LICENTIATE THESIS

Innovative Construction of Student Residences

Frameup Concept

Pedro António Pimenta de Andrade

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Luleå, November 2014

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Abstract

In the majority of university cities in Sweden, a strong demand for student accommodations has initiated various development and research projects focusing on costs reduction and fast execution. The present thesis brings up a solution based on the development of a feasible assembly concept and process, for a *Modular Building* erection, where prefabricated 3D Modules are assembled into a sway steel frame. The concept has been initiated within FRAMEUP project: *Optimization of Frames for Effective Assembling* (RFCS contract RFS-PR-10121) [1]. One of the main project objectives was to investigate and develop a competitive structural system suitable for fast in-situ execution and dismounting. Thus, in order to streamline the construction process, the use of optimized prefabricated frames and room 3D modules has become a very attractive alternative. The building is designed considering a six-story building, as it has been seen as the suitable choice of industrial partners in the project on market demands for the optimal payoff time. The use of *Intensive Use of Steel* together with *Modular Construction* enhances the conditions for industrialization of the construction process towards the cost reduction.

The development of the whole concept is described and followed up by a 4D construction sequence. The concept is based on the original structural system for which calculations, drawings and feasibility test at full scale are made to prove the credibility of the system. The 3D Modules are designed by Norrbotten based SME, which has influenced the global concept design. In addition, development of a novel joint, by means of laboratory tests and finite element models, is shown in the thesis. It is believed that its use in the frame, for the column splice connection, may be advantageous for the execution process. The issue of execution tolerances has been addressed by advanced FEA, which has been validated by experiments.

Sammanfattning

I majoriteten av svenska universitetsstäder har stark efterfrågan på studentbostäder initierat flera utvecklings- och forskningsprojekt med fokus på kostnadsbesparingar och snabbt uppförande. Föreliggande uppsats behandlar en lösning baserad på utveckling av ett koncept med prefabricerade byggnadsmoduler vilka monteras i ett ramverk av stål. Konceptet har initierats inom FRAMEUP-projektet *Optimization of Frames for Effective Assembling* (RFCS contract RFS-PR-10121) [1]. En av de främsta målsättningarna var att utveckla ett konkurrenskraftigt konstruktivt system som är lämpligt för såväl snabb montering som snabb nedmontering på plats. I syfte att effektivisera konstruktionsfasen är användning av optimerade prefabricerade ramar och rumsmoduler att attraktivt alternativ. Byggnaden är dimensionerad för sex våningar eftersom det har ansetts som ett optimum ur ett återbetalningsperspektiv av medverkande industriella partners. Användningen av koncepten *Intensive Use of Steel* och *Modular Construction* förbättrar möjligheterna till industrialisering av konstruktionsprocessen vilket möjliggör kostnadsbesparingar.

Utvecklingen av hela konceptet är beskriven och följs upp med en 4D konstruktionssekvens. Konceptet är baserat på det ursprungliga konstruktiva systemet för vilket beräkningar, ritningar och genomförbarhetsprov i fullskala är utförda. Modulerna är konstruerade av SME i Norrbotten vilket har påverkat det övergripande konstruktionskonceptet. Därutöver redovisar uppsatsen utvecklingen av en ny typ av förband vilket undersöks med provning och FE-beräkningar. Det är tänkbart att användande av detta förband i ramverkets pelarskarvar kan leda till ett optimerat uppförande. Frågan om utförandetoleranser har adresserats med avancerade FE-beräkningar vilka har validerats med provningar.

Table of Content

Preface

The present thesis is performed within the research group of Steel Structures at the Department of Civil, Environmental and Natural Resources Engineering, Luleå University of Technology. This work is conducted in the scope of an international project – *Optimization of the frames for effective assembling*, FRAMEUP – which has its main objective to develop a system which is suitable for an effective assembly of buildings. Thus, the focus of this thesis is based on the whole development of the system, from the concept to its final materialization.

I gratefully acknowledge the research project FRAMEUP, agreement number RFSR-CT-2011-00035, financially supported by the Research Program of the Research Fund for Coal and Steel. The partners of the project: University de Coimbra, University of Liege, RWTH Aachen University, Vallourec Deutschland and Acciona Infrastructure, so the acknowledge are extended for all the partners that directly or indirectly contributed for this thesis. A special thanks is addressed to the Part Construction AB staff, namely to: Nils Lundholm, Anton Lundholm and John Lundholm, for their direct participation, enthusiasm and support.

I am very grateful for the support of the whole staff of the CompLab, laboratory at Luleå University of Technology. As well as, with the students which directly contributed to this thesis, namely: Julien Guillon, Safira Monteiro and Sławomir Piniarski; best wishes in your personal and professional life.

Foremost, I would like to thank personally my supervisor, Prof. Milan Veljkovic, for once more, since my Master's Thesis, believed in my work, providing me this unique opportunity and full support in all its dimensions. I would like to extend my gratitude to my assistance supervisor, PhD Tim Heistermann and its valuable help, especially in its quality of colleague and friend. The same gratefulness is extended to Prof. Efthymios Koltsakis for its help and company in interesting discussions in all aspects of the knowledge.

A would like to thanks to PhD Marko Pavlović for having taught me all the necessary, to perform the FEA in this thesis.

Big thanks to all my dear friends wherever they are, especially to the Research Group of Steel Structures, which provide me all necessary help and constant good humor.

My gratitude to my family for their optimism, experience and endless support.

In the end, I would like to thank my wife for her infinite support and dedication.

Dear Sweden,

Sorry, for not being able to talk with you so much! As you know, the reality is that this adventure, at which you embarked me on, did not let me much time to dedicate to you. But I am not complaining, to be honest, the adversities that you crossed along my path, are far less compared to the opportunities that you did create to me. And so, I am really thankful for your hospitality and your truly and genuine altruism, even despite knowing that you would not get a word from me. So it has been a pleasure to have you in my company, even if the final outcome of this journey does not have the greatness of the joy I felt along this trip, it was worth it! Hence, I promise that soon I will thank you in your own words.

Tack så mycket!

Vi ses imorgon!

Table of Terminology and Acronyms

3D modules (single and double): [§3.4.1 (p.39), §3.6.1 (p.48) and §4.2.1 (p.55)]
4D modelling: 3D components or assemblies with time.
Activation force (AF): [§10.1 (p.117)]
Apparent friction coefficient (AFC): Ratio of the slip load on the sum forces in bolts at slip [2] [§10.4 (p.122)].
Bolt-row: [Figure 6.4 (p.83)]
Claddings: [§3.4.3 (p.41)]
Corridors: [§3.4.4 (p.42)]
Cover plates (CP): [§6.2 (p.81)]
Facade: [§3.4.3 (p.41)]
Finger connection (FC): [§6.2 (p.81)]
Finger tip: [Figure H.9 (p.208)]
Grid: [§3.5.1 (p.44)]
Horizontal gap (HG): [§6.2 (p.81)]
Inline Construction's Concept: [§3.2.3 (p.37) and §3.6.6 (p.51)]
Lift: [§3.4.5 (p.43)]
Lifting system (LS): [§3.2.1 (p.33) and §3.5 (p.43)]
LVDT (linear variable differential transformer): extensometer which allows measuring of displacements.
Minimum operational height: [§3.5.6 (p.47)]
Modular frames: [§3.4.2 (p.40) and §4.2.2 (p.55)]
Modular Housing Stock: [§3.2.2 (p.35)]
Operational columns: [§3.5.6 (p.47)]
Pylons: [§3.5.2 (p.44) and §4.3.3 (p.62)]
Self-climbing device: [§3.5.5 (p.46)]
Service shafts: [§3.4.6 (p.43)]
Sliding cantilevers (SC): [§3.5.2 (p.44), §3.6.2 (p.49) and §4.3.2 (p.62)]
Slotted holes: [§7.2 (p.88)]
Stairs: [§3.4.5 (p.43)]
Strain gauges (SG): device to measure strains.
Tightening round (TR): [§8.2 (p.95)]
Transition Panels: [§3.4.3 (p.41)]
Vertical gap (VG): [§6.2 (p.81)]

1 INTRODUCTION

1.1 Background

Sweden has a strong demand on the construction of student accommodations and therefore lot of efforts has been focused to find an affordable and easy to execute solution of the problem. A concept combining these requirements may be based on the use of steel frames in combination with prefabricated 3D modules, made by intensive use of steel, equipped for a short term residence and suitable for student accommodations.

Figure 1.1: 3D modules sited on the steel framed structure

Therefore, the need to investigate and develop a system which is suitable for an effective assembly of buildings is considered in this thesis, as part of an international project Optimization of the frames for effective assembling ”FRAMEUP” –RFS-PR-10121 [1]. In order to streamline the construction process, optimized frames, which are specifically designed for the construction of multi-storey buildings, are used. Hence, the Frameup concept is created by the intensive use of steel structural elements t and in 3D module built offsite, including either structural or non-structural elements. This concept creates adequate conditions for the industrialization of the building’s construction process, leading to the cost reduction. The present thesis is also based on an initial investigation developed by the same author [3].

Moreover, the present thesis introduces a novel joint for column splice connections, the so called Finger Connection, bringing a new solution for possible execution misalignments.

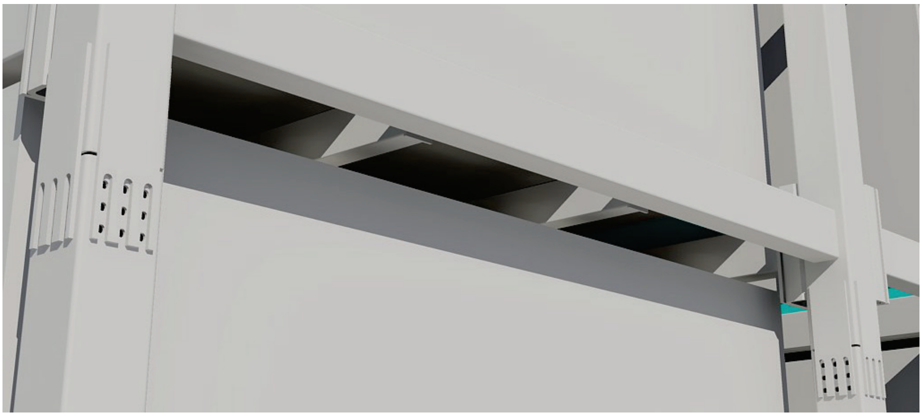


Figure 1.2: The column-splice, Finger Connection

This joint has two folded advantages: it is intended to reduce the time need for the assembly by accommodating deviations of the alignments of columns and creates minimum possible distance between a column and a façade element.

1.2 Structure of the thesis

The structure of this thesis combines two equally important parts, which are separated due to two different research methods used:

Part I Development and implementation of the Frameup concept: development of the concept throughout an interactive process, where the assembling process and its 4D modelling is assessed based on structural analysis of the building and Lifting system.

Two main points are considered:

1. Construction Method – Constitutes the materialization of the complete concept on the execution process, which itself constitutes an innovative construction method, described stepwise on a sequence of the construction.
2. Structural Performance – Structural optimization of the steel frame and joints is performed on the basis of the structural requirements imposed by the Construction Method;

On the first point of the Part I the Frameup concept is introduced and the execution process is materialized. The innovative execution process relies on the concept of starting the building assembly from the roof to the lower floors, wherein everything is performed at the ground level. The existence of a rigid frame, named grid, combined with a Lifting system, are used to erect the building on a one-storey height permitting a clearance at the ground level enough to assemble the next lower floor from below. This system creates the possibility to perform all work at the ground level and consequently without the use of a crane. Thus, the Lifting system is used to erect the building. The Lifting system should be also considered as erection equipment or “tool”, which is assembled and disassembled whenever it is necessary for the construction process. The same construction process and the same “tool” can be used for a construction of new buildings using the same lifting devices and the same grid.

The second point of Part I concentrate on the optimization of frames for global stability of the building. For the sake of the construction time, the multi-storey building is considered as non-braced frame. Therefore, an increase of bending moments in the joints and the sway of the building are expected. Thus, the structural performance of the building will be designed, using rigid (or semi-rigid) joints.

Part II Structural Performance of a Novel Joint – Finger Connection: design of the connection by means of laboratory tests and finite element modelling.

Effective design of the column-splice has been of particular interest of the structure. Inherent to the execution process, the structures always exhibit misalignments, which are, in any case, impossible to avoid. Therefore the finger connection is designed to deal with the problem insuring an easy assembling process. The finger connection is designed to accommodate execution tolerances without compromising its resistance. The connection consists of the upper part of the column and the so called fingers. The pre-fitted bolts are placed at the lower column. During the assembling, the upper part of the joint, slide with the fingers through the pre-fitted bolts, at the lower column. Once in the place, the bolts are tightened, filling an intentional gap, existent for accommodating the misalignments, accomplishing the assembly of the column-splice. The second part of the thesis mostly focuses on the assessment of the finger connection using commercial available software, such as ABAQUS, based on finite element method and tests in laboratory.

1.3 Objectives and research questions

Hence some questions arise upon the aforementioned chapters:

Part I - Construction Method and Structural Performance:

Q1. What is the minimum bending resistance of beams' joints necessary to provide to the non-braced multi-storey steel frame?

Q2. What types of joints are suitable for the efficient execution of the building?

Q3. How to prepare feasibility tests and provide credibility to the Frameup concept?

Q4. How to quantify benefits of the new type of construction system concerning to the following parameters: execution time, safety of execution, operational area in-situ and overall efficiency?

Part II - Structural Performance of a Novel Joint - Finger Connection:

Q1. How big tolerances can finger connection accommodate in the novel column splice connection?

Q2. How does the gap size influence the novel column splice resistance?

Q3. How the force is transferred in the novel column splice connection?

Q4. What is the resistance of the novel column splice?

1.4 Frame of application

It is expected that the Frameup system will be launched in the Swedish market therefore it is important to define its limits of application.

It is important to stress that the methods and lifting devices are comprehended within the specific objectives. The concept evolves from its central idea, based on the execution process, along to its all multiple facets. In order to achieve an effective assembling of the optimized frames, the design of the lifting devices is crucial having in mind the execution time and safety. The pilot building is designed to fits Swedish requirements, nevertheless the use of European standards may widen the range of application especially in places where the geographic structural characteristic are coincident.

1.5 Methods and means of productions

The development of the project implied the use of different approaches and software, therefore the methods employed in the thesis focused on the:

1. Conceptual development of the building and the Lifting system as an integrated concept. All phases of the construction are schematically presented, i.e. 2D and 3D computational drawings are provided – using SketchUp 8 [4];

2. 4D modelling by means of intensive production of very detailed 3D CAD components, with time, throughout the construction process – using Autodesk AutoCAD 2013 [5] and Autodesk 3ds Max Design [6] regarding the animations;

3. Structural design, including stability checks of the whole building and the Lifting system – using Autodesk Robot Structural Analysis 2013 [7];

4. Comprehensive Laboratory testing and Finite Element models to analyse the structural behaviour of the column splice connection – taking the advantage of ABAQUS [8].

This iterative process does not necessarily evolved from the strict order of the points considered.

1.6 Project accomplishments and decisions

The present chapter introduces some of the decisions taken throughout the Frameup process development. When it comes to the design of the building, a six-story building is considered. However due to growing interest in the project some of the solutions are focus on the development of a pilot building (three-story building).

In order to apply in practice, some of the accomplishments of the project, a full scale test is performed to attest possible problem in the sequence of construction. From the full scale tests some conclusions are traced and applied in the construction sequence considered in this thesis.

1.7 List of documentation

In the scope of the work performed in the Frameup Project, a large number of documentation was produced, therefore from the technical point of view:

- **Technical Reports**, documenting of milestones of the project which are part of the project's protocol in order to fulfil its requirements as European project;

- **Technical Documentation**, as background documentation for meetings with industry, 2D fabrications drawings and Structural specification documents;

- One **Industry Conference**: *Norwegian Steel Day 2014*, November 6, 2014, Oslo, Norway

- Three **Industry Workshops** integrated in the Frameup Project:

- 1st Frameup workshop, *International Workshop on Modular Steel Intensive Building Research and Market Opportunities*, June 13, 2013, Stockholm, Sweden;
- 2nd Frameup workshop within the *IX Congresso de Construção Metálica e Mista & I Congresso Luso-Brasileiro de Construção*

Metálica Sustentável, (held in portuguese), October 25, 2013, Porto, Portugal;

- 3rd Frameup workshop, *Modular Steel Intensive Buildings*, April 3, 2014, Dusseldorf, Germany;

While from the academic point of view:

- Three C**onference Papers**, namely:

- *Portugal SB13, Contribution of Sustainable Building to Meet EU 20-20-20 Targets,* October 30 - November 1, Guimarães, Portugal [9];
- two within the *EuroSteel 2014, 7th European Conference on Steel and Composite Structures,* September 10-12, 2014, Naples, Italy [10][11];
- *III International PhD Students Workshop*, October 30-31, 2014, Coimbra, Portugal

- Supervision/Contribution for **End-of-studies project** and **Master's thesis**

Supervision of two students at End-of-studies projects regarding Frameup building energy efficiency and its sustainability assessment [12][13].

Contribution for a Master's thesis regarding the fire resistance, as far as concerns to steel plate insulation of the 3D modules [14].

2 STATE OF THE ART

This chapter introduces and describes the current situation with regard to building concepts and technologies which contribute to improve the efficacy on the construction. Within the building's execution phase, more specifically, when it comes to the assembling process, there are some constrictions along the process, which may generate delays in the construction scheduling. Therefore the Modular construction concept and its main components are approached, as one of the solutions.

2.1 Modular buildings

Modular buildings are constructions which combine different prefabricated units assembled on site. The use of prefabrication in combination with standardization was insistently supported by [15], who appealed that *advantages include speed of construction, lower cost, reduced need for skilled labour and achievement of zero defects*. Most of these benefits take the advantage of off-site manufacturing, within industry environment, where mass production turns out to decrease the costs since work becomes more efficient and takes less time.

When it comes to choose modular construction, the choice is manly influence by the characteristics which follows:

- Speed of construction, since the work at the site can be performed simultaneously with the work off-site;
- Less area needed to construction operations, reducing the constraints in the vicinity of the construction site;

- High level of quality control from factory production, since everything is produced benefiting of the indoor production, followed up by the requirements and supervision that industry obligates;
- Economy of scale through mass production. For large projects, through standardisation of units.
- Low impact in terms noise and other pollution, especially for places where it has to be minimised within the construction operations;
- Less material waste, since most of the components of the building are produced off-site, therefore it also minimizes on-site waste.
- More sustainable in the sense that the modular buildings are more flexible to disassemble which allow modules to be relocated and refurbished for future reuse. Moreover at some cases, the building can be entirely recycled.

On the other hand, the modular buildings also have disadvantages, such as:

- The transportation of disproportionate sizes may increase the costs and create delays in the construction, especially if the production is located remotely from the construction site.
- Module sizes can be affected by the need to reduce the sizes for transport, affecting room sizes.

However the advantages are far more than disadvantages. Nevertheless it is very important to consider the sizes for transportation in the process design.

The modular construction has existed for decades, however, just more recently, it has been seriously considered in the market, as solution to improve quality and productivity [16].

Modular constructions, regarding to residential buildings geometry and its arrangement of modules, three basic forms units can be distinguished:

- Modular room units, which are assembled in row, accessed by corridors, stairs and other communal facilities.
- Modular bathrooms and kitchens, which can be combined with traditional on-site construction.
- Open-side modular units, which are combined to form large rooms.

From the structural point a view, modules can be divided in seven different forms [17]:

- 4-sided modules

- Partially open-sided modules
- Corner supported, open-sided,
- Modules supported by a primary structural frame
- Non-load bearing modules
- Mixed modules and planar floor cassettes
- Special stair or lift modules

Some of these types of modules are illustrated and described in the following paragraphs.

2.1.1 4-sided modules

Modules are produced with as a cellular type, where all sides are closed. Modules are able to transfer vertical load from the modules above and also horizontal loads, due to wind action, through their longitudinal walls. The Figure 2.1 shows an example of a structural modelling of a 4-sided module and one already manufactures.

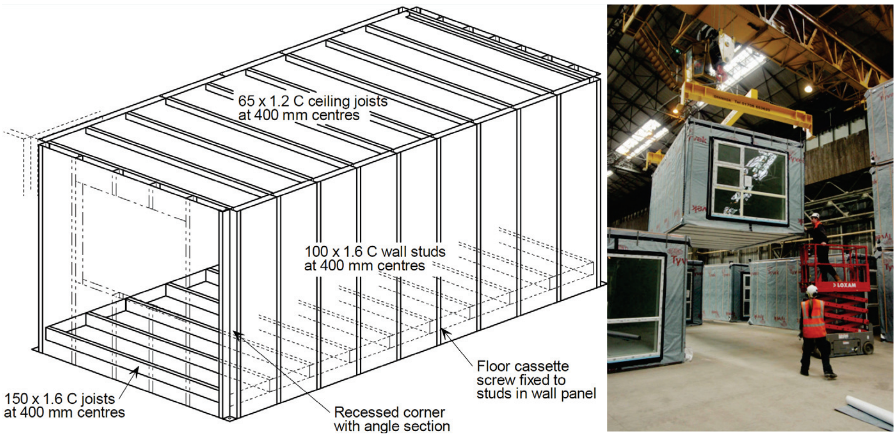


Figure 2.1: Typical 4-sided module [17].

Therefore this type of modules plays a role in the equilibrium of the structure, thus depending on the location and exposure to weather conditions, specially wind, the height of a building, in a fully modular construction, ranges from 6 to 10 storeys maximum. However additional angles may introduce to improve the resistance of the combined structure, when it comes to module-to-module connections, are performed by means of plates bolted on-site [17].

The Figure 2.2 shows a two-story building and a six-story building, where some its modules are provided with balconies.

Figure 2.2: Typical 4-sided module [17] [18].

As a drawback the 4-sided modules are limited in size to fit within the transport dimensions, which limits the cellular space that is provided.

2.1.2 Partially open-sided modules

The partially open-sided modules are very similar to 4-sided modules. As it is possible to conclude, its difference lies on the side openings along the length. In order to cope with the openings, in terms of stability, intermediate posts and continuous beams are introduce to ensure the module stiffness, allowing to span 2 to 3 m to create openings in the sides and ends of the module. Therefore modules also be placed together to create a wider space.

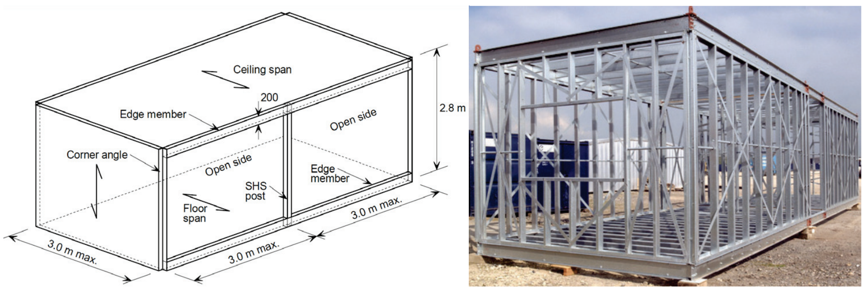


Figure 2.3: A partially open-sided module [17]

The Figure 2.4 shows the layout of apartments where partially open sided modules are combined in pairs. Alternate modules are shaded for sake of visualization. The right side of the figure shows the assembling of the module in the modular building.

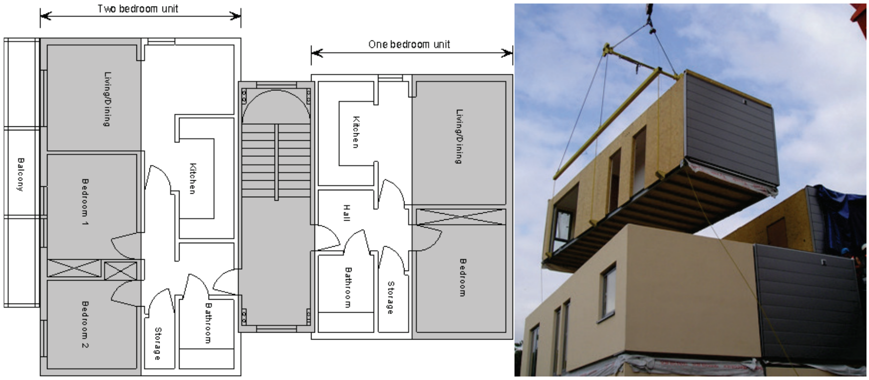


Figure 2.4: Layout of apartments using partially open sided modules [17]

The modules stability is affected by the opening at the modules sides therefore a rigid structure is needed for lifting of modules. Moreover, an additional bracing system may be considered in the building in order to provide additional stability.

2.1.3 Corner supported, open-sided

The open-sided modules rely on the posts at the corners which provide the compression resistance of the module, as show in the Figure 2.5.

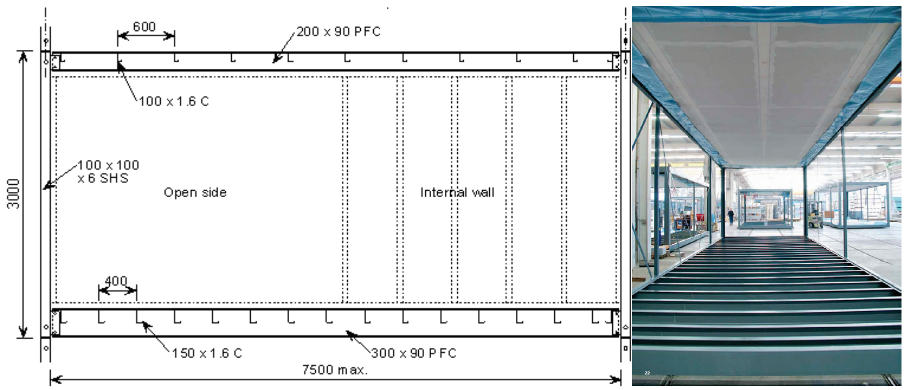


Figure 2.5: A open sided module [17][18]

The stability of the building generally is provided by separated bracing system in the form of x-bracing in the separating walls. Thus, the fully open-ended modules are not commonly used for building taller than three floors height.

2.1.4 Modules supported by a primary structural frame

As described in the previous chapters, the structural arrangement of the modules plays a very important role on the stability of the building. For this reason a primary structure at a platform level may be designed to accommodate the model units, where in each bay two or three modules are considered. This level platform or podium is generally braced to resistance to horizontal loads and a separate braced core is designed to stabilise the group of modules. Moreover an external steel structure, include in the façade, may stabilise the building. Non-load bearing modules can be considered in a primary structural frame. The left side of the Figure 2.6 shows a layout of mixed modules on a primary steel frame and on the right side the installation of the modules behind external steel framework.

