture, Engineering and Construction) industry, modular constructions, also called off-site constructions, are defined as whole building units prefabricated under controlled conditions and with a final subprocess of assembly on site. Part of the building, as the foundations or a structural core, can be constructed on site previous to the transportation and assembly of the construction units on site. Thus, the modular technologies can be seen as a more specific term within the field of prefabricated construction, which can be applied more easily to any pre-assembled part of a building. Any dry wall system, roof truss, plumbing system etc. can be considered prefabricated construction. [2]

In the spectrum of degree to which prefabrication is finished, modular is the greatest, offering the possibility of constituting up to 95 percent of completion before setting of the structure on-site [3]. Modules also constitute one of the largest definable industries in prefab architecture.

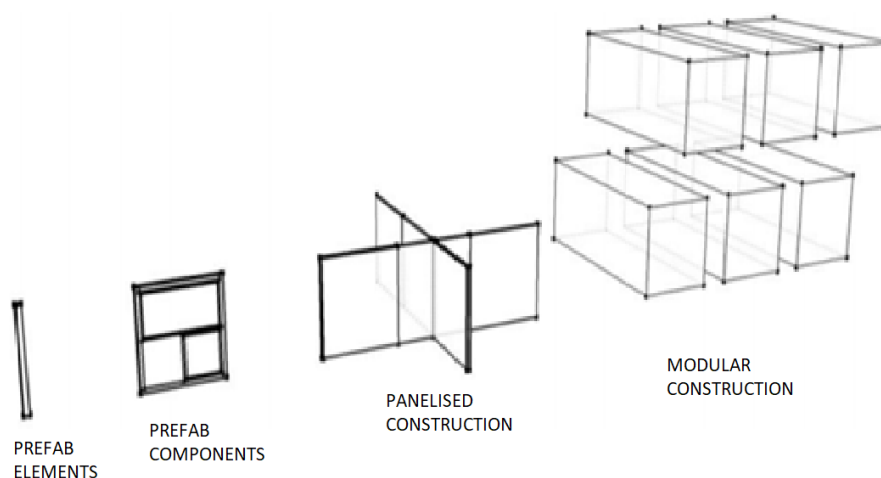


Figure 2.1.1 Degree of prefabrication in construction.

It has been historically associated with a repetitive plan to achieve economy of scale. This often resulted in buildings which were banal and homogeneous. However, this has been changed thanks to the recent evolutions of the non-construction industry, which has developed the technologies to allow mass customization instead of exact repetition. Modules can therefore come together in various ways to create a great diversity of spatial forms, including large span spaces such as multi storey urban buildings. [4]

Historically, prefabrication and modularisation have been a part of the construction industry for a long time, in various forms. During the second industrial revolution (1850), new materials and production processes made its entrance in the industry, like the steel or the concrete. The first example of prefabrication could be the Crystal palace during Britain's Great Exhibition of 1851, which was assembled using a series of prefabricated parts, and then was later reassembled at another site. This was the precursor to modular or factory-based fabrication of buildings. [1]

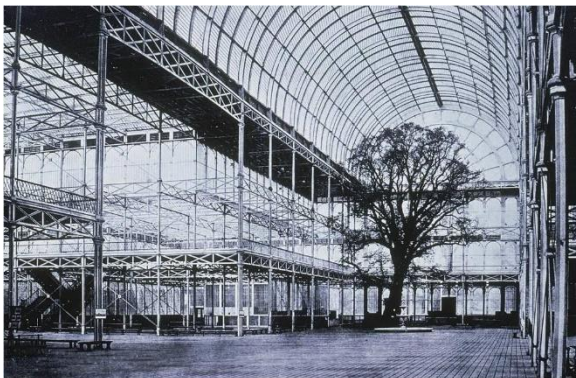


Figure 2.1.2 Crystal palace, London

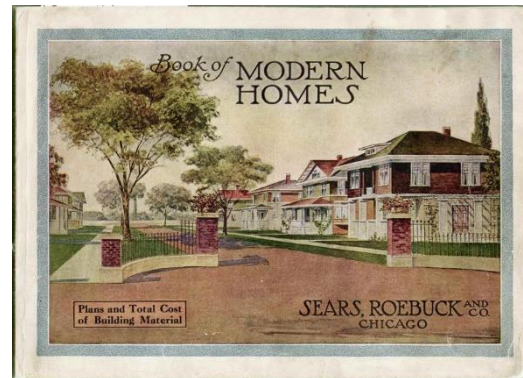


Figure 2.1.3 Advertisement image of the first modular homes

In the case of single family detached homes, the United States entered the market of modularisation "Sears, Roebuck and co." in the early 1900s. This company made the sending of prefabricated homes via mail order possible. The assembly was done by the purchaser following the instructions given by the company.

Mass fabrication was introduced in World War II when easy and fast to assemble accommodation was needed for soldiers, popularizing the "Quonsen hut", a lightweight prefabricated structure of corrugated steel with a semicircular cross-section [5]. Later, the rebuilding of war devastated areas was carried out using modular construction processes. Housing Demand at the end of World War II caused the modular market to truly explode and to greatly evolve, and the lack of skilled labour and high demand were a defining factor in both during and after the war. Apart from the provisional constructions, modular

construction became important in the single-family detached home market. These early modular homes were much simpler in design than today's modular buildings, and its simplicity and cheapness became a stigma of poor quality of the single modular homes that still endures.

Single family modular homes technology has evolved to become more appealing to new owners, distancing itself from the post-disaster image of a temporary home and the low-income housing. The minimal loads in low rise construction allowed for greater flexibility in application, serving as an entry level experience for other types of construction as the modular multi storey buildings.

Regarding to this kind, the multi storey modular building, in the 1960s the high rise modular building was introduced, with the Hilton Palacio del Rio Hotel as the first concrete modular high rise construction. It was developed for the Texas universal Exposition of 1968, and the project was completed in 202 days using pre-cast light weight structural concrete for the 500 modular rooms. These 35 ton modular units were installed in only 46 days, causing the building to be was the first single one to create an assembly line of inexpensive labour composed by 100 workers. A helicopter tale-like device installed during the collocation of the units helped the crane reach the accuracy needed to place them within the accepted tolerances. As it was the ground-breaking building of this field, costs and technologies needed for the installation resulted in an overpriced building, caused by the lack of expertise in the field. <sup>[6]</sup>



*Figure 2.1.4 Craning operation in Hotel Palacio Del Rio, San Antonio, U.S.A.*



*Figure 2.1.5 Actual image of Hotel Palacio del Rio in San Antonio, U.S.A.*

From this inefficient first try, the need for new installation methods and more manageable modules with greater application arose. Some builders started utilizing prefabricated

subassemblies such as kitchens and bathroom only pods (units) to reduce the need for trade coordination.

The modular units have been developed reaching a high level of complexity and sophistication in today's modular construction, thanks to the advent of computer aided architectural modelling and the capacity of the industry to manage larger modular buildings in a greater scale. Advancements in the capacity of transportation, assembly and management of the construction process have made possible to avoid many limitations attached to the modular construction, particularly the multi storey modular construction.

### 2.2. MODULAR CONSTRUCTION PROCESS

The process of a modular construction project is composed by four main stages. The first one is related to the design and planning of the project; second, the manufacturing process in a factory; third, transportation of model units to the project site; and fourth, on site placement of the modular units to form the building.

The main characteristic of this type of construction is that it primarily occurs indoors, away from bad weather conditions and full accessibility to the produced units. This will prevent damages and improve the quality of the work, allowing builders to work in optimal conditions.

Some different stages can be carried out simultaneously, allowing on site work while modules are being assembled in a factory. This, especially in larger scale projects, can be an obligation. Stock must be reduced to a minimum to reach a certain efficiency, so, modular units must be transported and finally placed while others are still in the assembly line. These synchronous stages make the planning and coordination aspect of the modular projects crucial. It also foments the short duration of the construction phase, allowing much earlier building occupancy and an overall reduction of labour, financing and supervision costs.

#### DESIGN AND PLANNING

Compared to traditional on-site construction, more coordination of design and engineering of the modules is required before the start of the next stages of construction. This first stage

can be shortened by similarities with other previously done projects, making the shortening of the schedule considerably more achievable for experienced companies.

The building has to follow the regulations inside the factory, as a classic industry, as well as the on-site building construction regulations. That also adds costs in comparison with the traditional construction process.

The design of modular units is carried out by architects and industry related engineers, to take into account the feasibility of the future manufacturing process in the factory. The off-site construction requires earlier decision making, due to the rapidness in which the next phases develop.

With the advancement of the design, information sharing and coordination techniques, such as BIM (Building information Modelling), a more reliable planning and coordination has become possible. A more precise design of the modular components can be done obtaining the benefits of the modern factory based industry. Also, modelling may be necessary in more complex projects, animating the setting process. It will help identify future conflicts on site, very difficult to single out without it. <sup>[7]</sup>

As all the future construction plan has to be developed in this early stage, the planning of the future stages must be done considering the limiting factors that modular construction imposes for the future transportation and on-site placing of the units.

In terms of creativity and organization of the units, modular construction is not a barrier, Modular single or in pair rooms or corridor modules can be used to create varieties of apartment types. These types can be put together to make interesting and varied buildings of many forms.

However, in the case of high-rise buildings, due to the nature of the structural system, some restrictions appear. One of them is the need for the arrangement of the modules around a central core. Also, the later explained corner supported modules usually used in high-rise show how the corner supporting columns must be aligned so that the loads transfer properly and no eccentricities appear. From a building layout point of view, two generic floor plans may be considered for the spatial arrangement of the modules, as it can be seen in the two figures under.

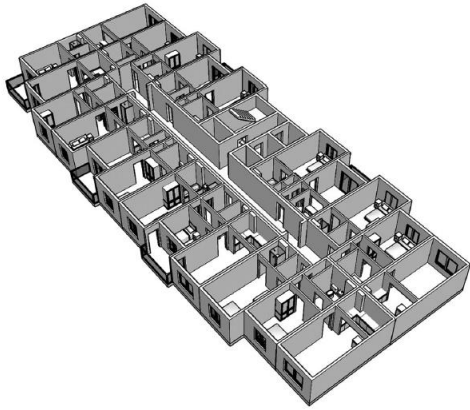


Figure 2.2.1 Modules in corridor form.

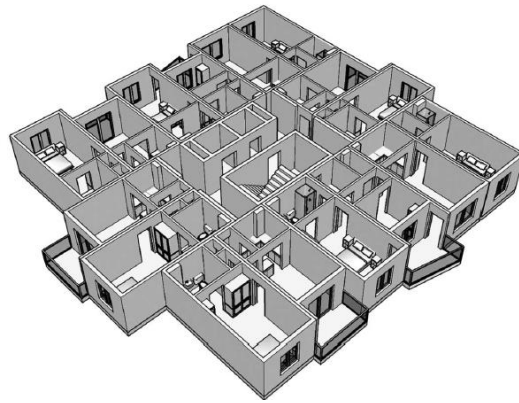


Figure 2.2.2 Clustering of modules around the core.

- In the corridor arrangement of modules, the modules are accessed from corridors either side of the core as illustrated in (Figure 2.2.1).
- In the clustering of modules, each one of them is accessible from the core or from lobbies next to the core (Figure 2.2.2). [8]

### FACTORY MANUFACTURING

After the design is finalized with an architect, construction plans are sent to a factory where the majority of the building is erected. Construction primarily occurs indoors away from harsh weather conditions preventing damage to building materials and allowing builders to work in comfortable conditions.

Factory construction of modular components varies greatly from static factory floors to conveyor belts to even robotic construction of modules with CAD and CNC works. Toyota Motor Corporation known for its automobiles successfully transferred robotic assembly line



Figure 2.2.3 Image of a manufacturing plant, where the finishes are being done.

manufacturing technology from the automobile sector to the construction industry. A typical modular factory works similar to other manufacturing facilities.

There are different grades of completeness of the modular units that can be achieved in a factory. Apart from the basic structural and architectural elements, everything from mechanical, electrical and plumbing (MEP) systems to painting, carpet, furniture etc. can be completed on the assembly line.

A key factor in the accessibility of the factory assembling process is the easiness of the application of insulation material in every corner of the units, since the exterior is not finished and installers have 360 degree access to the entire module. The same can be said for fire proofing applications and special exterior finishes. <sup>[9]</sup>

Modular building factories maintain a high level of quality control with inspections at each station, eliminating on-the-fly decisions or unexpected complications that can occur in the field. <sup>[10]</sup>

### TRANSPORTATION

The phase of transportation, being normally simultaneous to the manufacturing and the final on site assembly phases. In the case of medium to large scale projects, it acts as a continuous stream of modular units that has to minimize off site and on site stock.

Distances between factory and site are the most important factor in the transportation costs. Typically, it is not feasible to ship modules to extremely far distances, due to road size and load restrictions. Normally deliveries are made via highway on trucks. For single home modular construction, also ships have been used in cases of post disaster housing.

Most modular deliveries are made over the highway and governed by a complicated web of international and national regulations. Also, there are some issues that can become very important in terms of cost and viability of the project, such as potential time delays due to delayed transportation permits for special loads (oversized or overweight), potential delays due to custom issues along the borders and dimensional and weight restrictions on modules.

In the case of small module units (less than 3 meters of width more or less) there aren't almost restrictions in terms of transportation in highways, but when the size increases, apart from legal restrictions, many roads become impossible to use and often a police escort is mandatory. Some roads can only be used in certain hours of the day and maximum

dimensions and weights are to be considered, especially in urban areas and in the surroundings of the site, since the roads are eventually smaller. <sup>[1] [7]</sup>



Figure 2.2.5 Transport of a modular unit.



Figure 2.2.4 Transport of a modular single family home.

If there is a sufficient economy of scale the larger volume modules will actually reduce the total transportation cost even though the per trip cost is higher with the larger volume modules.

Despite the obvious difficulty inherent in such complicated transport it may often be a more cost effective alternative than utilizing a site built method in expensive labour markets or locations with poorly trained construction trades.

In the case of Europe, the small number of companies that are working on modular projects make the possible market more difficult, as the distances to make the transport are in larger. Because of that transportation cost related to the distance, high density of population zones such as central and western Europe would be a great opportunity for modular unit companies.

The number of visits to site by delivery vehicles is reduced by up to 70%. The bulk of the transport activity is moved to the factory where each delivery provides more material in bulk than is usually delivered to a construction site. <sup>[1]</sup>

With regards to the transportation condition of the units, temporary protection is used for weather phenomena, such as polyethylene sheets or tarps. For eventual forces that may occur during the loading and unloading of the units on the truck steel spreader rigs are used (later used for the on-site placing).



### ON-SITE ASSEMBLY

Once the modules arrive on-site, the last inspections are done previous to the final assembly of the building. Connections are reviewed and tolerances measured. These tolerances for such connections as the MEP ones have decreased considerably over the past years, allowing better precision and can be as little as 1 or 2 mm. The final construction stage usually includes completing exterior systems such as cladding and roofing components and internal spaces like lobbies, stairwells, and elevator shafts.

The crane is the most expensive part of the installation process with costs of \$3500-4500 per day, not counting police details or road closures. Therefore, careful planning needs to be undertaken so the crane is never idle. Since cranes are classified by tonnage the larger the crane the more operational flexibility one has, especially on challenging small sites in urban areas where it may be the only option to place the crane in a less than ideal position for efficiency which can negatively impact the number of sets per day. When selecting the type of crane, it is also important to consider operational manoeuvrability of the crane and airspace of surrounding uses.

Selection of the type of crane is based on weight and reach. The craning of modules require a crane of greater capacity than those commonly kept on site during in situ constructions. Site cranes often have a capacity of less than 5 tons whereas the cranes used for lifting modules often have a capacity in the range of 40-75 tons.

Various types of rigs or spreaded bars can be used to lift the modules. Although direct lifting is an option for smaller modules, spreaded bars are used for most projects in order to keep forces perpendicular to the module and reduce the possibility of introducing unwanted bending forces within the module. <sup>[3]</sup>

In most cases, modules will be lifted directly from the flatbed trailer into their final location. In case of the multi storey buildings, and if there is enough space to operate (not so common in urban areas) it is more usual to have a small stock to never stop the crane work.

The placing is usually done using the help of the rigs and guide ropes, but depending on the height of the building other ways must be used, as additional cranes. <sup>[11]</sup>

Modules are stacked between them with interlocking system that will have to ensure the force transmission between the different units of the building. Most simple ones consist on bolts and additional fastening with steel plates. These connections must always be especially resistant to different weather and ambient conditions. The protection also has to ensure a

certain fire resistance. The cladding can be applied in factory or on site, and most commonly it is a combination of both, due to the fact that some parts of the cladding usually cannot be applied previous to finishing the connection. [2]

### 2.3. MATERIALS

Modular construction units can be classified depending on the materials that are used as their main structure. Of course, the total modular unit is a combination of the basic construction materials. Within these structural materials are concrete, steel and timber. Also GFPR (glass fibre reinforced polymers) has been used but it is not common. GFPR is part of the new materials that are being tried in the developing market of modular construction.

Some of the non-structural parts of the modules as facades, bathroom fittings, plumbing and insulation etc. use a large number of newly developed materials for optimal performance, but they are not going to be analysed.

#### WOOD

Wood has been the most used structural material in modular units. This is because modular construction has been for a longer time tied to the single-family home detached houses, where wood stands out for its low price and good performance. The low weight of the wood makes it very easy to transport and place on-site with a medium crane (up to 40 tons). 9

However, not only in modular construction, the last few years have seen a trend toward taller wood buildings, driven by their acceptance in building codes and the value they provide. The designers appreciate it because of its ability to offer a high density at a cost that is typically



Figure 2.3.1 Wood made modular unit at the manufacturing plant.

less than other materials. They also recognize the versatility in design that helps with projects focused in affordable urban in-fill and community projects. Wood is also recognized as a renewable and energy-efficient material helping with LEED certification and sustainability overall.

In modular multi-storey buildings wood has gained that acceptance specially in low-rise buildings, as it has many restrictions in tall buildings. More than four storeys become very difficult to achieve using just modular construction without combining with other more traditional techniques that can support the building for lateral forces. This limitation with wood makes them require substantial structural elements added to them, which makes them uneconomical.

Wood modular units are limited in height and require a deep ceiling to floor connection. They are often finished with primed gypsum wall board before shipping, but appliances, millwork and heavy finishes like tile and stone are installed after the placement at the site. The reason for this not completed modular units is that wood structures are not usually prepared to withstand the loads of transportation and placing, so any added weight that can be added later won't be part of the basic modular unit. Often they require temporary bracing to resist those transit loads. <sup>[12]</sup>

### STEEL

Steel is used in modular buildings that require a more robust structural system than wood modular buildings. These requirements can be related to the height, high performance buildings, seismic-designed buildings or related to the transport and placing. Therefore, they have become popular in mid-rise to high-rise multifamily buildings, where they are the first choice for designers.

Steel frames are strong and rigid enough so they don't have to be over-structured for the transport and placing stage. This also allows the units to have a higher level of completeness, as the added weight can be supported and these added components won't have excessive deformations in the phase between the factory and the final on-site assembly. The modules are therefore generally finished out in the factory with insulation, infill framing, wiring, ducting, appliances and millwork to reduce the job to be done after the final placing. This makes a great difference in time and therefore cost savings. <sup>[9]</sup>



Figure 2.3.2 Corner supported steel module



Figure 2.3.3 Light steel frame modular unit

In a combination with the other materials, steel structures usually use a concrete deck for the floor slab, to add rigidity to the floor structure. Due to the fire vulnerability that only steel multi-storey buildings can have, a maximum effort has to be put in the fire protection of the key connection and structural elements. Wool insulation is often used for fire and also noise protection.