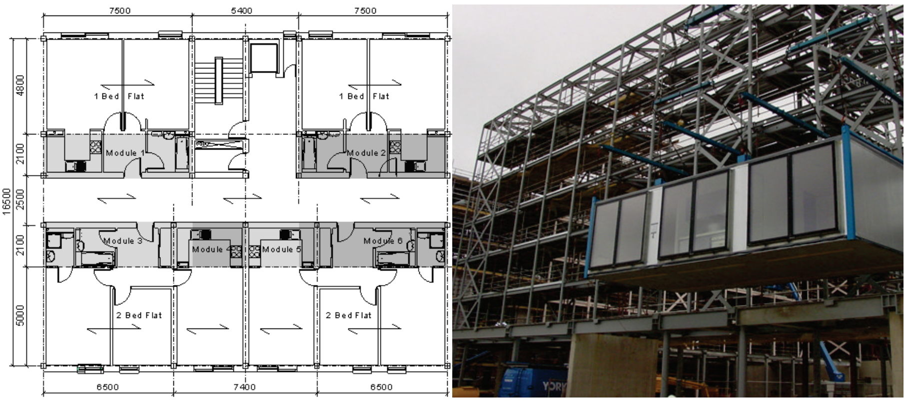


Figure 2.6: Examples of modules supported in a structural frame [17]

As one of the main advantages of the modular construction, regarding modules supported by a primary structural frame is that modules can be disassembled in a later stage of the life span of the building.

There are a significant number of technical characteristics which modules need to take into account, such as: dimensions, service interfaces, acoustic performance and fire safety, however, stability of modules, as described before, has a big influence when it comes to design a modular building.

As the speed of construction are one of the main advantages of the modular construction, modules and building should be design in order to facilitate the assembling process, taking advantages of erection equipment as the in majority of the modular building performed by a crane.

PART I

DEVELOPMENT AND IMPLEMENTATION OF THE FRAMEUP CONCEPT

3 SYSTEM DEVELOPMENT

The Frameup system arises from the idea of streamlining the building erection towards industrialization process in building construction. Industrialized building concepts aim to be the solution for some of the problems which engineers face on the off-site production, technologies, standardized products, elements and modules, etc. Therefore, in order to create a feasible system to streamline the construction process, the Frameup concept focuses on the execution process combined with modular construction.

3.1 Situational factors

The following chapters describe some of the factors that have influenced on the arising and development of the Frameup concept.

3.1.1 Economic aspects

Sweden is the seventh-richest country in the world in terms of Gross Domestic Product (GDP) and the twelfth country in terms of Human Development Index [19]. Countries with relatively high standard of living are known to have high construction costs [20]. According to Eurostat, Sweden occupies the first place in terms of hourly labour costs for the construction sector across the EU28 members states in 2013 with an hourly rate of 24.50 € [21]. Consequently, this has a great impact on the final price of a building.

However, it is important to distinguish between building prices and buildings costs. The building price shall be referred to as the market price to be paid by the customer, whereas building costs are defined as the costs incurred by a contractor in carrying out the work. The building price reflects the variation in profit whilst building costs do not [22][23]. Therefore, the price may be reduced by decreasing the direct costs such as land, labour, material and equipment.

As Luleå is located in northern Sweden, the construction costs may to some extent be higher than in other parts of the country due to e.g. longer transportation times. However, costs for land are relatively low due to the low population density and plenty of area available for construction. Thus, this fact partly counterbalances the higher other direct costs since land costs have a large share of the housing final costs. Nevertheless, when it comes to labour, material and equipment, one can expect an increase of costs when comparing with other European countries. Therefore, the present thesis aims to reduce costs, mainly in erection operation and equipment and labour costs, by the reduction of workers in situ, increasing the industrialization of the process, as much as possible, throughout Execution Process.

3.1.2 Housing situation

Higher construction costs reduce residential construction and thus affect fluctuation in housing prices and rent. According to *Boverket,* in 2003 the higher production cost was one of the major obstacles in housing construction, as illustrated in Figure 3.1 [24].

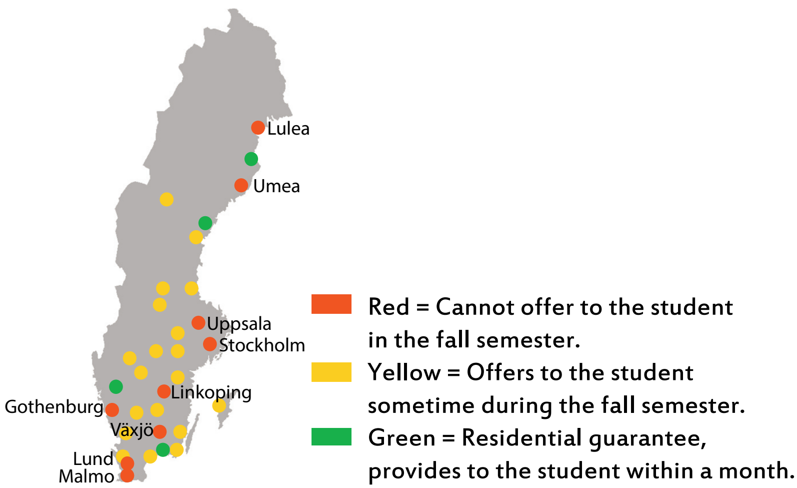


Figure 3.1: Housing situation in Sweden [25]

More recently, regarding students' accommodations, *SFS Bostadsrapport 2013* [25] highlights the big demand for dwellings due to housing shortage. It states that only 4 out of 32 cities in Sweden can really guarantee all students dwellings within 30 days. Thus, within the red list, which enumerates the cities where residences cannot be offered within the falls semester, the following cities can be found: Gothenburg, Linkoping, Lund, Malmo, Stockholm, Umea, Uppsala and Luleå. Basically, all major cities in Sweden are listed.

In Luleå, the increase of the student population has aggravated very much the problem, and so, according to *Studentbostadsservice* [25], around 1000 students are on the waiting list to get accommodations. They have to live in subsidized hostels and camping cottages, meaning that not all conditions are met for an effective study environment. Therefore, in the long-run this may affect universities reputation.

3.1.3 Climate

Although most of Sweden exhibits a temperate climate, the northernmost part is defined as subarctic climate. Nevertheless, climate constitutes, from the most differentiated latitudes and longitudes, an important factor to take into account throughout the whole project time schedule in order to meet project deadlines. The climate may create constraints for the normal development of the construction process, which generates delays and consequently is more costly.

As there is a demand to reduce the vulnerability of a construction investment, all companies adopt different methods to minimize impacts, as the one genera ted by weather constraints.

The most common is to schedule more sensitive tasks, for instance, the building foundations, to coincide with a period when its construction is most convenient. However, it is not always possible to have the task coinciding with the best period, either because the task needs more time to be performed or the period is too short to encompass the task in. For instance, the summer period in Luleå is shorter than in most of the other parts of Europe and, thus, the construction tasks need to be performed in a much shorter period of time. However when this is not possible new methods need to be implemented in order to either straightening the process or to create the adequate conditions for the task to be performed. An example is shown on the Figure 3.2, where an overall temporary roof creates the adequate conditions to perform the construction work.

Figure 3.2: Overall protection of construction site (Sunderby hospital, 2014)

For Sweden, especially in the northern parts of the country, the second reason may be the most common since there is a six-month snow season. Therefore, all construction investments, with duration larger than this period, face the problem.

Thus, this thesis aims to bring a new and feasible solution for the problem by starting the construction from the roof to protect the construction area and consequently avoid constraints within the construction schedule.

3.1.4 Sustainability

Building and infrastructures designed and constructed nowadays are intended to experience a life span of at least 50 to 100 years. Building construction industry consumes 40% of the materials entering the global economy and generates 40-50% of the global output of greenhouse gases. It is thus essential to involve the building construction industry to achieve sustainable development in the community [26]. Therefore, and since the scenarios in terms of climate changes are rather pessimistic, the scientific community found imperative to mitigate as much as possible the impact generated from the building's construction until end-of-life.

3.2 The Frameup concept

The Frameup concept introduces a new approach of execution technique which consists on the execution of a building starting from the roof to the first floor. The existence of a horizontal rigid frame - grid - in combination with lifting towers - Pylons - permits the erection of the building, promoting each time the building is lifted, a clearance of one-floor-height plus tolerances at the ground level. This creates room enough to assemble the lower floor from below the previously assembled floor. The procedure is repeated until the first floor of the building is assembled. The following chapter illustrates the aforementioned description.

3.2.1 Step-by-step execution

Figure 3.3 and Figure 3.4 introduces a stepwise procedure of the Frameup system in a conceptual development method described before, where for the sake of visualization, the façade is neglected.

Within the first step, the Lifting system is assembled and correctly aligned with the construction axes of the building [a]. The roof and all the elements attached to it are installed [b] and once finished, the roof is lifted up one-storey-height plus necessary tolerances [c] to accommodate the assembly of one-floor from below. The steel structure, 3D modules, claddings, utilities, etc. are assembled taking advantage of the benefits of being at the ground level and simultaneously being protected from the climate constrains [d]. Once ready, the grid can move downwards, until the roof's columns meet the floor's columns, so bolts can be tightened [e]. After this stage, the rigid frame is released from the structure and returns to the initial point [f], permitting erection, once again, of the structure above it (see Figure 3.3).

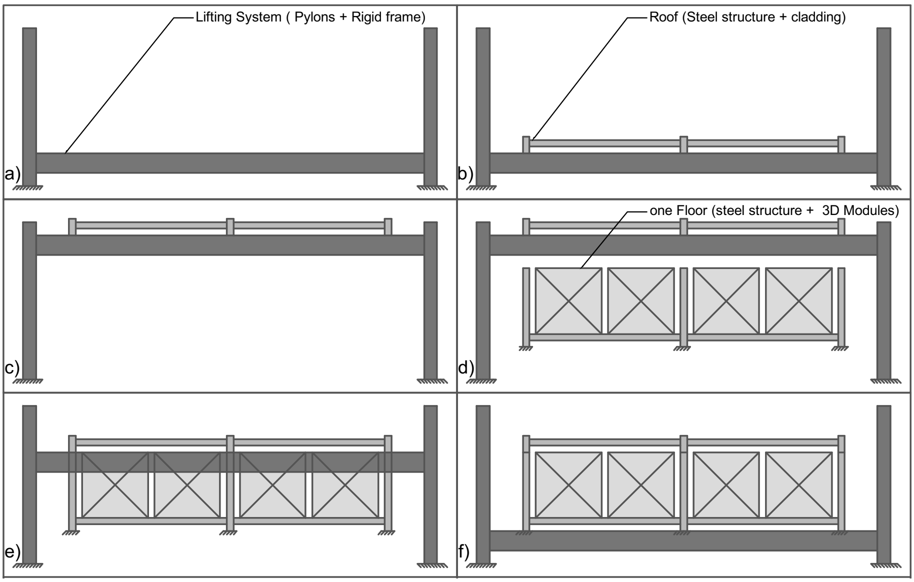


Figure 3.3: Six first stages of the Frameup concept

This time the lifting includes not just the roof but a floor too [g], as shown in Figure 3.4.

The next floor is assembled from beneath [h] and connected to the previous assembled one, by lowering the building down [i]. The assembling of the floor should include all the elements which constitute it, such as claddings, services and all kinds of installation. However, some internal tasks, namely, services connections and finishes, may be later on completed from inside the building.

The process is repeated until it reaches the number of stories proposed [j]. On the subsequent floors should be connected the services installations such as: water, electrical supply, etc.

Once finished the building construction, the Lifting system can be disassembled and reassembled in the construction of other buildings. So its utilization should be seen as an erecting equipment which is fully dedicated to this type of buildings.

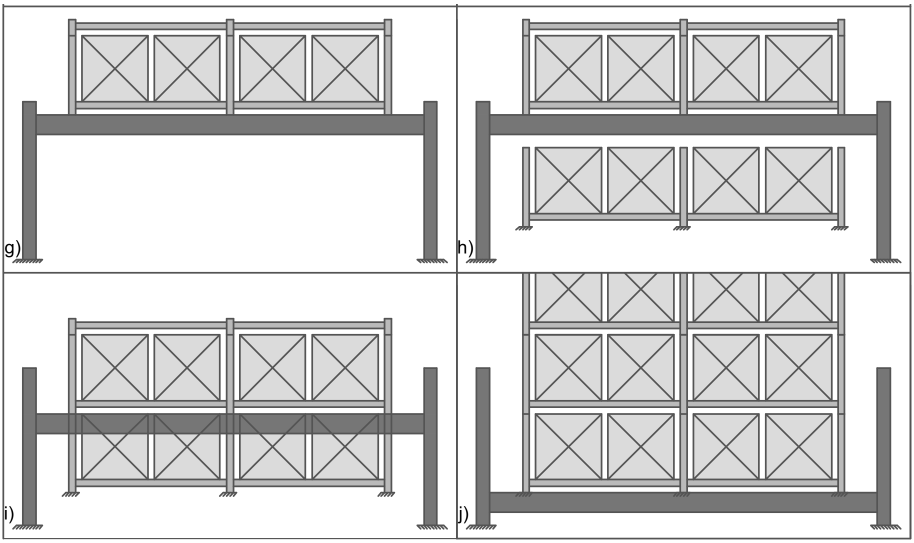


Figure 3.4: Four stages of the Frameup concept

The 3D modules do not have any contribution to the structural performance of the building. Since they just sit on the steel frame, modules can be taken out from the structure, for instance, by a forklift, and be replaced by a new or refurbished 3D module.

In addition, it may be considered that buildings, already constructed using the Frameup system, can be, in a later stage, provided with additional floors or some buildings devoid of some of its floors. Thus, in order to increase or decrease the number of floors, the Lifting system just needs to be installed once again and perform the similar procedure, either to add or to take floors.

3.2.2 The Modular Housing Stock Concept

Ultimately, taking further the concept previously described, the Modular Housing Stock Concept is introduced. This concept arises from the housing shortage, whenever the students' population fluctuation overcomes the housing market availability. Thus, the Modular Housing Stock introduces the idea of a stock of 3D modules/floors for students' residences, which could follow the fluctuations of students' population among the different universities and along different periods of time, to suppress the needs for housing. Therefore, assuming an established network of buildings on the main universities, with the same characteristics as the Frameup concept introduces, they would be used to accommodate, according to the stock of 3D modules/floors available, more or less number of floors according to house shortage at each place.

As an example, in a first scenario (see Figure 3.5), an increase on the number of students in Stockholm and an excess of housing in Luleå is observed. Consequently, from the buildings in Luleå, some of its floors could be moved to Stockholm, so to keep the balance and fulfil the needs.

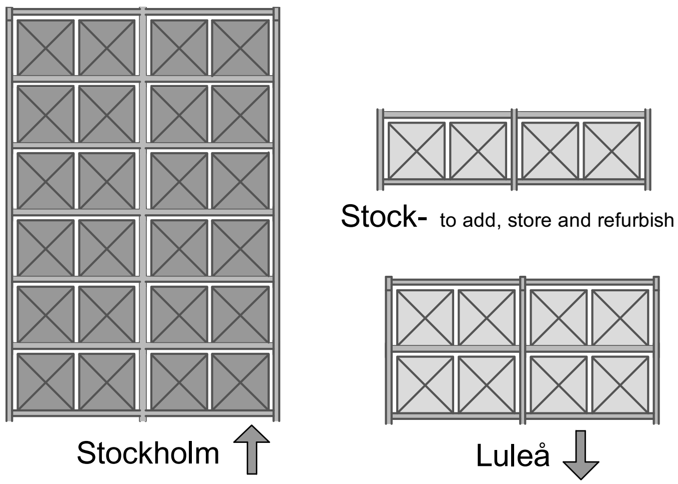


Figure 3.5: Illustration of the Modular Housing Stock Concept – scenario 1

Thus, assuming a contrarily scenario, (see Figure 3.6), where a great increase of students' population in Luleå coincides to a decrease in the number of students in Stockholm, the surplus of rooms available in Stockholm could be disassembled and transported to Luleå, in order to face the housing shortage. While for the case of an excess the 3D modules/floors could be stored in the Stock.

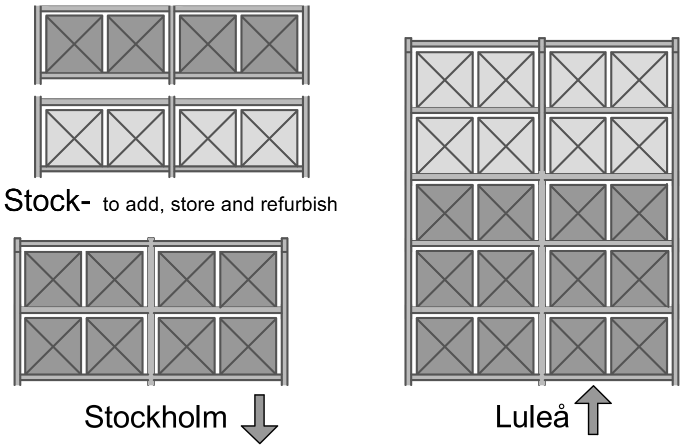


Figure 3.6: Illustration of the Modular Housing Stock Concept – scenario 2

Moreover, in the case that both populations of students would fluctuate very much, an available stock of rooms could overcome these extraordinary needs, providing more 3D modules/floors, in its shortage or store 3D modules/floors, when it comes to a surplus on the number of housing available.

Meanwhile, at the stock storage, the 3D modules would have the time to be repaired and refurbished to prolong its life span, while they might be also upgraded to meet students' requests.

In this sense, this network of buildings from the Housing Modular Stock concept could solve the problem of housing shortages or surpluses, in a sustainable way, without unnecessary new constructions. At the same time, it is believed that inflation of house prices, due to a sudden increase of students' demand for housing might be reduced, as well as decreasing of the parallel market of second-hand renting. Nevertheless, this concept is still in an embryonic status therefore, any further conclusions should be seen within the scope of early assumptions.

3.2.3 The Inline Construction's Concept

The present concept arises from the need to extend the construction of the Frameup buildings. Following up the Frameup concept towards the idea of erecting large edifices, a construction process may be performed following an erection line where the Lifting system is installed to erect several of individual building blocks in a construction line. Each time a block is finished, the Lifting system is dragged to erect a new block right after the previous one – Inline Construction Concept.

Figure 3.7 shows two already erected blocks of building whereas a third block is being built.

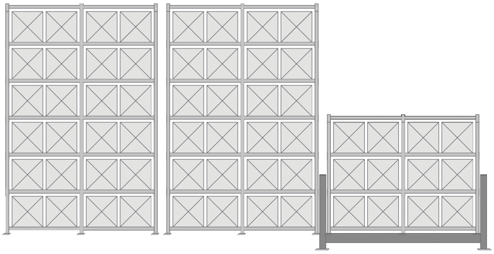


Figure 3.7: Sketch of the Inline Construction's Concept

The consideration of this concept introduces some issues, especially since it needs to consider a gap between previous and future blocks of building for the Lifting system to operate freely, as shown with more detail in Figure 3.8.

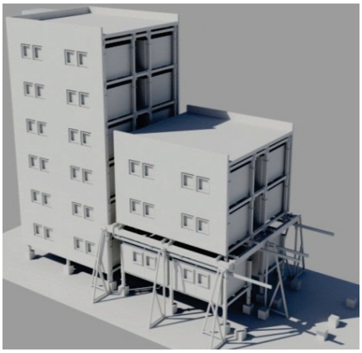


Figure 3.8: Illustration of the Inline Construction's Concept

Hence, the gap between buildings may be filled with structural elements and/or facade elements right after the subsequent block is completed.

3.3 Strategy for concept's materialization

The process of concept's materialization is followed up by a consecutive chain of solutions and decisions to be taken, since along its path many other issues cross its way. For instance, the sequence of the building construction involves a large number of steps to be taken and some of the solutions reveal to be, at some point of sequence of assembly, impossible or too much complex to be performed. Therefore, the strategy employed is to choose the simplest solutions which drive the project to the objectives initially proposed.

The concept's materialization involves, as shown in Figure 3.9, a constant iterative process where Frameup Concept is followed by 4D modelling, where 3D drawings are associated with the scheduling of the sequences of construction.

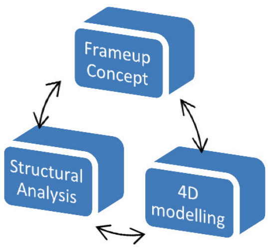


Figure 3.9: Materialization of the Concept

Finally, the structural analysis is performed according to the design standards. At the first stage of the materialization of the concept, just expeditious calculations and simple drawings are performed. However, as the projects advances, its accuracy is raised in the same proportion.

The 3D drawings are intended to provide the necessary accuracy, not just for the sake of verification along all the assembly processes, but also, at a later stage, to create 2D drawings for production for the steel workshop.

The thesis implies not just the assembly sequence throughout the whole process but also the structural design of the building and Lifting system. Therefore, both structures are in some kind of "symbiosis", i.e. they are very much interrelated. However, in the design process, building should always take the design lead on the project, whilst the Lifting system should follow building's design. The building constitutes the final objective and product, so it should be optimized to meet market requirements, and the Lifting system the tool that makes it possible. Nevertheless, the building may be assembled or disassembled by other means, whereas the Lifting system is only prepared for this specific building.

3.4 Components of the Building

The building is a six-story building and is designed to host students, where 3D modules are intended to provide accommodations to students. The Building structure has 21 m high (from which, 3.203 m per floor), is 11.6 m long and 10.8 m width; totalizing 125.3 m^2 of gross area. The Building is composed of eight 3D modules per floor, resting on the beams. The common use area per floor, i.e. the corridor area is 1.620 m x 11.205 m, therefore 18.152 m^2 per floor, making a total area of 108.913 m^2 for the whole building. Thus, the total utility area of corridors and modules is 106 m^2 per floor, which totalize for the six-story building a utility area of 638 m^2.

3.4.1 3D modules

The 3D modules are intended to provide proper conditions for students to live. Most of the student residences consist of small rooms - corridor rooms - furnished with a bed and a desk, while others include a bathroom and some even a private kitchen. Therefore, a survey among one hundred students from LTU [12] was performed in order to identify their preferences concerning accommodations. Some of the figures are considered in the following paragraphs.

According to this survey, most students are rather satisfied with their actual accommodation. The main complaints are due to prices, location, heat insulation and noise from the ventilation and neighbours. The majority is paying attention to environmental issues and in average people are willing to pay 150 SEK more per month for that. The same observation is done for sound insulation.

Most students spend between 4 to 8 hours per day in their rooms, excluding sleeping hours. Counting 8 hours for sleeping, students are spending between 12 and 16 hours in their rooms. That confirms that the quality of interior air should be good enough to avoid health problems.

As majority of the interviewed students prefers to meet their friends in the living room and/or kitchen, the modules should be well designed and with facilities to make people feel comfortable in those areas. The survey also shows that students like some privacy and, thus, prefer their own apartment or shared flat with private room and bathroom. Finally, students prefer to live on the university campus or suburb, and concerning the kind of building, multi storeys, from 2 to 4, are their favourite ones.

The conclusions collected from the survey were taken into account for developing the 3D modules in co-operation with the company *PartAB* [27] – responsible for the design and production. As a final outcome, single 3D modules are equipped with the normal rooms' conditions plus a private bathroom. Double 3D modules are additionally equipped with a small social area and kitchen, as can be seen in Figure A.9 and Figure A.10 in annex C. Single 3D modules have a usable floor area of approximately 10 m², double 3D module 20 m².

Regarding the insulation, each module has its own insulation and ventilation system. The exterior shell of the 3D module is made up of interconnected 400 mm wide cassettes (1 mm steel plates), as shown in Figure A.7. Attached to the cassette walls there are two gypsum boards (2 mm x 15 mm) that cover all the module (see Figure A.8), and 50 mm of rock wool in cassettes' core. The walls of the modules guarantee a good sound insulation and fire protection of EI60 between apartments. The rock wool has both good acoustic and fire properties and the two layers of gypsum board create a fire barrier to the module and create a fire cell. The floor of the modules is composed by a concrete slab (average thickness of 60 mm) that is enclosed in a frame made of steel C - beams.

Complementary information regarding the 3D modules, concerning their optimization for the concept, can be found in chapter 3.6.1, whereas structural considerations are presented in chapter 4.2.1.

3.4.2 Modular frames

The main objective is to optimize all elements for quick assembling. Thus, for the structure of the building, and following up more in consideration the concept of modular elements, the building structure is composed of modular frames, i.e. columns and beams that are welded already in a workshop. It is believed that time and costs can be reduced by dividing the building skeleton in substructures, which reduces the number of connections needed to be assembled. Advantages from a structural point of view are described in chapter 4.2.2.

3.4.3 Claddings

Concerning the claddings, the main idea is to adopt sandwich panels in the façade and roof, since it is believed that long panels may be easier to handle and, thus, assembled quicker.

Two alternatives are possible to be considered: Attaching the façade to the modules in the factory (increasing modularization), remaining just the gaps left to be fitted in-situ; Installation of the façade elements in-situ. The first option implies a further study of the fastening of the façade against the 3D modules and, of course, some further changes in the production line. Therefore, at this stage, all panels are assembled in-situ. However, it is still believed that the first option is worth to be further analysed at a later stage.

Panels' support conditions

During the installation of the panels some problems may arise, especially concerning the fastening of the sandwich panels against the structure, i.e. the columns. These issues are mostly associated to column splice's end-plate and the constrictions introduced, and not directly to the architectural, nor the thermal point of view. In Figure A.12 it is shown that there is a distance of 122.5 mm, caused by the column splice's end-plate geometry plus tolerances, which keeps the panels away from the columns' walls. To fill this gap, *LindAB* [28] suggested using a hat profile, fixed to the column, where panels could be fastened against (see Figure A.13 and Figure A.14 from Annex A). This avoids the fastening of panels directly into the columns' profiles, hence does not interfere with the strength of the columns, i.e., the cross section's net area remains the same as the gross area.

Consequently, in order to avoid the airspace between 3D modules and façade, generated by the shifting of panels away from columns, it is decided to move the 3D modules together with the panels, and so removing the gap. From a thermal perspective, the absence of the gap should also be complemented with the sealing of airflow between floors, more precisely: in the columns and between modules, from floor to floor.

Alternatives for interaction of column-splice with façade

The previous chapter introduces the problem originated from the column splices' interaction with the façade. As it is described previously, the present thesis focuses on a new concept of connection, the so called Finger Connection. Besides its interest within the Project, when it comes to the assembly process, it may also bring up other advantages. The Finger Connection is a smaller connection compared to the common end-plate column splice. Therefore, it reduces the distance needed between façade and columns. In this sense, it brings up a new argument for its utilization. In Figure A.15, the slenderness of the connection, which enables the reduction in distance between modules and columns, can be observed. However, by closely studying Detail D, it is possible to conclude that modules may need to be re-designed in order to take away the corner that accommodates the flush system.

Alternatives to fit panels

Sandwich panels are equipped with a sort of connector which creates the sealant when both panels fit together. Horizontal panels are installed by pressing downwards, one against the other, in a consecutive vertical assembly of panels. However, since the assembly of the building is performed downwards, consequently the panels need to be connected pressing upwards, instead, and this might generate problems performing this installation, since gravity is no longer assisting the connection of panels. For this reason vertical panels, since they are installed by pressing horizontally one against the other, are possibly more suitable to be considered in this building.

Though, the vertical panels, horizontally connected, one by one, at each floor, need to be connected to the panels from the floor above. Therefore, a horizontal panel that creates the transition between floors, i.e. it is connected to the lower and upper panels of consecutive floors, is considered (see Figure E.14). The second reason for the existence of the transition panel (assuming the use of the conveyor system for the assembly of the panels) is related to the fact that, when Lifting system moves downwards to connect upper to lower floors, a gap is needed to accommodate the Sliding cantilevers (see Figure E.12).

3.4.4 Corridors

The corridors are shaped by the 3D modules' walls, which are already provided from factory with a finish surface, so no additional work is needed in-situ. Regarding the corridor floors, the solution found, is to consider the same type of concrete slabs employed in the 3D modules, since these slabs have proved a good structural behaviour and are not considered to be heavy, hence easy to handle. The concrete slabs are of the dimension 1480 mm x 2675 mm and four of these are intended to be assembled in between the 3D modules, which at the same time create the ceiling of the floor below (see Figure A.6).

3.4.5 Stairs and lift

The building structure is prepared to be attached with a stairs structure in one of its extremities. It is intended, when it comes to the pilot building, that a modular stairs structure can be installed, either during the assembly of after the building erection. However, regarding a six-story building, the requirements are obviously very much more demanding and not just a staircase is needed but an elevator as well. This solution was not deeply investigated; however, one possible solution may be to consider one module fully dedicated to these purposes – shaft 3D module. This 3D module shall have the same dimensions and be devoid of floor and ceiling. This creates the possibility to create a shaft allowing the access between floors, so the proper equipment shall be installed to either create a stair case or a lift shaft.

3.4.6 Service shafts

The crossing of pipes through building floors should be hidden for aesthetic and protective reasons but in any time easy to access for technicians, through a service door. Thus, the area in between modules, close to columns and corridor, are intended to accommodate the sewage system and drain system of pluvial water coming from roof, power supply, etc. The Figure A.6 shows a generic plan of the building where it is possible to see the free areas close to the columns and modules which are intended to accommodate the service areas. Detail B shows with more detail the areas located for the shafts in the core of the building.

3.5 Components of the Lifting system

The Lifting system is constituted by different subroutines and subsystems that make its functionality possible. Therefore, from the Frameup concept to the materialization of process the Lifting system integrates some of the following mechanisms which allow the concept to become possible. Thus, in the following chapters, the components of the system are introduced along the conceptual process.

3.5.1 Grid

The grid, before denominated as rigid frame, constitutes the skeleton of the Lifting system since it bears all vertical and simultaneously supports horizontal loads coming from the building, forwarding them through the Pylons to the foundations. The grid is also responsible to accommodate parts of the subsystems which are included in the Lifting system, as the internal cantilevers and conveyor system, but also minor systems, such as:

- **Guardrail**, that is intended to be docked into the grid, during assembling of grid, and is used to keep workers within safety limits, while they perform working on the safety corridors of the grid.

- **Grid-Hook**, for docking the guardrail to the grid.

- **Grid-Holder**, where self-climbing devices fixe to the grid.

The grid moves partially outside the building's perimeter and inside, coincident to building's corridors. For a closer look see Figure B.5 in Annex B. In order to make the assembling of the façade possible, the grid is considered to be distance from the building.

3.5.2 Sliding cantilevers

Sliding cantilevers (SC), as shown in Figure 3.10, are mainly composed of two tubes attached to the grid, where the internal tube moves freely inside the outer tube welded to the grid.

In order to adapt two distinct positions: **in**, beneath the building, , to promote the building erection by applying a vertical ascending force at the beams, in the vicinity of the columns; or **out**, allowing the grid to move freely within the outer perimeter of the building. The previous concept is described in Figure 3.10, where pulling of Sliding cantilevers promoted the sliding of cantilevers **in**, whereas by pushing shift LC outwards to the position **out**.

In Figure B.6 the 24 Sliding cantilevers that constitute the Lifting system are represented. Two different types can be distinguished: the long Sliding cantilevers, which are present in the outer part of the grid, and the short Sliding cantilevers, that are located at the inner part of the grid, coincident to building's corridors.

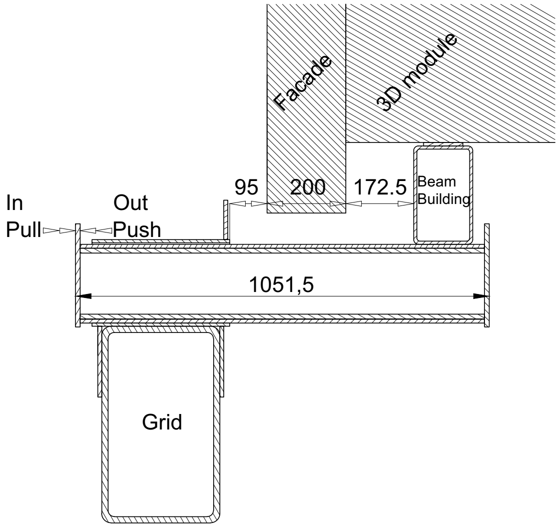


Figure 3.10: Section of the sliding cantilever integrated in the structure

The Sliding cantilevers cover the distance which is kept from the grid to the 3D modules in order to accommodate the claddings on the façade plus tolerances, of 95 mm, for the grid to operate along a parallel plane to the façade.

3.5.3 Pylons

The Frameup system is initially considered with 8 Pylons (as in Figure B.8) and later on with six Pylons, which can be seen in Figure B.7. The reason lies in the fact that, in order to fully take advantage of the conveyor system, the lorries would need to have enough room for manoeuvring to align the elements (3D modules, steel structure, etc.) with the conveyor system, to be posteriorly grabbed and slide into the structure. Moreover, as described in chapter 3.2.3, – the Inline construction's concept - it is intended that the Frameup system is able to be built in a row and, it needs to have one of the sides free of any structure that may interfere in the gap between building's parts to be connected. Therefore, for this reason the removal of Pylons from the extremes of the Lifting system, as described in Figure B.7, allows the future consideration of the Inline construction's concept.

3.5.4 Conveyor system

The conveyor system (CS) is the result of the solution found to streamline the assembly of all the elements in the building. The CS is bolted to the grid's beams and it is constituted by rails, where an auxiliary rigid structure (hanged in the conveyor system) transports, by sliding, the elements beneath the building (see Figure B.9). The slide mechanism is activated by a winch, installed in the grid, which has a closed pulling system, i.e. the winch slides the elements in or out, of the building perimeter, according to its direction of rotation. This conveyor system has not been tested up to now on a real scale test. However, it is strongly believed that the Frameup system will have plenty to gain from this system.

3.5.5 Self-climbing device

Within the scope of the Frameup project, a lifting device (Figure 3.11), the so called self-climbing device is developed, tested and optimized at RWTH Aachen University (partner of the project). One of the main advantages is to find a good relation between manufacturing costs and the task which performs.

The self-climbing device is composed, as shown in Figure 3.11, of an upper and lower device, where each one has a wedge, where jack either press or pull; a shoe, where wedge operates and a friction pad, which works as a parallel safety measure. Therefore while one of the two “shoes” is fixed to the pylon, the other device is pulled /pushed upwards by the jack. The stroke of the jack is limited as the whole system (upper device, lower device and jack) climbs up the lifting column in caterpillar-style.

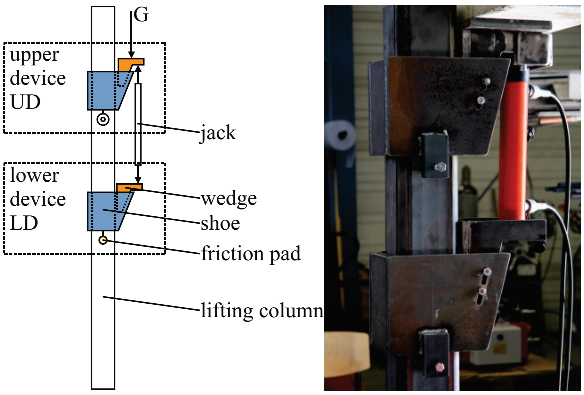


Figure 3.11: Self-Climbing device developed at RWTH Aachen University [10]

Advantage of such approach is that all components are standard products, easily available on the market. The fixation of the devices to the column is achieved by friction. Both devices consist of a shoe and a wedge, whereas clamping is realised by pressing the wedge into the shoe, using the load to be lifted. During the clamping process (e.g. while pressing the wedge into the shoe), the shoe is able to shift downwards as friction is not acting. Therefore, additional friction pads are used to carry a part of the load during the clamping process. Initially, two friction pads have been used for each device. In a second step, four friction pads have been used to increase the maximum capacity of the system and improved safety of the execution. For the final prototype, the friction pads have been replaced by two self-acting safety brakes. During the lifting process, all self-climbing devices are controlled and monitored by a central station to ensure synchronized movements and guarantee that the grid is always levelled [10].

3.5.6 Operational columns

The operational columns are fixed to the foundation and are intended to make the transition from the building column bases to the foundations anchors each time the building needs to be fixed, i.e. for a stepwise fixation of the building, along its erection according to the sequences of construction.

Therefore, the operational columns are fixed directly to the anchors coming from the foundations. Thus, they are not considered directly as part of the Lifting system, but indirectly since they play an important role for the assembling process to be performed smoothly. Moreover, its use is intended to be transitorily, i.e. just during construction phase and taken away in the end from the building. And so, at that time the column splices of the building are fixed directly to the foundation’s anchors.

The use of the operational columns facilitates the construction process and it constitutes the solution for different issues, namely:

- The operational columns allowed the Lifting system to operate adequately, by elevating the building to an upper level during the execution phase performed in the full scale test taking place in Sangis, Sweden at the old *PartAB* [27] facilities as described in annex F. The building’s elevation (considered as the distance from the foundations to the bottom of the beams) should be in accordance with the minimum operational height of the Lifting system (described in Figure F.3). The minimum operation height of the Lifting system refers to the minimum height, from its foundations top level up to the level where it performs the lift. Therefore in this case the building needs to be in accordance to be coherent with the Lifting system.

It is known that column bases are considered to be very time-consuming for assembling to be performed (since needs to be accurately aligned and levelled). Taking into consideration that roof and different floors are intended to be connected quickly, seven column-bases connections would have been needed to be connected and disconnected in the case of a six-story building. In this sense, the substitution for a column splice reduces dramatically the time needed for operation;

- Moreover, the repetitive process of fixing the building would have created irreparable damage in the anchors which would seriously compromise the schedule of the construction. Hence, by using these operational columns, the building can be connected a column splice which is much easier to be accomplished.

3.6 Additional key factors for project functionality and enhancement

The Lifting system preparation for implementation in the market constitutes a long way to go. Thus, to optimize the Lifting system mechanism, some mechanisms shall be complemented towards its full operation. The following chapters highlight the most important characteristics which each element needs to possess in order to fully achieve the objective of its use.

3.6.1 3D modules

In order to move properly and efficiently the 3D Modules, especially during Execution Process, they are already equipped from factory with two systems.

The first system allows hanging the module from the ceiling and is composed of a hook on the tip of a rod which crosses all the way from the steel rigid frame of the floor, up until it reaches the ceiling of the 3D modules. Therefore, during all the operation with the 3D modules, especially to move from the lorry to its final position, this hook allows taking advantage of the conveyor system and makes this solution the most suitable for the optimization of the assembly stage. While the second system is composed by a fixing point at the steel rigid frame, and permits to hang the 3D module as well. Both system described are intended to aid the operations in-situ in order to facilitate all procedures.

Moreover, in order to optimize the process of assembly of the 3D modules concerning the utility services, such as power and water supply, swage and ventilation, everything should be easy and quick to connect. Regarding the power supply, 3D modules are equipped with a “plug-and-play” system, i.e. a unique plug, from which the whole module is supplied, and, thus, everything simplifies its assembly. Concerning the water supply and sewage system, the plugging process may be more time consuming. However, this process can be postponed to when the building is already assembled and performed from inside. For this reason and for maintenance purposes, a service door is considered in between 3D modules on the corridors to be accessed by personnel, (Detail B from Figure A.6).

In order to transmit the loads of the 3D modules efficiently into the beams, an elastomeric bearing (EB) is used in eight specifically located places underneath, as shown in Detail A, Figure A.5. The EB has 54 mm x 100 mm and is 10 mm thick which shrinks down to 9 mm when loaded. EB are specifically located to balance loads of the 3D modules, avoiding a possible tilt effect (generated, for instance by movable loads) and EB may also enhance the thermal and acoustic of the 3D modules, by creating a steel discontinuity between beams and Modules.

3.6.2 Automation of Lifting system

In order to streamline all the procedures included in each step of the assembly sequence, the human work should be reduced to a minimum, which in an idealistic scenario human contribution would be just to program and supervise the operations, while everything would performed automatically, as far as concerns to the Lifting system. Therefore, the idea is to automate the involved mechanisms as much as possible towards the industrialization of building construction. During the lifting process, all lifting devices should be controlled and monitored by a central unit to ensure synchronized movements and to guarantee that the grid is always levelled.

Sliding cantilevers

The 24 Sliding cantilevers that form the Lifting system need to be manoeuvred – either for the position **in** or **out** – at least two times per floor assembly. Due to its characteristics, its handling does not constitute an easy task and does not consist of an operation feasible to be performed manually. For this reason, Sliding cantilevers were provided with a plate fixed, either in the inner or outer tube, in order to accommodate a hydraulic jack that enables the sliding movement, in or out, by pulling or pushing, respectively, the plate fixed at the tubes, as shown in Figure 3.10.

3.6.3 Column-splice – Finger Connection

The Frameup project aims to erect a building within the minimum amount of time. However, among the different phases of the execution process, the connection of the building, on hold, supported by the Lifting system, and the floor already assembled from underneath, constitutes one of the most critical stages. The reasons relate mainly to the fact that there may be some deviations introduced by the system itself. Thus, the consecutive floors need to be efficiently connected and to accommodate the misalignments introduced by the Frameup construction method. Therefore, the finger connection described in detail in Part II aims to connect columns that exhibit different misalignments in a feasible way without compromising the structural behaviour of the building. The finger connection constitutes a cornerstone for the whole system to work. In Figure G.5 and Figure G.6 it is possible to see some snapshots from the *Frameup's Concept - Animation of Execution Process* [29], where it is more elucidative the advantages allocated to this type of connection when it comes to assembly.

3.6.4 Pylons and self-climbing device

The full scale test performed in Sangis, as described in chapter 5.8, revealed to be insufficient to perform the lifting efficiently. For this reason some requirements are defined: the Lifting system should be able to perform the lifting 3300 mm within 1 h, both for ascending and descending operations; the Pylons should be considered possibly 6, in order to clear area, at the conveyor system, dedicated to unload the trucks.

3.6.5 Foundation

The foundation plays an important role within the project. Its importance may be elucidated when it comes to consider the critical stage where the whole building (for instances, five floors of the six-story building considered in the study) is on hold, before it can be connected to the floor at the ground level. At this stage, the entire load is taken by the Pylons and transmitted to the foundation. However, most of this load case is based on the self-weight of the building, which constitutes a much lower share of the load which foundation needs to bear when it comes to consider the loading levels of an ULS combination. In chapter 4.6.2, this scenario will be described in more detail from a structural point a view.

The consideration of the footings coming out from the slab foundation i.e. where column-base of the building meets the foundation it is intended to bring upwards the rigid point for. This solution creates the necessary space to fit the minimum operational level for the Lifting system to work. This avoids the unnecessary reduction in strength that column would need to undergo by coming from the slab of the foundation. Especially taking into account that building column-bases are considered fixed.

In the eventuality of having a Lifting system, like the one introduced in the previous chapter, that can ensure a much lower minimum operational level for the Lifting system to work, then this extra level in foundation could be neglected, and consequently reduce foundation costs.

3.6.6 In Line Construction's concept

In order to optimize the concept, grid's size and width, play an important role. As illustrated in chapter 3.2.3, the gap considered in between buildings, is considered for grid's operation during erection of the building's blocks and for its later dismounting. Therefore, in order to optimization the concept, the grid needs either to be reduced in its width of the beams or to consider a different place to occupy, to decrease its need for a large gap.

3.6.7 Transport of components

The transport of the building's components has a quite significant impact on the final costs of the building erection. For this reason, the modular construction - since it implies sets of already assembled components - represents a substantial reduction on the number of tours needed, when compared to individual transportation of components to the construction site.

However, the reduction in costs is not only defined by the reduction of the number of tours needed per element of the building assembly, but as well by the size and weight of those elements. Among the European countries, there exist small differences in terms of rules for transportation. In Sweden and Finland, there is a different concept for transportation – the module system – where different combinations of truck, tractor and semitrailers from different sizes and number are believed to bring up advantages. Nevertheless, the Swedish Transport Administration – *Trafikverket* [30] – is responsible for the transport infrastructures and provides, among other rules, the limits for weight and its dimensions. When it comes to weight, it does not constitute a big problem. However, regarding dimensions, especially once out of the ordinary range of transportation, this may generate additional transportation fees, which are absolutely inconvenient. Therefore, the whole structures, especially when it comes to the Lifting system, are within 12 m, i.e. within the maximum transport dimensions to be considered as an ordinary transport.

3.7 Cost assessment of the concept

The cost assessment of the Frameup building, within its innovative construction method, intends to assess the payback time, in order to check the project feasibility. An assessment of the costs, based on the whole concept of the Frameup building, at its configuration of a three-story building, revealed to have a payback period of the investment of 17 years [12]. Assuming profits obtained from the fifteen students: six at single modules and nine at double modules.

4 STRUCTURAL ANALYSIS

Global analysis implies the determination of a consistent set of internal forces and moments in a structure, which are in equilibrium with a particular set of actions on the structure. Eurocode 3 applies to the design of buildings and civil engineering works in steel. It complies with the principles and requirements for the safety and serviceability of structures, the basis of their design and verification that are given in EN 1990 – Basis of structural design [31].

4.1 Introduction

The material coefficients, such as: modulus of elasticity, shear modulus, Poisson's ratio in elastic stage and coefficient of linear thermal are considered in accordance with EN 1990 requirements. EN 1990 is complemented with the National Annexes which for this case are considered the Swedish National Annexes. Thus, according to the standards, building structural elements are assigned to safety class 3.

The uniform members – constant cross-section along their whole lengths – are hot-rolled structural steel, square and rectangular hollow sections, with nominal thickness of the elements less than 40 mm, and yield strength f_y equal to 355 N/mm^2. The hollow sections are quite consensual concerning their excellent properties with regard to loading in compression, torsion and bending; in all directions and have also a wide acceptance among the architects. As an additional advantage, the hot-rolled allow the weld at the corners, which is very much convenient for the project, since some its joints take this property as an advantage. The database of profiles used contemplates the S355J2H hot-rolled structural hollow sections: square and rectangular sections. Vallourec Group, as one of the contributions of this project, has provided the totally of the profiles – hollow sections – needed for the project to be implemented.

4.2 Building

The structure is composed of semi-continuous three-dimensional frames, in which the structural properties of the members and joints need explicit consideration in the global analysis [31]. The multi-storey building, is modelled in a grid of 11.085 m x 10.290 m, where along the length, parallel to the corridors, there are two bays of 5.355 m long and, in its perpendicular direction, three bays of 3.832 m, 2.250 m and 3.832 m. A total height of 20.337 m, 3.203 m per floor, from top-of-steel to top-of-steel, and 1.190 m height of the structure of the roof.

The present chapter describes the background design of a six-story building, which is considered at the LTU campus, and is intended to be a student residence (see Figure C.1). Moreover, following up the Frameup project, a pilot building arises from the need to demonstrate the accomplished achievements, therefore a three-story building is planned to be built (see Figure 4.1).

Figure 4.1: Pilot Building Location: 65º37’12.71”N 22º08’22.78”W

The pilot building has the purpose to investigate also further valances which this kind of constructions it is believed to have. In Figure 4.1 the location of the pilot building is indicated within the black circle. Nevertheless, following up the fundaments of the Frameup concept, this pilot building is intended to be added with three floors more, in order to achieve the target of the structural design. Hence, the 6-story design, meets its fully applicable at the long run.

The building is designed taking different possible locations in order to wide its applicability, by keeping similar structural characteristics. Therefore, the design of the building includes Luleå and Stockholm requirements, which creates also the possibility of implementing the modular housing stock concept.

The building is designed without a bracing system, as it has been seen as the suitable choice to accommodate the 3D Modules and to provide a clear access to the façade, allowing the consideration of large windows without constrains. For this reason, joints gain a special relevance in the building since they are fully responsible to transmit the totality of the bending moments generated in the sway building. As consequence the cross-sections, especially from the columns, increase the size in order to compensate the large moments generated in the structure.

The majority of the structural modelling is performed taking advantage of the software Autodesk Robot Structural Analysis Professional 2014 [7] and it is double check by means of hand calculations.

4.2.1 3D modules

The 3D modules do not have any contribution to the stability of the building, however is shall be needed to guarantee its fixations to the structure. In order to fixate 3D modules in place, specific pins are designed to be considered along the beams, permitting, by the time a 3D module is assembled, it be docked in place, at the respective holes at the bottom frame of the modules. These pins should bear the horizontal forces that may be generated in the modules as a safety measure for building sways.

4.2.2 Modular frames and beams

In order to increase the modularity of the building, the modular concept is applied to the structural components of the building, as well. Thus the modular frames are at the axes *1-1*, *2-2* and *3-2* between axes *A-A* to *B-B* and *C-C* to *D-*

D as described in Table 4.1, which summarizes the elements illustrated in Figure A.1. From Figure A.3 is also possible to identify that modular frames are a considered as two columns of SHS 250x10 welded together by SHS 250x150x8 beam. Therefore, instead of isolated columns and beams, a total of 6 modular frames per floor are considered, reducing from 36 to 24 the number of bolted joints needed per floor. Consequently, the time needed for assembling and cost are reduced, while it increases the stiffness, promoting the global stability of the building.

The building can be divided in: basement, below ground level, where operational columns are located; the floors, where 3D modules sit and the roof. From the structural point of view, the separation of these levels is made at the column splices. Table 4.1 summarizes all the elements of the building which can be divided in main structure and auxiliary structure.

Table 4.1: Modular elements from the basement, generic floor and roof

Type	Elements and position	Profiles	Level	Amount	Total
Temporary	Operational columns	SHS 250x10	Basement	12	12
Main Structure	Modular frames: *C1-D1* and *A3-B3*	2·SHS 250x10 SHS 250x150x8	Floor	2	2
	Modular frames: *A1-B1* and *C3-D3*		Floor	2	2
	Modular frames: *A2-B2* and *C2-D2*		Floor	2	2
	Modular frames: *C1-D1* and *A3-B3*		Roof	2	2
	Modular frames: *A1-B1* and *C3-D3*		Roof	2	2
	Modular frames: *A2-B2* and *C2-D2*		Roof	2	2
	Main beams: *D1-D2*, *D2-D3*, *C1-C2*, *C2-C3*, *B1-B2*, *B2-B3*, *A1-A2*, *A2-A3*	SHS 250x150x8	Floor	8	16
			Roof	8	
	Main corridors' beams: *B1-C1*, *B2-C2*, *B3-C3*		Floor	3	6
			Roof	3	
Auxiliary Structure	Auxiliary modules' beams: *AA1-AA2*, *CA1-CA2*, *AA2-AA3*, *CA2-CA3*	SHS 200x120x6.3	Floor	4	4
	Auxiliary corridors' beams: *C1A-B1A*, *C2A-B2A*	SHS 200x120x6.3	Floor	2	2
				Basement	12
				Floor	23
				Roof	17
				Total	52

Figure C.2 shows a printout from the structural analysis software where definition of the structure is described in different scales of colour, considering the different levels and divisions, as previously described. Figure C.3 illustrates, in two scales of colour, the two profiles adopted in the main structure, namely: SHS 250x10, for columns and SHS 250x150x8 for the beams. The figure represents the main structure considered in the structural modelling of the building. The remaining elements do not have any main relevance for the global stability of the building.

The main structure of the building considers: the modular frames, main beams, which connect consecutive modular frames; main corridors' beams, which connect modular frames at its longitudinal length in the axes 1, 2 and 3, and finally, just temporarily, during execution process, the operational columns. The structural analysis takes in consideration just the elements integrated in the main structure.

The design of each floor considers: 8 main beams, partially responsible for bearing of the modules and for global stability; 3 main corridors' beams, which mainly bear the slabs in the corridor and 6 modular frames, which have as main function, to ensure the global stability of the building. Therefore the main structure, which is considered in the structural analysis, contemplates 17 elements per floor.

In addition, the use of square hollow section, gains special relevance in the project since they allow the variation of the thickness along building height without compromising its outer geometry. This advantage, allows the optimization of the building design, since it permits the utilization of different columns and beams strengths for each floor while it ensure the architectural design repetition at each floor.

4.2.3 Joints

One of the main objectives of the Frameup project it is to establish structural performances of novel joints. Therefore the structural design of the building contemplates the consideration of new type of joints.

Influence of joints

According to 5.1.2(2) of EN 1993-1-8 [32], simple and continuous connections may be assumed not to have any effect on the structural analysis of the building. Included in the simple connections and continuous are those related typed as auxiliary elements in the previous Table 4.1. These beams are considered not to have any contribution for the global stability of the building, therefore they are neglected. All the other types of connections in are considered in the design.

Steel joints can behave in a range from rigid to extremely flexible. However, as stated before one of the assumptions of the building is to consider a non-bracing frame-structure. This fact endows to the joints, especially beam-to-column, of an increase of importance in the role of the keeping the stability of the structure. Thus, joints experience elevated moments due to the absence of a bracing system, leading to a consequent increase of its rotation. Therefore, it is important that initial rotational stiffness of the connection can be big enough to avoid the developing of exaggerated rotations in the structure in order to fulfil the serviceability limit states. For this reason, it is important that its initial rotational stiffness can be as high as possible, in the range of rigid joints, in order to transmit full bending moment, without undergoing exaggerated rotation.

The majority of the joints considered in the building are investigated and designed by other partners of the Frameup Project, hence in the global stability design of the building, its characteristics, namely the initial rotational stiffness and design resistance values, for bending moment and shear, are considered for global design of the six-story building.

In order to prepare a framework for joints investigation, a parametric study is performed to find out the minimum initial rotational stiffness allowed to fulfil the requirements in terms of global stability of the building. In the parametric study different dimensions of profiles and thicknesses are considered. Different combinations of the initial stiffness and profiles are found. However since joints' initial rotational stiffness end up to be difficult to obtain from the novel joints investigation a higher column profile has been chosen. Therefore, an initial rotational stiffness of 19000 kNm/rad shall be guarantee assuming a SHS 250x10 for the columns.

Not the whole stiffness is investigated, especially the non-linear part, which would have allowed a plastic global analysis of the frame. However, since the initial rotational stiffness - the elastic part - is the only information available, an elastic global analysis has to be performed.

As the described before, the serviceability limit states end up to govern the design, nevertheless the ultimate limited stated (ULS) had to be verified as well. Since there is a lack of information, when it comes to non-linear behaviour of the joint, an approximation, by the consideration of a linear elastic analysis with linear springs, is performed. These linear springs should be representative of the joint behaviour throughout the higher loading levels which are characteristic of the ULS.

Therefore, since the design moment value of the joint, $M_{j,Ed}$, is found to be close to the design moment resistance of the joint, $M_{j,Rd}$, so:

$$\frac{2}{3} \cdot M_{j,Rd} \leq M_{j,Ed} \leq M_{j,Rd} \tag{4.1}$$

According to EN 1993-1-8 [32], which defines an equivalent elastic stiffness in the following equation 4.2, called secant stiffness.

$$S_j = \frac{S_{j,ini}}{\eta} \tag{4.2}$$

A new rotational stiffness need to be considered in the design. Therefore, the stiffness needs to be divided by the stiffness modification coefficient $\eta = 2$ according to table 5.2 from EN 1993-1-8 [32]. So the linear springs introduced in the structure are representative of the joint behaviour throughout the large loading values.