The strength that steel gives structurally specially in its resistance to lateral forces makes it the primary option for high-rise buildings, proving to be even cheaper than a cast-in-place concrete structure. The rigid and robust structure allows larger opening spans, reduced need for lateral bracing and more design flexibility. As mentioned before, the self-supporting strength is also enough to resist the transport without needing temporary support, making the costs of transport cheaper than in the other structural material cases. Mate lines are more structurally sound due to ease of connections and higher capacity of connections.

Its higher quality construction than wood stick-built and wood modular will help mitigate the negative market perception of modular construction as cheap construction.

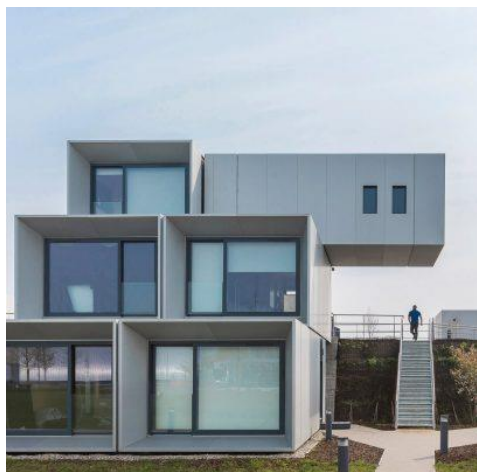
### CONCRETE

Concrete modular buildings are not very common. Even if the first high-rise modular building had a concrete based structure (Palacio del Rio hotel in San Antonio, USA), the material has proven to be considerably more expensive and its performance doesn't match the light and rapid to build spirit of the modular buildings.

The precast concrete on the modules acquires a great quality, but its weight for the transportation and placing requires an over-structured unit, causing even more added weight. This results in higher costs of transportation and placing, need for bigger trucks and cranes. Also, corner areas are usually have a high potential to crack. <sup>[13]</sup>

Another problem of the concrete is the sustainability aspect. It is considerably more difficult to reuse or recycle its materials, as connections are more rigid (many times by poured concrete), losing one of the main advantages of modular.

Concrete is more used in prefabricated buildings as a core in high rise buildings (that can be combined with the modular units) or in panels for partially prefabricated buildings.



*Figure 2.3.4 Concrete unit based modular construction.*

## 2.4. OPPORTUNITIES

### SCHEDULE

Modular construction allows for compression of the building schedule, due to the ability to overlap the different post design stages, allowing the overlap of module construction and site work. As foundation work is being done on site, fabricators and manufacturers can start building the first modules at the same time, speeding the construction process.

Less time on site also means a lower probability of disrupting events such as the impact of weather, which helps ensure on-time delivery of components to the job site.

The shortened construction schedule is the greatest cost saving cause for the modular construction system. Construction times can be reduced up to 50% (DeLuxe Building Systems estimation) <sup>[14]</sup>. Reducing the time that large expenses such as cranes, hoists and permits needed for a construction is further reduction of the overall cost.

## Modular construction in multi-storey buildings

In that overall schedule reduction, the key part that makes modular construction unique is the factory time efficiency. This refers to the decreased time required to perform a given task in factory relative to in-situ construction environments. There have been estimations (Kullman company) were 70% of the reduction was achieved relative to the in task time for work performed in their factory compared with the same tasks performed in the field. <sup>[14]</sup>

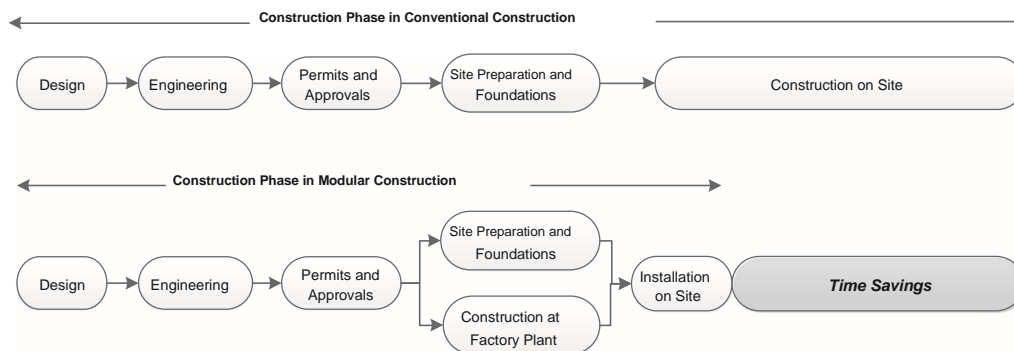


Figure 2.4.1 Schedule comparison in flow charts.

In regard to the module construction speed it is clear that it depends on the project type. It varies depending on the scale of the project, the customization of each module (more similar repetitive units are built faster), the site conditions and the investment done for the shortening of the duration. Modules can typically be installed at a rate of 6-10 modules per day in multi storey buildings with one crane, depending on the conditions and scale of the projects.

It has to be taken into account that the design process will take more time than in a traditional-built project, as the customization and planning for the modular projects can be longer.

## COSTS

The combined advantages of the modular construction can be synthesized into one; the reduction of the building's costs throughout its life, from the building construction project to the final disassembly.

Many are the factors that can lead to the lower costs. Two types of costs are going to be differentiated: hard costs and soft costs. The first ones are relative to the costs that the client pays to the contractor. The second ones refer to other expenditures or lost revenue associated with the contractor.

### *Hard Costs*

- Factory time efficiency: It will help to lower labour quantity and therefore paid hours. That higher efficiency is achieved by the easier access to all the parts of the modular units and the non-disruptive off site conditions, as compared to the weather changes, city logistics etc. problems that can appear in a traditional construction process. Factory organization and optimized repetition of tasks make the manufacturing of modular units considerably cheaper. Also the scale of the projects has to be taken into account, where bigger scale projects as the multi storey modular buildings can shine.
- Lower labour rate: The rate of labour in urban areas and in on site production is more expensive than the factory work's rate of labour. The repetition of tasks allows less specialization in the work force. Also, on site traditional construction work has high union controlled labour rates that take into account risks on the workplace and that are much lower in the factory-based production. <sup>[14]</sup>
- Decreased general conditions: These are typically 10-12 % of total hard costs. Modular construction allows for fewer components, shorter use and even the elimination of many components. Things as required urban space, use of dumpsters, security service, craning and temporary adaptation of the work site are notably reduced. <sup>[1]</sup>

Also, regarding to the used components and materials, prefabricated components, systems and modular units are assembled under controlled conditions using materials which are often ordered from the supplier cut to exact lengths. This results in more efficient material utilization.

- Fewer incidences: This refers to the costs of unplanned incidents in the process. It considers defective material, accidents in the workplace component, terrain or machinery. In the case of components, for example, in the sequence of being ordered, stored and installed can occur a number of incidents that are reduced thanks to a factory based manufacture. The budget allotment that contractors usually make for this incidents can be reduced thanks to a more precise and controlled process.
- Transportation: Modular construction has an overall lower transport demand. The transportation of the modular units is done in a more continuous and rapid stream that

reduces costs in comparison with the classical more divided in time transport of a rawer material.

In the costs aspect, two major ideas have to be also considered: First and foremost is the off-site manufacturing expenses. These of course are the most important cost that are exclusive to prefabricated (including modular) construction. As in any other industry, in this part of the cost the scale of the economy is crucial. Secondly, other expense that is inherent to the modular construction is the redundancy and robustness requirements, that lead to additional use of materials. Each unit has to be resistant enough to endure its own loads during the whole process, which derives in a 5% more structural material than similar in-situ construction. <sup>[15]</sup>

### *Soft Costs*

- Financing: The mentioned certainty and reduction in the schedule makes modular construction projects an easier investment opportunity for the lenders. This is because the risk in forecasting future market conditions increase with time. There is also a lower risk of contractor cost overruns or delays and an increase in the reliability and quality of project outcomes. <sup>[1]</sup>  
This lower risk and shorter schedule provokes a reduction on the loan costs, with a lower interest.
- Less out-of-time service: For certain projects such as building additions or replacements, reducing out-of-service time results in a very significant cost savings. Cost of temporary alternatives for the reconstructed building are reduced.
- Faster return on initial investment: For almost all income-producing projects a faster return on investment is a significant financial benefit. Shorter construction period means an earlier occupancy, therefore a quicker revenue. <sup>[16]</sup>



### BUILDING PERFORMANCE

#### *Factory climate conditions*

It is one of the greatest contributors to the high quality in off-site construction. Inside a factory with a controlled environment, the work is not subjected to the changes and hardening of weathers. This will result in a better quality for the product since it won't be deteriorated by water events and was built by individuals not burdened by their environment.

The climate inside the factory can be controlled and monitored for achieving a proper air quality and ventilation. Many of the indoor air quality issues identified in new construction result from high moisture levels in the framing materials. The potential for high levels of moisture trapped in building materials is reduced with modular construction since the modules are assembled in a dry factory setting. <sup>[14]</sup>

However, sometimes in the industry open-air facilities or not climate controlled factories are used, and even if the workers are not directly in the sun, snow or rain, outside temperature is still a factor to consider and some issues related to the traditional building system appear, as the loss of quality due to the humidity of the air.

#### *Worker safety*

The more a construction relies on prefabricated elements, the safer the construction can be from a worker's standpoint. The chances of injuries are reduced drastically because assembly takes place in a monitored environment, with much less hazards than in an on-site workplace.



Figure 2.4.2 Permanent scaffolding erected around building modules on a Factory floor. Photo by Hopkins, Anthony Scott.

The risk levels reduce due to changing from a traditional on-site construction environment to a classic manufacturing industry, with a much shorter phase on-site.

In traditional on-site work, it happens often at excessive heights, urban areas with crowded traffic, and fall hazards are commonplace. In a modular facility, however, work is often performed at ground level, and if elevated, there are permanent scaffolding structures in place to make that possible <sup>[17]</sup>. As seen on picture, elevated platforms with railings prevent falls and provide a continuous path around the perimeter of the structure. Without a railing, workers are required to have fall protection on construction sites when working at heights greater than six feet. This is typically a harness worn by the worker and tethered to an anchor on the building.

Moreover, a safety plan is easier to apply and monitor in a factory, where the workforce is more constant and routine protocols are common as opposed to the on-site work, where there are many subcontractors and the enforcement of security measures is much more difficult. <sup>[12]</sup>

### *Overstructure*

Due to the loads that the modular unit are going to suffer during the transportation and final assembly, a higher level of structural strength is required compared to the traditional construction. Furthermore, the materials must be lightweight, durable and resistant to weather <sup>[18]</sup>. So, by the very nature of its transportation requirements, the housing product is ensured to be of a higher standard.

Since each module has its own support, when modules are put side-by-side and on top of one another, floor, roof and walls get a double layer corresponding to the next module in that direction. These redundancies, while they are not optimal in the material saving aspect, can provide some architectural benefits:

- From the acoustic insulation viewpoint the quality difference is readily apparent: a double layer means a thicker wall for the sound to pass, which is very useful specially in one room residential buildings as hotels or dorms. Marriot hotels have been implementing modular and in their words “guests have indicated that they hear very little outside noise in their rooms. Because the modules have to be built sturdier to be transported, they end up having better sound insulation” [19]
- In the thermal insulation aspect, it also applies the double layer wall benefit. Also, the insulation systems are much easier to apply on a factory based work than on-site.

However, this need for an independent and self-supporting structure also results in a deeper floor structure and wider walls at module mate-lines than would be typically found in a traditional building project. The result is either a taller, wider building, or a shorter ceiling heights. (Abigail R. Brown, Fabulous pre fab).

### *Material and process controlled quality*

The controlled fabrication is a key factor in the betterment of quality aspect of the modular unit. As in any manufacturing industry, the monitoring and inspection is an everyday task in the modular unit factories. Throughout the whole building process quality inspections are made to ensure a high quality assembly. As the primary elements become a part of bigger systems, in each and every step quality control checkpoints can be established. On comparison, the traditional stick-built receives the tested primary materials or building products on site and few accurate controls can be carried out once these are within the building system. Therefore, modular construction allows a better monitoring of the work quality with the quality controls in each assembly station, which eliminates error and is more time efficient than the testing of bigger systems at the end of the production, that is, the testing of the building itself. [20]

Modular units are tested prior to leaving the workshop, and all the subsystems within are checked. Electrical, mechanical and plumbing systems are tested and their quality ensured,

so the final on-site assembly of the building has a more certainty of the correctness of every part of the assembly, leaving the connections as the main part to be tested on site.

### *Repetition, stability and predictability*

Repetition, stability and predictability are tightly related between them and make the factory based work monitoring and quality control possible. Hence, not only time savings are a cause but also an overall top quality is achieved thanks to that repetition.

Similarly to any manufacturing industry, a higher level of consistency is produced by the repetition of construction tasks in the modular unit industry, and the use of automated machinery is more easily brought to the process. Skilled labour working in the fabrication shop is more permanent than the temporary skilled labour onsite, causing a better knowing of the task and therefore a more precise and more quality work. <sup>[21]</sup>

In probability theory, the law of large numbers describes that performing the same experiment (factory task in this case) a large number of times results in an average result closer to the expected value, that is in the case of the modular unit factory, the time that each task takes. Consequently, repetition of tasks allows a greater stability in factory-based work for each modular unit and so a greater predictability in the manufacturing of modular units and the overall construction process.



Traditionally the general manufacturing industry work has been as automatized as the level of repetition that the product allowed, which was a constraint in terms of varying the design

from the basic product. However, with the third and fourth industry revolution and the appearance of the automatized customization aspect, repetition doesn't hold down the modular industry to the basic completely identic design of modular units.

### ENVIRONMENTAL IMPACT

The building of the models in a controlled factory makes it easier to examine all the elements that will be a part of the assembly and the environmental costs of the whole factory based process.

The duration and impact on the surrounding site environment is reduced because of the lesser time the on-site work takes and the fact that most of the works, except for the foundation aspect, is pure assembling of the modular units transported from the factory. This makes it a good choice for urban infill as well as for greenfield sites. It takes a lot of acoustic contamination and traffic problems from the urban areas.

In regard to the material waste, modular construction makes it possible to optimize construction material purchases and usage while minimizing on-site waste. Even if there is the double layer redundancy mentioned before, cost control can come from the fact that manufacturers buy material in bulk and often in advance or immediately upon contract execution which helps to avoid material cost escalation. Bulk materials are stored in a protected environment safe from theft and exposure to the environmental conditions of a job site. <sup>[14]</sup>

Also the previously mentioned better thermal insulation possibilities that a ground level work with full access to the units offer lead to a better environmental behaviour during its life cycle. At the end of its life cycle the aspect of reusability comes into play. Even if prefabricated (permanent) multi storey buildings haven't been disassembled yet, it is known that prefabricated components are much easier to disassemble and relocate to different sites if needed be. If a building has become obsolete or disused modular parts can be saved so that they don't go to waste. <sup>[22]</sup>

All these environmental benefits lead to environmental certifications that the buildings can obtain, causing a better portraying of the building from the buyer and possible government help in the reducing of future costs depending on the country.

These environmental benefits will be further assessed in the Sustainability chapter.

### 2.5. BARRIERS

#### MARKET PERCEPTION

There has been a stigma associated with modular construction with being made of poor quality, low ceiling, not aesthetically pleasing, poor layout and buildings being boring (lack of intelligent building being incorporated in the design and construction) <sup>[23]</sup>. These problems are very much existent today but to a much lesser extent.

The association of modular built homes with the poor quality and simplicity comes from a history of trailer-type and post disaster temporal single family homes that for lack of resources later become permanent <sup>[24]</sup>. Against these popular beliefs the industry is focusing on showing clients the unique architectural opportunities and increased construction quality that modular allows. There is an effort made to avoid pre-fabricated looking houses and making them resemble to traditional stick-built multifamily housing projects.

Participants in a survey <sup>[25]</sup> from larger firms, while conceding that at one time the perception of poor quality was a barrier to the wider adoption of modular construction, felt strongly that anyone working with modular products today, especially in the commercial and industrial marketplace, is convinced of the quality of the process/product.

#### ARCHITECTS

The lack of expertise and knowledge in the Architecture, engineering and construction industry is another important barrier. Architects maybe be unfamiliar with the design type of modular construction, as it involves another type of involvement in the project different from a traditional project. This confirms Schoenborn's <sup>[26]</sup> premise that most architects are unversed in modular fabrication and fail to consider it as a primary design option, thus limiting the broader adoption of modular construction.

Architects don't receive a proper education in modular construction as there are very few courses for teaching up-and-coming architects how to design for modular production. This would mean giving more control to the engineers in the production of the building and working with the constraints that a modular project can have This results on a safer approach and sticking with the traditional system where design is basically controlled by the architects.

### MEP ENGINEERING AND WORKING STAFF

As with the architects, the lack of expertise in the engineering world is a barrier to the development. Very few mechanical and electrical consultants have the discipline to execute the additional up-front planning and connectivity reviews required for modular construction. Most mechanical and electrical consultants work under

the direction of an architect. Thus, as with architects, very few mechanical and electrical engineering companies understand the specialized requirements of modular design. Most engineering consultants are accustomed to providing 50% design drawings, then completing and refining the design during the construction phase. In order for modular production to run efficiently, all of the design and complete drawings must be provided before the modular units go into production. <sup>[27]</sup>

The ground level worker's skill set and education is also a limiting factor. They are usually the less permanent part of the contractor's workforce, so companies can be more hesitant to invest in the education of the unskilled labour force in the changing from traditional methods to modular ones.

On the contrary, modular manufacturers suggest that the modular industry tends to hire staff with construction experience, rather than manufacturing or production backgrounds, which stifles innovation and improvement of modular manufacturing processes. <sup>[25]</sup>

### GENERAL CONTRACTORS

As with architects and engineers, there is a lack of awareness and education about modular construction within the general contracting community. Their lack of familiarity serves to limit a broader acceptance of modular production as a preferred method of construction. Those who are intrigued by the possibilities of modular construction may have limited avenues to learn about the project. The inadequate familiarity may limit their profits and slow down their efficiency, consequently, they are reluctant to move away from known processes that make them considerable money. Also, it is said that general contractors unfamiliar with the assembly of modular buildings view modular as a competitive threat to their established business model <sup>[28]</sup>.

However, as traditional general contractors unfamiliar with or resistant to modular construction begin to retire or otherwise exert less influence on the construction industry,

new, aggressive and innovative general contractors are appearing, many of whom are familiar with or specialize in the assembly of modular structures. [25]

### FINANCIAL

Traditional construction financing is based on monetary draws secured by a structure that is attached to a specific piece of property, which can have a lien placed on title. That means that the land acts as a guarantee for the bank, even if the construction is not finished it will have an increased value once the on-site construction process starts. The uncertainty associated with any project, including a modular project, makes the banks reluctant to invest in a project that will not have the increased value of the land as an asset. This gradual increase of value won't happen as all the added value will be completed almost all at once when the final on site assembly occurs.