Modelling joints stiffness

As the building connections are not considered infinitely rigid, the building sway behaviour gains especial relevance in the design. The serviceability states has a great relevance for the design verification, while in most of the buildings, especially those with vertical bracing systems, its design requirements it is largely imposed by the Ultimate limit states. Therefore, in order to obtain the right sway behaviour of the structure the initial rotational stiffness is considered in the building model for all the joints by means of an elastic spring at each joint with the respective value of initial rotational stiffness for each type considered.

Furthermore, the consideration of linear spring at each joint allows its definition for 6 degree of freedom. Therefore, when it comes to initial rotational stiffness of the bending moment on the *y-y* axis is considered as stated before. However since the stiffness of the joint on the *z-z* axis is very low, its initial stiffness is neglected in the model and so $M_{j,z} = 0$ kNm/rad. In other words, on the *z-z* direction of bending the joint it is considered to be pinned, which is a conservative assumption. The remaining degrees of freedom are considered infinitely rigid since the joints are able to cope well with the remaining respective stiffness.

Joints characteristics

The majority of the joints are designed by the partners within Frameup project. Table 4.2 summarizes the relevant information, as far as joints are concerned, regarding those included in the main structure and consequently in the structural modelling used for the design of the building.

Table 4.2: Joints in the building

Name	Topology	Position	$S_{j,ini}$ [kNm/rad]	$M_{j,Rd}$ [kN]
Reverse channel	Beam-to-column	C1, B1, C2, B2, C3, B3, at each floor and roof	19000	178
Double joint	Beam-to-column	A1, B1, C1, D1, A2, B2, C2, D2, A3, B3, C3, D3, at each floor and roof	55000	185
Welded joint	Beam-to-column at the modular frames	A1, B1, C1, D1, A2, B2, C2, D2, A3, B3, C3, D3, at each floor and roof	55000	185
Column-base	Column-base	A1, B1, C1, D1, A2, B2, C2, D2, A3, B3, C3, D3 at the basement	42000	158
Column-splice	Column-splice	A1, B1, C1, D1, A2, B2, C2, D2, A3, B3, C3, D3, at each floor and roof	42000	158
Auxiliary modules' beams joint	Beam-to-beam	CA1, 2xCA2, CA3, AA1, 2xAA2, AA3, at each floor	-	
Auxiliary corridors' beams	Beam-to-beam	B1A, B2A, C1A, C1B, at each floor		

The present thesis approaches a new type of column-splice, Finger Connection, which is believed to contribute very much to a reduction of assembly time. However, since the Finger Connection is still in preliminary stage of its structural analysis, is not considered in the design of the building.

For the column-splice no accurate values of stiffness are found in the literature. The same value of initial rotational stiffness as for the column-base joint is assumed since they exhibit similar properties. Moreover, the column-splice presents relatively high stiffness and the column-splices are intentionally located, as shown in Figure C.6, in the vicinity where bending moments, at the envelope of the combinations, is null, so the initial rotational stiffness does not need to deal with high levels of bending moment. When it comes to the welded joints, its resistance characteristics are considered as the double joint, since they possess similar properties too.

4.3 Lifting system

The Lifting system constitutes the process develop to perform the erection of the Frameup building. Therefore, the structural design of the Lifting system should be performed on the basis of the actions during the execution. As far as actions during the execution are concerned, EN 1991-1-6 [33] is to be followed. For the execution process the Lifting system should be able to keep its integrity during all the process: from its transport; assembling in-situ; disassembling, by the end of the execution process and especially during its operation.

The initial design of the Lifting system, considered the existence of 8 supports – 8 lifting mechanisms at each of the 8 Pylons (see Figure B.8) – however in order to facilitate the access to the building by lorries and forklifts, only 6 Pylons are considered in the Lifting system, so its design is adjusted (see Figure B.8).

4.3.1 Grid

The grid constitutes a horizontal very rigid frame which is intended to transmit the loads comings from Sliding cantilevers directly to the Pylons and consequently to the foundations. The grid is composed of 6 long RHS 500x300x16 beams, where two of these beams cross throughout the corridors of the building, while the remaining four occupy the external perimeter of the building.

The stiffness of the grid is very important for the stability during erection of the building. In order to keep the balance on the grid, the Pylons, and more precisely the lifting technology, should be able to maintain the grid balance. Therefore, the supports of the grid - the lifting mechanism on the Pylons - should be able to bear different load, since is not uniformly distributed among its supports. However, the lifting mechanism existent in the Pylons may not be, at some point of the erection process, accurately levelled therefore the grid needs to compensate the uneven in the support. Untimely can be considered that any of the supports are accurately levelled, and so the grid stiffness assumes big relevance in the problem.

4.3.2 Sliding cantilevers

Sliding cantilevers are supposed to make the transition of forces from the Lifting system to the building. They support the building in the beams in the vicinity of the columns, where the vertical forces are. Moreover, by supporting in the vicinity of the columns, the bending moment generated in the beams is very small, while the shear is proportional to the number of floors at the time of the support.

Sliding cantilevers are movable structural elements which, when in operation, constitute cantilevers. Hence, in order to ensure that Sliding cantilevers are able to be retracted, back to their initial position, inside the outer tube, its design shall be performed within the elastic range. This helps to ensure that the 4 mm gap considered for sliding, as shown in Figure 3.10, are enough. The Lifting system is composed of twenty four of these structural elements, where two different kinds can be distinguished: long Sliding cantilevers, placed along the outer beams of the grid (in the axes *L1*, *L3*, *LA* and *LD*), and small Sliding cantilevers (in the axes *LB* and *LC*), as represented in the Figure B.2.

The sliding cantilever (SC) is a composite RHS 180x1050x12.5 profile with two plates welded at the flanges of the profile, in order to increase the second moment of inertia of the cross section. Therefore, for thicker plates, a larger elastic resistance is achieved.

Taking in consideration a self-weigh of the 6-story building to lift (five-story building) of 330 tons, plus 30 tons of live load, means that, assuming an equally distributed load for every SC, each one has to bear 15 tons. The Sliding cantilevers considered in the full scale test are designed for a three-story building, since it is assumed to resist to a two-story building.

4.3.3 Pylons

Pylons are intended to withstand all the vertical loads, as well as, some horizontal loads, therefore a bracing system is considered to perform constrain laterally the Pylons.

Regarding the full scale test performed, a cross-section of SHS 250x16 is considered, since by the time of design it was already determined for the self-climbing device. Therefore, for its structural design remained just the option to vary its cross-section thickness and the need to design a Pylons' bracing system to take the additional horizontal forces which the Pylons would not bear by themselves. Moreover, since the self-climbing device take the advantage of friction, at the Pylons surface, just a primer is consider along the path of the self-climbing device.

4.4 Load cases

Actions are classified by their variation in time:

- permanent actions (*G*), e.g. self-weight of structures, etc.;
- variable actions (*Q*), e.g. imposed loads on building floors, beams and roofs; wind actions [34],snow loads [35] and thermal actions [36];

Table 4.3: Load cases considered

Label	Case Name
G_1	Permanent Action: Steel Skeleton (78.5 kN/m^3) [31]
G_2	Permanent Action: Modules (4.2 tons) [27]
G_3	Permanent Action: Corridors slabs, floors (1.60 kN/m^2)
G_4	Permanent Action: Corridors ceilings (0.50 kN/m^2)
G_5	Permanent Action: Facade Panels + accessories (0.50 kN/m^2)
G_6	Permanent Action: Roof panels + accessories (0.50 kN/m^2)
G_7	Permanent Action: Other loads (0,20 kN/m^2)
Q_1	Variable Action: Building floors, Category A (2.0 kN/m^2) [31]
Q_2	Variable Action: Roof, Category H (0.40 kN/m^2) [31]
Q_3	Variable Action: Wind at 0°, Front [34]
Q_4	Variable Action: Wind at 90°, Right [34]
Q_5	Variable Action: Snow load [35]
Q_6	Variable Action: Thermal [36]
F_7	Frame imperfections at 0°, Front
F_8	Frame imperfections at 90°, Right

Regarding the wind load, according to EN 1991-1-4 [34], its recommendations are addressed to the Swedish National Annexe [38], the basic wind speed for Stockholm is $v_b = 24$ m/s whereas for Luleå is $v_b = 22$ m/s, hence Stockholm's characteristic value is adopted. The wind forces apply on the finished structure - claddings of façade and roof.

Concerning the snow, the load basic value, with regard to Luleå $s_k = 3.0$ kN/m^2, whereas $s_k = 2.0$ kN/m^2 for Stockholm, thus the Luleå snow load basic value is the adopted. These design increases very much the spectrum of application, at least with respect to the Swedish territory.

When it comes to consider seismic actions in Sweden, since earthquakes are relatively rare or exhibit a low magnitude, hence is not considered in the design process. Regarding fire resistance of the structure, the modules are intentionally prepared to work as an isolate cell, as well as corridors, creating the necessary conditions for fire not to propagate. An assessment of the fire resistance of the 3D modules is performed [14] however the present thesis does not focus on this issue.

4.5 Load combinations

The combination of actions is performed taking in consideration serviceability limit states and ultimate limit states.

4.5.1 Serviceability limit states

Regarding the serviceability limit states, which primarily relates to safety and health, where additional requirements related to appearance and comfort, may be imposed from the client/owner. Calculation of deformations and sway is performed according to the elasticity theory with a calculation model that describes the structural rigidity [38]. The frequent combination, which follows in the equation *4.3*, is used since it addresses reversibility limit states.

$$\sum_{j\geq 1} G_{k,j} + \psi_{1,1} Q_{k,1} + \sum_{i>1} \psi_{2,1} Q_{k,\mathrm{i}} \qquad 4.3$$

As explained before, due to the characteristics of the building, the serviceability limit states combinations have a big relevance in terms of the design requirements, since the building, which is considered as a sway frame, undergoes large displacements and deflections. Therefore, for the most severe combinations, the vertical deflections are verified at each beam of the roof and floor, as $w_{\max} = L/200$, while for horizontal displacements over each storey height of $u_i \leq h_i / 300$ and overall horizontal displacements over the building height, of $u \leq h/500$.

4.5.2 Ultimate limit states

The consideration of the ultimate limit states attest the: loss of static equilibrium, internal failure of the structures or its members and joints.

The EN 1990:2002 together with Swedish National Annexe provides a set of equations - Set B – wherein the values of action and permanent actions, need to be considered. The set of equations, which follows, should be considered. The addends of the equation, regarding the value of the permanent action *j*, may be considered the upper or lower characteristic value, whether the load is unfavourable or favourable, respectively. For the case of the variables actions, its addends in the equations, it may be considered null when the load is favourable.

$$\gamma_d \cdot 1.35 \cdot G_{kj,\sup} + 1.00 \cdot G_{kj,\inf} + \gamma_d \cdot 1.5 \cdot \psi_{0,1} \cdot Q_{k,1} + \gamma_d \cdot 1.5 \cdot \psi_{0,i} \cdot Q_{k,i} \qquad 4.4$$

$$\gamma_d \cdot 089 \cdot 1.35 \cdot G_{kj,\sup} + 1.00 \cdot G_{kj,\inf} + \gamma_d \cdot 1.5 \cdot Q_{k,1} + \gamma_d \cdot 1.5 \cdot \psi_{0,i} \cdot Q_{k,i} \qquad 4.5$$

The more onerous from the previous expressions is considered for design.

4.5.3 Values of ψ factors

According to the Swedish National Annexe, the ψ factors in the Table 4.4.

Table 4.4: Values of ψ factors

Load	ψ_0	ψ_1	ψ_2
Category A: residential rooms and spaces	0.7	0.5	0.3
Category H: roofs	0	0	0
Wind	0.3	0.2	0
Snow $s_k \geq 3.0kN/m^2$	0.8	0.6	0.2
Temperature	0.6	0.5	0

4.6 Global analysis

A global analysis is intended to provide the internal forces, moments and its resulting displacements, taking into the specific sway building in this thesis. As it is approached previously, a global analysis is intended to be performed taking in consideration a global elastic analysis. However, an elastic analysis is based on the assumption of a liner stress-strain relation for steel therefore assuming elastic stresses in structure, whatever the stress level is, indeed. Therefore it disregards the stresses generated into the structure however any yielding is noticed in the structure. The internal forces and moments may be calculated using the present analysis, even taken into account the plastic resistance of the cross-sections.

4.6.1 Building

The six-storey building, as stated before, undergoes large displacements mainly due to the absence of a bracing system. A second order analysis ensures results on the safe side although its mandatory applications it is only required, according to (5.1) in EN 1993-1-1 [31], whenever:

$$\alpha_{cr} = F_{cr} / F_{Ed} \leq 10\left(in\ elastic\ analysis\right) \qquad 4.6$$

The determination of the critical loads is attended by means of the software, Autodesk Robot Structural Analyses [7], which provides directly the quotation for α_{cr} for every load combination under the demand of ultimate limit state. Since every structure has more than one buckling mode, and the following buckling modes can be relevant to the 2^{nd} order effects, it is analysed the first four buckling modes for each combination. The lowest value found, at the first buckling mode, is $\alpha_{cr} = 7.56$, therefore it is mandatory to perform a second order analysis. Thus a 2^{nd} order analysis is taken in consideration with the *P-δ* effects and the local member imperfections are incorporated.

Global analysis of the building is performed, for all the combinations, to identify, within the envelope of internal forces and moments, the extreme values to be verified with regard to the resistance of the each member. Due to the characteristics of the building, the resistance of the members are more sensitive to the bending moments. Figure C.6 shows, as an example, the diagrams of bending moments found with respect to the *y-y* axis.

4.6.2 Lifting system

The Lifting system is a structure which aids in building construction, thus its design should be coherent with the period estimated for its operation. Since the execution of the building is expected to be performed in a workflow of one floor per day, Lifting system will be in operation for no seven days, however one day at the time. Therefore, the consideration of the same standard loads, available for buildings, such as wind and snow, in the design of the Lifting system, is rather disproportionate, since its returns period is rather small. Accordingly, the European standards approach some of these issues, as, for instances, in Table 3.1 of the EN 1991-1-6 [33]. It provides some information regarding the return periods, for the determination of the characteristics values of climate actions. However although the erection of the building may take days, in fact, the Lifting system operates just for a few hours a day, thus according to the Table 3.1, the concept of mean return period is generally not appropriate for short term duration. Therefore, the concept employed on the design of the Lifting system, relies on the consideration of mean values of wind and snow, either for Luleå and Stockholm. The average daily maximum wind speed for Stockholm is 7 m/s, and rarely overcomes 10m/s. Therefore since stability of the Lifting system is sensitive to horizontal loads, the wind speed considered for design is 10 m/s. Therefore, the load combinations for the design of the Lifting system include: permanent loads and just the variable actions, regarding climate actions with the assumptions described before.

In order to set the work frame and boundaries of Frameup concept design, it is important to look throughout the problem and identify which factors may affect the behaviour of the building within the execution and operational stages of the Lifting system. One of the most important factors may be the deflections and stresses induced by the execution process. In this sense it is very difficult in a first glance to determine a limit for the maximum deflection which the building is allowed to experiment, within the execution process. As a rule of thumb, the execution process should not affect, at any time, the future structural behaviour of the building. In another words, the assumptions taken trough design of the building, should remain unchanged until the last step of the execution process, placing the building in the same initial work frame for which the building was assumed for design. For that reason the structural design of the Lifting system is constrained by the serviceability limit states in the building. Thus all the components of the building, such as the structural elements, should remain within the elastic range, and the non-structural elements within its geometry and without jeopardising its properties.

5 4D MODELLING - CONSTRUCTION SEQUENCE

A 4D modelling combines 3D CAD models with construction scheduling. It facilitates the dissemination of information in a more intuitive manner, rather than use the traditional 2D drawings and construction schedule information separately. Moreover, it tests the feasibility of the construction scheduling while it helps to clarify potential conflicts of structural activities or elements during the construction process.

The process of development of the Frameup project involves a large number of steps within the construction sequence and the manipulation of complex 3D forms. From the logistic point of view, tools, as the CAD, need to be employed in order to perform efficiently and accurately this task. Therefore, the 3D modelling was the natural choice taken, while 4D modelling arises from the need to develop to verify all the steps of the construction sequence.

The whole Frameup system is described along its sequence of construction, following by detail descriptions, taking advantage of the 4D pictures in the Annex E. The flowchart in Figure 5.1 synthesizes stepwise the construction sequence, while it provides the chain of vertical movements - descending or ascending - which the grid performs. The flowchart considers the sequence in five phases and three routines.

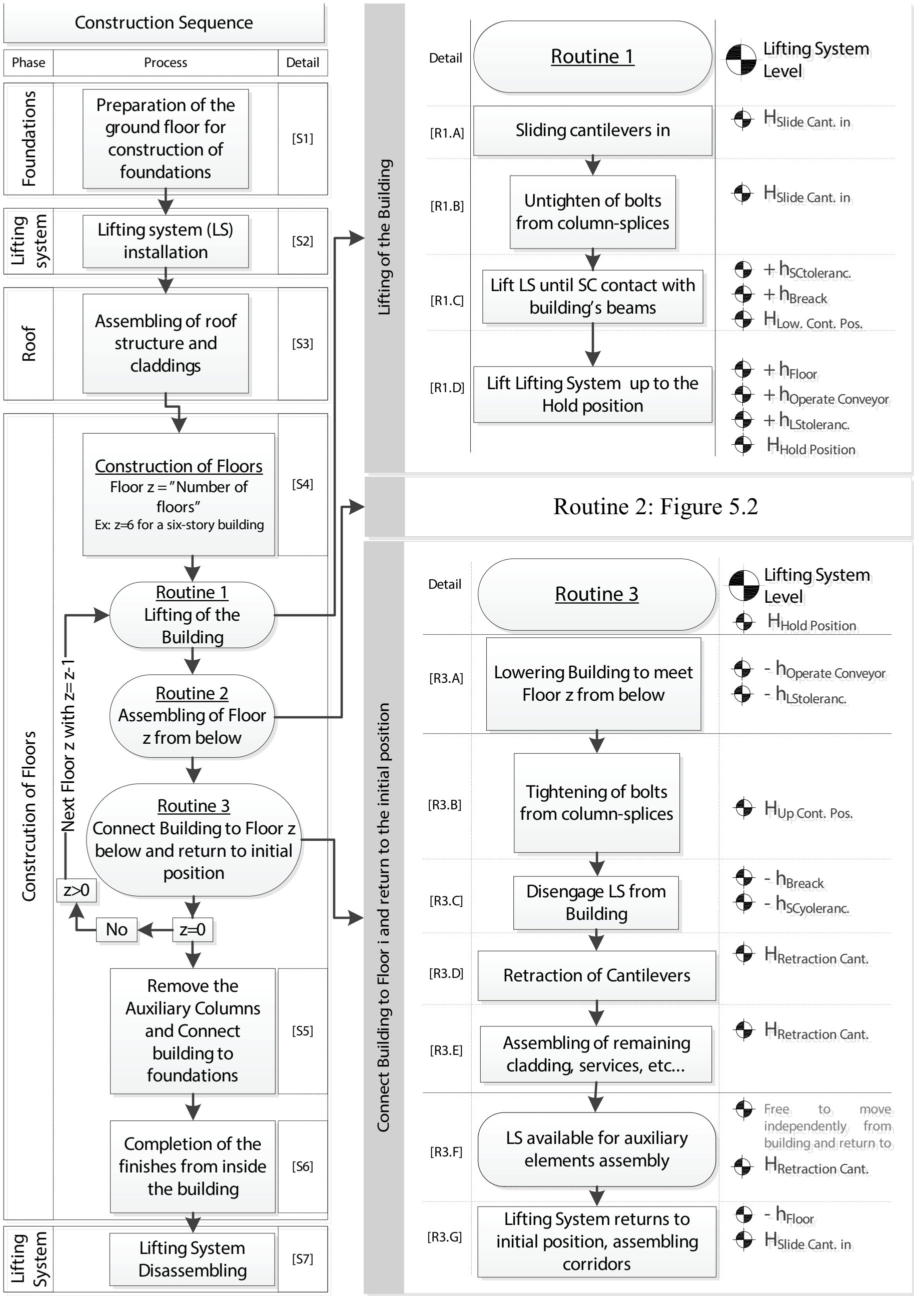


Figure 5.1: Flowchart of the construction sequence of Frameup System

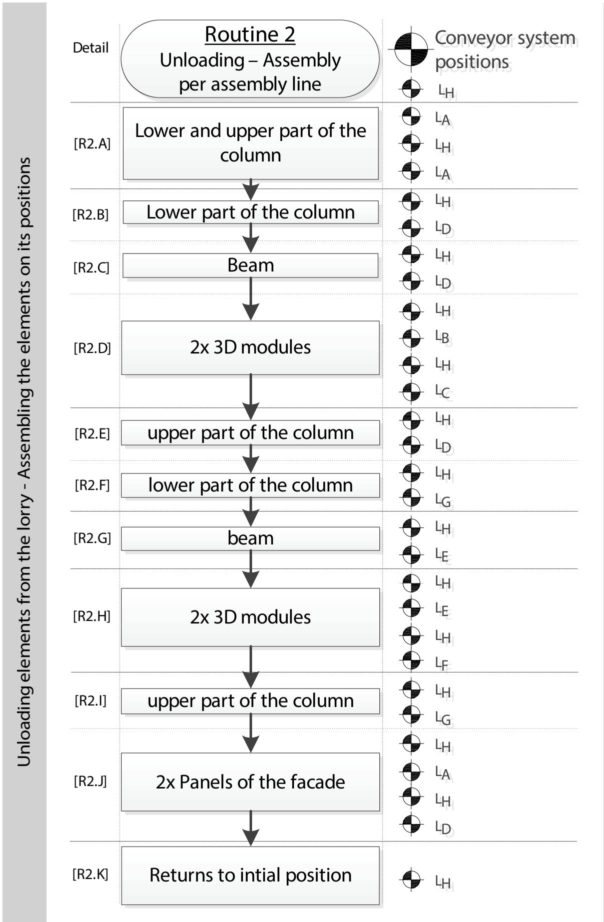


Figure 5.2: Flowchart of the construction sequence of Frameup System

The previous flowcharts present along the construction sequence, three columns which organize the chain of events in: *Phase*, *Process* and *Detail*. As a complementation to flowcharts, the Annex E, from Figure E.1 to Figure E.20, illustrate some of the relevant steps, while Figure E.21 and Figure E.22, provide more detail information, especially related to the values from the levels and positions, of the Grid and Conveyor system, respectively.

Each *Phase* and *Process*, as well as its *Detail*, are described in the following paragraphs, by addressing for each *Phase* the description for its corresponding *Detail*, present at the previous flowchart.

Moreover in order to automatize the system all the steps are described in terms of heights, in terms of Lifting system and depths, when it comes to conveyor system, stepwise described in the flowchart, and illustrate in the *Figure E.21* and Figure E.22.

5.1 Foundations [S1]

The first phase includes the preparation of the terrain for the foundations. It is vital for the project success that the foundations, from the building and Lifting system, are correctly executed and aligned. In order to take fully advantage of the Frameup concept, the foundations should be designed for a six-story building, even if at that stage of the construction, not all the floors are intended to be considered in the building construction.

5.2 Lifting system [S2]

The Lifting system should be transported to the construction site benefiting that all elements lie within the transport dimensions (see Figure E.1). Pylons should be installed in first place, followed by its bracing system and the lifting mechanism. The beams from the grid, starting from the two which cross the building's core, are placed with its supports aligned with the lifting mechanism, based on auxiliary supports, correctly aligned with the reference axes. Once assembled, the lifting mechanisms are lifted and naturally fit with the grid's supports – grid holder. The guardrails are fitted into the grid-hooks, along the beams of the grid. The next step is to install the conveyor system below the beams of the grid (see Figure E.2). The final task contemplates the assembling of the operational columns, taking fully advantage of the Lifting system, more specifically with conveyor system, as shown in Figure E.3.

5.3 Roof [S3]

The assembling of the roof structure and claddings, benefit from the conveyor system, since the elements can be unloaded directly from the lorry to its final position. During the assembling of the structure, in order to guarantee the correct alignment, the structural elements should be bolted in the operational columns. At this stage, all the work, regarding the structure, should be correctly performed however the focus concentrates on the finishing with regard to the roofs panels, which should be finalized completely, before the roof is lifted.

5.4 Construction of floors [S4]

The construction of the first floor, *z*, starts from the future last floor, which corresponds to number of planned floors to be considered, at least, at the first erection of the building. The subsequent floors are *z-1*, *z-2* culminating in the last floor of assembling process, the 1st floor of the future building.

5.5 Routine 1: Lifting of the building

Once the assembling of the structure is completed, in this case the roof, the building can be lifted. The sliding of the Sliding cantilevers is performed at the $H_{slideCant.in}$ level of the Lifting system. Once untightened the bolts, the Lifting system is lifted ($h_{SCtoleranc.}$ + h_{Break}) for the Sliding cantilevers to contact the building's beams. From this level the building is lifted one-floor height plus the necessary height for the conveyor system to operate (h_{floor} + $h_{operate\ conveyor}$ + $h_{tolerancB}$) until it reach the final position which holds the building, $H_{Hold\ Position}$.

5.6 Routine 2: Assembling of floor below

The assembling of the structural and non-structural elements takes fully advantage of the conveyor system. In order to systematize the movements of the conveyor system, throughout the assembling phase, all the displacements are identified and its values provided in the Figure E.22.

The assembling of the elements is prioritized in order to avoid the collision of the succeeding elements. The elements follow the planned sequence in the Figure 5.2, for each of the two assembling lines.

5.7 Routine 3: Connect building to the lower floor and return

Once all the structural and non-structural elements are assembled, the Lifting system descends the height dedicate for operation of the conveyor system and tolerances ($-h_{operate\ conveyor} - h_{tolerancB}$) in order to connect the columns, at the column splices. Once the columns are correctly connected, the Lifting system descends, releasing naturally from the building ($- h_{break} - h_{tolerancA}$) to finding its next position at the level of $H_{Retraction\ Cant.}$. The Sliding cantilevers have now the clearance to be retracted to its initial position, out from the building perimeter. By returning the conveyor system back to its initial position, out from the building perimeter, the grid is able to move independently, down and upwards, which may be taken as an advantage for the assembling of the façade's claddings. For the elements in the corridors be assembled the Lifting system needs return to its initial position

If there are still remaining floors to be assembled, the tasks described at the routine 1 are repeated and the process follows as before until all the floors are assembled. When the number of floors planned is assembled, all the exterior details and finishes need to be performed before the Lifting system is disassembled. The remaining tasks which were left to be performed inside the building can now be completed.

5.8 Description of the full scale test

The full scale test is performed to attest the solutions found within the development of the Frameup system. The test is performed at the old facilities of the *PartAB* [27] in Sangis, Sweden.

5.8.1 Test setup

The test setup is carefully prepared since it involves a big logistic to include the following planned activities, within one week. In order to perform the test, some requirements, regarding the space available at the warehouse (see Figure F.1 and Figure F.2) and the minimum operational distance, are required for the Lifting system to operate properly (see Figure F.1).

Planned activities

The test contemplates the assembling of the Lifting system, followed by the operational columns for the erection of the roof and one floor.

The test is performed to attest:

- Layout and fitting of the produced structure at the workshop and possible issues on the assembling. The assembling of the Lifting system is executed in two working days: from tracing the layout of the building, align the precast foundations, assembly of operational columns, fixing of the Pylons and assembly of the grid.
- Testing the self-climbing device operating on the Lifting system
- Perform the assembling of the roof structure
- Lifting the roof structure, 3.210 m height, as shown in the Figure 5.3.
- Assembling of floor steel frame from below (see Figure F.6)
- Partial lifting of the roof and one floor frame structure (see Figure F.7)

Figure 5.3: Full scale test – lifting phase

Some conclusions are traced based on the performance of the test. Especially those regarding the self-climbing device since it is concluded to be not automatic enough to lift in a short period of time. Thus, new solutions need to be found to be able to lift one-story-height at once, enhancing the lifting speed. The automation of the Sliding cantilevers manipulation will also reduce the time. The inclusion of the conveyor system in a new test is rather necessary. The assembly of the panels and claddings on the building's roof and façade and its iteration with the structure. Therefore a new full scale test needs to be performed with all the upgrades and solutions which are planned.

PART II

STRUCTURAL PERFORMANCE OF A NOVEL JOINT – FINGER CONNECTION

6 DESCRIPTION OF THE FINGER CONNECTION

Columns are often transported to site in lengths corresponding to the building height, especially in multi-storey buildings' construction. Various details are available for column-splices (connections). The Frameup project ambition to create a novel joint which aim to be as much as possible coherent to its main principal: to optimize the frames for effective assembly. In this sense, the Frameup introduces a system which performs one floor at a time execution, where each individual column occupies each floor height, and its column-splices promote a feasible execution of the columns.

6.1 Concept of the novel joint

The Frameup project focuses on the development of innovative solutions able to streamline the assembling process. In this sense, the column-splices in the building gain special relevance, especially since the whole building is intended to be assembled on its lower floor in an instantaneous and synchronized movement, as previously described. The beams since they are fully assembled at the ground level do not represent a big difficult on its assembly.

Thus, the 8 column-splices, which divide each floor of the building, need to be fitted at once, without the direct human intervention, in the first stage. In addition, inherent to the execution process, structures always exhibit misalignments. Therefore, the finger connections should be able to accommodate these misalignments by themselves since no direct human intervention is intended to be performed during this stage. Just once the columns are in place, then the tightening procedures can be started by the workers on the construction site, accomplishing the assembly of the column-splice.

Figure 6.1 schematically represents possible misalignments which the joint can deal with, such as:

- Horizontal misalignments; [(b)]
- Rotation of the upper column, which generates a misalignment on the vertical axis, since it is not completely in contact with the lower column, and horizontal misalignment, due to the natural shift of the column to side; [(a)]
- Vertical misalignments, where it is considered that any of the columns is contacting, therefore the whole force is transmitted by friction. [(b)]

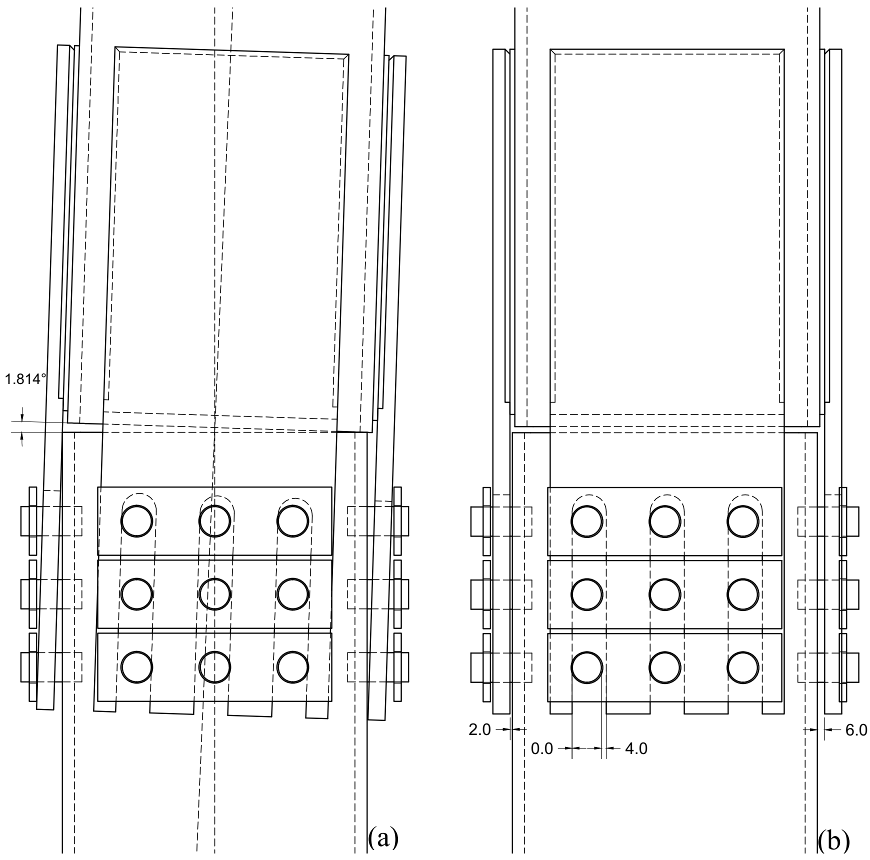


Figure 6.1: Scheme of some of the conceptual misalignments allowed

Therefore in order to enable this misalignment the joint need to consider gaps which may allow covering these possible misalignments.

6.2 Description of the Finger Connection

The Finger Connections are supposed to connect two columns made of SHS profiles. The main characteristic is a plate, named as finger plate, with long slotted holes. This plate is detached from the profiles walls by using a filler plate, welded to both elements, that creates the Horizontal gap, which permits to accommodate the misalignments at the horizontal plane.

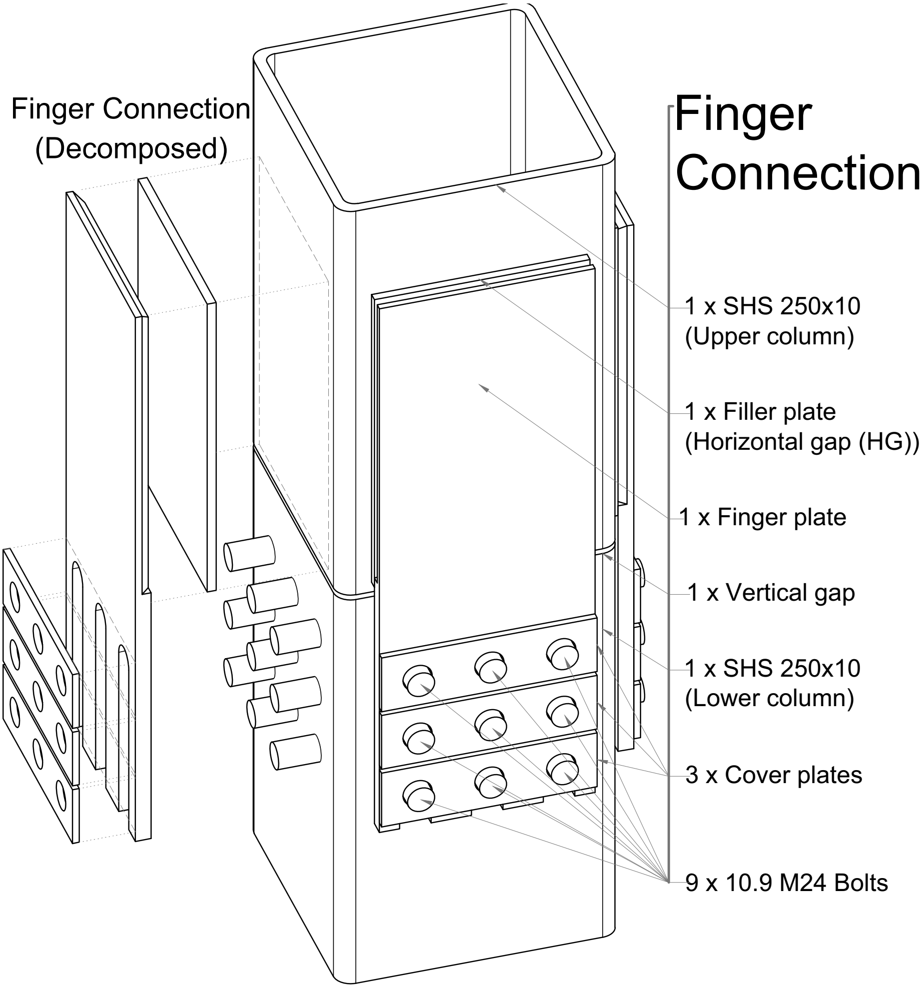


Figure 6.2: Description of the Finger connection components

Pre-fitted bolts are installed in the Lower column in advance (see Figure 6.3) in order to be connected to the slotted holes of the finger plates.

Since the Finger connection allows the possibility of a Vertical gap, the connection can be defined as slip connection. However it is assumed that in case of the slip the columns contact, which create a bearing type of joint. This assumption is just considered for the ultimate limit states, while the slip is designed for serviceability limit states.

During the Assembly Process, the Upper column's fingers slide through the lower column's spaces between bolts and the slotted holes coincident to the lower bolt-columns. Once both columns are in place, the bolts are tightened. Consequently, the fingers start to bend progressively, initiating the clamping of the lower column, right after the horizontal gap is filled. This process creates the friction enough to resist against the future loads considered into building's design.

Moreover, the cover plates, washers and nuts should already be assembled from the workshop. Once in situ, the assembling of the column splice implies just the tightening of the nuts, optimizing to a maximum the work performed in the assembly, as it reduces the material within the construction site. The turning of the nut is guaranteed by the friction generated between the pre-fitted bolts and the non-clearance holes surface.

Figure 6.3: Pre-fitting of bolts

The column splice has one finger connection on each side. Each Finger Connection has nine bolts each and consists of three bolt-rows. Assuming the method employed in a 3x3 matrix, bolts are numbered from 1-1 to 3-3, following the same principal and so bolt-rows are matrix lines.

Figure 6.4 describes the terminology employed to address the forces at each bolt taking into consideration its relative position in the finger connection.

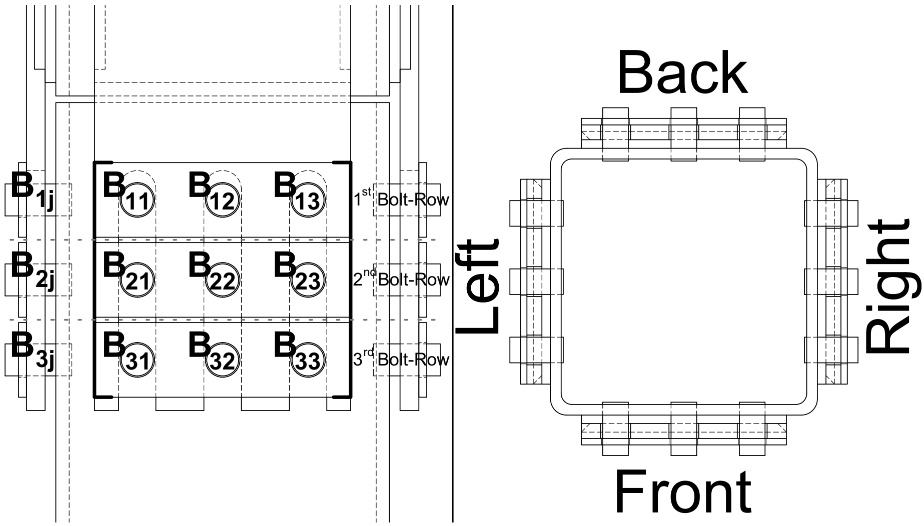


Figure 6.4 : Bolts organization and terminology

As an example the following matrix represents the clamping forces in the connection:

$$F_{Clamp,\mathrm{Bij}} = F_{\mathrm{Clamp(Front),Bij}} + F_{Clamp\mathrm{(Back),Bij}}$$

$$F_{Clamp,Bij} = \begin{bmatrix} B_{11} & B_{12} & B_{13} \\ B_{21} & B_{22} & B_{23} \\ B_{31} & B_{32} & B_{33} \end{bmatrix}_{Front} + \begin{bmatrix} B_{11} & B_{12} & B_{13} \\ B_{21} & B_{22} & B_{23} \\ B_{31} & B_{32} & B_{33} \end{bmatrix}_{Back}$$

Thus, the clamping force in the connection is:

$$F_{Clamp} = \sum_{i=1}^{3} \sum_{j=1}^{3} F_{\mathrm{Clamp,Bij}}$$

6.3 Requirements for execution

From the execution point of view, according to EN 1090-2 [39], *the contact surfaces shall be prepared to produce the required slip factor which shall generally be determined by test as specified* in the Annex G included on the current standard. This test determines the slip factor for a particular surface treatment while it ensures that the procedure accounts for the possibility of creep deformation of the connection. The test validation is limited to cases where all significant variables are similar to those of the tests specimens [39].

The EN 1090-2 [39] also provides recommendations for the assembly, namely:

a) *the contact surfaces shall be free from all contaminants, such as oil, dirt or paint. Burrs that would prevent solid seating of the connecting parts shall be removed;*

b) *uncoated surfaces shall be freed from all films of rust and other loose material. Care shall be taken not to damage or smooth the roughened surface. Untreated areas around the perimeter of the tightened connection shall be left untreated until any inspection of the connection has been completed.*

Regarding the bolts it suggested the tightening processes performed by the rotation of the nut. Moreover, *tightening shall be carried out progressively from the most rigid part of the joint to the least rigid part. To achieve uniform preloading, more than one cycle of tightening may be necessary* [39].

Inherent to the tightening there is *the potential loss of preloading force from its initial value due to several factors, e.g. relaxation, creep of surface coatings* [39].

The requirements in this chapter are taken into account for the design of the novel joint.

7 HAND CALCULATION APPROACH

The use of cutting edge software does not invalidate a simultaneous check of the whole design process. Thus, simple hand calculations should always accompany throughout design. This strategy is especially of relevance when it comes to a first estimate for the design and the assessment of the computational results.
In the present chapter the resistance of the connection is calculated by means of hand calculation, which implicates an ideal scenario, establishing therefore an upper bound for the resistance of the Finger Connection.

Firstly, the upper bound resistance of the connection regarding its mechanical properties should be calculated. As it is explained in chapter 4, the SHS 250x10 columns have a gross cross-section area of 94.9 cm^2 which can resist, within the elastic range, an uniform compression of 3369 kN. However, by considering the net cross-section of the Fingers Plate only there is a resistance reduction of 32% to 2300 kN. Since the building is to be considered without a bracing system, its final resistance drops even more due to buckling phenomena. The joint location is chosen to be as little as possible to be subjected to bending moments.

Among the categories of bolted connections that EN 1090-2 [39] distinguishes, this connection considers high-strength hexagonal bolts HV 10.9 M24. The finger connection, since it relies solely on friction, can be integrated as a shear connection with slip-resistance, depending whether it encompasses serviceability or ultimate limit states. The slip resistance depends generally on the forces in the bolts, on the friction coefficient and on the geometry of the holes. However, in order to generate friction, the clamping of the Finger Plate against the lower profile, is not fully dedicated to create friction, since at the first bolt-row a different behaviour is involved.

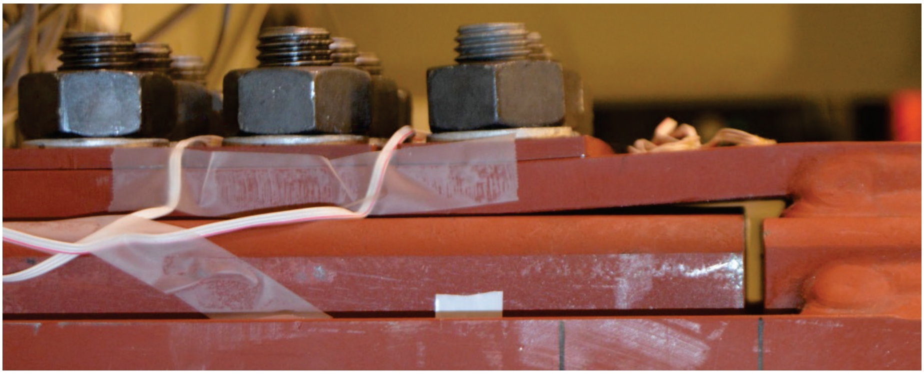


Figure 7.1: Bending of the Finger Plate (rotated 90º for sake of visualization)

Therefore, the force employed in the first bolt-row is constituted of two components, both with the same directions but different amplitudes. Those components can be characterized as:

- the first force component, exclusively dedicated to overcome the bending stiffness of the finger plate, sufficient enough to create contact with the lower column and to ensure the effectiveness of the
- the second component of force employed to generate friction.

According to EN 1991-1-5 [36] the slip-resistance per bolt can combine tension (in blue) and shear (black painted characters), based on the serviceability limit states and equation 7.1 applies as follows:

$$F_{s,Rd,ser} = \frac{k_s \cdot n \cdot \mu \cdot (F_{\mathrm{p,C}} - 0.8 \cdot F_{\mathrm{t,Ed},ser})}{\gamma_{M3,ser}} \qquad 7.1$$

Where:

$\gamma_{M3,\mathrm{ser}}$ is a partial factor taken as 1.0, according to Swedish National Annexes [38];

μ is the slip factor obtained from predefined categories or from standardized tests according to EN1090-2 [39], which for this case is obtained from laboratory tests;

k_s is the correction factor, which is based on holes characteristics;

$F_{\mathrm{p,C}}$ is the bolt characteristic pretension and

$F_{\mathrm{t,E}d,ser}$ is the tension needed to overcome the stiffness of the Finger Plate, assuming a Category B of the shear connections, where the slip-resistance at serviceability is assumed , for the reasons mentioned in the chapter 6.2.

In the following chapters each parameter it is investigated.

7.1 Slip factor

The slip resistance of the connection depend not only on the initial clamping force, but also on the slip factor. The value of slip factor depends on the surface treatment of connected elements. According to EN 1090-2 [39] four classes of friction surfaces are distinguished: A, B, C and D. The value of slip factor is the result of a standard test as listed in the Table 7.1.

Table 7.1: Slip factor according to EN 1090-2 [39]

Surface treatment		Class of friction surface	Slip factor (μ)
1	Surfaces blasted with shot or grit with loose rust removed, not pitted	A	0.50
2	Surfaces blasted with shot or grit; spray-metallised with aluminium or zinc based product with alkali-zinc silicate paint with a thickness from 0.50 μm to 0.80 μm	B	0.40
3	Surfaces cleaned by wire brush or flame cleaning, with loose rust removed	C	0.30
4	Surfaces as rolled	D	0.20

The mentioned slip factors are mostly useful in the absence of available values, but since the present thesis contemplates the existence of laboratory tests, its use may, ultimately, be considered for sake of comparison. However, as it is aforementioned, the values are result of standard tests which are fully dedicated on obtaining its slip factor. The tests performed in the laboratory were intended to assess the behaviour of the connection and its resistance. Thus, it is possible to obtain, the so called Apparent Friction Coefficient which is the ratio of the slip load and the sum of the bolts forces at slip. Slip failure is defined to occur at 150 μm of slip, according to [39].

7.2 Correction factor, k_s

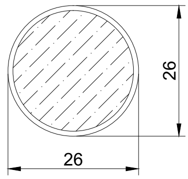
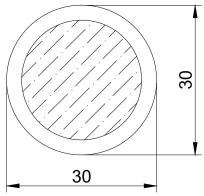
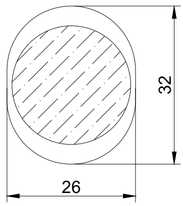
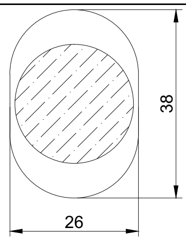
The influence of the geometry of the hole on the slip resistance of the connection is introduced by the correction factor k_s. The k_s presented in EN 1993-1-8 [32] varies according to Table 7.2.

Table 7.2: Values of the correction factor k_s

Description of the hole's geometry	k_s
Normal hole	1.00
Oversized hole or slotted hole with axis perpendicular to load transfer	0.85
Short slotted hole with axis parallel to load transfer	0.70
Long slotted hole with axis parallel to load transfer	0.63

Holing characteristics are described in EN 1090-2 [39]. Definition of the nominal holes diameter combined with the nominal diameter of the bolts to be used in the holes determines whether the holes are *normal* or *oversized* and *short* or *long* for slotted holes (see Table 7.3).

Table 7.3: Nominal clearance described for M24 bolts (mm) [39][40].

Holing	Nominal clearance	Hole size	Illustration	k_s	
Normal round holes	2	26		1.00	← ← Load direction ← ←
Oversized round holes	6	30		0.85	
Short slotted holes	8	32		0.70	
Long slotted holes	1.5 *d*	36		0.63	

As described in chapter 6.1, the finger connection is composed by long slotted holes of 28 *mm* across the width of the slotted holes, in order to accommodate the tolerances needed for the assembly. In Figure 7.2 the hole characteristics of the connection are illustrated, where it is possible to distinguish two different types: “infinitely” long slotted holes (from the d) to i) details) and half “infinitely” long slotted holes (at the examples a) to c)).

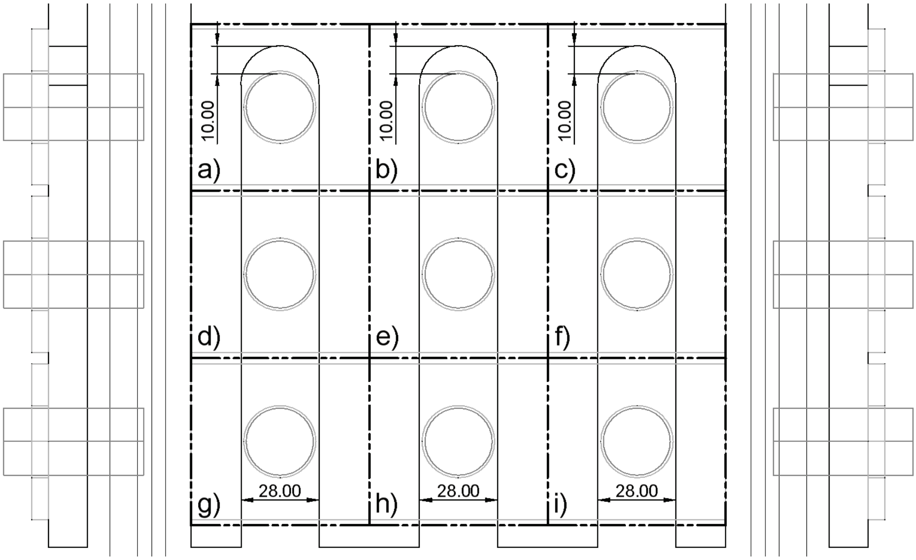


Figure 7.2- Detail of Finger Connection and its different hole characteristics

The terminology employed is not considered in the EN 1090-2 [39] since it contemplates different geometries presented in the finger connection and consequently does not provide a specific k_s value. Nevertheless, k_s=0.64 [1] may be assumed where long slotted, oversized holes are used.

7.3 Preloading force in the bolts

The preloading force $F_{\mathrm{p,C}}$ to be used in equation 7.1 should be taken, according to EN 1993-1-8 [32], as follows:

$$F_{p,C} = 0,7 f_{ub} A_s \qquad 7.2$$

Therefore, for a M24 bolt of steel grade 10.9, taking in consideration the ultimate tensile strength, f_{ub} of 1000 N/mm^2 and the tensile stress area of the bolt, A_s, of 353 mm^2, the preloading force is 247 kN.

7.4 Applied tensile force

The 1st bolt-row is subjected to a tensile force which needs to be introduced in the bolts to close the existing gap by bending the Finger Plate and consequently to activate friction. On a side note, not just the Finger Plate is bent but also the Lower Profile. This behaviour is described in detail in chapter 10.1.

Therefore, this component of the preloading force, at which 1st bolt-row participate with, creates conditions for 2nd and 3rd bolt-rows just to dedicated their efforts in the creation of friction. Therefore, the force in the bolts which creates the conditions for the slip-resistance connections to be activated is hereby considered as Activation Force.

In order to calculate the slip resistance of the connection, a Finite element analysis (see chapter 10.1), based on a calibrated model, its performed considering just the tightening of the two outermost bolts of the 1st bolt-row. Forces in bolts are read, at the exact moment when the finger plate touches the lower column at the plane which crosses the centre of the 1st bolt-row holing (see Figure 10.1).

7.5 Conclusions

The evaluation of the Finger connection implies an interactive process where Hand calculations, Finite element modelling and Laboratory tests are assessed in order to achieve a model-solution, which shall be coherent in all its approaches. Thus, in order to obtain the final resistance of the connection, additional finite element analysis (FEA) need to be performed in order to draw fair conclusions. Therefore, in order to conclude the calculation of slip-resistance, introduced in this chapter, the following chapters provide data which guide towards conclusions.

8 LABORATORY TESTS

The laboratory tests are one of the most common and recommended procedures, when it comes to validate finite element modelling. While for the laboratory tests, hand calculations can be taken as the procedure for its validation. Thus, laboratory tests should be performed as accurate as they can be and follow up by a monitoring of all processes for a posteriori critical assessment of its quality and results.

The laboratory tests are performed in conformity to the research questions addressed in chapter 1.3 regarding the Finger Connection. The connection characteristics are described in chapter 6 and its geometry in Annex H. The experiments are intended to determine the influence of the friction coefficient, taking into consideration the gap that the fingers need to fill in order to clamp the lower column. For this reason the experiments are tested in pure compression, where is found that the correct assembling process plays a role in its slip resistance.

8.1 Testing program

In order to assess the influence of a vertical and horizontal gap in the connection, three different types of setup are considered: 4, 6 and 8 mm of horizontal gap. A vertical gap is introduced to achieve a pure friction connection, and consequently forcing the load paths to develop throughout the fingers until reach the lower column. The vertical gap is thus kept at 5 mm for all experiments.

The connection which is selected for assessment is with the 8mm horizontal gap. The reason lies in the fact that this connection is the one that undergoes the largest stress fields and deformation. Therefore it becomes more demanding to replicate and so it routes the modelling process towards more refined results. Consequently the results tend to converge to those obtained in laboratory when it comes to reduction of gap sizes.

Along the tests program, two phases are considered: the assembling phase and the loading phase. The first phase addresses the sequence of the bolt tightening, whereas the second focuses on the resistance of the connection, which culminates into the slip, as the failure of the finger connection. An intermediate phase is considered to evaluate the loss of preload in the bolts, which has implications along both phases of the laboratory tests.

Although the column-splice joint presents four Finger Connections, one at each face of the tubes, as shown in Annex G, when it comes to the tests, just two sided connection (two finger plates on opposite sides) is considered. The reason lies in the fact that, by considering the two sided connection, the tests become easier to control. Moreover the behaviour of the joint is intended to be considered as symmetric. This assumption is guaranteed since the specimen is relatively short (805 mm) and its profiles large (SHS 250x10) enough to ensures that no significant bending moments are generated so uniform compression is considered.