However, some new construction funding vehicles are now being offered by innovative financial institutions, utilizing novel methods such as independent quantity surveyors to measure and guarantee performance, perhaps explaining why both the barrier and the severity are rated low. [25]

### MECHANIZATION OF THE PRODUCTION PROCESS

Modular construction represents a transfer of construction expertise from the field to the factory, a major change for all the parts involved in the construction process thus involving a change of mind-set from "building" to "manufacturing". To fulfil this change, a great investment in equipment to automatize the process is needed.

While a return on investment can be realized with a regular production cycle of large projects, high initial costs leave modular manufacturers ill-equipped to compete on smaller projects. With the undergoing changes on the manufacturing industry, the developing ability to customize the products may change that. Future equipment of the industry may be able to do that.

Nevertheless, the total automation of the process is something very difficult to achieve in the modular unit manufacturing for now. Most individual parts allow a great degree of automation but doing the total assembly of the unit and the work to do on some details as mechanical electrical and plumbing and finishes, for example, is for the moment impossible



to achieve. A lack of mechanization in the production is stifling productivity increases and, thus, limiting the broader adoption of modular construction, making large companies less eager to enter in the modular construction business.

### TRANSPORTATION

The transportation barrier consists on the challenges that appear in between borders of states and countries in regard to the different regulations of transport. The transport of oversized modular products isn't well established as common in many areas, which can cause problems from the authorities.

The cost of transportation is also another factor to consider. If the factory location is far from the building site cost of transport increases notably, losing the cost advantage over the traditional system. This makes modular construction more difficult to implement on areas with low density of population, as the area that the factory is going to cover is smaller.

### COMPANY SIZE

Finally, the company size barrier is partly a consequence of some factors mentioned before: The scale of the investment needed for starting the mechanization of the process, which makes it very difficult for smaller companies to start from zero on the modular unit production; the transportation factor can be seen as a source of problems that affect more the small size companies as in smaller projects it can have more effect. Also, the small market that actually the modular construction occupies makes it very difficult to have a more classic distribution of smaller and bigger companies facing the same market.

While smaller manufacturing companies seem to more quickly embrace the innovation of modular construction due to the difficulties of big companies to change completely from the traditional system, these new ideas are done more individually and without a common "baseline" of standards in the construction process, from design to the on-site assembly. This makes modular construction easier to apply on bigger projects where the developing company is a single one with its standards.

Likewise, smaller companies are less inclined to spend the money required for the evolution off the process in a fast changing business as the modular construction manufacturing is.

Larger companies are more likely to be using innovative design tools, such as BIM, very necessary for the developing of modular projects. <sup>[29]</sup>

Larger modular companies are more likely to view modular production as a manufacturing, rather than a building process, and to have invested heavily in the quality control programs necessary to overcome the stigma of poor quality <sup>[30]</sup>. They can invest more easily in all the parts of the process and be less dependent of the lack of expertise that outsourced companies can have.

### 3. STRUCTURAL BEHAVIOUR

#### 3.1. MODULAR UNIT TYPES

Modular construction offers a limited variety of types of structure for its units. As on the different degrees of prefabrication like the panelised prefabrication, these elements (in the case of modular constructions the units themselves) can be a part of the supporting structure of the building to diverse extents. Regarding the structure of the individual units that later assembled form the modular building, three main systems are observed:

1. Load bearing modules: Loads travel from the walls directly to the foundations



Figure 3.1.1 Load bearing module made of

2. Corner supported modules: Both gravity and small lateral loads of each unit goes to the corner columns where they are directed to the foundation.



Figure 3.1.3 Light steel corner supported module



Figure 3.1.2 Steel corner supported module.

3. Advanced Corner Supported Modular Structural System: Where gravity loads are transferred through the side walls of the modules and lateral loads are transferred through lateral column to column connections as those in corner supported modules.

[31]

### 3.2. STRUCTURAL SYSTEMS

These types of modular units are the base for the principal four structural systems in modular buildings:

#### 1. Load Bearing System

These types of systems are typically one or two stories in height and occasionally slightly taller. The gravity loads of stack of load bearing modules are run down through the side walls down to the foundation. There is no collaboration in the support against lateral loads from the connections between modular units.

For these cases, usually used for single family home or temporary buildings light steel frames are used. This material allows to integrate lighter weight materials, and is also easier to transport and lift in the installation process, but its limitations for multi-storey construction are evident. For heavy loaded structures where lateral loads are more important, that is, all multi-storey buildings, mostly structural steel shapes are used, such as Rectangular or Square Hollow Sections, I-Sections, and so forth.

Axial load is transferred via direct wall-to-wall bearing, taking into account eccentricities in manufacture and installation of the modules, which causes additional build-up of moments and accentuates the local bearing stresses at the base of the wall. <sup>[9]</sup>

#### 2. System with central reinforced concrete core

As the height of the modular buildings go up load bearing structural system cease to be a choice and more conventional ways to resist the lateral loads, as the reinforced concrete core, are used.

With taller buildings also erection and installation issues gain importance, that is why prefabricated modules should be kept light (for example, by using light gage steel) and as a result they have lower lateral stiffness in comparison with regular rolled steel framings. However, conventional concrete shear walls and frames, braced steel frame, and steel moment frames have higher lateral stiffness in comparison with prefabricated modules. By installation of one or more of these stiff systems between modules as the core, lateral

deformations of the whole structure can be reduced. Under lateral loads, the diaphragms at the floor levels will transfer most of the lateral loads to the stiffer (core) parts of the structure. Therefore, the connection between the core structure and the modules should be strong enough to transfer tension-compression and vertical loads between these two structures. <sup>[31]</sup>

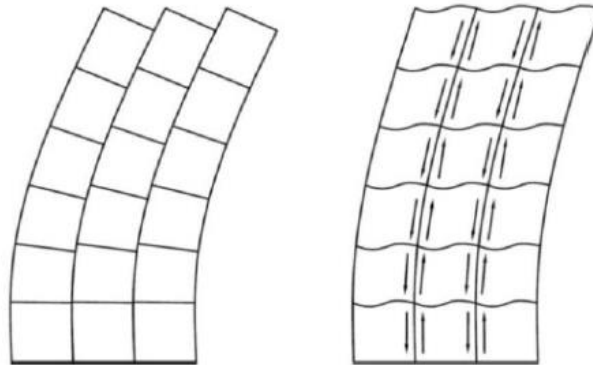


Figure 3.2.1 Vertical shear transfer between stacked units. Left side, no vertical transfer. right side, coupled at vertical joints.

### Modules that are connected to the core directly

This system consists of corner-supported modules as introduced previously. The gravity loads are transferred down via the perimeter or corner columns of each module. In the case of the lateral loads are supported by the central core column solely, and the modular units act only as a road to pass the lateral loads from the outer perimeter (in the case of wind loads) and also the interior (for seismic loads) to the central reinforced concrete core.

One vertical stack of modules acts as one block of vertical loads. The modules are connected laterally to the central core either directly or through neighbouring modules, but no vertical shear is transferred.

This system can go up to any height, therefore being a structural system available for high buildings made with modular construction. The lateral connections are crucial in the safety and stability of this system, and become very expensive as the lateral loads go up. That is the main reason why this arrangement of modules is used in structures that have no more than 8 or 10 stories high typically. <sup>[31]</sup>

The central eliminates the chances of the building being a complete modular structure. Effectively it reduces the amount of benefits such as reusability and reduction of construction waste that a fully modular solution would otherwise present to the end user. It is, in other words, a semi-prefabricated form of construction, as a part of the structure is built in the

traditional way. Anyway, the RC core can be built in advance, before or while the modular units are being assembled on site.

### System with central reinforced concrete core where modules are stacked up in rows and the floors are eventually poured with concrete

The poured concrete fills the void between the modules above and under of the floors. This concrete will act as a stabilizer against lateral loads, being a rigid diaphragm connected to the core to transfer the lateral loads to it, and transfer vertical shear through the stacked units. The concrete core column will gain axial stiffness and will put the perimeter columns in compression (leeward columns) and tension (windward columns) as show in figure. This equals in a floor scale to the outrigger structural systems against lateral loads for high multi-storey buildings, where the outer columns of the floor are tensioned and compressed. This system has been used for the tallest skyscrapers made until the time in modular construction. However, this system relies on an excessive use of material (concrete) and makes impossible to reuse the modular units as a whole. The disadvantages that were mentioned in the previous structural system are even more evident, as a bigger part of the upper structure is built in the traditional system, and concrete has to be poured in each floor without being able to make it in advance. Even if the core can be built before the assembling of the units, the concrete diaphragms will slow down the construction, because of the waiting period on each poured concrete slab.

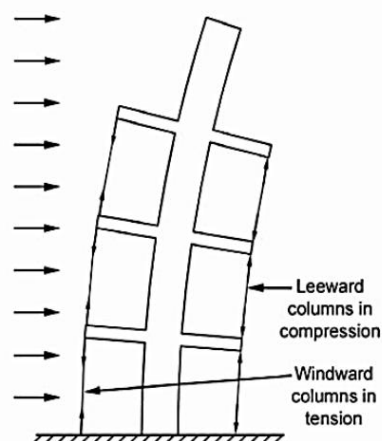


Figure 3.2.3 The response against lateral loads of modular buildings with a slab of concrete.



Figure 3.2.2 Image of a building with this system.

### 3. Advanced corner supported modular system with stiff modules

This is a system where the dependency of the central core is no longer a constraint to the structural system. All the loads are resisted by the modules themselves, that are not only self-supporting but also able to resist lateral loads thanks to their stiffness achieved by stiff concrete walls. In this new structural system, a cast-in-situ or prefabricated core is avoided in the superstructure, as the modules themselves will resist the lateral loads.

This technique stacks the modules vertically and connects them horizontally through bolted plates. The lateral consistency for lateral loads is provided by these connections and improved by a series of modules with stiff walls, which are strategically located to resist the majority of lateral loads and centralize the rigidity and mass centre of the building so eccentricities are avoided.

The result is a mixed system of steel columns, that are more focused on the gravity loads and the concrete walls, that will resist the lateral loads. Walls and columns work together in both cases, but each being the most important one in its specialty.

As opposed to the placing of the elevator shaft and staircase in an imposed central core, the disposing in a prefabricated module gives the opportunity to locate these anywhere. It eliminates the time and costs incurred in building the traditional core of a low-rise building. Vertically running building services that are traditionally housed in the central core can also be placed in prefabricated modules.

As we can see on figure, a structure against lateral loads that relies solely on a central core will have to be placed on the centre of the building so that the shear centre and the centre of mass coincide. On figure there are presented different arrangements of the elevator shaft in an advanced corner supported modular system with stiff modules that locate the shear centre in the middle point. This centre coincides with the gravity centre, independently of the location of the elevator shaft. Hence, a great level of architectural freedom is achieved in the design. <sup>[31]</sup>

It also gives the opportunity for stiffer walls to be constructed using innovative materials, such as composites and high strength concrete and steel. These stiff walls can also be built by filling after the modules are placed.

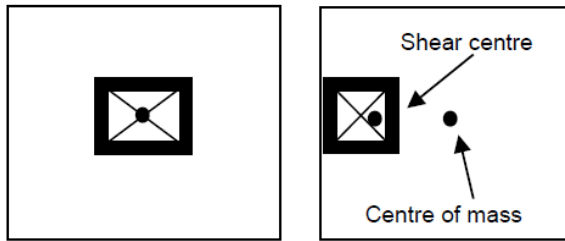


Figure 3.2.4 It is shown how the elevator shaft does change the shear centre in a conventional building with RC core

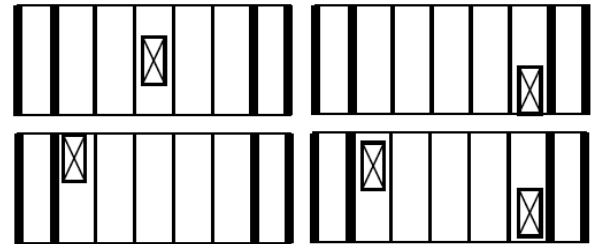


Figure 3.2.5 In advanced corner supported modular system the shear centre does not change, being able to move the elevator shaft with freedom.

This advanced corner supported system was introduced by Tharaka Gunawardena <sup>[31]</sup> in his thesis analysing the behaviour of prefabricated modular construction against lateral loads. It is presented as a fully modular approach for designing low to medium-rise multi-storey buildings, without the need to add structural supporting systems as RC cores that resist the lateral loads.

This way of constructing with a purely modular approach has given very good theoretical results, but it is yet to be seen in a real constructed building. The preliminary structural analysis showed that the system results in a structure that behaves within the parameters set out by design standards for conventional structures under normal loading conditions. A nonlinear earthquake time history analysis was also done considering the possible geometric and material nonlinearities that may arise in the system when subject to more severe dynamic lateral loads. The resulting drift values were mostly within the specified limits, but further studies are required to obtain a more detailed understanding on the failure mechanisms and redundancies of the system <sup>[31]</sup>. This thesis fills a knowledge gap that has resulted in a lack of confidence in the structural engineering design against lateral loads, causing an uneconomical over-design in order to ensure structural stability and safety

### 3.3. FOUNDATIONS

Foundations are built always before the modules begin to arrive on site. The “Just In Time” production that is a part of the modular construction philosophy limits the stock of modular units to have constructed before carrying them to the building site, therefore foundation construction has to start while the modular units are being manufactured.

Almost any foundation system can be used with modular construction depending on the superstructure, site and soil conditions. In the case of load bearing construction, usually



distributed loads are placed on the foundations, whereas steel framed modules often produce point loads. Hence, perimeter concrete, pre cast concrete footings and bored pile based foundation systems are more common for steel buildings.

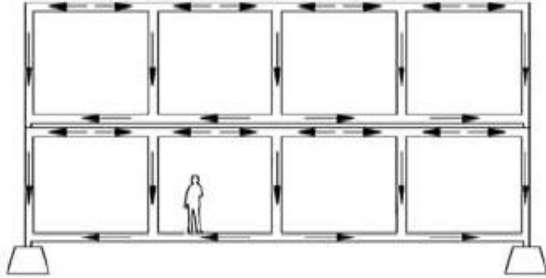


Figure 3.3.1 Sketch of how the loads travel through the structure to the shallow foundations

Concrete podium construction is a good choice for multi-storey residential buildings since it allows for the larger spans required for parking and retail, but it makes the modular construction less prefabricated losing part of its advantages, as the first storey is built in a traditional manner.

The hybrid podium-modular system is normally used in structures that need longer bay spans in lower stories. In podium-modular systems, some of the bottom stories (usually two stories) are built using conventional structural steel or concrete frames with long spans. Then, the modular part of the building would be installed on top of the podium. In other words, the podium is like a foundation for the modular parts. The modules transfer their uniform load to the beams of the podium. In addition, a podium structure with long spans behaves as a soft story for the structure leading to an increase of the period of the structure, which results in a decrease of design earthquake forces. [32]

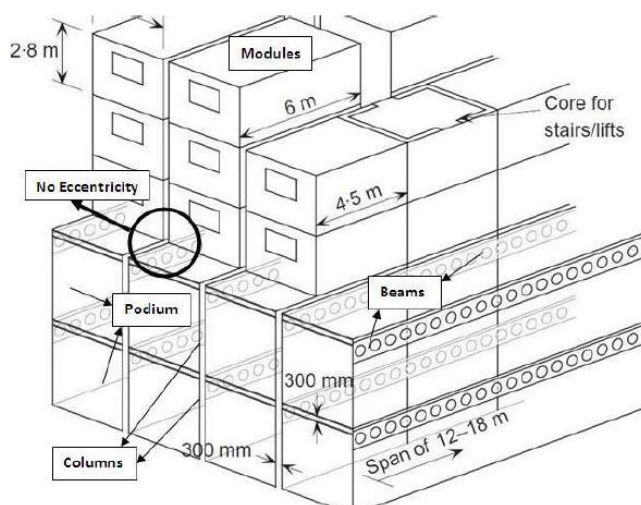


Figure 3.3.2 A 2-Story podium beneath a multi-story modular building (Lawson et al., [32])

The levelling of foundations or grade beams is crucial to the subsequent installation and alignment of modular units. Often it is necessary to provide for some adjustment in the foundation or in the legs of the modular unit. Each manufacturer had developed its own proprietary system for locating and fixing mechanisms to aid in the positioning of units on the foundations. Generally base plates, steel strips, or cement particle board are fixed to the foundations and grouted and levelled as necessary to take up any inaccuracies in the top of the foundation. <sup>[33]</sup>

Low rise modular buildings located in areas with high lateral loading may be vulnerable to overturning and sliding failures if not adequately restrained by connection to an appropriate foundation. Building modules are commonly connected by chains, cables, keeper plates or welding to concrete or steel piles, or large mass concrete footings. Each connection type has associated disadvantages including tensioning requirements for chain and cable. In medium and high-rise construction foundations are more substantial. Base plates may be incorporated in modules and fixed to cast-in anchors, or welded on site to accessible cast-in plates. <sup>[34]</sup>

### 3.4. STRUCTURAL ISSUES

In addition to specific issues related to each structural system of multi-story modular buildings, there are some common issues that should also be addressed in all different types of these modular structures.

In the design of any structure of a building against earthquake loads, as the international codes require, the ability of the elements to convert seismic energy into deformation of the elements is taken into account by the ductility aspect of the structure. That ductility will lessen the design earthquake forces by a factor called R (Response Modification Coefficient). As for the modular structures that R value cannot be estimated easily without doing model testing due to the difference in lateral resisting systems from one modular construction to another. In nonlinear design of conventional buildings, plastic hinges form in members near the connections, but in the case of modular construction such plastic hinging in members is not expected to occur because there are usually various flexible joints in the system. Therefore, less conventional ways must be sought to dissipate this seismic energy. <sup>[35]</sup>

Another difficulty of the modular structure happens in the design process. Its modelling is complicated because of the variety of joint and support types with unknown load-deformation properties. For practical application of finite element modelling of modular systems some simplifying modelling assumptions are necessary, like the use of individual sub-frame models for each module.

Other possible structural problems may arise in the highest kind of multi-storey modular skyscrapers, where any small eccentricity can cause considerable added loads. That causes lower modules to be sometimes too over dimensioned, with too much redundancies to keep an efficient use of the materials. <sup>[31]</sup>

### 3.5. CONNECTIONS

Due to the possible discontinuities that are intrinsic to the union of independent elements as the modular units, special attention is placed on tolerances and connections. Significant differences exist between the methods of construction of modular buildings and conventional steel or reinforced concrete buildings. For example, the floor-system is typically designed as a grid structure that consists of floor stringers and beams.

Modules must fit into their small locations within the main structure and between adjacent modules, often carrying great loads and subjected to tight tolerances. Inadequate fit is unacceptable and costly to adjust onsite.

These connections must be accessible connections so that onsite installers can reach work simply and fast during the final assembly. The low height of the modules also helps make the inside connections that sometimes are to be done. Those are the connections that do not allow workers to access parts in order to bolt, screw, seal or nail. The accessibility of the connections is also needed in the disassembling process or during maintenance. <sup>[36]</sup>

Connections are grouped into three types: inter-module (module to module); intra-module (inside module) and module to foundation connections. In the following figure (3.5.1) it can be seen what those three types encompass.

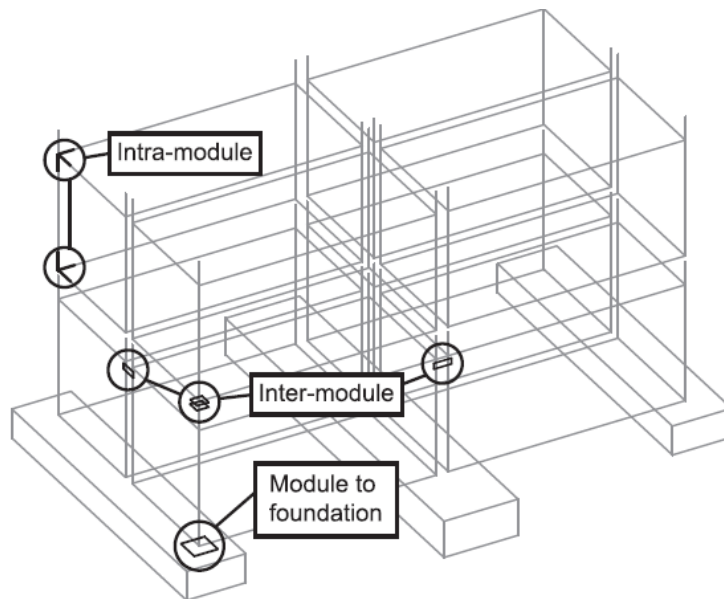


Figure 3.5.1 Drawing of the three types of connections mentioned.

### *Inter-module connection*

These types of connections include horizontal connections between adjacent modules in the horizontal plane, and vertical connections between stacked modules. Researches show that bolted on site tensioned connections are the most used ones over site welding unions. This is due to the reduced site work they require and its simplicity to be handled in the disassembling. Welded connections offer a better stiffness and alignment of the units and also require less space, but demand more on-site work and are disassembled at great cost, which goes against the modular purpose <sup>[13]</sup>. However, bolted connections can be complex to accommodate in points where three direction inter-modular connections are done. Use of long-slotted holes may introduce the potential for tolerance accumulation over multiple levels, and vulnerability to slip failure in the event of large horizontal force. The potential for connection slip may be controlled with the use of friction-grip or pre-tensioned bolts <sup>[32]</sup>. In some cases, concrete or grout is used to lock the joint in-place, creating a composite concrete-steel connection.

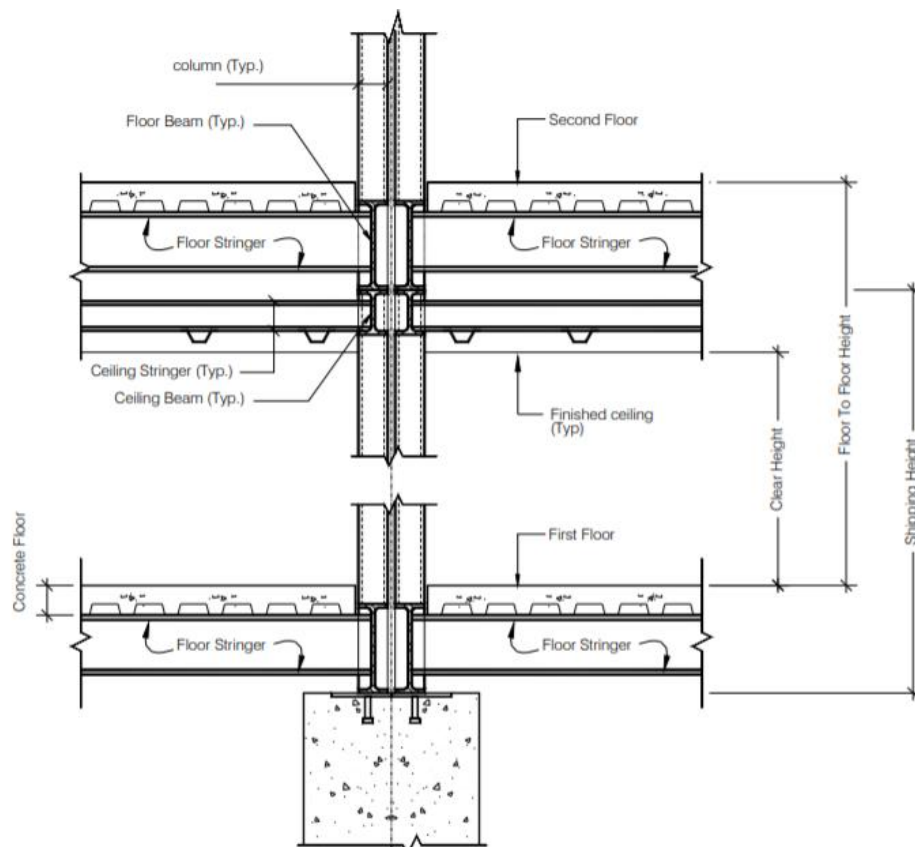


Figure 3.5.2 A section of a typical modular floor assembly, retrieved from [36]

A small gap is usually left between the floor and ceiling beams, as show on figure 3.5.2, allowing for external access to the connections and giving space for services to pass between modules.

Generally bolted type connections are used, but there are a wide variety of inter-module connections, some of them patented and of exclusive use of module construction developers.

[36]

### *Intra-module connections*

In the connections within a module in steel buildings both welded and bolted connections are used. Bolted connections are more simple to be deconstructed for later reuse of the steel elements, but they offer relatively low moment capacity, rotational capacity and ductility. Usually strengthening of the connections is done to avoid these weaknesses. Within bolted connections, the common ones are single fin plates, double angle cleats and bolted end plates.

Welded unions with the use of plates are better to ensure module uniformity and they are suited to a factory based construction, but they do not permit rotation and should be designed for the hogging of steel members. [32]

### *Module to foundation connections*

Foundations, as explained in the previous chapter, may consist of in situ or precast concrete footings, bored concrete piles or some combination, and including their connections to the lower modules are the part that takes more time to build.

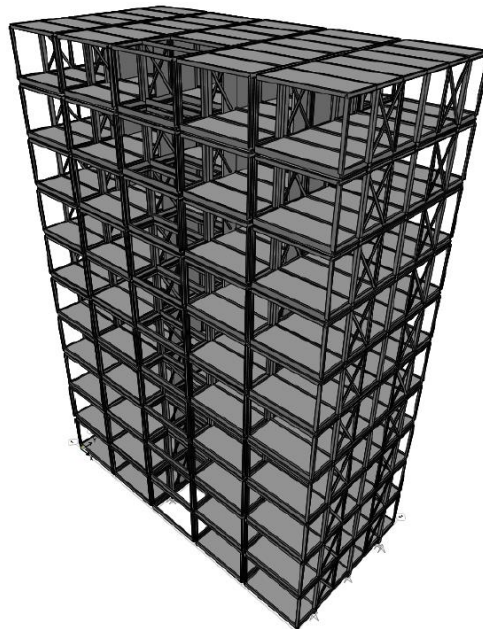
Modules are commonly connected by chains, cables, keeper plates or welded into the piles or mass concrete footings. Each connection type has associated disadvantages including tensioning requirements for chain and cable, that are low cost and limited to low rise construction for the lower risk of overturning moments. Base plates may be incorporated in modules and fixed to cast-in anchors, or welded on site to accessible cast-in plates. [32]

## 4. CASE STUDY: SIX STOREY MODEL

### 4.1. INITIAL MODEL

The design of the six-storey medium-rise modular building model is based on a ten-storey hypothetical modular structure made by Tharaka Gunawardena <sup>[31]</sup> in his doctoral thesis where he introduced the advanced corner supported modular system.

A great part of the design is based on that model that appears on the figure 4.1.1, that was modelled using the software RUAUMOKO 3D, where a global structural analysis including non-linear time history analysis was carried out. Also, later it was verified by modelling it again in SAP2000 software, from which the rendering is taken.



*Figure 4.1.1 3D image of the ten storey modular building from SAP2000 on which the six storey building is based.*

### 4.2. DESIGN

The hypothetical six storey building is based on the previously introduce advanced corner supported modular structural system. Using this system, no concrete or steel cores are necessary for the resisting of lateral loads, making it a fully modular system.

Five modules with different structures are used in a row for each storey, as it can be seen on figure 4.2.1. The placement of the elevator shaft or service core would not bear any

implications on the main structure as it is not important for its stiffness against lateral loads. Therefore, it doesn't have to be centred in the middle of the floor to avoid eccentricities between shear centre and mass centre. It won't cause very different additional loads comparing to the normal dead loads, as it can be stacked from the foundation level. So, the shear centre won't be almost affected. In this case it is decided to put it on a lateral side as it can be seen on figure 4.2.1. The elevator shaft has been omitted from the model and substituted by the loads it produces, and the ceiling and floor slabs and beams have been taken out in its place of the central module.

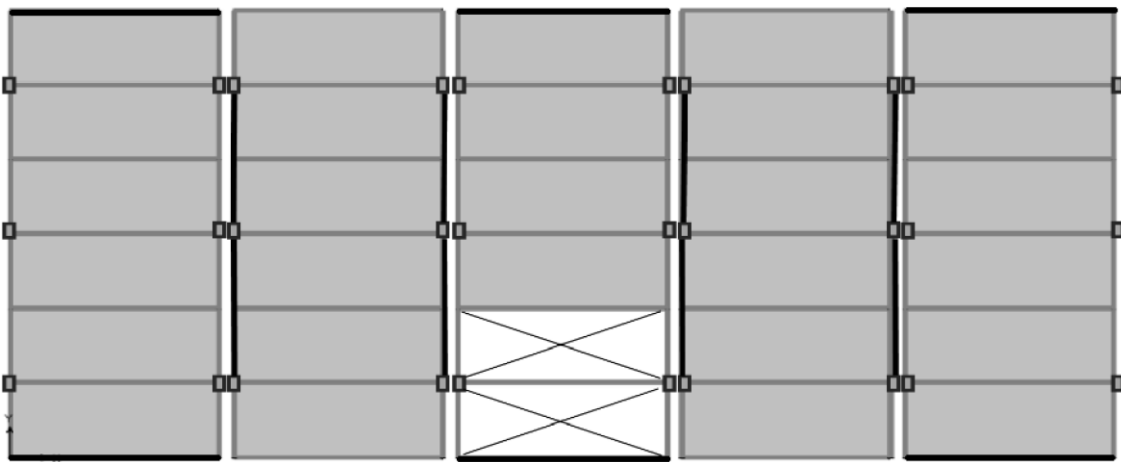


Figure 4.2.1 A plan view of a typical floor of the ten storey modular building considered for the analysis, with the reinforced concrete walls highlighted

Two main types of modules were used for each storey. Both of them have most of the elements in common. Each module has six corner columns with rectangular hollow sections (RHS) of the size 220 mm x 250 mm x 14,2 mm, three on each longitudinal size. Since the building is only 10 stories high and for simplicity, the columns size remains constant for all stories.

The modules are 4,2 metres wide, with 25 mm of space between module node to module node, and 10,8 metres long. The sizes are compatible with the size of transportable prefabricated modules that are used in the industry at present. The height of each module is taken as 2,8 metres, to be compatible with the storey height.

Both of the modular unit types are made up with self-stabilised steel frames, since the modules need to be structurally stable by their own since it is necessary for transportation and on-site handling. This internal frame is composed by internal columns made up of 180 mm parallel flange channels (180 PFC) on the vertical part of the frame. For the horizontal part 300 PFC are used, spaced by 1.8 meters each. Ceiling beams have the same space



between them, but are of the 180 PFC type. Floor and ceiling slabs have 125 mm and 100 mm of thickness each. All the steel members in frame are considered to be of a yield strength of 350 MPa.

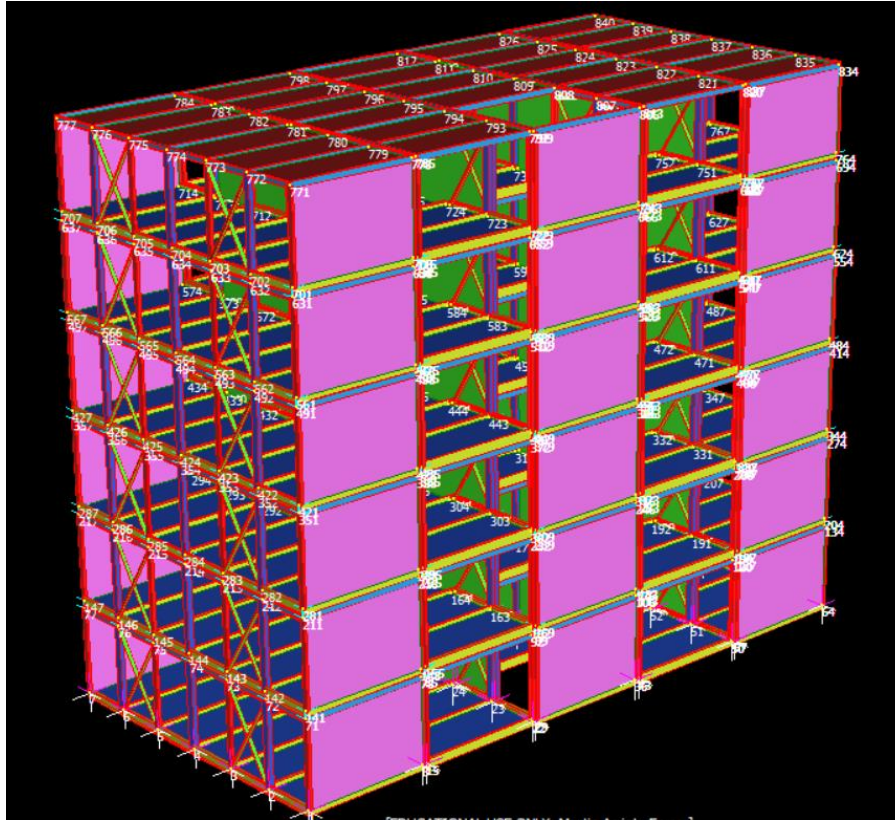


Figure 4.2.2 Model of the six-storey building in Strand7.

They are reinforced against lateral loads in one direction each (X or Y), and therefore vulnerable in the other direction. Depending on the reinforcement direction, two types are defined

- The X type module: This type of unit has reinforced concrete walls of 125 mm in the outside of the shorter side (X direction) of the module (figure 4.2.4). For the Y axis to hold a minimum of lateral loads, the modules have steel bracings made up of universal angle sections (UA) of 100 mm x 75 mm x 8 mm.
- The Y type module: In this case the reinforced concrete walls are in the Y direction, and have a thickness of 125 mm. (figure 4.2.3).

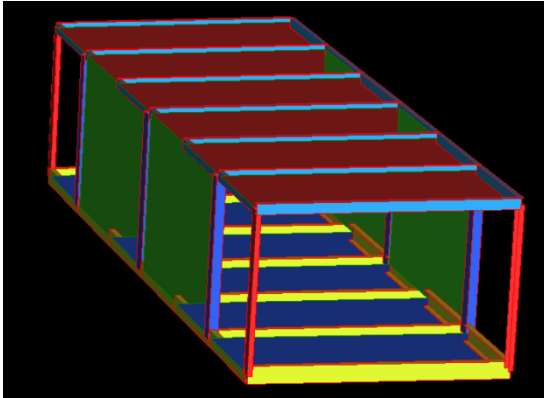


Figure 4.2.3 Y type modular unit, modelled in Strand7.

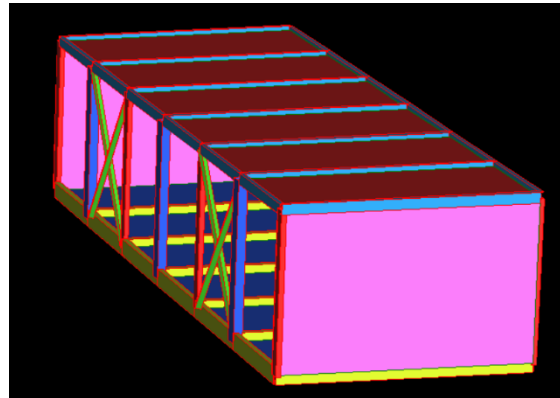


Figure 4.2.4 X type modular unit, modelled in Strand7.

The outer non reinforced walls are supposed to be lightweight wall panels, but the model was to be kept simple, so only the load-bearing frame was considered.

In the Strand7 modelling, concerning the module to module and overall structural connections, the following decisions were taken:

- Foundations are not going to be analysed. Hence, the ground level nodes are going to be completely fixed to the ground during this modelling.
- Module to module connections on the same floor (nodes 1 to 2 and 3 to 4) are done using a beam element of spring type, which has been given an axial and torsional stiffness of  $7 \times 10^6$  N/m for axial and a lateral stiffness of  $5 \times 10^6$  N/m.
- The connections between the module columns (both PFC and RHS sections) and the module above (nodes 1 to 3 and 2 to 4) are done with rigid links that are supposed to represent the continuity of the beams. As long as the failure point of the columns do not happen in the exact connection it is a valid simplification.

These last two module to module connections can be seen on figure 4.2.5, which has been taken from the Strand7 model.

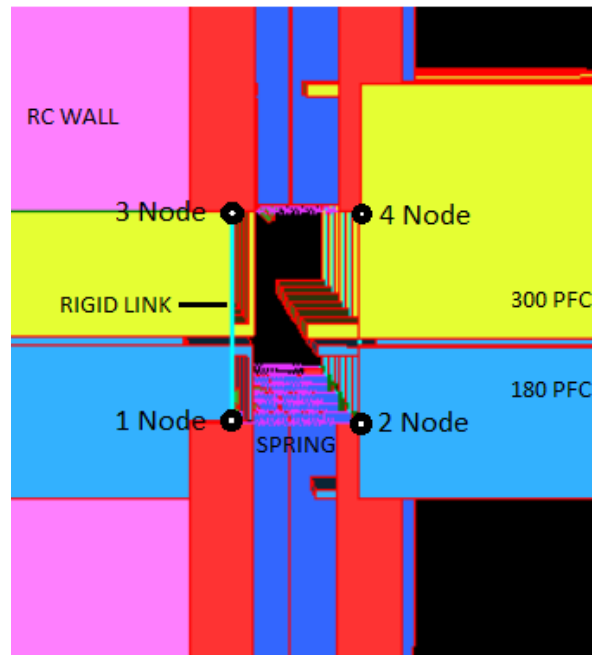


Figure 4.2.5 Inter modular connections (module to module), seen on the model in Strand7.

### 4.3. LINEAR STATIC ANALYSIS

For the linear static analysis the following load cases are considered to do an Ultimate Limit State-based design :

- Gravity loads of the structure ( $G_1$ ): As all the buildings modelled elements are structural, only the effect of gravity is added so that the loads consist on the elements' own weight.
- Dead loads ( $G_2$ ): Making an estimation of the loads, for a typical residential building 3 KN/m<sup>2</sup> has been taken in the intermediate storeys and 1,6 KN/m<sup>2</sup> for the rooftop dead loads.
- Live loads ( $Q_0$ ): 2 KN/m<sup>2</sup> for the intermediate stories (residential building), and 1,3 KN/m<sup>2</sup> (0,5 KN/m<sup>2</sup> of a rooftop only accessible for maintenance; 0,8 KN/m<sup>2</sup> caused by possible snow loads).
- Wind loads in X and Y directions ( $Q_1$ ,  $Q_2$ ): According to the Eurocode, two independent wind directions have been calculated to later be combined. For the calculations a tool from "The Steel Construction Institute" <sup>[37]</sup> has been used, which depending on the buildings location and shape gives you de maximum net pressure

on the different sections of the building. Taking that data the force that each node takes has been calculated following a triangular distribution on each part as it can be seen on Appendix 1, where all the calculations and node forces caused by the wind are shown. Vertical suction forces on the ceiling have been ignored as they are not relevant comparing to the downwards gravity-caused vertical loads.