The tests are intended to provide value information to be a posteriori compared to hand calculation and finite element models. The values are obtained from the different sources according to the needs, namely:

- Instrumented bolts: 18 bolts, 9 at each connection are instrumented in order to obtain strains (see Figure H.0.*1*). However the bolts need to be calibrated in advance to obtain forces out from strains. Basically the bolts each bolt is installed in a tension machine which gives a very precisely graph of tension along time, while it simultaneously reads the strains from the bolt. So one can get the coefficient that relates both (see Figure H.0.*2*).
- Strain gauges: 14 unidirectional SG, 7 each connection to read strains. These SG are very accurately installed to obtain the strains from the middle of the bolt-rows (see Figure H.3), which are intended to assess the bolt-row contribution for the connection resistance and are aligned parallel to the fingers to obtain strains due to compression. Remain SG are intentional placed to record the bending of the Finger Plate, therefore perpendicular to finger alignment.
- LVDT: 2 extensometers are considered in the vertical gap to measure the relative displacement of the upper and lower column and the

second, placed in the tip of the finger to measure the slip of the connection.

Moreover the testing machine provides the reaction force from the load cell placed in the bottom, since the test is performed under displacement control. The global displacement introduced in the specimen, by the stroke, it is also included in the available data. The frequency of record is 10 times per second whereas its displacement rate of 5μm/s.

The test setup of the experiments is considered in the Annex H in the Figure H.4 and Figure H.5, where SG and LVDTs location are shown.

It is important to highlight that just the two juxtaposed Finger Connections are considered active in the test, i.e. since the columns are relatively bulky, its symmetry can be ensured during the Loading Phase (see the upper right corner in the Figure H.5).

Thus, the test program comprehends two main phases, namely:

Assembling Phase – addresses the sequence of the bolt tightening for later interpretation of results, since it is believed that this phase may play a role in the final resistance of the connection, since the loss of pretension affects the clamping force. In addition, a sub phase is considered to track the loss of pretension that bolts undergo during a 60 hours period, after the assembly of the joint.

Loading Phase – the specimen is subjected to a compression force, which culminates with the slip of the Finger Connection that represents the failure of connection.

8.2 Assembling Phase

8.2.1 Procedure

In this phase the assembling of the connection is performed, where process of tightening the bolts constitutes the task of the major relevance.

Wherein, by definition, for a 10.9 bolt, the pretension is achieved when 90% of the ultimate strength of the bolt is achieved. Thus, this requirement, gains special relevance considering that ultimate strength f_u = 1000 N/mm^2. This means, in practical terms, that the tightening process implies the use of wrenches especially dedicated to achieve this magnitude of torque.

As mentioned before all the bolts are equipped strain-gauges recording the force in the bolt, even during the tightening procedure. Therefore in order to obtain the right force in the bolts, tightening is performed based on the forces read in the computer.

As it is explained before, bolts should be fitted in advance in the holes. They should be very well fitted avoiding the head to freely turn during the tightening of the nut. However the process of fitting the bolt in the hole, implied that nut has to be tightened from outside just to force gradually the bolt to fit in the hole. Once the bolt in place, the nut is untighten to its outer position before it can be once again tighten to clamp the fingers.

According to EN 1090-2 [39] tightening shall be carried out progressively from the most rigid part of the joint to the least rigid part. At the present can be interpreted that the bolts shall be tightened downwards i.e. from the stiffest part of the Finger Plate (1^{st} bolt-row) along bolt-finger to the 3^{rd} bolt-row, where stiffness is lower. It is also stated that to achieve uniform preloading, more than one cycle of tightening may be necessary, which, in fact, have revealed to be needed.

In order to promote the correct assembly process, profiles need to be constrained laterally to avoid, during the tightening of bolts, lower profile from moving towards Finger Plate. For this reason a technique is used to prevent this unintended shift of the columns towards finger, which is described in the Figure H.6.

As it is mentioned, a second round of tightening it is recommended, and, in fact, it was expected at the time, which revealed later on to be mandatory. The Flowchart from in the Figure H.7, illustrated the sequence of tightening. Basically the bolts should be tightened in two rounds, where in each round, bolt-rows are tightened downwards i.e. from the 1^{st} to 3^{rd} bolt-row, where the middle bolt takes the lead, followed by the left and by the remaining, rightmost bolt. By doing so, it is guaranteed that the best combination to achieve a proper assembly of the connection.

The Figure H.8 shows the bolt forces along the sequence of tightening applied in the nine bolts. This figure is elucidative of the need for a second round of tightening, since the 247 kN, needed to achieve preload force in each bolt, drops dramatically, with tightening of the subsequent bolts.

8.2.2 Assessment of results

Thus, firstly, the data collected along the Assembling Phase is treated and assessed (see Table 8.1). As it was found during the tightening procedure, and suggested by Eurocodes, the first tightening round reveal to be insufficient to achieve the level of preloading desired in the bolts.

For sake of clarification, the average of the 18 bolts force is exactly 200*kN*, at the final limit of 1st round, and assuming the requested preload in each bolt is 247*kN*, than represents 81% of the total required of the preloading force. Whereas to 2nd round, the average is 237*kN*, which is rather satisfactory, and does represent 95% of the total required clamping force.

The Table 8.1 summarizes the tightening process described at the Figure H.8, where preloading force is stated at the peak (at the moment right before the wrench stops to apply the torque force).

Table 8.1: Summary of forces of the Assembling Phase on the front face

Tightening sequence		1st Bolt-row			2nd Bolt-row			3rd Bolt-row		
		1st	2nd	3rd	4th	5th	6th	7th	8th	9th
Bolt Position		Bolt 1-2	Bolt 1-1	Bolt 1-3	Bolt 2-2	Bolt 2-1	Bolt 2-3	Bolt 3-2	Bolt 3-1	Bolt 3-3
1st round	Max (at peak)	224	230	208	231	210	221	229	233	235
	Min due to drop	170	215	190	199	195	201	201	219	219
	Loss of pretension	54	15	18	31	15	20	28	14	16
	Loss of pretension (%)	24%	7%	9%	14%	7%	9%	12%	6%	7%
2nd round	Max (at peak)	251	246	250	246	246	249	247	247	248
	Min due to drop	238	236	234	233	233	234	238	236	237
	Loss of pretension	14	11	16	13	13	15	9	11	10
	Loss of pretension (%)	5%	4%	6%	5%	5%	6%	4%	4%	4%

In the Figure H.8 is quite clear this phenomenon, where force drops abruptly, right after the bolt tightening stops. Denominated as *Pretension losses*, is classified in Figure H.8 as *loss of preload*, and is the result of the phenomenon of Short Term relaxation. This phenomenon presents a peak, as described before, and its magnitude of the pretension loss depends on the surface and plate thickness as well as on the geometry [1].

When it comes to the denominated, *Loss of preload due to assembly,* established in the Figure H.8, it can be observed that the bolt exhibit a sudden drop, which is coincident to the tightening of the subsequent bolts. This phenomena has two components; first, described in the literature has Elastic interaction, which affirms that bolts forces tend to decrease when consecutive bolts are tightened [1]; second, which is identified as a proper characteristics of this connection, and its pretension loss arises from the fact that the bolt, along the tightening process, pulls outwards the walls of the lower profile, since the fingers are stiffer. This creates terrain for the bolts to behave differently whenever a new bolt is tightened. This phenomena as it big expression in the 1st bolt row and it is better explained in the chapter 10.1.

Thus, some conclusions can be traced from the observation of the Table 8.1.

-The first bolt to be tightened, i.e. the middle one, from each bolt-row, undergoes the major loss of preload from the respective bolt-row;

- The major component of loss of preload, in an early stage, experienced in one bolt, arises from the tightening of bolts in its vicinity.

-Loss of preload tend to decrease from the 1st to 3rd bolt-row, according to tightening sequence, and from 1st to 2nd round of tightening.

The total force in the bolts plays a very important role, when it comes to ensure a good connection resistance. For this reason, a successful tightening process creates the adequate conditions to obtain an expected resistance of the joint, which is the focus of next chapter.

8.3 Loading Phase

8.3.1 Procedure

Once the joint assembled, follows the loading test phase, where the specimen is mounted on the testing machine (see Figure 8.1). This phase is the corollary of the work performed in the lab and its result attest how accurate the measurements and tasks are performed.

Figure 8.1 – Apparatus of the Finger Connection Compression test

The axial compression test shall be executed as smoothly as possible, so the rate of loading is set to5 μm/s. The slip, by definition, according to EN1090-2 [39], takes place when displacement in the fingertip reaches 150 μm*,* which occurs 5 minutes after test starts, at 676 kN. This establishes the end of the first stage – slip of the connection – and officially marks its failure. The second stage concerns the remaining displacement before the columns touching, which takes place 12 min later and requires the mobilization of 1205 kN force.

8.3.2 Assessment of results

The main objective of the loading phase is to evaluate the conditions of the joint at the exact moment at which the slip occurs. As previously explained, in order to measure the slip, the LVDT2 is located at the fingertip to read slip along the test. When slip, by definition, takes place the bolts forces are recorded in order to calculate the apparent friction coefficient.

From the observation of the table Table 8.2, it is possible to obtain the apparent friction coefficient, which by definition, is the ration of the slip load on the sum forces in bolts at slip. This value allows a better comparison of the friction properties without accounting for the different variations of clamping forces [1]. However this value is calculated taking into account the full clamping force, but, in fact, the two outermost bolts of the 1st bolt-row are responsible to bend Finger Plate.

The Table 8.2 summarizes the forces per bolt during the relevant periods of the test.

Table 8.2: Summary of forces at the Loading Phase on the front face

	Bolts Forces [*kN*]	1st Bolt-row			2nd Bolt-row			3rd Bolt-row			Force from stoke
		1st	2nd	3rd	4th	5th	6th	7th	8th	9th	
	Bolt Position	Bolt 1-2	Bolt 1-1	Bolt 1-3	Bolt 2-2	Bolt 2-1	Bolt 2-3	Bolt 3-2	Bolt 3-1	Bolt 3-3	
Start	Force	260	155	168	70	189	251	209	103	180	0
	average (2 bolts)	243	127	171	134	217	179	193	161	186	
	average (9 bolts)	179									
	Force (9 bolts)	3225									
Drop	Value	-4	-1	0	-3	0	-4	-1	-1	-3	n/.a.
	%	-1%	-1%	0	-4%	0%	-2%	0	-1%	-1%	
Slip (SLS)	Force	264	156	168	73	189	259	210	103	183	676
	average (2 bolts)	247	128	172	137	218	182	195	161	188	
	average (9 bolts)	181									
	Force (9 bolts)	3254									
Drop	Value	-32	-10	-24	21	19	8	30	14	21	n/a.
	%	-11%	-6%	-13%	40%	11%	3%	17%	16%	13%	
Final (ULS)	Force	296	167	192	52	170	248	180	89	161	1120
	average (2 bolts)	266	129	184	116	197	170	171	126	163	
	average (9 bolts)	170									
	Force (9 bolts)	3055									

So in this sense the value of the total force considered to calculate the apparent friction coefficient should be subtracted of the equivalent tensions forces in the bolts.

From the perspective of the fingers in the Finger Plate, it is important to estimate its contribution for the resistance of the connection. This information is relevant to assess bolt-rows contribution and its transition of loads, in order to discriminate connections in its major components.

Moreover it is interesting to observe that the clamping forces are higher at the slip, when compared with in the beginning and also at the end of the test. The reason is related to the fact that, since the Finger Plate is stiffer then Lower profile walls, as the Finger Plate goes downwards, due to the loading, the distance Finger Plate support and 1st bolt-row decreases i.e. the cantilever distance decreases and consequently increases the forces just at 1st bolt row. This phenomena is captured in terms of forces in the bolts in the graph in the Figure H.11, where it is noticed the gradual increase of forces in the bolts at the 1st bolt-row. Moreover, but as a lower component this increase is also induced by the expansion of the plates due to compressive load, Poisson's effects.

In order to perform this assessment unidirectional Strain Gauges (SG) were thoroughly placed at the intermediate axis that separates bolt-rows (see Figure 8.2 and, for a large scale, in Figure H.4 and Figure H.5). All the SG, except *1D SG 1E* and *1D SG 8E*, are recording strains, during the loading test, along the vertical axes which pass through them, namely, from *Finger 1 F* to axis *Finger 4 F*. The exceptions to the statement previously made, are for the two SG mentioned, which capture the strains that develop in the perpendicular direction.

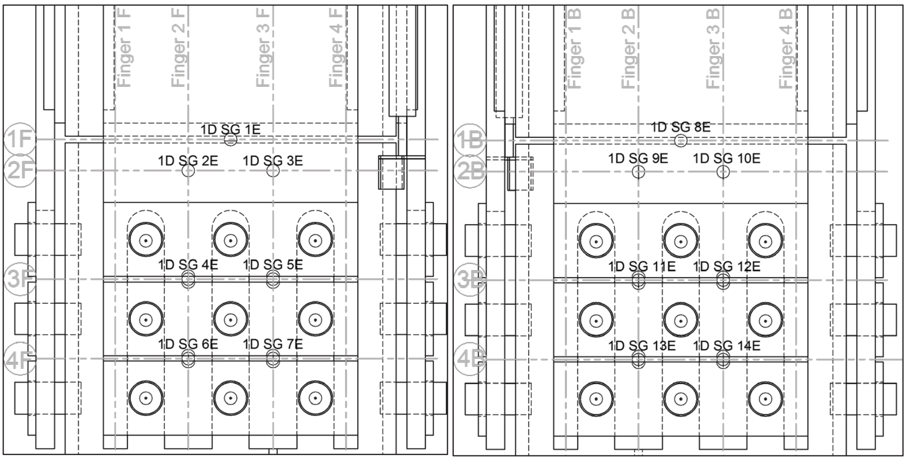


Figure 8.2: Representation of test setup for SGs - front and back, respectively

For the sake of clarification, the explanation of the attainment of forces for each bolt-row focuses just onto the front face of the specimen. As strain gauges provide just strains, taking the advantages of Hook's law with Young's modulus (according EN1993-1-1 [31]) and moreover from the cross-section area, of the element in analysis, it is possible to obtain the force.

Thus, for instances, assuming that, at the 2F axis, the force is uniformly distributed along Finger Plate gross-section width. Which is reasonable due to FP length, taking the Saint Venant's principal into account. From SG 2E and 3E, is possible, from its mean value, to obtain the total force that comes from the testing machine and extends downwards throughout fingers length. The data in the following Table 8.3 and Table 8.4 correspond to the moment of the slip. The analysis of this data it is conducted to identify the bolt-rows relative contribution for the slip resistance of the connection. The conversion to from strains to forces is based on the Hooke's law.

Table 8.3: Summary of the strains and its conversion to force, at Front FP

Axes	Front Finger Plate Width		Finger 2F	Finger 3F	Finger 2F	Finger 3F
			3F		4F	
Strain Gauges	1D SG 2E	1D SG 3E	1D SG 4E	1D SG 5E	1D SG 6E	1D SG 7E
Cross-section area [mm^2]	2880		540	540	540	540
Strains [$\mu m/m$]	-503	-673	-1044	-1007	-452	-430
Average [$\mu m/m$]	-588					
Stresses [*MPa*]	-124		-219	-211	-95	-90
Force [*kN*]	356		118	114	51	49

Table 8.4: Summary of the strains and its conversion to force, at Back FP

Axes	Back Finger Plate Width		Finger 2F	Finger 3F	Finger 2F	Finger 3F
			3F		4F	
Strain Gauges	1D SG 9E	1D SG 10E	1D SG 11E	1D SG 12E	1D SG 13E	1D SG 14E
Cross-section area [mm^2]	2880		540	540	540	540
Strains [$\mu m/m$]	-402	-510	-745	-852	-278	-326
Average [$\mu m/m$]	-456					
Stresses [*MPa*]	-96		-156	-179	-58	-68
Force [*kN*]	276		85	97	32	37

From the observation of the forces, at the front and back of Finger Plate, it is possible to check that its sum results is 632 kN, which corresponds to a deviations in 6.5% from the load that is introduced by the testing machine in the specimen at the slip, 676 kN (see Table 8.2). This proves the reliability of such assessment process for the force applied to the specimen.

From the observation of data, is possible to conclude that, back and front Finger Plates, exhibits some eccentricity, which may be induced by the misalignment of the specimen (as shown in Figure 6.1), and also the different preloading forces at each Finger Connection. Nevertheless the relative distribution of forces along the bolt-rows is relatively even.

9 DEVELOPMENT AND VALIDATION OF NUMERICAL MODEL

The finite element modelling consists in the formulation of a complex mathematical model, where its bounds are not often easy to track and not infrequently difficult to solve. Therefore it is imperative that the finite element analysis is followed by a comprehensive calibration and validation of the modelling, based on laboratory tests, hand calculations.

9.1 Systematic approach to problem solving

In order to reproduce the correct behaviour of the Finger Connection with a satisfactory level of accuracy, a quite large number of assumptions - from a structural point of view – and consequently its application in the software, need to be implemented. Thus the strategy employed, involves an iterative design process which encompasses three major phases:

- pre-processing – implies the geometrical and structural definition of the connection and its mechanisms;

- processing – tuning of the model towards a sustainable computational convergence;

- post-processing – interpretation of the results and creation of outputs

The Figure 9.1, shown below, describes in a flow chart, the iterative design evaluation process used along the design process within ABAQUS software [8].

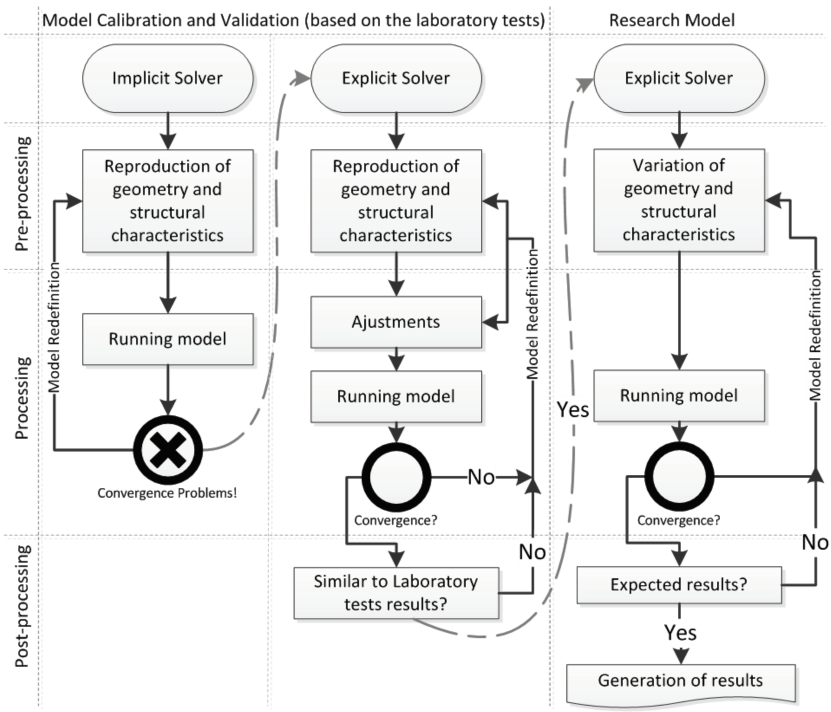


Figure 9.1: Overview of the iterative design process in ABAQUS

A first attempt for modelling the joint is performed using the ABAQUS/Standard [8], where an implicit solver governs the computing process. Later attempts on the model revealed to be fruitless due to convergence problems, mostly originated from the amount of contact interactions presented in the connection. Thus this processed was rejected.

A second approach is performed using ABAQUS/Explicit dynamic solver which does not have convergence issues. In order to use the explicit dynamic solver efficiently for a quasi-static analysis, the calculation speed needs to be increased artificially. This can either be achieved by increasing the loading rate or by mass scaling [8]. Thus, although in the short-term implies additional parameters to be tuned, in the long run creates a more stable model for manipulation.

Good practices

In the path of achieving the connection structural behaviour, its reproduction within the software is not always an easy task. The connection should be firstly dissected in its major components/mechanisms, for instance, by considering just two preloaded bolts in a lap joint. In a very simple model, one can evaluate, with precision the results. By analysing each component of the connection separately and adding more components to the model in an ascending chain of complexity, the model can be manipulated in way to control results.

In a later stage, the mechanism of evaluating the reliability of the model's results, involves the reproduction of the laboratory tests and consequent comparison. For this method, all the characteristics and situation occurred during the test, should be replicated in the model. By comparison of both results, it is possible to conclude, based on its similarities, how reliable are its outcomes. This is an iterative approximation that just has its terminus when model results are satisfactorily close to the ones obtained in laboratory tests.

Computing phases

Two phases can be distinguished in the modelling: the assembling phase and the slip phase. The first one, focuses mainly on the sequence of the bolt tightening, whereas second focuses on the computation of connection resistance, during the slip failure. The phases considered are coincident with the phases considered in the laboratory tests.

9.2 Description of the finite element model

9.2.1 Mechanical properties of materials

The mechanical properties of a material can either be considered as nominal, e.g. included in design codes, or by means of experimental results using coupon tests.

Within the present work it is noticed that joint does not undergo significant stresses, where its large majority of stress field can be delimited, far below, yield strength of the steel. The reason for this arises from the fact that failure of joint is a consequence of connection slip and not from a yielding failure. The same applies for the bolts. Therefore the consideration of coupon tests does not represent a significant achievement for the development of the present work, and nominal values of material properties are used.

Isotropic material with initial modulus of elasticity of E_0 = 210 N/mm^2 and Poisson's ratio in elastic stage of υ = 0.3, is defined for all the materials used in the model. Since modelling is performed using ABAQUS/Explicit the density of steel is 78.5 kN/m^3 is taken into account according to EN 1991-1 [31].

Simple plasticity is defined for all materials with no strain hardening. The finger plate, cover plates and profiles are defined with yield strength of f_y = 355 N/mm^2. The bolts modelled are considered with the same characteristics as preloaded HV 10.9 bolts with yield stress f_y = 900 N/mm^2.

9.2.2 Contact interactions

The contact interactions consist in a relevant point within the modelling process, indeed, if modelling implies a large number of surfaces to be defined, it might degenerate in convergence problems, as mentioned before. By using the ABAQUS/Explicit solver, the contact surfaces do not need to be thoroughly defined, as with implicit solver.

For the whole structure, a *General Contact* is assigned as *"Hard" Contact,* permitting separation after contact for the *Normal Behaviour*. In practical terms, for instance, the cover plates, when bolts are preloaded, get into contact with the finger plate which consequently, clamps it against the profile beneath. Whereas for A friction coefficient of μ is defined using *Tangential Behaviour*, with *Penalty* friction formulation which is just tuned later on in the validation of the model, according to description in chapter 9.4.

The exception, in terms of friction coefficient, is made, when it comes to consider friction, on the coincident surfaces between bolt shank and nut. For the correct performance, in the application of pretension in the bolts, the nut should be able to slide, without frictionless, trough the bolt shank. Thus, just one individual property is created and assigned to disregard friction throughout bolt shank - *Tangential Behaviour, Frictionless*.

The welds

As previously mentioned, the failure of connection is governed by slip therefore the welds' do not play any relevant role in structural resistance of the connection. Thus the consideration of the welds in the model is neglected. It is replaced by *tie constraints* among the elements to seam.

9.2.3 Boundary conditions

Boundary conditions should define as much as possible structural interactions existent throughout the laboratory tests. The Figure 9.2 illustrated the three *boundary conditions* assigned to the structure, on *reference points* (RP) and *surfaces* considered in the joint.

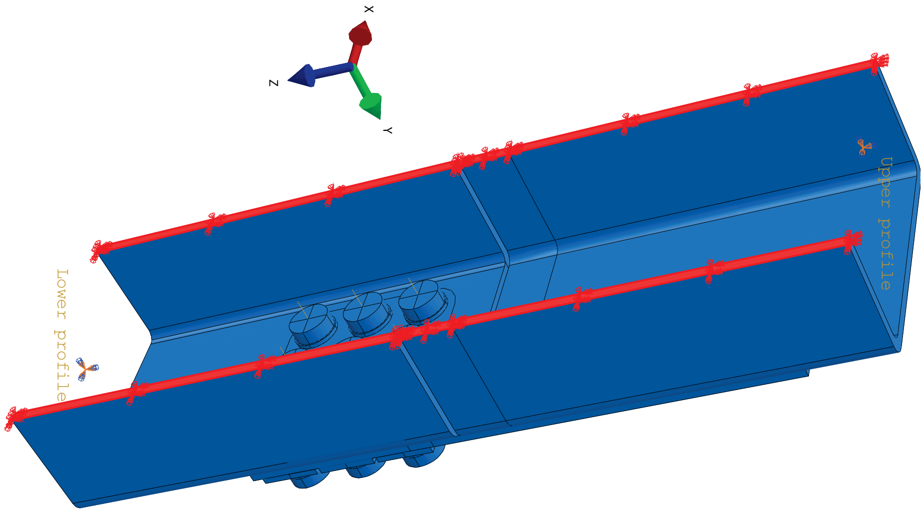


Figure 9.2: Boundary conditions defined in the model

The degrees of freedom of the bottom cross section of the lower column are all constrained (not allowing any translation or rotation) whereas on the top cross section of the upper column, the vertical translation is free. The incited translation is applied on the RP of the top cross section of the upper column in the slip loading phase (so called Slip Phase).

As a matter of simplification, the modelling of the joint is approached considering just one Finger Connection, assuming other juxtaposed FC, as symmetric. Symmetrical behaviour of the specimens is discussed in chapter 8.1. Therefore, the symmetry boundary condition is defined for the mid-plane surface indicated in Figure 9.2.

9.2.4 Element type

For the modelling process an eight-node, reduced integration continuum element, known as C3D8R, is considered.

The use of hexahedral elements, as the C3D8R, usually provides a solution of equivalent accuracy, as for tetrahedral elements, at less cost.

Columns and cover plates are meshed with 4 elements across the thickness in order to properly take into account their bending.

9.3 Fastening set modelling

9.3.1 Fastening set as an isolated mechanism

Preloading concept

Typically the preloading force in the bolt is introduced by elongation of the bolt shank against the contraction of the clamping package which is achieved by the rotation of the nut. The preloading of the bolts starts right after the clamp length of the bolt equalizes thickness of members subjected to clamp (see Figure 9.3). Therefore, the preloading in the model can be introduced by a relative displacement of the nut which is constrained to a certain surface of the bolt representing the thread zone.

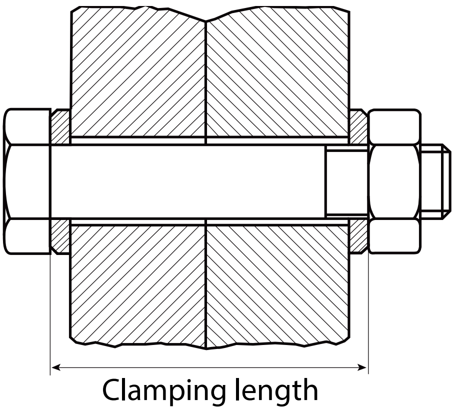


Figure 9.3: Illustration of clamping length

Modelling

Bolt and nut are considered as separated *Parts* in the model, where each has its own *Reference Point* (RP) coupled to the thread zone of the bolt and nut internal surface. The Figure 9.4 shows the modelling of the bolt and nut isolated and assembled.