Different combinations of them are made with favourable and unfavourable coefficients according to the nature of the loads to identify the worst case scenarios and the critical points.

### Results

The linear combinations considered are 32 in total, making combinations by multiplying the forces with the corresponding coefficients according to the Italian building technical code (NTC 2018). On the Appendix 1 the factors for these combinations can be seen. As it is a symmetrical building with its symmetry axis on Y, the wind has been considered from -X to +X direction and wind on Y axis in both directions, from +Y to -Y.

Load comb.	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>	<b>8</b>	<b>9</b>	<b>10</b>	<b>11</b>	<b>12</b>	<b>13</b>	<b>14</b>	<b>15</b>	<b>16</b>
<b>G<sub>1</sub></b>	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
<b>G<sub>2</sub></b>	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5
<b>Q<sub>0</sub></b>	0	0	0	0	1,5	1,5	1,5	1,5	0	0	0	0	1,5	1,5	1,5	1,5
<b>Q<sub>1</sub></b>	0	0	0,9	0,9	0	0	0,9	0,9	0	0	0,9	0,9	0	0	0,9	0,9
<b>Q<sub>2</sub></b>	0	0,9	0	0,9	0	0,9	0	0,9	0	0,9	0	0,9	0	0,9	0	0,9
Load comb.	<b>17</b>	<b>18</b>	<b>19</b>	<b>20</b>	<b>21</b>	<b>22</b>	<b>23</b>	<b>24</b>	<b>25</b>	<b>26</b>	<b>27</b>	<b>28</b>	<b>29</b>	<b>30</b>	<b>31</b>	<b>32</b>
<b>G<sub>1</sub></b>	1,3	1,3	1,3	1,3	1,3	1,3	1,3	1,3	1,3	1,3	1,3	1,3	1,3	1,3	1,3	1,3
<b>G<sub>2</sub></b>	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5
<b>Q<sub>0</sub></b>	0	0	0	0	1,5	1,5	1,5	1,5	0	0	0	0	1,5	1,5	1,5	1,5
<b>Q<sub>1</sub></b>	0	0	0,9	0,9	0	0	0,9	0,9	0	0	0,9	0,9	0	0	0,9	0,9
<b>Q<sub>2</sub></b>	0	0,9	0	0,9	0	0,9	0	0,9	0	0,9	0	0,9	0	0,9	0	0,9

Table 4.3.1 Load case combinations

An example of these combination is shown on 4.3.1, in this case combination 32. In this arrangement of forces, wind loads in both directions are combined so that on the windward side on X direction wind and the suction produced by the Y direction can be added.

The most critical points of nodes, beams and plates have been noted, its value, and which combination makes it.

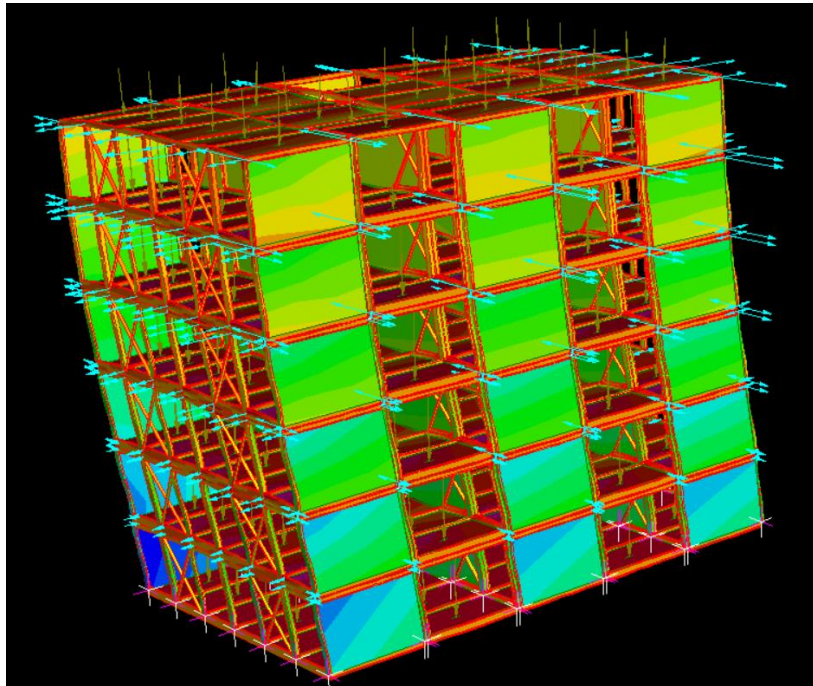


Figure 4.3.1 Load case combination 32

#### NODES

PARAMETER	NUMBER OF NODE	VALUE	COMBINATION
<b>F (Z)</b>	53	8,503e+5 N (x2)	32
<b>F (XY)</b>	9	5,52e+4 N (x2)	32
<b>F (XYZ)</b>	53	8,504e+5 N (x2)	32
<b>M (XY)</b>	44	1,92786e+4 Nm (x2)	32

Table 4.3.2 Maximum node reactions

These values correspond all of them to central nodes, therefore for the connection a double of the value shown on table must be considered. This occurs because of the double-node structure of the connections between two modules, supposing a rigid connection. An image of the node F(XYZ) forces is shown in figure 4.3.1, and two details of critical nodes; node 9 for the shear XY plane force and node 53, which is the critical node in terms of vertical (F(Z)) and overall (F(XYZ)) force resisted.

The maximum overturning moment for the ground nodes happens in the 44<sup>th</sup> node, next to the elevator shaft in the module adjacent to it (the second module in order).

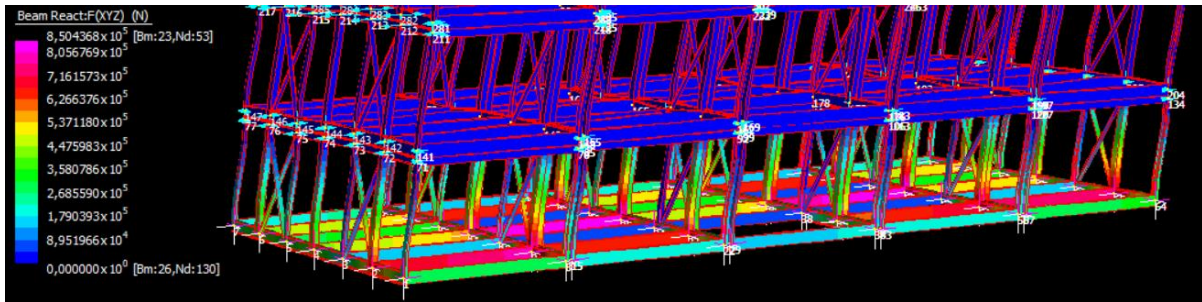


Figure 4.3.4 F(XYZ) forces by node, in the 32nd combination, being the 53<sup>rd</sup> node the most critical.

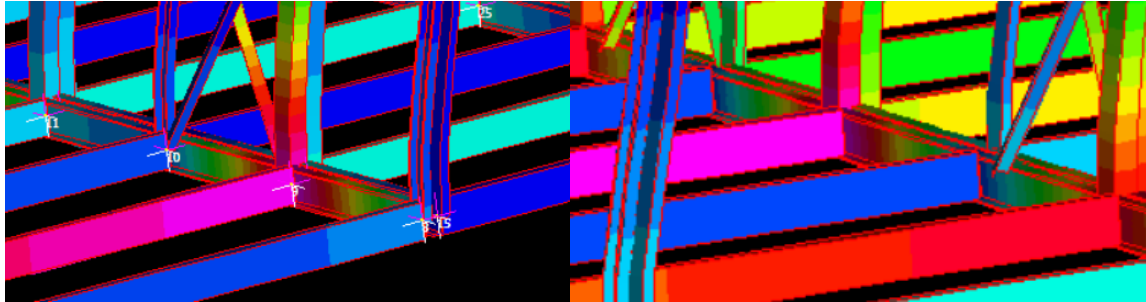


Figure 4.3.3 Node 9 for the maximum F(XY) shear force. Figure 4.3.2 Node 53 for the maximum in F(Z)

## BEAMS

PARAMETER	NUMBER OF BEAM	VALUE	COMBINATION
<b>T (+)</b>	72	2,17e+7 Pa	4
<b>T (-)</b>	59	-1,078e+8 Pa	32
<b>BENDING PLANE 1</b>	335	4,049e+7 Pa	32
<b>BENDING PLANE 2</b>	1564	6,17e+7 Pa	32
<b>TOTAL FIBRE (+)</b>	1591	6,94e+7 Pa	32
<b>TOTAL FIBRE (-)</b>	38	-1,408e+8 Pa	32
<b>AV. SHEAR PLANE 1</b>	28	9,6e+5 Pa	32
<b>AV. SHEAR PLANE 2</b>	400	5,29e+6 Pa	32
<b>TORSIONAL STRESS</b>	1364 & 1370	3,8759e+6	32

Table 4.3.3 Critical parameters of the beams.

Maximum traction and compression of beams in the axial forces happens in the truss beams (UA beams in the ground floor) the traction force, and in the compression maximum axial force in the corner column on the ground floor.

Maximum traction takes place is the 4<sup>th</sup> combination, where vertical forces are reduced to a minimum and lateral loads are maximized. The most critical beam is the 72<sup>nd</sup>, showed on figure 4.3.5, a truss beam on the ground floor.

The maximum compression beam is a corner 180 PFC column, that has probably been mistakenly modelled to suffer too much loads with the rigid connection to the top modular units. This corner column is showed in figure 4.3.6.

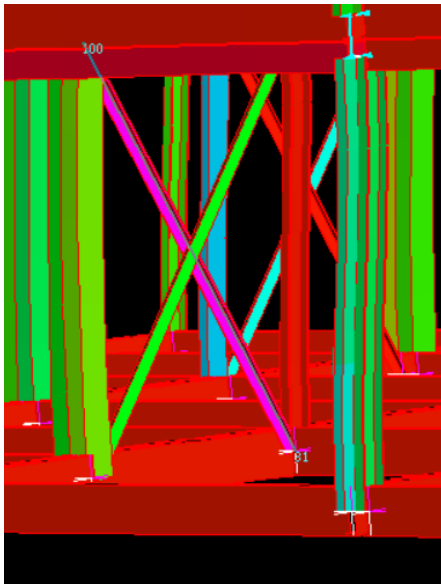


Figure 4.3.6 Beam 72 for the maximum axial traction.

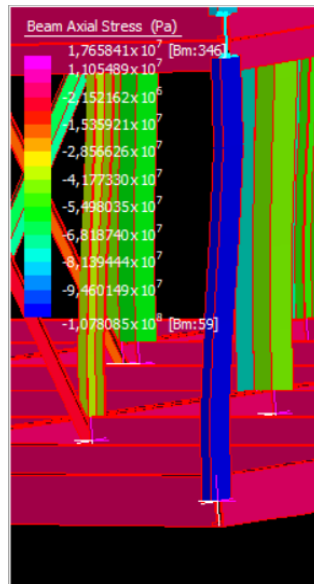


Figure 4.3.5 Beam 59 for the maximum axial compression..

Bending planes are the most critical in outside columns in the case of vertical planes (Beam 335, figure 4.3.7) and on the horizontal plane on the top roof beams (Beam 1564, figure 4.3.8).

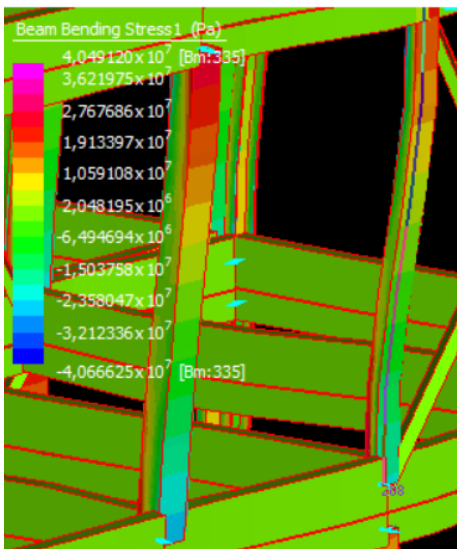


Figure 4.3.7 Beam 335 where the maximum bend happens in the vertical plane.

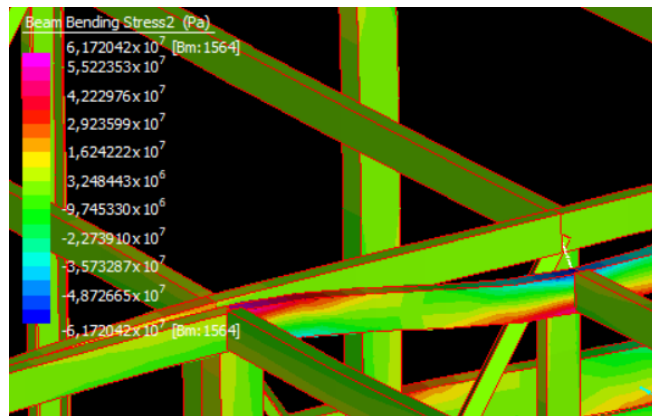


Figure 4.3.8 Beam 1564 where the maximum bend happens in the horizontal plane.

On the total fibre traction also a top floor beam is the critical element, but taking into account that the yield strength is 350 MPa, 69,4 MPa has a considerable safety factor.

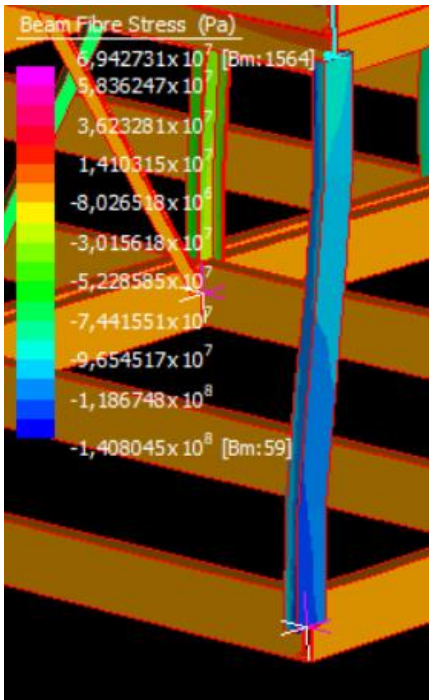


Figure 4.3.9 Beam 59, the maximum compressed total fibre

In the case of total fibre compression, a corner column of the ground floor (see figure 4.3.9) is the most compressed element with a 140,8 MPa of compression pressure. It is still below the yield strength but only with a safety factor of 2,48, the most critical point of the linear case tested load combinations.

The maximum shear pressures are far from the yield strength, and the most critical cases occur in central horizontal beams connecting columns in the Y direction (beam 400) and beam 28 on the vertical shear plane, which is an outside 220 HSS type column. This low values in the shear stress and also in the torsional stress are due to the non-continuous beams and columns, that are connected with rigid connections instead of being part of the same element.

## PLATES

PARAMETER	NUMBER OF PLATE	VALUE	COMBINATION
<b>FIBRE TENSION T(+)</b>	75	5,276e+3 Pa	32
<b>FIBRE COMPRESSION T(-)</b>	389	-7,5639e+3 Pa	32

Table 4.3.4 Maximum pressures of the plates.

Regarding the plates, the most critical traction happens in the plate 75, which is the floor plate next to the elevator shaft, on the previously mentioned combination 32. This plate is



part of the second floor, as the first floor, which would presumably have bigger loads on the floor plates due to the accumulative loads travelling through the columns, is fixed to the ground. Its value should not be a problem even more if reinforced concrete is used in the floor plates.

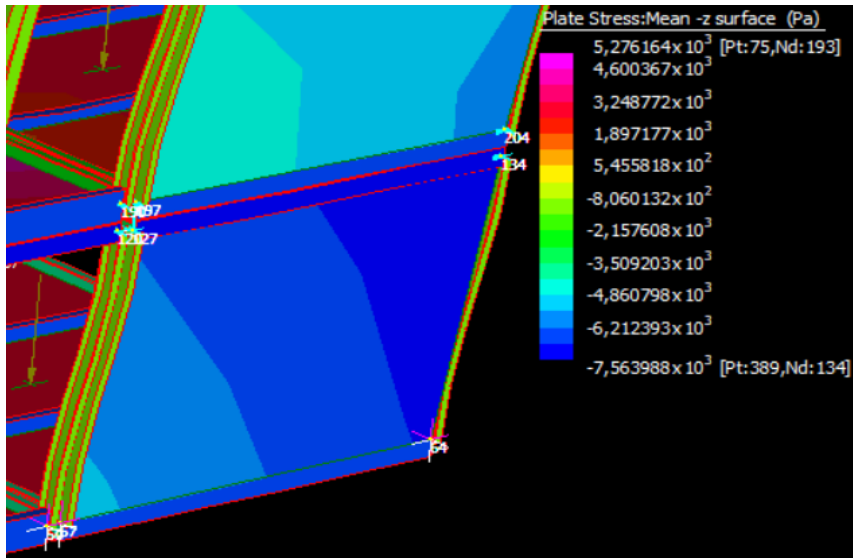


Table 4.3.5 Maximum compression of a plate, in plate 389.

The most critical compression on plates results in plate 389 (figure 4.3.5) which is a loaded wall in X direction for the support of lateral actions on the ground floor. This compression level is given by combination 32, where on X direction lateral loads are added on one side of the building.

#### 4.4. NATURAL FREQUENCIES

It helps determine the modes of vibration the structure has. This is useful for the analysis of the dynamic actions, which are not going to be investigated any further. Four modes of vibration are look upon, and the final results are shown in table 4.4.1, where the frequencies, modal mass on each mode and the modal stiffness is shown.

TOTAL TRANSLATIONAL MASS PARTICIPATION FACTORS				93.825	79.979	0.000
MODE PARTICIPATION FOR ROTATIONAL EXCITATION						
Mode	Frequency (Hz)	Modal Mass (Eng)	Modal Stiff (Eng)	PF-RX (%)	PF-RY (%)	PF-RZ (%)
1	7.8564E-01	5.0344E+05	1.2268E+07	0.000	24.765	7.004
2	1.7426E+00	2.5117E+05	3.0109E+07	0.003	0.000	11.948
3	1.8781E+00	4.0190E+05	5.5961E+07	42.918	0.000	25.600
4	2.3463E+00	3.4688E+05	7.5391E+07	0.000	2.029	0.152
TOTAL ROTATIONAL MASS PARTICIPATION FACTORS				42.920	26.794	44.704

Table 4.4.1 Four primary modes.

- The first mode is flexural- translational (one node on the ground level and other one on the roof) on the X direction, as it can be seen on figure

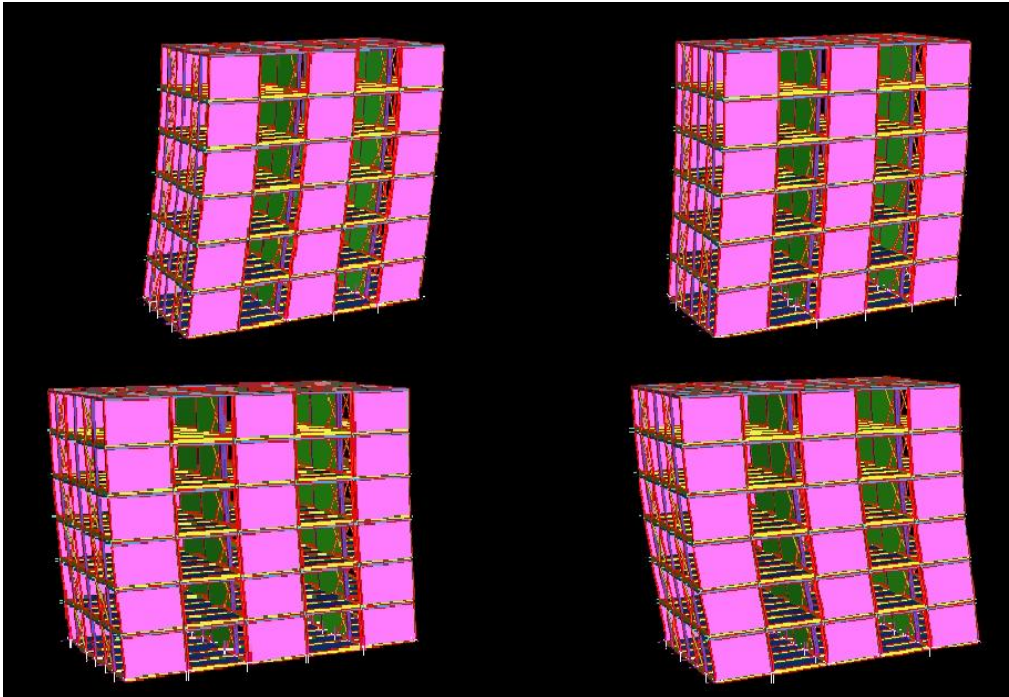


Figure 4.4.1 First mode of vibration. Flexural-translational.

- The second mode is rotational.

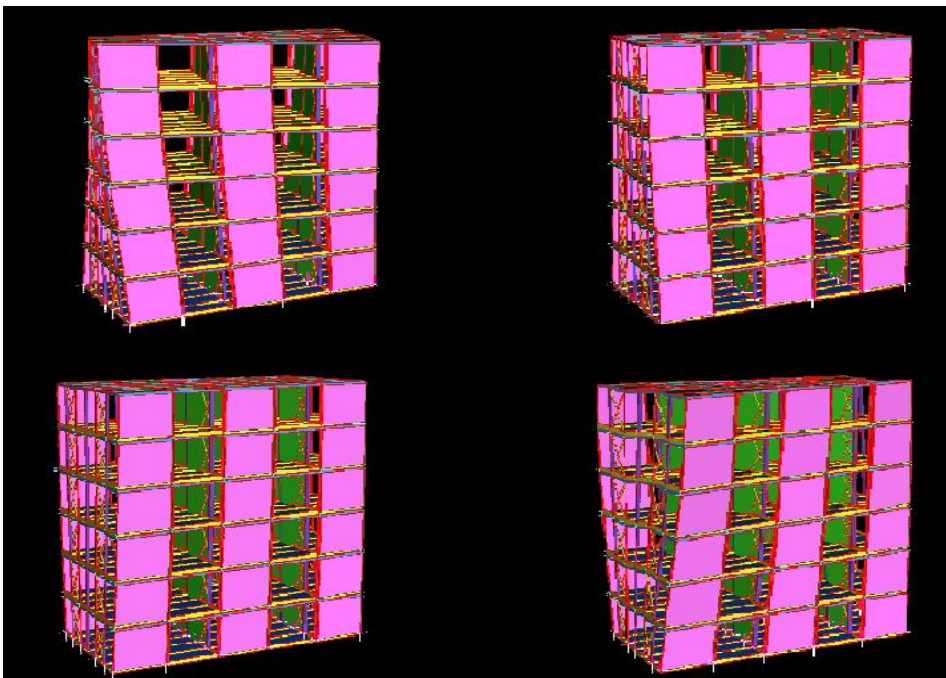


Figure 4.4.2 Second mode of vibration. Rotational.

- The third mode is flexural- translational one node on the ground level and other one on the roof) on the Y direction, as it can be seen on figure

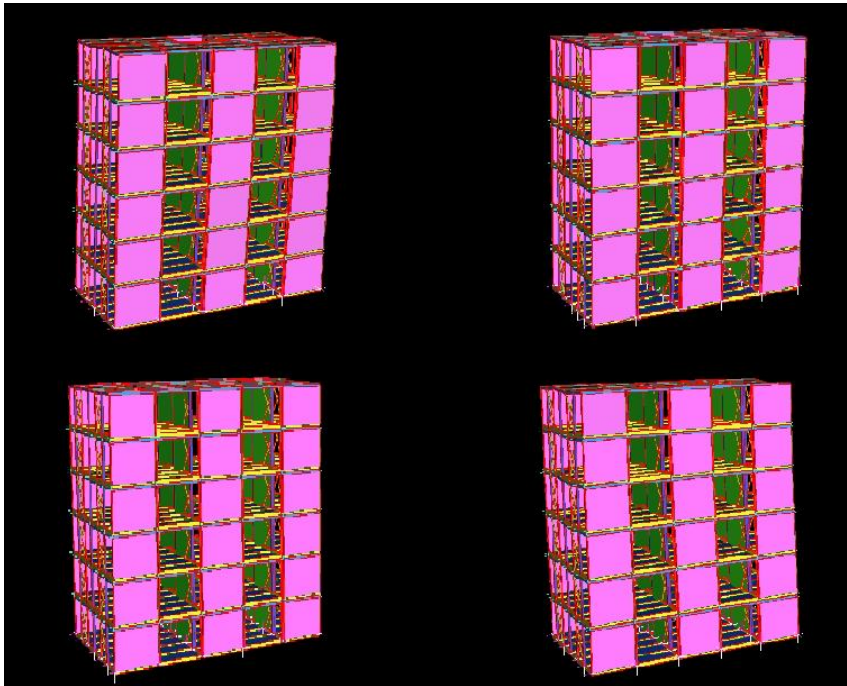


Figure 4.4.3 Third mode of vibration is flexural-translational on the Y direction.

- The fourth mode is also flexural-translational but in this case of the second order, with three nodes (ground floor, middle floor ceiling and top roof).

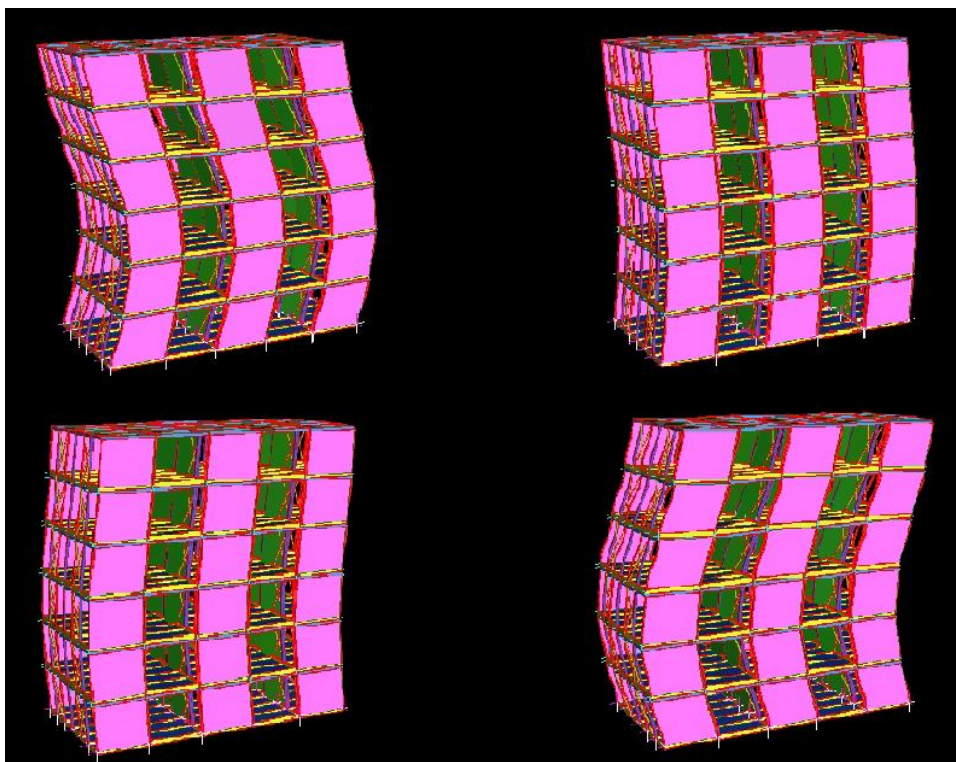


Figure 4.4.4 Fourth mode of vibration. Second order flexural mode with three nodes.

The spring stiffnesses have been decided according to the primary modes of vibration. When using the initial model's stiffness, as it was not prepared to a natural frequency analysis, and all the vibration modes were completely dependent of the horizontal inter modular connections. Finally, the stiffness was raised until a plausible value that makes the vibration modes as shown in past figures, and not modes where the five stacks of modules move independently.

## 5. BIM IN THE CONSTRUCTION PROCESS

Off-site construction and modular in particular are benefited notably by the implementation of the new technologies such as BIM (Building Information Modeling). In this type of construction there is very little room for error and design must be agreed early in the process. The ability to produce high-quality, detailed 3D virtual models is the aspect that is most commonly associated with BIM. However, the information attached to the building elements within the model is where BIM becomes truly useful. This information can offer a more efficient way of working, from scheduling actions in the build process, to allow end-user or facilities managers keep track of the building information for maintenance purposes.

Whereas 3D CAD technology is limited to generating drawings in graphical entities in terms of lines, arcs and circles, BIM allows the creation of information-filled digital models with all the context required. In addition, BIM technology allows for a creation of a model that contains information related to the building physical, functional and procurement information. For instance, the BIM model would contain data about the geometry, location, its supplier, operation and maintenance schedule, flow rates, and clearance requirements for an air-handling unit. <sup>[38]</sup>

Working hand-in-hand with BIM, in Integrated Project Delivery (IPD) all key stakeholders during the design phase work in an interdisciplinary collaboration. The objective a relationship that encourages frequent communication, shared responsibilities, and collective problem solving will result in a better quality project. This may act as a bridge between traditional construction professionals and modular manufacturers <sup>[39]</sup>. It integrates the expertise of project teams during a project's early stages, ensuring each discipline understands the others' scope and requirements to ensure that overall design decisions meet the needs of all involved parties. <sup>[40]</sup>

The implementation of BIM systems in modular construction normally involves in the following process:

- *Visualization*: ability to create a 3D presentation of building modules geometry, location, space, contained systems in relation to each other
- *Modelling*: ability to generate a 3D rendering tool to present the final product and finishes to owners, designers and constructors

- *Code reviews*: allows for building officials and fire officials could use the 3D models with related data for code compliance reviews
- *Fabrication/ shop drawings*: facilitates for the generation of detailed shop drawings could be easily produced once the BIM model is completed
- *Communication*: facilitates simultaneously creation of construction documents, product imagery, rapid prototypes, exterior envelope, interior finishing, and MEP fixtures of building modules. Through this single information platform, BIM promote collaborations among the design team, consultant, constructors and the clients
- *Cost estimating*: provides for cost estimating, material quantifications, and pricing to be automatically generated and modified while changes are applied for each building module
- *Construction sequences*: provides a complete construction schedule for material ordering, fabrication, delivery and onsite installation of each building systems. With the integration of 3D rendering, 4 D (3D model + scheduling information) could be easily generated during the project design and construction phase
- *Conflict, interference and collision detection*: ability to determine building system interferences which can be visually presented. For instance, an air distribution duct for the HVAC system physically interfering with a concrete beam <sup>[41]</sup>

Coordination problems are repeatedly caused in some locations. These include building corridors, points of entry and exit, openings in shear walls, and vertical utility chases. Reserving space for access is key in a modular design as on occasions services are not installed fully until the modules are assembled on site, and connections between modules' services are always made on site. Therefore, a procedure that can resolve which system has priority is needed. In these cases priority is typically determined by evaluating the functionality of each system.

One of the most challenging tasks faced in the delivery process in modular construction is the coordination and fabrication of the Mechanical, Electrical and Plumbing (MEP) systems. <sup>[42]</sup> The MEP coordination and fabrication process involves defining the locations for components of building systems, often in congested spaces, to avoid interference and to comply with diverse design and operation criteria. There are three primary reasons contributing to the challenges of MEP fabrication in modular construction. First, the process is highly fragmented between design and construction firms. Second, the level of technology used in different coordination scenarios has historically varied significantly between

engineers and construction contractors. Third, historically the process did not provide a model for use by specialty contractors plan prefabrication. [43]

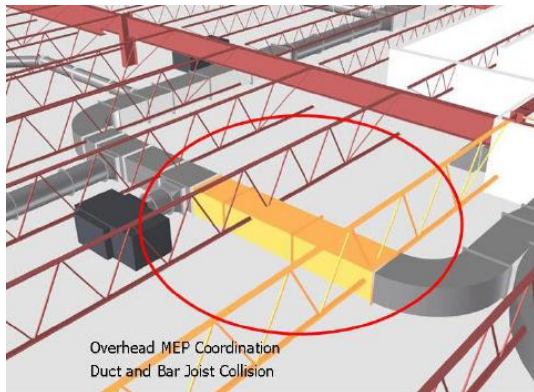


Figure 4.4.2 Ductwork conflicts with bar joists seen on BIM

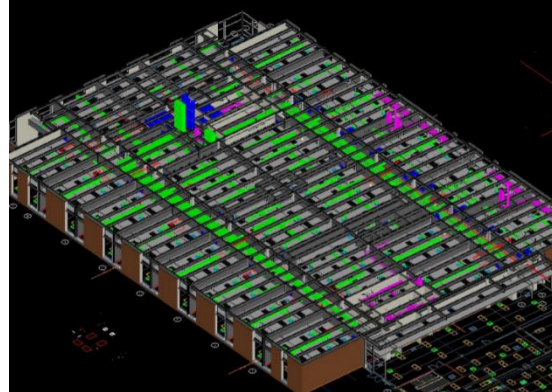


Figure 4.4.1 High school project BIM model.

Applying a high-end and accurate system of information-sharing like BIM allows tracking of modules and components from the manufacturing line through to installation onsite using barcoding and every action is recorded to provide the supply chain and the client with up-to-date data.

Broader adoption of this practice by modular manufacturers can make it easier to architects to incorporate standard modular products into their design, even if the building isn't fully modular-based. The rise of BIM as a design tool helps to highlight the potential benefits of a modular approach to building, identifying early on possible problems in the construction and the scheduling. [4]

In a recent study about the use of BIM on green projects, McGraw-Hill Construction (MHC) found that the use of BIM model-driven prefabrication on more than one quarter of their projects is expected to increase from 37% to 73% among practitioners who use BIM for green work. [45]

Overall, researchers identified that the most effective use of BIM models was for design coordination, walk-through animation and clash detections. This was more so for modular construction project which requires extensive design coordination especially for MEP systems. The greatest challenge of using BIM in construction project is the implementation process itself, regardless of the software capabilities. Development of accurate BIM model requires extensive resources and in-depth knowledge of construction methods and process.

[42]

## 6. SUSTAINABILITY AND LIFE CYCLE

Construction activities and the built environment have an enormous effect on the environment, human health, and the overall economy; therefore, the construction industry has the potential to significantly advance sustainability practices'. The most widely accepted definition of sustainable construction is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". To fulfil this definition, the entire construction supply chain needs radical changes, not only from a materials perspective but also from a production methods perspective.

Sustainable homebuilding with its three dimensions, economic, environmental and social, is attainable through practical innovations and technologies, such as the modular off site construction. Because of their production methods, modular houses already achieve higher levels of sustainability compared with site-built construction. However, there are great barriers to make this transition and make these new practices more widespread, being the most important ones the learning curve of workers and the added cost resulting from ill-defined construction processes.

To make an estimation and assess the sustainability aspect there are various methods depending on the country, each with its different laws and certifications, as the Code for Sustainable Homes (CfSH) in the UK, the various homogeneous laws for the European Union's countries or the Leadership in Energy and Environmental Design (LEED) certification in the United States.

The global requirements for environmental management systems are presented in ISO 14001 (2004). Also the Specification for the assessment of the life cycle greenhouse gas emissions of goods and services, PAS 2050 (2011), applies this methodology to the environmental impacts more specifically. These methods are internationally recognised and compatible between them and with other many carbon footprint methods.

In the case of off-site manufacturing, and in modular construction in particular, the sustainability is one of the principles in which this type of construction is built.

These codes are always based on a number of environmental criteria, which have a different weight according to their importance and earn a percentage of available credits. Depending on the code, minimum scores are necessary to make an overall aggregation, areas such as



energy/CO<sub>2</sub>, water savings, and material resources. For new construction projects in the current regulations in these codes, overall minimum scores are necessary.

CATEGORY	CREDITS	% OF TOTAL CREDITS
1. Energy and CO <sub>2</sub>	29	36,4%
2. Water	6	9%
3. Materials	24	7,2%
4. Surface water runoff	4	2,2%
5. Waste	7	6,4%
6. Pollution	4	2,8%
7. Health and well-being	12	14%
8. Management	9	10%
9. Ecology	6	12%

Table 4.4.1 Available credits for the Code for Sustainable Homes.

### 6.1. ENVIRONMENTAL ASPECT

The construction industry is one of the largest contributors to pollution and waste through its life cycle. According to the U.S. Environmental Protection Agency <sup>[46]</sup> in the case of the United States the building industry during the buildings entire life cycle, is responsible for 39% of total energy use, 12% of total water consumption, 68% of total electricity consumption and 38% of carbon dioxide emissions. Also, according to a study regarding material usage in construction, construction composes 40% of landfill material. <sup>[47]</sup>

To evaluate the environmental impact and asses the betterments to be made usually the life cycle assessment is used. The life cycle phases of a regular building consist of four main phases: the production phase, the construction phase, the occupancy or use phase, and finally, the operational phase. These phases are quite different comparing modular buildings to conventional ones, as it can be seen on figure 6.6.1.

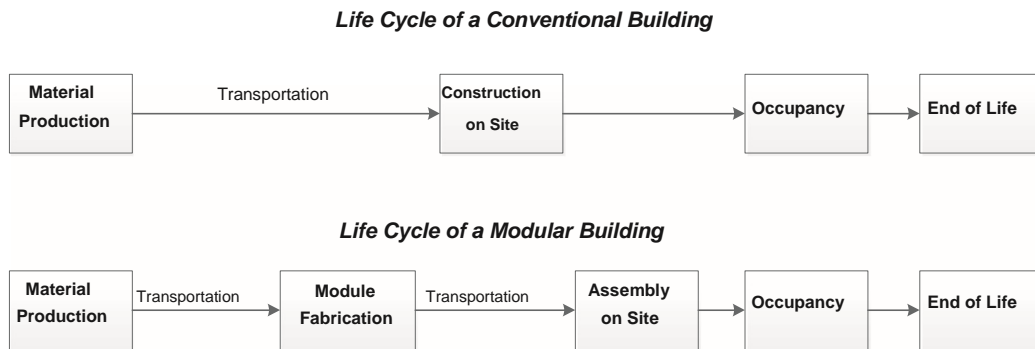


Figure 6.1.1 Flow chart of conventional and modular life cycle.