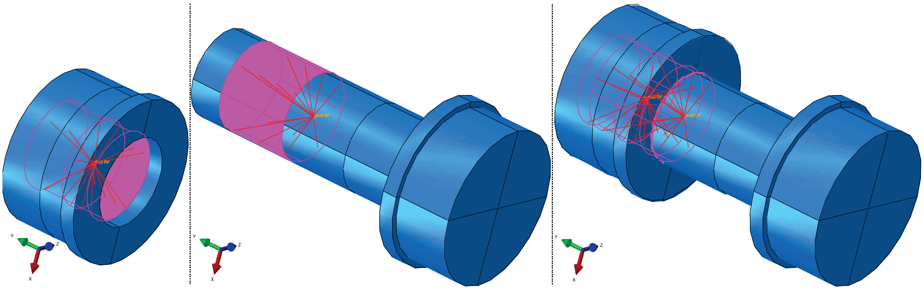


Figure 9.4: Bolt and nut isolated and assembled

By the surfaces to the RPs, the stiffness of the bolt shank is transmitted through its surface to the surface coupled with nut's RP. Therefore to create accurate results, both RP should be working closely from each other, especially when preloaded. For this reason, the RP where located to get almost coincident by the time the set creates the maximum pretension.

A *Wire Feature*, attaching both RP of bolt and nut, permit a *Connector Section* to be assigned as a *Translator*. Briefly, it allows just axial translation, along the wire, of the set: bolt-nut, to take place (see Figure 9.5).

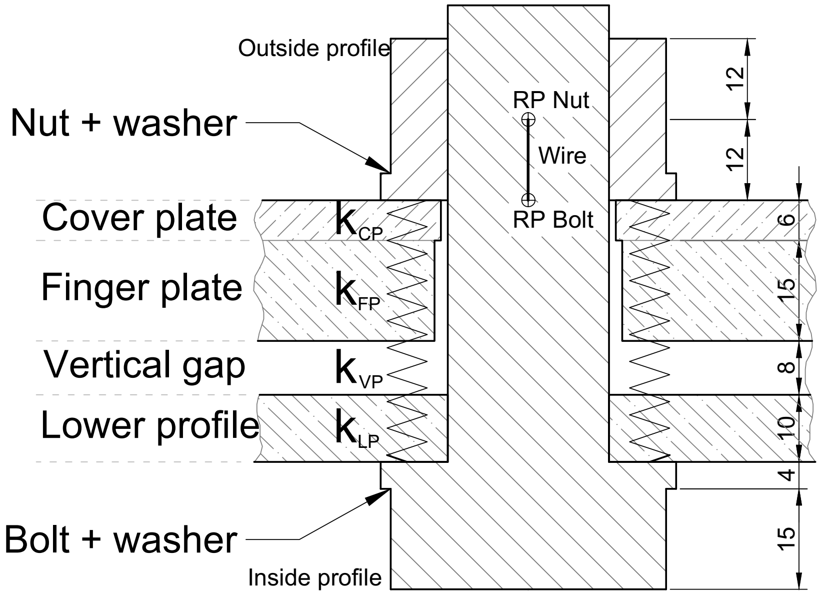


Figure 9.5: Detailed section within the bolt's middle-plan

Within the *Boundary Conditions*, a *Connector Displacement* is created, allowing control of the translation of the set. The Figure 9.5 illustrates the mechanism previously described. In other words, it allows generation of clamping of the members, through the application of a displacement on the nut towards the bolt head. Also the force can be introduced by definition of the connector force. In that case the solver automatically increases the connector's displacement to reach the desired force.

9.3.2 Fastening set as a group mechanism

For the assembling process, is assumed that opposed finger connections are assembled at the same time. In practice, at the working site, the tightening process should be performed by one worker at each FC. According to EN 1090-2 [39], the tightening procedure should be performed from the stiffer part to the less stiffened part of the connection. Thus, the tightening should start from 1^{st} bolt-row towards the 3^{rd} bolt-row.

Investigation on the assembling process revealed to gain special interests for its assessment and modelling, therefore the present chapter introduces the mechanism of tightening sequence and the phenomena of loss of pretention described in the chapter 8.2.2. As it was previously described, the preloaded force it is generated right after the nut contacts the members to be clamped and is limited by the its upper bound which is its yield strength. Thus for the bolts M24 and 10.9 grade, the forces correspondent is 247 kN.

Clamping Stiffness

Modelling preloading mechanism can either be performed by using force or displacement. For the Assembling Process, is desired at all, that, for first tightening round, gap shall be fully closed. To do so, preloading of bolts should be, as much as possible, loaded until is reached the requested preload.

In order to introduce forces in the bolts and to assess assembling process, each bolt is loaded in one step at the time, when it comes to assess the assembling phase. Whereas for the Slip Phase its model is designed to clamp all bolts at once in order to simplify the process.

Therefore, for the Slip model, its preloading force it is considered as the same force obtained from the tests. However since the model is symmetric, the force at each bolt, is considered to be the partial average of preloading force from the test (see forces considered in the model in Table 8.2).

In the following step, translation of the nut is locked, keeping the nut in position, and so it fulfils the bolts mechanism. Otherwise it would be pushed out at next step. The finger plate applies a prying force since it acts as cantilever so it possesses flexural stiffness. Lower profile creates force as well that nut has to withstand (see Figure 9.5). Although, since lower profile's walls are thinner (10 mm) than the finger plate (15 mm), its bending stiffness is lower. As a consequence not just the Finger Plate is bended, in fact, Lower Profile wall is pulled out as well (see Figure 9.6).

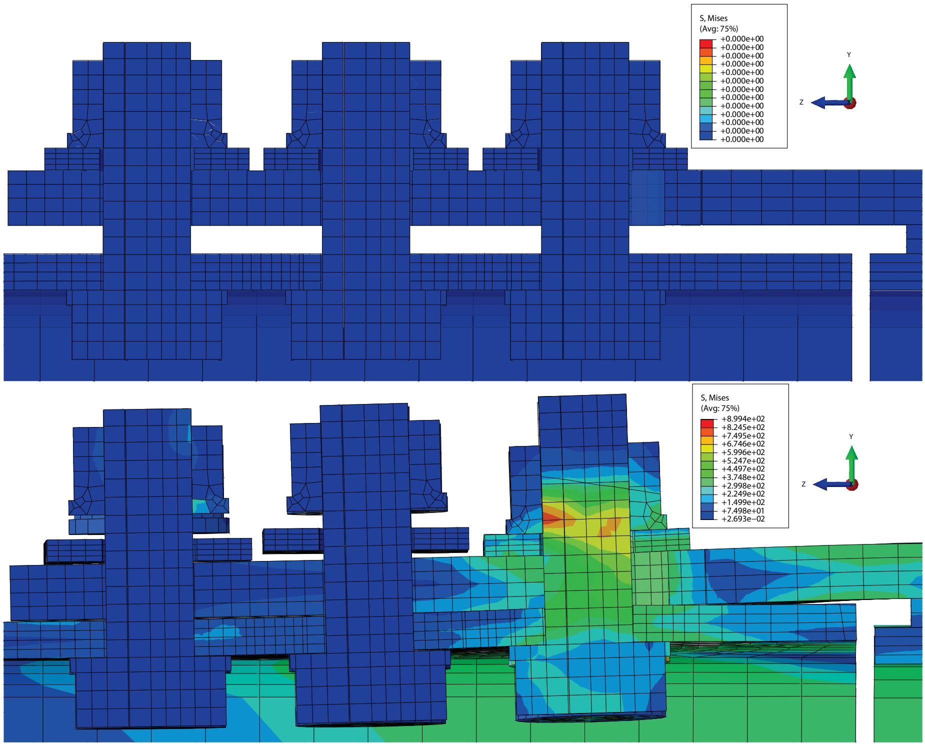


Figure 9.6: First and last frame of Bolt B_{12} step

Therefore, for the first bolt-row it is assumed, to be loaded in a combination of shear, generated by friction and tension generated by the pulling of lower profile and finger plate. The 2nd and 3rd bolt-row are dedicated just deal with friction.

However as estimated in advance, and confirmed during the laboratory tests, first tightening round, which includes all 9 bolts, is not enough to close the gap in between finger plate and the lower profile of the 1st bolt-row. Therefore a second tightening round must be performed, which, once again, is executed downwards (see chapter 8.2).

9.4 Replication of the laboratory tests

The operations performed in the laboratory, can be divided into:

- Assembling Phase, where tightening process is accomplished.
- Slip Phase, where the specimen is placed into the testing machine, which submits the specimen to a displacement control test and consequently slip failure takes place.

The Calibration Model relies on the most important indicator – apparent friction coefficient – as it certifies how reliable modelling is. The apparent friction coefficient (AFC) is defined as the ratio between the slip resistance and the sum of bolts forces at major slip and it allows a better comparison of the friction properties without accounting for the different variation of clamping force [1]. Since from the laboratory tests, described in the chapter 8, the whole test was constantly monitored, the modelling shall be set to replicate as much as possible its characteristics. Therefore, from the Calibration Model, different load-displacement curves, for different AFC, are intended to be compared to the laboratory test curve, in order to find the one that fits it most.

As explained in Figure 9.1, the model used for the sake of calibration – Calibration Model - considers the exact amplitude of force in the bolts, as the one used within Assembling and Slip Phase, performed in the laboratory. However, since the modelling is based on the symmetry of the joint considered in the laboratory i.e. just one Finger Connection is considered, while the test contemplates two. It means that the forces, at each bolt in the modelling constitute the average of the two juxtaposed bolts at the two Finger Connections from the tests. As an example, the force in the bolt B_{11} in the modelling constitutes the average of the force at the B_{11} in the front and the B_{13} in the back (the two juxtaposed bolts).

The bolt forces considered in the Calibration Model are considered as in the Table 8.2.

From the tests, the load-displacement curve is traced based on the information provided by the LVDT.

The slip in the model is traced as the relative displacement between the finger plate and the lower column at the end of the finger (the fingertip).

Comparison of the experimental and FE results in a form of force-slip curves is shown in Figure 9.7 for the initial loading phase and in Figure 9.8 for the whole loading range. Different values of friction coefficient have been used in FEA in order to match the experimental results. It can be concluded that the value of friction coefficient of $\mu_{FEA} = 0.17$ meets numerical and experimental results for the slip.

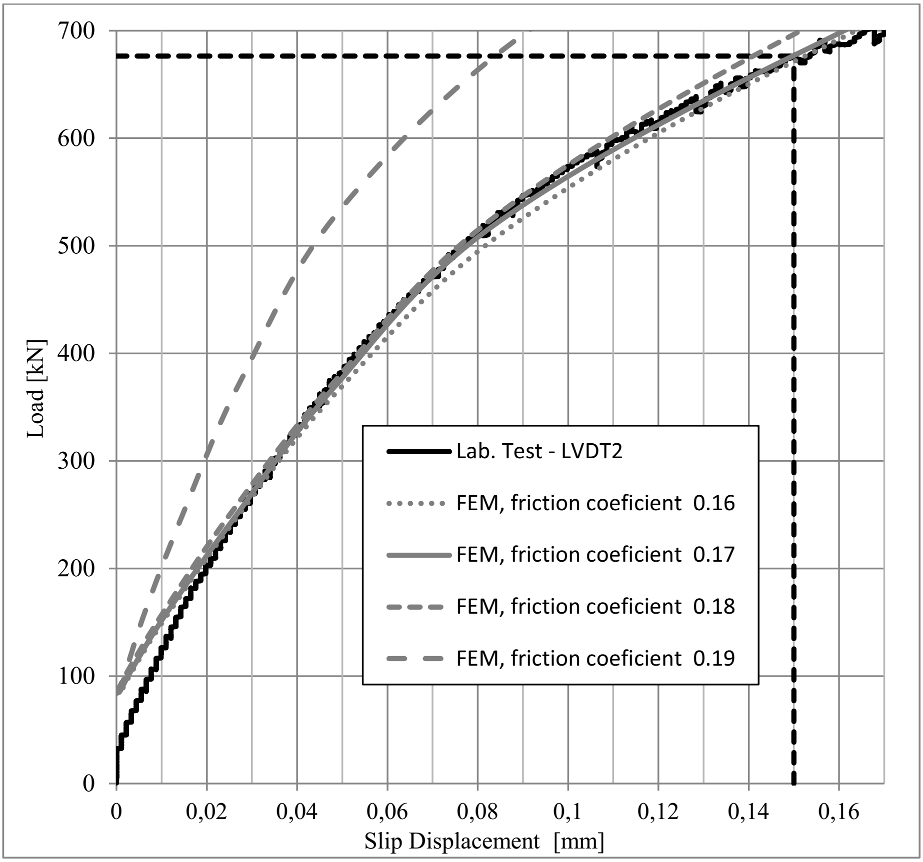


Figure 9.7: Load-displacement curve for slip

However, taking a closer to look to the Figure 9.8 it is possible to observe that the load-displacement curve from the FEA modelling does not fit any more after the slip. However as it explain before, the connection is intentionally designed for serviceability limit states therefore the ultimate resistance of the connection is not relevant in this sense for the Finger Connection considered.

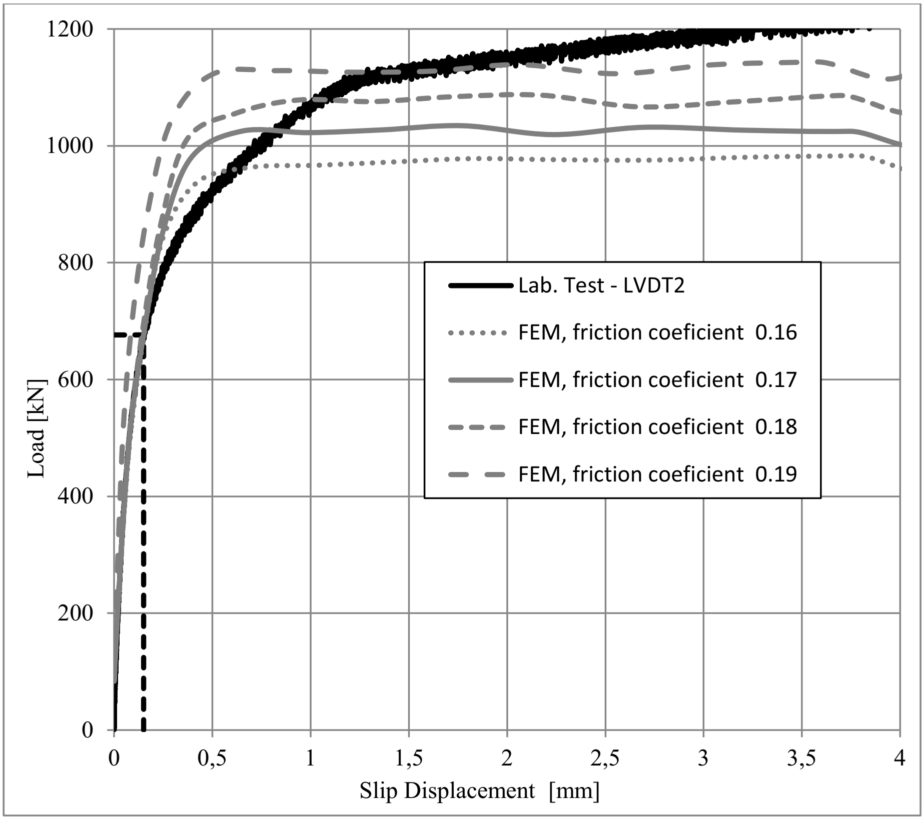


Figure 9.8: Load-displacement curve for slip

10 DISCUSSION AND RESULTS OF COLUMN-SPLICE – FINGER CONNECTION

Analysis of components using Finite Element (FE) represents a big gain, compared to laboratory test, in terms of time and cost while it offers the possibility to analyse deeply the problem. However in order to formulate the correct modelling, it should not be neglects other means of analysis for a posteriori validation.

10.1 Activation force for Finger Connection

The Finger Connection is considered as a friction connection. Closing of the gap between the lower profile and the fingers plate requires certain force. Pretension forces in the 1st bolt-row are mostly reduced due the gap closing. A closer look in the FEA models, have shown that the outermost bolts of the 1st bolt-row, i.e. B_{11} and B_{13}, are placed in the stiffer part of the connection and thereby the most loaded during the gap closing. . The middle bolt-row, B_{12}, does not contribute to the gap closing and can be fully utilized in the friction connection.

The two outer bolts establish are enough to force the finger plate to bend totally. Any additional force, in any of the bolts, contributes to the friction force of the connection. The force applied in the bolts used for the finger plate bending, is called the Activation Force.

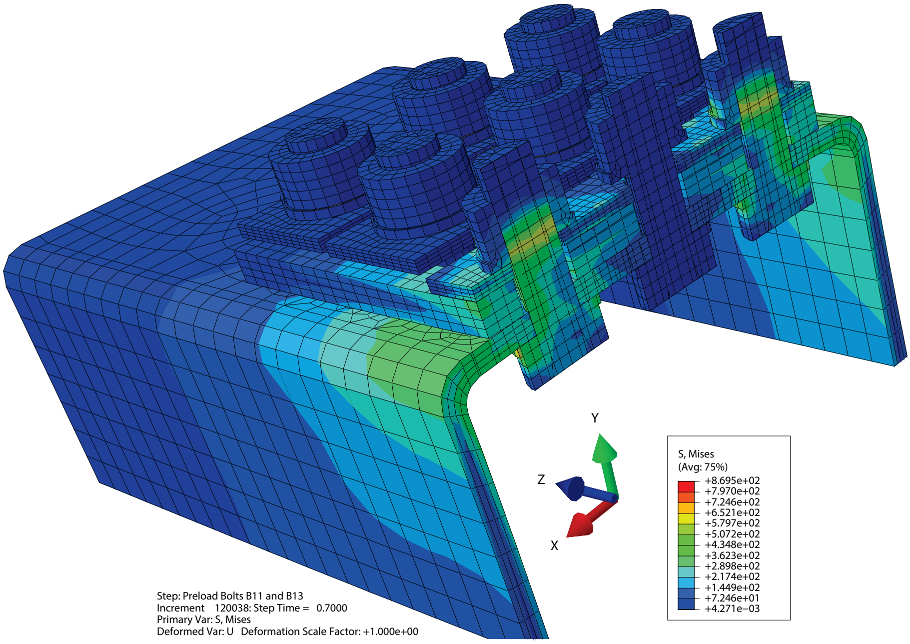


Figure 10.1: Model of 8mm gap to calculate the Activation Force

The force development in the bolts B_{11} and B_{13} depending of the gap is shown in Figure 10.2 . During the slip test, from the Table 8.2, it can be noticed that the bolts, B_{11} and B_{13} experiences, until slip, a very slight increase of force, which does not represent a relevant difference. Therefore this difference is negligible.

The following Table 10.1 show the summary of the Activation Forces needed for each case.

Table 10.1: Activation forces for 4, 6 and 8 mm gap

Models		Bolt B_{11}	Bolt B_{13}
Model 1 (4mm)	Force [kN]	44	44
	% of the preloading Force required, 247kN	18%	18%
Model 2 (6mm)	Force [kN]	80	80
	% of the preloading Force required, 247kN	32%	32%
Model 3 (8mm)	Force [kN]	112	112
	% of the preloading Force required, 247kN	45%	45%

The Figure 10.2 describes the filling of the gap along with the force applied.

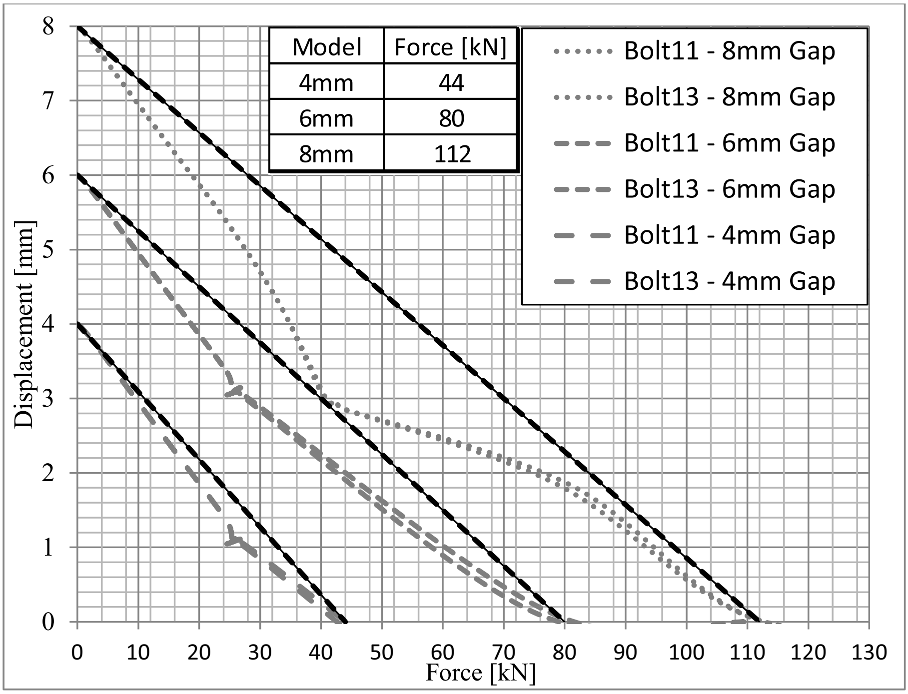


Figure 10.2: Activation force, per bolt, for the case of 4, 6 and 8mm gap

It can be seen that there is a parallelism on the relation of the Activation Force and the gap of Finger Connection (FC). As a expedite calculation method for Activation Forces, on FC with a different gap, from the tracing of intermediate lines, it is possible to obtain approximate values.

10.2 Contact pressure

In order to increase the slip resistance it is very important to increase the contact. The contact zones and wear patterns are in good agreement with the obtained from the finite element models.

The Figure 10.3 shows the pressure applied at the cover plate by the preloading force on the washer. By taking a closer glance in the picture us possible to observe that the washer does not slip over the cover plate the interface washer-cover plate, produces friction enough so the washer does not slip. In the Figure 10.4 the washer exhibits the wear mark created by the preloading of the bolt against the washer.

Figure 10.3: Wear at the Cover Plate

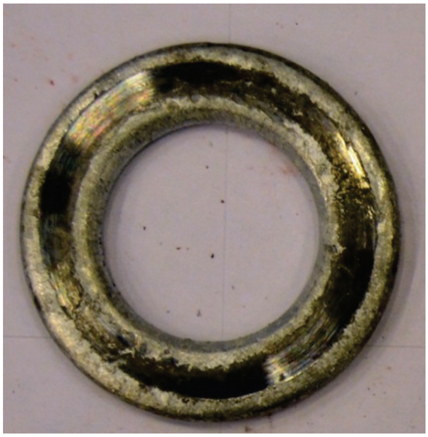


Figure 10.4: Wear mark in the washer

The Figure 10.5 and Figure 10.6 are represent the contact pressure applied in the Cover plates and in the Fingers plate in comparison with the results obtain from the ABAQUS.

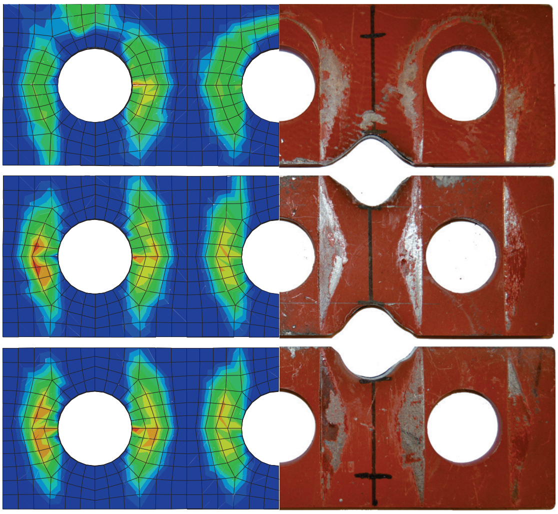


Figure 10.5: Wear pattern in Cover Plates

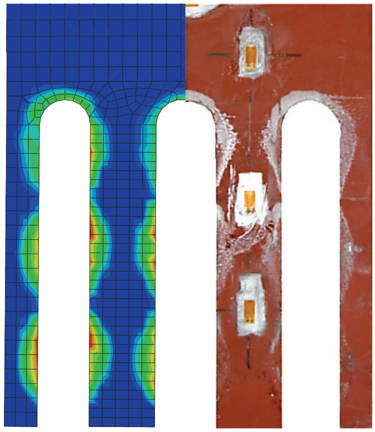


Figure 10.6: Wear pattern in the Fingers Plate

10.3 Influence of the gap for resistance

The Figure 10.7 describes the influence of the gap on the slip resistance based on the FEA models with 0, 4, 6 and 8 mm, and the preloading of the bolt in its full capacity, 247 kN.

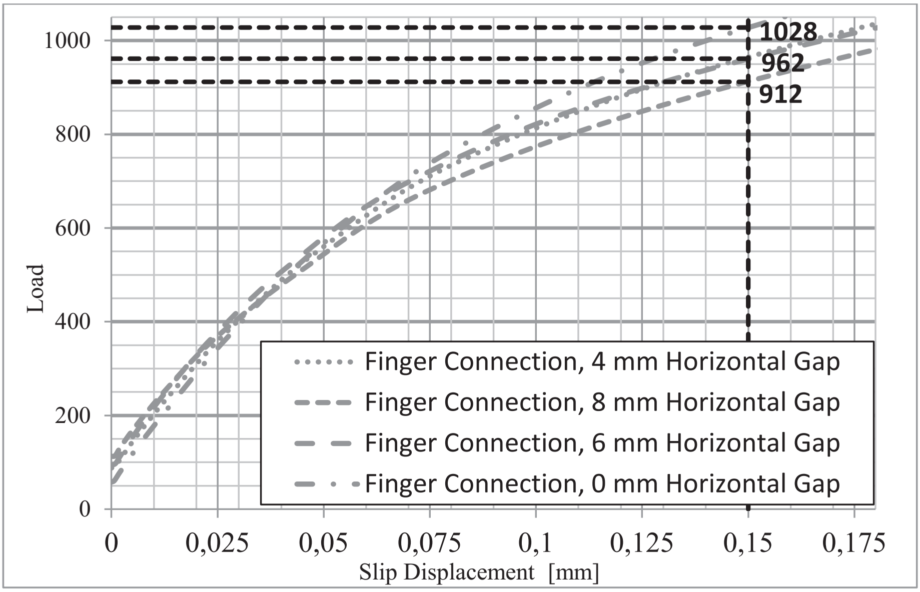


Figure 10.7: Influence of the Horizontal Gap on the final slip resistance

The slip resistance for the finger connection drops in 7% in its configuration of 4 mm and 6 mm, and 12% for 8 mm gap, when compared with the configuration devoid of the gap. The drop in resistance is responsibility of the Activation Forces.

As described previously the connection design is just considered for the serviceability limit states until the slip occur, therefore its ultimate resistance is out of the scope the thesis.

10.4 Apparent Friction Coefficient

The resistance of friction connections should be ideally determined by testing on its actual configuration, which indeed is performed in this thesis [1]. Since apparent friction coefficient is a very single and specific of each connection, so it encompasses the entire phenomenon that leads to the slip. Therefore it allows a better comparison of the friction properties without accounting for the different variations of clamping forces.