It is evident that among the life cycle phases of a building, the occupancy phase is the biggest contributor to the environmental impacts, in particular on the energy consumption and greenhouse gases. Depending on the design and type of building, energy consumption in the use phase accounts for 70-98% compared to production and construction phases. [48]

With more efficient technologies being implemented on recent constructions, the occupancy phase is becoming considerably more energy efficient. Consequently, other not-so-improved phases gain importance in the overall life cycle, such as the construction and the end of life phases. Embodied carbon

The following points in the environmental aspect of sustainability are most of the based in the different credits that codes like "code for sustainable homes" seen on table 4.4.1 have.

### ENERGY AND CO<sub>2</sub>

Buildings use approximately 40% of total EU energy consumption [49] Reduction of energy use in buildings is one of the most economical ways to mitigate carbon emissions. The Energy Performance of the Buildings Directive (EPBD) [50] is the main policy tool by the European Union to reduce energy use in buildings within the EU member states. Furthermore, the Renewable Energy Directive (RED) [51]. aims at increasing the share of renewable energy in supply to buildings, further driving down carbon emission from the use of buildings.

In its life cycle the major energy use over the building's life is its operational energy that is due to heating (and in some cases cooling) and lighting. Low U-values of less than 0.2 W/m<sup>2</sup>C can be achieved in the external envelope of the modules by using "warm frame" construction, in which the majority of the insulation is placed externally to the unit. Modular

buildings can also be designed and manufactured to be very airtight by the use of additional membranes and sheathing boards.

Even though some codes like the Code for sustainable Homes do not address the embodied energy in its materials over its entire life span, it is of main importance

The code does not address the embodied energy in its materials over the design life span, which can be important as the operational energy of the building reduces. The embodied carbon is the equivalent amount of CO<sub>2</sub> produced in the manufacture of the materials. In the case of light steel elements, very used in modular construction, embodied energy is 70% higher than in concrete elements of the same function, due to the high energy required to produce the light steel components. In that regard concrete modules have less embodied energy, but can't be easily reused and are difficult to use in medium to high-rise modular constructions <sup>[52]</sup>. According to a case study, at the end of the building's useful life up to 81,3 % of the embodied energy of the initial steel building could be saved by reusing the main steel structure of the prefabricated modules and other components. <sup>[48]</sup>

### **Materials**

On the use of material aspect, modular construction, with its off-site precision manufacturing, reaches high levels of efficiency, ordering to the sizes and quantities required, and results in less waste.

For example, the Building Research Establishment (BRE) *Green Guide to Specification* (2009) measures the environmental impact of building systems according to various criteria, including embodied carbon, waste, recycled content, etc. The ratings are presented on a scale of A\* (highest) to E (lowest). The lightweight building elements in modular construction conform to the A\*, A, or B ratings.

In terms of materials use, 98% of all steel is recycled after its primary use, and 50% of current steel manufacture in Europe comes from recycled steel (scrap). No structural steel is sent to landfills. For concrete modules, the more repetitive factory approach ensures efficient placement and reuse of concrete formwork, when compared with in situ construction. Reinforcement used in concrete modules is almost 100% manufactured from recycled steel, as is in the case of stick-built construction. <sup>[53]</sup>

Furthermore, the National Association of Homebuilders' (NAHB) green building guidelines include in their rating system the use of prefabricated components as an approach to reduce the quantity of materials and also waste (using modular construction methods for the entire house is rated the highest in the material category). In addition, utilizing materials that do

not require additional resources or on-site assembly optimizes plant manufacturing efficiencies and offers protection from adverse weather conditions (lessening the site impact through less time and resources spent on-site).<sup>[54]</sup>

However, the amount of material used is considerably higher than in conventional buildings (steel buildings, for a fair comparison). Research suggests that from 10 to 25 % more of structural material is used<sup>[1]</sup>. This is due to the necessity of a self-supporting structural system in each unit, which makes them appropriate to transport and assemble on site but requires more material than needed in its operational use. Because of this the net usage of total building materials (not only structural) in a modular project is only slightly less than the utilized by a conventional onsite project.

### **Waste**

Waste in on-site construction arises from various sources:

- Over-ordering to allow for off-cuts
- Damage and breakage, and losses and theft on site
- Rework due to errors on site

According to the Building Research Establishment (BRE), the construction industry average for material wastage on site is 10% to 15%, although this varies with material.<sup>[55]</sup>

In modular construction waste is minimized in both manufacturing and installation process. All off-cuts are directly recycled in the factory, avoiding intermediaries and useless transportation costs. It is estimated that less than 5% of materials during construction end up as waste a better rate than other modern construction techniques, such as panelised or prefabricated pods.<sup>[56]</sup>

Numerous studies have been carried out on this regard of material waste, as the one from WRAP on waste reduction and waste recycling,<sup>[57]</sup> of the use of modular construction in the regeneration of the Woolwich barracks in London.

Concrete used in the modular units, as a structural system or as a slab in a steel unit, allow the minimization of waste specially in the batching and also in the placing operations. In traditional construction concrete is ordered typically from an external ready-mix company that transports it to the building site. In this ready-mix transportation high quality is very difficult to obtain and small wastages are unavoidable. Commonly it is ordered 10% more than it would be necessary to ensure adequate supply for a given on-site pour. The majority

of waste in traditional construction (over 80% according to <sup>[58]</sup>) projects is generated in the wet processes. As mentioned in the previous point of Material usage, the overall use of materials is more efficient therefore also less waste is created. A Hong Kong study by Jaillon and Poon <sup>[59]</sup>, showed that, on average, a production of precast concrete panels and units leads to a reduction of 65% in comparison to in situ concrete casting.

Less transportation of different components to the site also permits less usage of packaging. Most of these components are transported to the factory where greater in bulk transportation is permitted. The final assembled modular units are transported using weather protective shrouds that are made for multiple uses.

In the modular unit on site assembling process a more intensive and shorter in time construction is carried out, with much less materials laying on the building site that can be damaged or lost.

Also, Factory assembling of the different components achieves a greater precision that avoids the bad usage of materials that cannot be reused, achieving a low wastage of materials on the manufacturing part of the process.

### **Water**

The use of water in the construction process depends more on the use of materials and the water resources required to get to their final form. As mentioned before on the material and waste aspect, even though highest precision allows less wastage, over dimensioned and doubled walls and floors can cause unnecessary usage of materials. However, typically "dry" process materials as steel and timber are the over dimensioned ones.

In concrete construction, water is used more effectively than on in situ pouring, due to a more controlled factory environment.

### **Pollution**

Much less noise, dust, and noxious gases are generated on site when using modular construction systems of all types. In highly prefabricated construction systems, transportation of materials to the site is reduced by around 70% in comparison to brick- and blockwork construction, which leads to a consequent reduction in deliveries to the site and local traffic pollution. <sup>[60]</sup> <sup>[61]</sup>

Raw materials are delivered in bulk to the module factory, to the correct quantities and sizes, which is more efficient than the multiple smaller deliveries to site.

### **Performance improvements**

Modular units are strong and robust to damage. Steel and concrete are non-combustible and do not add to the fire load. High levels of acoustic isolation and thermal performance can be achieved, and precast concrete is also inherent in terms of its thermal mass and security. All those benefits come largely due to additional materials used in construction. Several manufacturers estimate that anywhere from 10 to 25% more structural materials are used in a modular home.

Shrinkage or long-term movement on site is reduced by building in dry factory conditions, and “callbacks” to rectify errors and snagging are largely eliminated by the checking of the modules before delivery to the site. The durability of galvanised steel sections has been assessed in site trials, and a design life of over 100 years is achieved in warm frame applications, where the majority of the insulation is placed outside the light steel frame <sup>[62]</sup>. Air tightness and thermal performance of the building fabric can be much higher than is usually achieved on site due to the tighter tolerances of joints that can be achieved in a factory environment, which reduces the need for higher utility expenditure.

### **Adaptability and end of life**

The open-plan space of the modules can be fitted out and serviced to suit the user’s requirements, and modular buildings can be later disassembled and reused. New modular units can easily be added on top of the building as long as the foundations are strong enough, or lateral combinations with other modular constructions can be made.

Concrete modules are extremely robust, and it is possible to make attachments by chemical anchors or expanding bolts. Open-ended concrete modules are more flexible and adaptable. The modules are designed for the easy access and replacement of non-structural components, such as electrics, plumbing, and furnishings. Those can also be easily removed at the end of life of the building.

With steel modular units, the wall and roof frames are typically constructed using the stud and track method of connection, whereby sections are joined together using self-drill fasteners, bolts and rivets. Consequently, at the end of life, these should be easy to disassemble. With the floor and ceiling elements, as no mortar is used, the reusable materials can also be disassembled.

There are some recent examples of the reuse of modules as the one in a training centre at Freeman Hospital in Newcastle-upon-Tyne. In this case 10 preowned steel-framed modules

that were recycled and refurbished for the project, enabling it to be delivered in just 11 weeks from receipt of order to handover. It was also claimed that using refurbished modules generated less than 10% of the embodied carbon and used less than 3% of the energy during construction, compared to a site-constructed building of equivalent size. <sup>[9]</sup>

### 6.2. SOCIAL ASPECT

The social dimension of sustainability protects human lives and well-being throughout the life cycle of a product. The social dimension is the widest of them all, including, among others effect on climate change, human health, ecosystems change, infrastructure deterioration and apart from the mentioned human lives, which is considered from different perspectives. Fundamentally all the stakeholders affected by the construction process and product are part of this dimension, from workers making the product, users of the product and the general public that may unintentionally impacted by the product.

Module manufacturing and installation processes make notable change on the social aspect, especially in the job market. It A more specialized and skilled workforce is needed to carry out both off-site manufacturing and on site assembling. This requires an evolution of the job market to fulfil the requirements needed for these new task. That is one of the main reasons why building construction will suffer a slow evolution from traditional and less skilled construction to off-site manufacturing.

Other social aspect associated with the evolution to an off-site construction is the quality and risks of the jobs. Factory-based processes, including modular manufacturing, according to the Health and Safety executive data <sup>[9]</sup>, are five times safer than construction processes in terms of the number of reported incidents. A cleaner and safer environment is achieved obtained by avoiding the outside uncontrolled environment, where assembling operations have to made with different machines. This means that illnesses, disabilities, accidents and other causes are reduced. In addition to being ethically responsible, high safety levels also mean less costs associated with accidents, fines and workers' compensations, therefore an economic benefit is obtained.

Risks associated with working at height are also avoided, thus improving workers' safety on site. The modules can be installed with pre-attached protective barriers or in some cases, a protective 'cage' is provided as part of the lifting system. In a study that analysed the prefabricated urban construction environment in Hong Kong <sup>[59]</sup>, the safety risk associated with manufacture and installation of precast concrete was up to 63% lower than with conventional on-site concrete construction. Also a more cared management, planning and

logistics of the modular construction process minimizes risks through the reduction of motions, tasks and materials required. In return, these reductions make the probabilities of incurring with hazardous material lower. Overall, factory controlled production can be monitored much easily than on site production, specially due to the repeatability of the actions and the closed environment control. Consequently, in the construction of a building all off-site work is presumably safer than on site work, making modular construction a great choice in terms of Health and safety of the workers.

Regarding other stakeholders, it must be noted that on-site noise and disruption is further diminished by the 30 to 50% reduction in the construction period (MIT modular) modular construction does not affect the neighbourhood adversely during the construction process compared with more traditional construction processes. <sup>[59]</sup>

### 6.3. ECONOMIC ASPECT

Traditionally, lean and sustainable construction practices were used as two isolated and independent strategies. Whereas lean aimed at improving economic metrics, sustainability aimed at improving environmental goals. However, in recent years, after extensive research and industry practices, results showed that these two practices are interdependent, particularly the fact that both share similar basics of eliminating waste <sup>[63]</sup>. Potential construction cost savings realized from improved construction methods and productivity can be critical for achieving sustainable modular homebuilding, because these savings can be used to offset the initial cost of high performance building components. Bae et al. <sup>[64]</sup> argued that the key effect of using lean construction methods for the purpose of sustainability positively affects the economic dimension by possibly reducing upfront costs, operating costs, and resource savings, and improving performance capability.



## 7. APPLICATIONS

### 7.1. "THE STACK" IN NEW YORK, U.S.A.



Figure 7.1.2 Actual image of "The Stack".



Figure 7.1.1 Assembling process of units.

- Modular company: Gluck+
- Seven storey building with 3500m<sup>2</sup> located in Manhattan, New York.
- Awarded with the 2015 NCSEA Annual Excellence in Structural Engineering in the new buildings (10M \$to 30M \$) category.

It is composed by 56 modules that create the space for 28 apartments. The modules are 3,6 meters wide and have a 115 mm and 100 mm thick slab-on-metal deck incorporated on the floor and ceiling for rigidity. The shipping height limit on the city of New York was 11 feet (3,35 m), so a ceiling height of 9 feet (2,75 m) was the maximum height achieved. The rectangular Hollow Structural Sections (HSS) columns section vary (from 3x3" (76x76 mm) to 6x3" (152x76 mm)) to take into account the dimensional impact of the double walls. These columns take care of the gravitational loads, and the lateral loads are resisted with crossed braced frames located within the walls of the modules. Connection details between the modules were developed such that the boxes could be lowered into place onto alignment pins, and then be bolted or welded in place. Only minimal field finishing was required.

The foundations and the ground level were built in the traditional way. They supported the point loads carried downwards by the modules, and ended up in the foundations

As it can be seen on figure 7.1.2 some key architectural features were added like differing geometries on each floor that have cantilevered “boxes”, creating some small spaces to use as terrace and get out of the regular and simpler stacking.

Modules were constructed 260 km away from the site in Berwick, PA, at the Deluxe Building Systems’ factory. A tight schedule was to be kept during the assembly process, as the distance was quite long and the process had to be continuous during the 19 days of erection of the building. A 14-worker crew specialized in modular construction projects and a single crane were necessary during the on-site assembly of the modules. A lean concept of construction was adopted, with the Just In Time philosophy that allowed the schedule to be so short. According to the developers, this schedule could have been shortened to 10 days if government regulations to avoid traffic congestion had allowed more modules to be delivered each day. <sup>[65]</sup>

On the subject of sustainability, “the Stack” achieved the previously fixed goals in the building’s design, manufacturing and construction. The economic aspect was fulfilled thanks to the shortening of the schedule, which was overall 30% faster than a conventional construction project, saving indirect and financial costs. architect reported that the project cost for The Stack was 15% lower than that which would have been needed for conventional construction with the same quality. In addition, working efficiency was key thanks to the specialized workers at the manufacturing plant and at the on-site assembly, since over 50% of the project was completed in the factory. Workers conditions (safety, comfort) were well cared for and the on-site disturbance was kept to a minimum, contributing to the social aspect of sustainability. Also, some of the housing units were assigned to low and medium income residents, addressing the need for affordable housing in New Also, some of the housing units were assigned to low and medium income residents, addressing the need for affordable housing in New York City. <sup>[66]</sup>

Regarding the environmental aspect of sustainability, the high quality finishes and materials will reduce considerably the energy consumption, which will be beneficial for both occupants and the carbon emissions reduction. Material waste and water and air pollution were reduced, although it entailed higher transportation costs and energy costs at off-site locations. Finally, when the building will reach the end of its operational life, all the main components of the modular part of the building will be recyclable after renovation. <sup>[65]</sup>

### 7.2. STUDENT HOUSING IN WOLVERHAMPTON, U.K.

Modular Company: Vision Modular Systems

Key Dates: 32 week modular construction time, 58 weeks in total.

Financials: \$34,000,000 Hard Cost

Height: 25 stories, 77m

The building is composed of three blocks, A, B and C, from 8 to 25 stories high. Block A is the tallest reaching the 77 m of altitude. A total of 824 modules are used, with a maximum of 36 m<sup>2</sup> built area each. The total floor area in these three buildings is 20700 m<sup>2</sup> including a podium area that acts as a rigid foundation, built in a traditional on-site way.

The lateral load resisting system consist on a reinforced concrete core and the modules, stacked in three different adjacent blocks, are connected with a poured concrete slab on each floor. This was at the time the only way to build the tallest modular construction, and it became the highest modular building.

The modules were manufactured in Cork (Ireland) and transported to the site via ship and truck. The weight of each module varied from 10 to 25 tons depending on their floor size and the module self-weight was approximately 5,8 KN per m<sup>2</sup>. For modules at higher levels, approximately 14% of the module weight is in the steel components and 56% in its concrete floor slab. At the lower levels the steel weight is increased to 19% to resist the accumulative gravity loads in the columns and the lateral loads in the connections.

The usage of steel varied from 70 to 115 kg/m<sup>2</sup> depending on the storey and position of the modular unit, which is considerably higher than the usual 50 to 60 Kg/m<sup>2</sup> that are used on low to medium rise modular buildings. This is caused mainly by the lateral resisting system floor slabs and the added weight they cause.

The project started on site in July 2008 and was handed over in august 2009 (a total of 59 weeks). Installation of the modules started in October 2008 after completion of the podium slab, and construction of the concrete core to Block A was carried out in parallel with the module installation on Blocks C and B. The modules on site assembly lasted for 32 weeks.

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The ones in the first Block C were installed by mobile crane, whereas the modules in Blocks A and C were installed by the tower crane that was supported by the concrete core.

The installation of the 824 modules was carried out by eight workers plus two site managers. On the main part of the assembly on site an average rate of 7 modules per day was acquired, corresponding to 14,5 man hours per module in installation.

The overall construction team for the non-modular components varied over the 58 weeks project from 40 to 110 with 3 to 4 site managers. It was estimated that the reduction in construction period relative to site-intensive concrete construction was over 50 weeks (or a saving of 45% in construction period).

Site deliveries were monitored over the construction period. During installation of the modules, approximately 6 major deliveries per day were made, in addition to the 6 to 12 modules delivered on average. The concrete core progressed at a rate of one story every 3 days. [66] [67]



Figure 7.2.2 Photo of the building during its construction, without the exterior finishes. A slab can be seen on each floor, that is connected to the core.



Figure 7.2.1 Finished construction.

The estimated breakdown of man effort with respect to the completed building was; 36% in manufacturing, 9% in transportation and installation, and 55% in construction of the rest of the building. The total effort in manufacturing and constructing the building was approximately 1.5 man-hours per ft<sup>2</sup>, which represents an estimated productivity increase of about 80% relative to site-intensive construction.

Waste was removed from site at a rate of only 2 debris containers of 210 cubic ft (6 m<sup>3</sup>) per week during the module installation period and 6 skids per week in the later stages of construction, equivalent to approximately, 3 Tons of general waste, including waste and packaging. This is equivalent to about 8,8 kg/m<sup>2</sup>. The manufacturing waste was equivalent to 25 kg/m<sup>2</sup> of the module area, of which, 43% of this waste was recycled. For the proportion of module floor area to total area of 79%, this is equivalent to about 5% of the weight of the overall

construction. This may be compared to a construction industry average of 10 to 13% wastage of materials, with little waste being recycled. It follows that modular construction reduces landfill by a factor of at least 70%. [8]

The research was made by Lawson [8], who made a study of different modular constructions in the UK. These numbers only take into account the construction part of the project, without considering the design and planning period, which is a main part of the modular construction process and considerably longer than in a traditionally built construction. This would add approximately a 20% of the overall time to the project.

### 7.3. ONE9 CONDOMINIUMS IN MELBOURNE, AUSTRALIA

- 9-story, 34 unit condominium building erected in 5 days in November 2013
- One and two-bedroom market rate units
- Building comprised of 36 modules built off-site complete with façades, finishes, and balconies; cantilevered terraces on all levels
- Built with the Unitised Building (UB) System, a modular pre-fab system developed and used in Australia
- Manufacturer: Hickory Group, Vaughan Construction

One9 Apartments' is a ten storey modular building built in Melbourne, Australia, that consists of 34 single and double bedroom apartments. The assembling period of the modular units lasted only for 5 days, which was optimal for a congested urban site that required minimal disturbance. That avoided significant costs associated with the constraints that the urban area causes. Production of the modular units started on August 2013 but it wasn't until November of that year, when every modular unit was ready, that the on-site assembling happened. [68]



Figure 7.3.1 Performance of Modular Prefabricated Architecture: Case Study-Based Review and Future Pathways (Fred Edmond Boaf<sup>1</sup>, Jin-Hee Kim<sup>2</sup> and Jun-Tae Kim, 2016)

One of the aspects to highlight from the One9 apartments is its energy efficiency and sustainability. It has acquired the “6-star rating” from Green Star Australia, a voluntary sustainability rating system for buildings that assesses the sustainability of projects at all stages of the built environment life cycle, being the 6 star rating the maximum category. The high quality off-site construction system adopted for this building was essential to achieve this category, adopting features that included double glazed windows for thermal and acoustic performance, grey water recycling, and solar hot water panels on the roof. [8] [69]

The modules were installed with finished façades, natural timber floors, cantilevered balconies and built-in furniture to minimize future transports. The structure consists on aluminium composite and interlocking service systems, and all the modules connect with a central reinforced pre cast concrete core that acts as a stabilizing system against lateral loads.

The building was designed and built by the Unitised Building (UB) technology group of which the construction company and the unit manufacturing company are a part of. This group of companies has developed a system that enables a wide range of property developments using modular construction, sharing knowledge and innovations to help simplify the unique design part of the modular projects, giving more flexibility. <sup>[70]</sup>

### 7.4. 461 DEAN (ATLANTIC YARDS B2), NEW YORK, U.S.A.

- 32-story, 109 m 350 unit tower, tallest modular building in the world with 930 modular units.
- 60% of work done in factory, 40% on site
- 40 months of construction time due to legal problems between contractor and developer
- Manufacturer: FCS Modular, Skanska and Forest City Ratner
- SHoP Architects

The 32 stories Atlantic Yards B2 tower, also known as 461 Dean, is the tallest modular construction based building that has been built, with a height of 109 meters to the top.

The foundations consist of on-site built cast-in place concrete, that hold the two story basement in which the building will lay. The ground floor acts as a podium level and is stick built with steel. On top of that podium, the modules are stacked around a set of brace frames, two in each direction, providing overall lateral stability for the structure (figure 7.4.1). The steel braced system is similar to others used for steel offices already built, and could be installed two floors above the erection floor. Although the building utilizes this central core, the height of the building dictated additional use of steel bracing that allow the modules to attach and transfer loads downwards without directly attaching to the central core. <sup>[71] [72]</sup>

## Modular construction in multi-storey buildings

More detailed information on the project is not available due to Forest City's desire to maintain proprietary data in house.

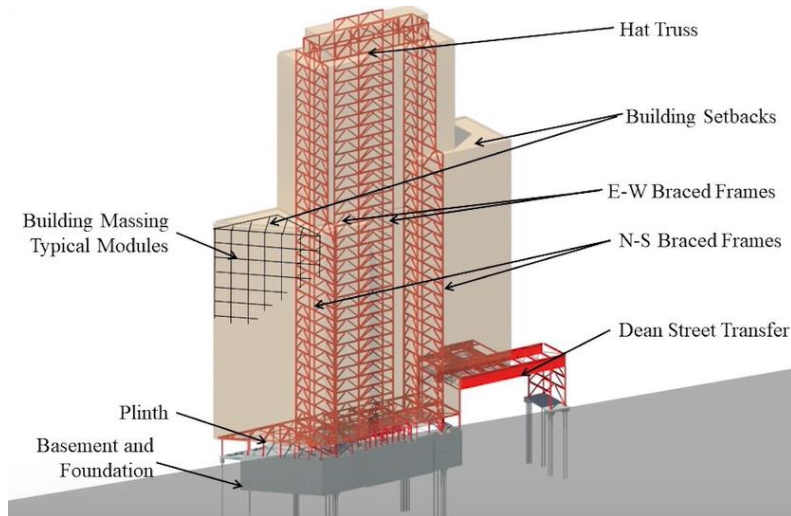


Figure 7.4.2 Structure of the 461 Dean where the central steel core can be seen.



Figure 7.4.1 Actual image of the building.

The structure of the modules consists on corner post steel construction with lateral bracing. Concerning the seismic resistance, a tuned liquid damper is used instead of the more typical tuned mass damper.

Due to the extremely high price of building area in New York, site constraints give the building a non-usual shape, that had to be maximized to the last  $m^2$ . As it can be seen on figure 7.4.3 It has a triangular shape in one of the side, which is not typical for modular buildings. Also, a 34-meter transfer with 20 stories above it was constructed. [73]

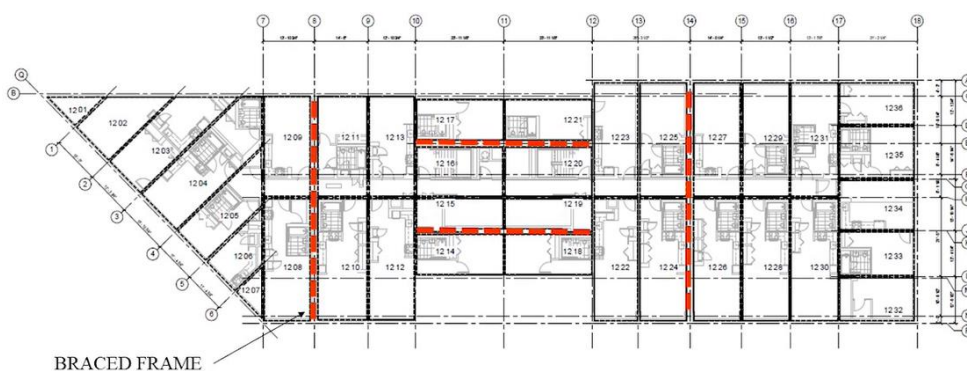


Figure 7.4.3 Diagram explaining the basic structural system of the tower [73]



The diverse floor plans at different heights demand a wide variety of modular unit geometries and shapes. 225 unique types of modules were developed in the manufacturing process, which was allowed by a great flexibility and a careful planning of the off-site assembling. The maximum length, width, and height are 14,6 4,5 and 3 meters, and are dictated by the floor plan solely. <sup>[72]</sup>

Modular units have a steel chassis that supports a metal deck roof and floor. The interior and exterior finishes are pre-built reaching a 95% of completeness. All the service connections were to be made on-site as the modules were being stacked, therefore accessibility of the service connections was key. <sup>[73]</sup>

Regarding the sustainability aspect, the building has a LEED Silver certification, which has to be emphasized due to the difficulty to acquire top certifications on urban skyscrapers. Only the minimum transport of the modular units was required thanks to the proximity of the factory, which was only two miles apart, in the same district of Brooklyn. That helped cope with the strict transport regulations that New York has and it permitted not having any unit stocked on the construction site, assembling them as soon as they were delivered.

During the construction several problems appeared, which delayed the construction time from 24 months to almost 40 months. The project was delayed due to economic market conditions and local politics, which caused problems between Skanska, the manufacturer and FCR, the developer. That ended with the creation by FCR of a new modular construction subsidiary that ended being propriety of FullStack Modular once the building was completed. The delay also caused issues with the local unions and workers. It was further anticipated that modular construction could save 20% of construction cost and at least 60% of the total construction would be done in the factory, but with the delay of the construction extra costs were added and it has ended up being costlier than a traditional stick-up built skyscraper of similar conditions. <sup>[74]</sup>

## 8. CONCLUSIONS

Modular construction refers to the application of a variety of structural systems and building elements involved in an off-site process of construction. As opposed to traditional buildings, the main on-site work to do is site interconnection for the off-site manufactured elements. Analysis, designs and construction technologies of modular multi-storey buildings are currently under development and several key areas are identified for further study.

Bringing modular technologies to the forefront of the modern building construction markets seems like a necessary evolutionary step towards a more efficient and productive industry. It must be noted that this system has many advantages which ensure high profit outcomes to both builders and developers.

Modular construction will address several of the challenges faced by the construction industry. Increased productivity and safety in a manufacturing setting will serve to change the stalled construction workforce towards a more factory based efficient one. The reduction of the schedule brought by the parallel project activities and the high productivity entails reduction of costs as the industry evolves.

Differences with conventional construction can be found from the first phases of the process. An increased effort is needed in the design and planning phase, and the work performed earlier in the project is increased. Planning is more involved and complex because of the increased interdependency among construction activities like plant manufacturing, transportation and on-site assembly. An interdisciplinary design process means that the next phases can hardly accept changes in an ongoing project.

The involvement of modular process in larger projects and experience will result in a better execution and ability to do more complex projects, minimizing the risk of cost overruns and scheduling delays as the one explained in the 461 Dean project. A better understanding from the architects and other parts involved in the process is also needed for the modular construction to be established in the AEC industry.

The structural system of modular buildings is still an area that needs greater research by the engineering community. Modular structures differ a lot one from another, especially in medium to high-rise buildings. Companies have their own patents and a base shared

knowledge is needed. That can be improved with the introduction of international codes specifically referred to modular construction.

Until the time, for high rise buildings conventionally constructed cores and modular units have been combined, losing part of the modular system's advantages. The structural system used for the six-storey model allows a fully modular construction for at least medium-rise buildings. The basic structural analysis of the six storey modular building carried out in this thesis shows the good response against lateral wind loads and gravity loads of a fully modular system, the advanced corner column supported system. The model offers a quick look at how the connections are modelled, although its results can be better if the main corner columns take on a bigger part of the loads, instead of making the lighter columns work as hard.

Even though in this study seismic analysis has not been carried out, it is one of the weak points of modular construction. In high seismic areas special care must be taken to ensure that the critical columns are not vulnerable to hinge formations. A design that sacrificing less critical elements safeguards human lives and prevents collapse is done, using the reusability characteristics of modular construction. <sup>[31]</sup>

As mentioned before, all the structural design together with the fabrication specification need to be efficiently organised to ensure the complete procedure takes place with the correct scheduling and efficiency, as it is the main reason for the existence of the modular system. The great level of interoperability of high performance that Building Information Modelling (BIM) offers is key for modular to reach its full potential in the construction market. The continuing development and standardization of BIM protocols will be essential as a platform for the integration efforts.

On the environmental and social aspect, the need of the construction activities to become more sustainable makes modular construction a great choice. Modular construction results in a significant environmental effect by reducing material waste and maximizing the reusability of the construction elements. A significant social effect is attained by the lessening or even elimination of safety hazards that take place on the on-site part of the conventional building processes.

In conclusion, modular construction offers many advantages in various areas of the building process and life cycle for the multi-storey buildings that have yet to be more furtherly understood and adopted by the construction industry.

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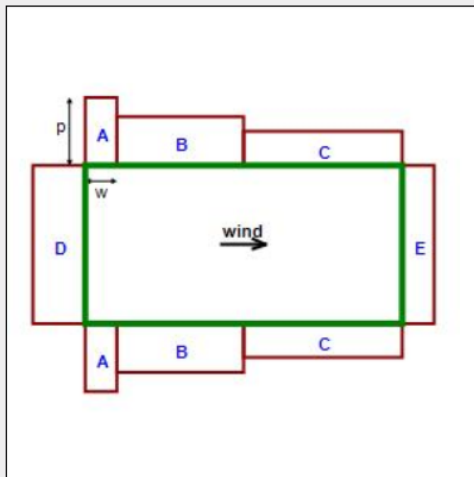
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## APPENDIX A

<b>Building Length (m)</b>	10.8	<b>Negative Internal Pressure Coeff., <math>C_{pi}</math></b>	-0.3
<b>Building Width (m)</b>	21.6	<b>Positive Internal Pressure Coeff., <math>C_{pi}</math></b>	0.2
<b>Building Height (m)</b>	18.05	<b>Wind speed, <math>V_{b,map}</math> (m/s)</b>	23
<b>Eaves Height (m)</b>	18.05	<b>Terrain Type</b>	Country
<b>Roof Type</b>	Flat	<b>Site Altitude (m)</b>	100
		<b>Seasonal Factor, <math>C_{Season}</math></b>	1
		<b>Pressure Calculation Method</b>	360 Method

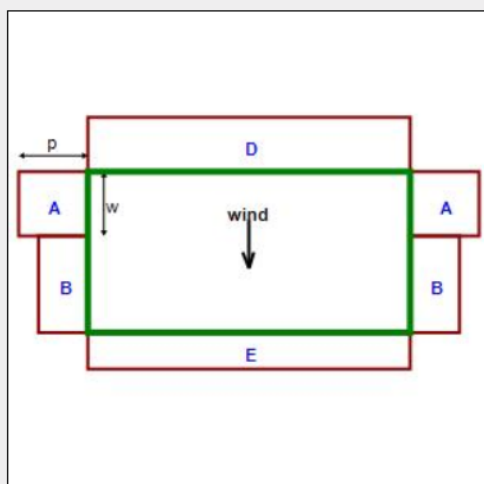
<b>Direction</b>	0°-360°
<b>Directional Factor, <math>C_{dir}</math></b>	1
<b>Closest Distance to Sea (km)</b>	100
<b>Peak Velocity Pressure (kN/m<sup>2</sup>)</b>	1.045
<b>Max. Peak Velocity Pressure (kN/m<sup>2</sup>)</b>	1.045

### Wind Loading on Walls - Wind Parallel to Building Width



Zone	Max Net Pressure $p$ (kN/m <sup>2</sup> )	Width of Zone $w$ (m)
A	-1.464	2.16
B	-1.045	8.64
C	-0.732	10.80
D	1.127	10.80
E	-0.686	10.80

### Wind Loading on Walls - Wind Perpendicular to Building Width



Zone	Max Net Pressure $p$ (kN/m <sup>2</sup> )	Width of Zone $w$ (m)
A	-1.464	4.32
B	-1.045	6.48
D	1.150	21.60
E	-0.767	21.60

## X AXIS WIND LOADS IN NODES (KN/m2)

<b>D</b>	height	18,050				
	column span width	1,800				
	outer width	0,900				
	top node area height	1,400				
	interstorey node area height	3,050				
	maximum net pressure	node height	KN/m2	outer nodes	inner nodes	
	1,127	18,050	2,254	2,840	5,680	ONE top node
		15,125	1,889	2,592	5,185	2 nodes for each height
		12,075	1,508	2,070	4,139	
		9,025	1,127	1,547	3,094	
		5,975	0,746	1,024	2,048	
2,925	0,365	0,501	1,003			

<b>E</b>	height	18,050				
	column span width	1,800				
	outer width	0,900				
	top node area height	1,400				
	interstorey node area height	3,050				
	maximum net pressure	node height	KN/m2	outer nodes	inner nodes	
	-0,686	18,050	-1,372	-1,729	-3,457	ONE top node
		15,125	-1,150	-1,578	-3,156	2 nodes for each height
		12,075	-0,918	-1,260	-2,519	
		9,025	-0,686	-0,942	-1,883	
		5,975	-0,454	-0,623	-1,247	
2,925	-0,222	-0,305	-0,610			

<b>A</b>	height	18,050			
	outer width	2,100			
	top node area height	1,400			
	interstorey node area height	3,050			
	maximum net pressure	node height	KN/m2	outer nodes	
	1,464	18,050	2,928	8,608	1 top node
		15,125	2,454	7,857	2 nodes for each height
		12,075	1,959	6,273	
		9,025	1,464	4,688	
		5,975	0,969	3,104	
	2,925	0,474	1,520		

<b>B</b>	height	18,050			
	column span width	4,350			
	top node area height	1,400			
	interstorey node area height	3,050			
	maximum net pressure	node height	KN/m2	inner nodes	
	-1,045	18,050	-2,090	-6,364	2 top node
		15,125	-1,751	-5,809	4 nodes for each height
12,075		-1,398	-4,638		
9,025		-1,045	-3,466		
5,975		-0,692	-2,295		
2,925	-0,339	-1,123			

<b>C</b>	height	18,050				
	column span width	4,350				
	outer width	2,100				
	top node area height	1,400				
	interstorey node area height	3,050				
	maximum net pressure	node height	KN/m2	outer nodes	inner nodes	
	-0,732	18,050	-1,464	-4,304	-4,458	Top 1 outer 2 inner
15,125		-1,227	-3,929	-4,069	2 nodes for each height in outer nodes and 4 for inner nodes	
12,075		-0,979	-3,136	-3,248		
9,025		-0,732	-2,344	-2,428		
5,975		-0,485	-1,552	-1,607		
2,925		-0,237	-0,760	-0,787		

**Y AXIS WIND LOADS IN NODES (KN/m2)**

<b>D</b>	height	18,050				
	column span width	4,350				
	outer width	2,100				
	top node area height	1,400				
	interstorey node area height	3,050				
	maximum net pressure	node height	KN/m2	outer nodes	inner nodes	
	1,150	18,050	2,300	6,762	7,004	Top 1 outer 2 inner
15,125		1,927	6,172	6,393	4 nodes for each height in inner, 2 in outer	
12,075		1,539	4,928	5,103		
9,025		1,150	3,683	3,814		
5,975		0,761	2,438	2,525		
2,925		0,373	1,194	1,236		

<b>E</b>	height	18,050
	column span width	4,350

	outer width	2,100				
	top node area height	1,400				
	interstorey node area height	3,050				
	maximum net pressure	node height	KN/m2	outer nodes	inner nodes	
	-0,767	18,050	-1,534	-4,510	-4,671	Top 1 outer 2 inner
		15,125	-1,285	-4,117	-4,264	4 nodes for each height in inner, 2 in outer
		12,075	-1,026	-3,286	-3,404	
		9,025	-0,767	-2,456	-2,544	
		5,975	-0,508	-1,626	-1,684	
	2,925	-0,249	-0,796	-0,825		

<b>A</b>	height	18,050				
	column span width	1,800				
	outer width	0,900				
	top node area height	1,400				
	interstorey node area height	3,050				
	maximum net pressure	node height	KN/m2	outer nodes	inner nodes	
	-1,464	18,050	-2,928	-3,689	-7,379	1 top node
		15,125	-2,454	-3,367	-6,735	2 nodes for each height
		12,075	-1,959	-2,688	-5,377	
9,025		-1,464	-2,009	-4,019		
5,975		-0,969	-1,330	-2,661		
2,925	-0,474	-0,651	-1,302			

<b>B</b>	height	18,050				
	column span width	1,800				
	outer width	0,900				
	top node area height	1,400				
	interstorey node area height	3,050				
	maximum net pressure	node height	KN/m2	outer nodes	inner nodes	
	-1,045	18,050	-2,090	-2,633	-5,267	1 top node
		15,125	-1,751	-2,404	-4,807	2 nodes for each height
		12,075	-1,398	-1,919	-3,838	
9,025		-1,045	-1,434	-2,869		
5,975		-0,692	-0,950	-1,899		
2,925	-0,339	-0,465	-0,930			