Apparent friction coefficient (AFC) is calculated based on the ratio of the slip force on preloading force in the bolts at the time of the slip. However, since the Finger Connection has, as its main characteristics the horizontal gap, the forces needed to bend Finger Plate should be neglected. And so, by way of conclusion, apparent friction coefficient is the ratio of the slip load, F_{slip} (mentioned in the Table 8.2) on total clamping force at the slip. The clamping force constitutes the forces in the bolts at the time of the slip, $F_{\text{Slip,Bij}}$ (from the Table 8.2), subtracted by the total Activation Forces, $F_{\text{AF,Bij}}$ (summarized in the Table 10.1).

Thus, assuming a mathematical approach, the bolts forces, at each position in analogy to a matrix representation (as described in Figure 6.4), are indicated [kN].

$$AFC_{Test,8mmGap} = \frac{F_{slip}}{F_{Clamp}} \qquad 10.1$$

$$F_{Clamp} = \sum_{i=1}^{3} \sum_{j=1}^{3} F_{\text{Clamp,Bij}}$$

$$AFC_{Test,8mmGap} = \frac{F_{slip}}{\sum_{i=1}^{3}\sum_{j=1}^{3} F_{\text{Slip,Bij}} - \sum_{i=1}^{3}\sum_{j=1}^{3} F_{\text{AF,Bij}}}$$

$$F_{\text{Slip,Bij}} = F_{\text{Slip(Front),Bij}} + F_{\text{Slip(Back),Bij}} \qquad 10.2$$

$$= \begin{bmatrix} 156 & 264 & 168 \\ 189 & 73 & 259 \\ 103 & 210 & 183 \end{bmatrix}_{Front} + \begin{bmatrix} 99 & 229 & 176 \\ 248 & 201 & 109 \\ 219 & 179 & 194 \end{bmatrix}_{Back}$$

$$F_{\text{AF,Bij}} = \begin{bmatrix} 112 & 0 & 112 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}_{F(Front)} + \begin{bmatrix} 112 & 0 & 112 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}_{B(Back)} \qquad 10.3$$

$$F_{slip} = 676$$

$$AFC_{Test,8mmGap} = \frac{676}{3254 - 448} = 0.24$$

Therefore the Apparent Friction Coefficient of the Finger Connection is 0.24.

10.5 Comparison with the standards

In order to assess design requirements within the European standards, which in this case applies for EN 1993-1-8 [32], the following equation 7.1 shall be used neglecting the partial safety factor, for sake of comparison, and the component $k_s \cdot \mu$ since are based on standard friction tests (see chapter 7.1) which is not the case.

$$F_{s,Rd,ser} = \cdot n \cdot \mu_{FEA} \cdot (F_{\text{p,C}} - 0.8 \cdot F_{\text{t,Ed},ser}),$$

Each parameter is known, with exception to n, which is the number of frictions surfaces, hence it is considered as the variable of the equation. Thus,

μ_{FEA} is obtained from the finite element analysis of the calibrated and validated model (chapter 9.4),

$F_{s,Rd,ser}$ is considered as F_{slip} (described in Table 8.2),

$F_{\mathrm{p,C}}$ is considered as $F_{Clamp} = \sum_{i=1}^{3}\sum_{j=1}^{3} F_{\mathrm{Clamp,Bij}}$ (described in the chapter 10.4)

$$676 = n \cdot 0.17 \cdot (3294 - 0.8 \cdot 448) \Leftrightarrow n = \frac{676}{0,17 \cdot (3294 - 0.8 \cdot 448)},$$

$\Leftrightarrow n = 1,4$ (Friction surfaces)

The previous result expresses the possibility of existence of more than one friction surfaces that can contribute for the slip resistance of the connection.

By considering the some calculation but taking in consideration the ultimate limits states:

$$F_{s,Rd} = \cdot n \cdot \mu_{FEA} \cdot (F_{\mathrm{p,C}} - 0.8 \cdot F_{\mathrm{t,Ed},ser})$$

$F_{s,Rd}$ is considered as F_{slip} (described in Table 8.2),

$F_{\mathrm{p,C}}$ is considered as $\sum_{i=1}^{3}\sum_{j=1}^{3} B_{\mathrm{fij},AF_{8mmGap}}$ (described in chapter 10.1)

$$1120 = n \cdot 0.17 \cdot (3044 - 0.8 \cdot 448) \Leftrightarrow n = \frac{1120}{0,17 \cdot (3055 - 0.8 \cdot 448)}$$

$\Leftrightarrow n = 2.4$ (Friction surfaces)

Therefore, the value expresses the existence of a second friction surface. However the value of n it is greater than $n = 2.0$ (which would be expected value to be obtained) by 16% which may be related to the reduced value of friction coefficient obtained from the FEA, which in fact, is adjusted to fit serviceability limit states (see chapter 9.4). The consideration of a friction coefficient for ultimate limit states would result in much higher value, of friction coefficient, and consequently a much accurate number of friction surfaces, *n*. Nevertheless it can be concluded that the second friction surface it is not totally activated at the serviceability limit states, therefore it increases along the loading, until it reaches its full development, before the ultimate loads. To corroborate this hypothesis the next chapter describes the phenomena more in detail, with respect to the existence of a second friction surface.

10.6 Second friction surface

The previous chapter brings up the existence of a second friction surface. In order to prove this hypothesis the present chapter takes the advantages of the finite element analysis models performed, as well all the material, which in this case, multimedia support, in the form of picture and videos during the laboratory tests. The objective is to collect evidences that permit to substantiate the present hypothesis.

In order to identify the evidences which allow substantiating the hypothesis of a second friction surface it is important to define the concept firstly. So in this case a friction surface may be defined as the area at which two elements create contact by sliding one against the other. Therefore the Finger Plate creates a friction surface, when it slips over Lower Profile's wall. It may be important to refer that exists slip, generally speaking, even before and after the slip by definition, set as 0,15 mm in the standards.

From the Figure 10.8 and Figure 10.9 (a finite element analysis printout) it is possible to observe the slip of the Finger Plate over not just the Lower Profile walls but also under the Cover Plates, at start and at the end, respectively. The Finger Plate shows a large displacement when compared with the other components of the connection, expressed by its red colour.

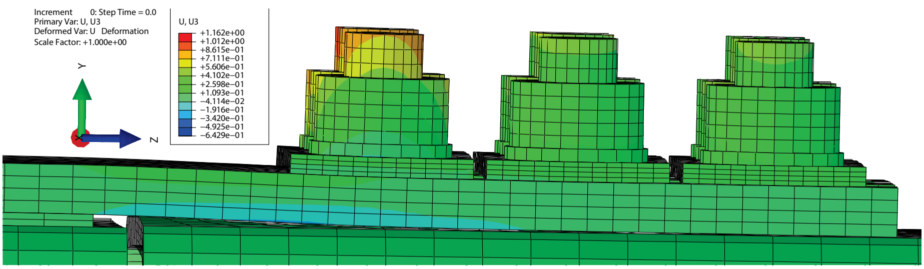


Figure 10.8: 4 mm Horizontal gap - displacements in z-z axis at start

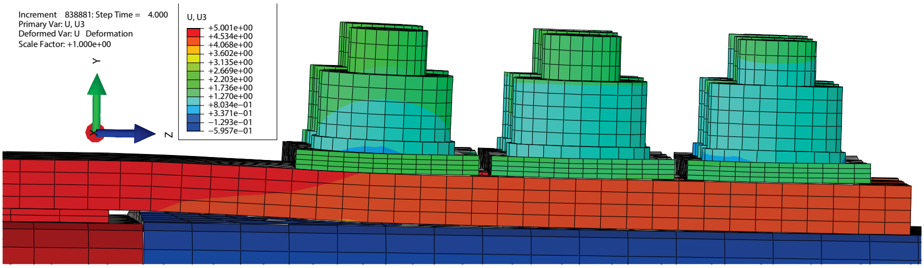


Figure 10.9: 4 mm Horizontal gap - displacements in z-z axis at the end

In the previous pictures is possible to observe that fingers plate slides downwards at a range 4.5 mm while Cover Plate displace rate it is not coincident, therefore, necessarily the Finger Connection slips in between Lower Column's wall and Cover Plates, creating a second friction surface. This also proves that this friction surface withstands a part of the force since the bolts are short, preloaded and fitted into the holes in the Lower Column they are able to transfer the force from the second friction surface to the Lower Column.

The Figure I.2 shows two snapshots from the video recorded along a second test performed at the 4 mm Horizontal gap specimen. This figure clearly shows the slip of the Finger Plate in between Cover Plates and Lower Profile's walls. It can be also noticed that Friction Surfaces remain approximately with the same area, as Finger Plate slides through the both friction surfaces. However the Increasing of stiffness behaviour describe before, produces growing pressure against Cover Plate as Fingers Plate slips whereas for Lower Column wall it decreases. Therefore as the Finger Plate slips the Second Friction Surface contributes more for the slip resistance, contrarily to what happens with the friction at the Lower Column's walls.

10.7 Slip Resistance

The previous chapters bring up some of expedite methods to design the connection, however the present thesis just intend to make an overview on the design process, since, for a better understating an accurate design of connection, deep investigation is needed. Most of the phenomena were identified however it is very important to delimitated them in order know when to be used.

Apart from the slip failure mode, three other can occur: compressive yielding or buckling of the finger plate and local buckling of the column. Those failure modes will occur if the friction coefficient is high enough. Taking in mind the real behaviour of the connection, having the slip resistance from the two friction surfaces, those other failure modes can occur naturally if the connection is designed according to the current engineering practice taking into account only one friction surface. Therefore the knowledge of the existence of a second friction, works from the safe, when it comes to consider the slip resistance of the connection, although, the second friction surface should be taken in consideration regarding the situation where slip does not occurred an connection fails by one of the three failure modes described before.

This idea gains special relevance since, it is noticed, taking the example of the 8 mm Horizontal gap, that by doing an parametric study, where slip factor is varied, the connections exhibits different phenomenon, namely:

Table 10.2: First failure mode identified for Finger Connection

First failure mode identified for Finger Connection with 4 and 8 mm Horizontal gap (HG) and 5 mm Vertical gap (VG), according to μ		
4 mm HG		8 mm HG
$0 \leq \mu \leq 0,35$	Slip failure mode	$0 \leq \mu \leq 0,32$
	Failure by compressive yielding or buckling of the finger plate; local buckling of the column	$\mu > 0,32$

The slip failure of the connections has been addressed in the previous chapters. Whilst for second type of failure mode its prediction is not intuitive, at first sight. In fact, for the case of the 8 mm Horizontal gap, during the loading phase, the Fingers plate bends outwards, and, despites the fact that has the same slip factor as the 4 mm Horizontal Gap specimen, it does not slip, at the fingertip (see Figure I.3). Thus the upper column displaces downwards, and, when Finger plate is about to yield, both columns touch, and so the forces are transmitted by bearing to the Lower column (see Figure I.4).

However for the generality of the cases, if any of failure modes occur (slip, yielding or local buckling) two column parts will come in contact and there is no danger in means of structural failure. Therefore the connection can be designed for the serviceability limit state loads.

11 CONCLUSIONS AND FUTURE WORK

Some of the conclusions traced on the following points, constitute a direct answer for each of the research questions formulated in the first chapter. Thus, each conclusion is followed by the identification of the respective index of the question.

11.1 Part I - Frameup Concept

Regarding the structural performance of the six-story building, the following conclusions can be drawn:

a) The solution with a non-bracing system required the consideration of the component stiffness (linear springs) into the structural modelling of a joint in order to calculate its minimum rotational stiffness. A parametric study indicated the need to ensure a minimum of $S_{j,ini} = 19000$ kNm/rad at each beam-to-column connection in order to fulfil the SLS and ULS requirements. **Q1**

b) The novel column-splice – Finger connection – is rather suitable for the Frameup system since it requires less space between the column and the façades, mitigates negative influence of the air gap and possible misalignments. **Q2**

c) The novel column-splice - Finger connection – allows different misalignments at the joint, while it enables the feasibility of the Frameup system by allowing the building to fit with the lower floor without direct human intervention. **Q2**

Thus, following conclusions are drawn upon the work performed on the construction method:

a) The validation of the Frameup system is performed by the consideration of a full scale test. The full scale feasibility test has demonstrated the validity of the Frameup system since the majority of the sequences of construction were tested successfully. **Q3**

b) The Lifting system is able to reduce the execution time, firstly because it takes the advantage of prefabricated, modular elements. Secondly, the 3D modules are directly assembled on its final position by the originally designed conveyor system, which reduces in-situ space for execution. **Q4**

c) The risks and time losses associated with work at height and erection of construction material do not exist since the majority of the assembly work is performed at the ground level. Quantity of the work to be performed in-situ is heavily reduced which additionally improves safety and execution speed at the construction site. **Q4**

d) The specific construction method introduced by the Frameup system has the advantage of performing the whole work under protection of the building. This may allow the extension of the of the construction period, with less costs, especially in the places where climate is an issue. **Q4**

The combination of the aforementioned factors proves the feasibility of the Frameup system.

11.2 Part II - Novel column-splice (Finger Connection)

The finger connection may exhibit different failure modes: slip failure, compressive yielding or buckling of the fingers and local buckling of the column. The slip failure mode is thoroughly examined in this thesis using experiments and FEA, which leads to the following conclusions:

1) The Finger connection permits the accommodation of misalignments, which are inherent to any building execution phase. The column-splice

covers horizontal misalignments up to 8 mm and a possible gap between columns up to 5 mm. **Q1**

2) The columns-splice is simple to be executed in-situ since it requires just the tightening of the bolts, because all other components of the connection are already pre-attached during the fabrication, in the workshop.

3) The first bolt-row is the most loaded during the gap closing, i.e. for bending of the finger plate. A part of the preloading force is used to bend the fingers - the activation force - and the remaining portion of the preloading force is used for friction resistance of the connection. **Q2, Q3**

4) The amount of the activation force is established experimentally on the real size of the column-splice designed for a six-story building. It depends on the size of the gap and it varies from 18 % to 45 % of the total preloading force in the two bolts of the first bolt-row, in case of 4 mm and 8 mm gap, respectively. This effect leads to a reduction on the slip resistance of the connection of approximately 7 % and 12 % in these cases. **Q2, Q3**

5) Both experimental and FEA results indicate presence of a second friction surface between the Finger plate and the Cover plates at the ultimate state. This increases the slip resistance of the connection approximately twice compared to hand calculation models used in engineering practice (i.e. according EN1993-1-8). This increase cannot directly be accounted for in design because of the large slip that precedes the ultimate load. However, it gives additional safety of the connection. **Q3**

6) The novel joint in its full configuration, with one Finger Connection on each face of the profile, as the potential to generate a reaction – slip resistance – to uniform load, within the serviceability limit states limits, up to 2056 kN at its configuration without horizontal gap. Thereafter, the slip resistance is reduced on its configuration with 4 and 8 mm, to approximately 1924 kN and 1824 kN, respectively. **Q4**

7) Whichever the failure mode of the connection occurs the two column parts will come in contact and therefore the connection may be designed only for the serviceability limit states loads, as assumed.

A design nomograph is proposed in Figure I.5 which is based on the analysis of the behaviour of the complete column splice. The nomograph is intended to provide a simple and fast guideline to obtain the maximum slip resistance of the connection for Serviceability Limit States, assuming uniform compression. The monograph is based on equation 7.1, which is provided in EN1993-1-8 and takes into consideration the parameters calculated from the laboratory test.

11.3 Future work

The self-climbing devices are fully prepared for the system although it has revealed not to be automatic enough to lift in a short period of time. Therefore, a posterior study, based on the Lifting system, has to be performed in order to optimize the costs, execution time and safety, at the construction site.

Possible accidental situations during the execution need to be identified and assessed for the specific lifting technology to be used.

The fire design of the 3D modules is approved by the local building authority. However the safety of a commercial building (six-story building) and longer building has to be investigated.

The location of the pilot building is already established. The commercial and safety aspect of the execution are responsible for the delays generated in the development of the project.

Thus, it is intended to gather all the requirements needed to erect a pilot building at the Luleå University of Technology Campus.

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ANNEXES

A. Description of the components of the Building

B. Description of the components of the Lifting system

C. Structural Design of the Building

D. Structural Design of the Lifting system

E. Construction Sequence

F. Description of the Full Scale Test

G. Finger Connection Drawings

H. Finger Connection Laboratory Preparation and Tests

I. Finger Connection Modelling

ANNEX A

Description of the components of the Building

Some of the drawings hereby considered are a fraction of the whole document submitted to Steel Workshop [41] and extracted here for consultation.

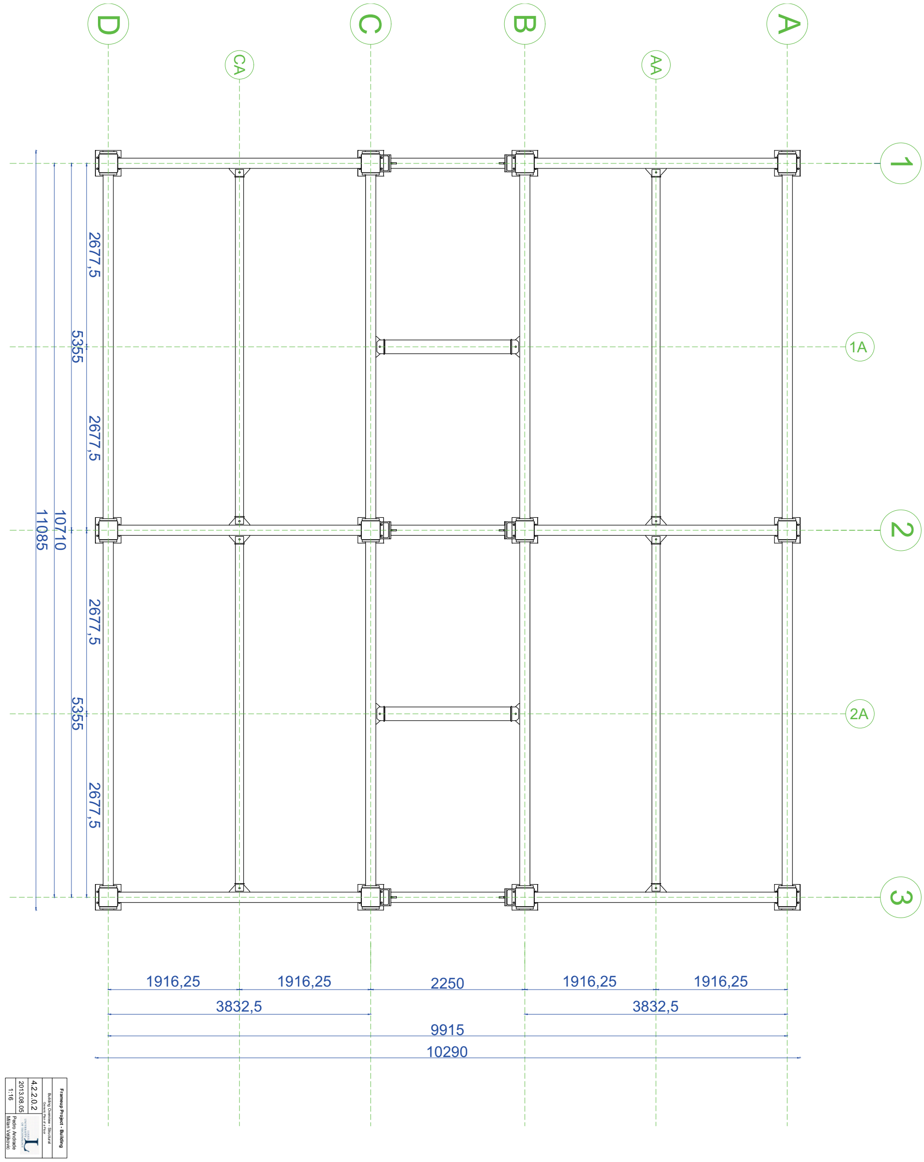


Figure A.1: Structural plan view of one floor

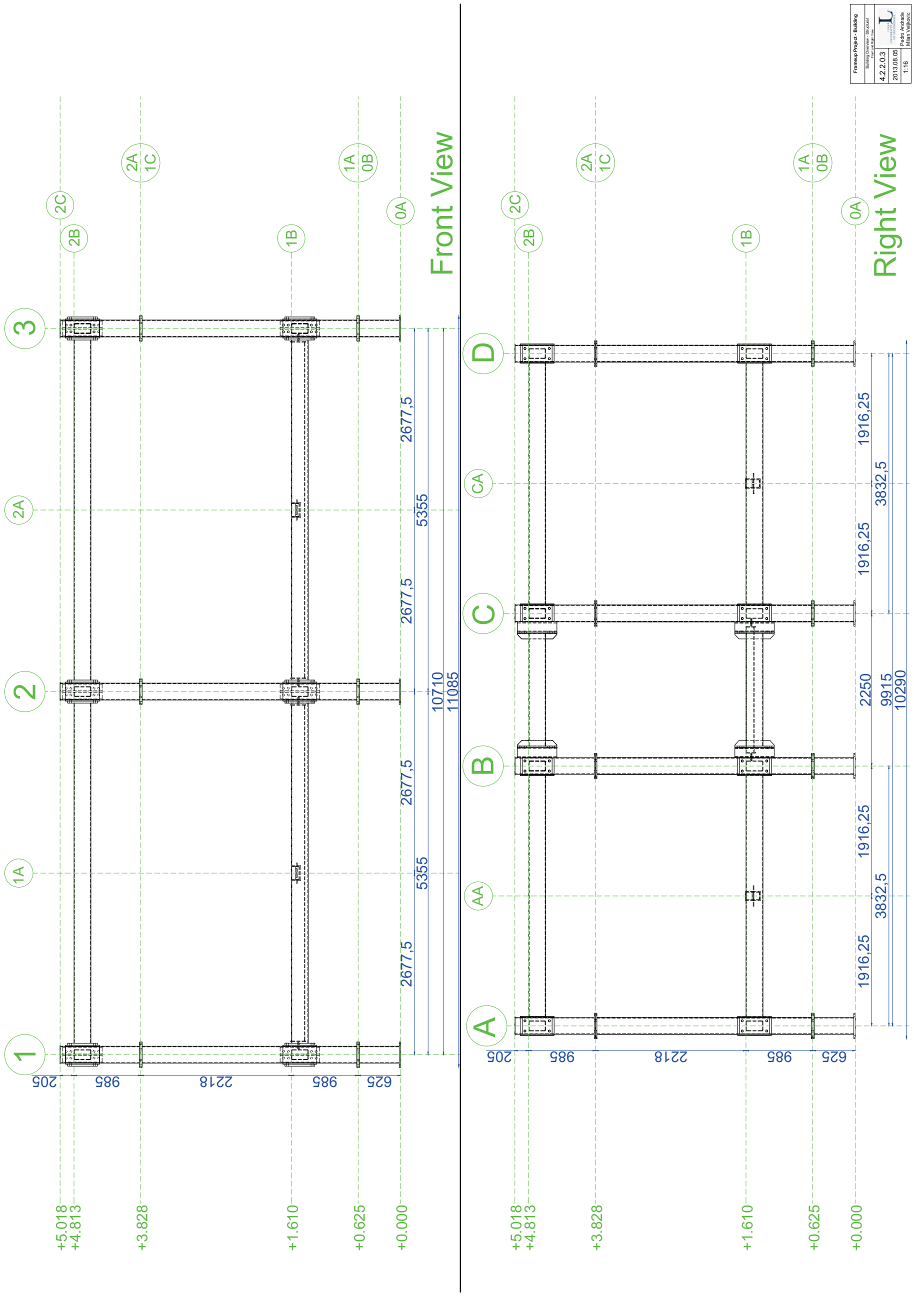


Figure A.2: Structural front and right detailed view of the roof and floor

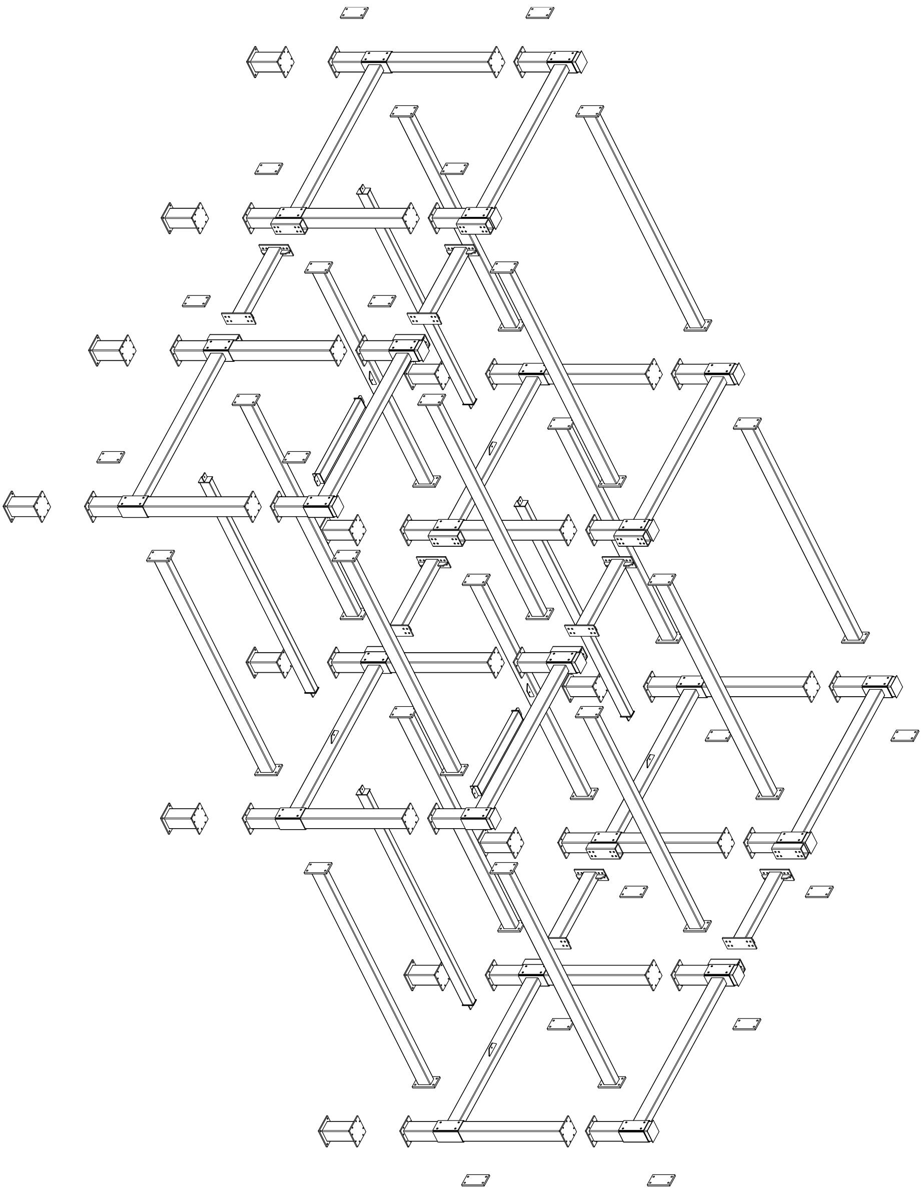


Figure A.3: Structural perspective view of the roof, floor and columns

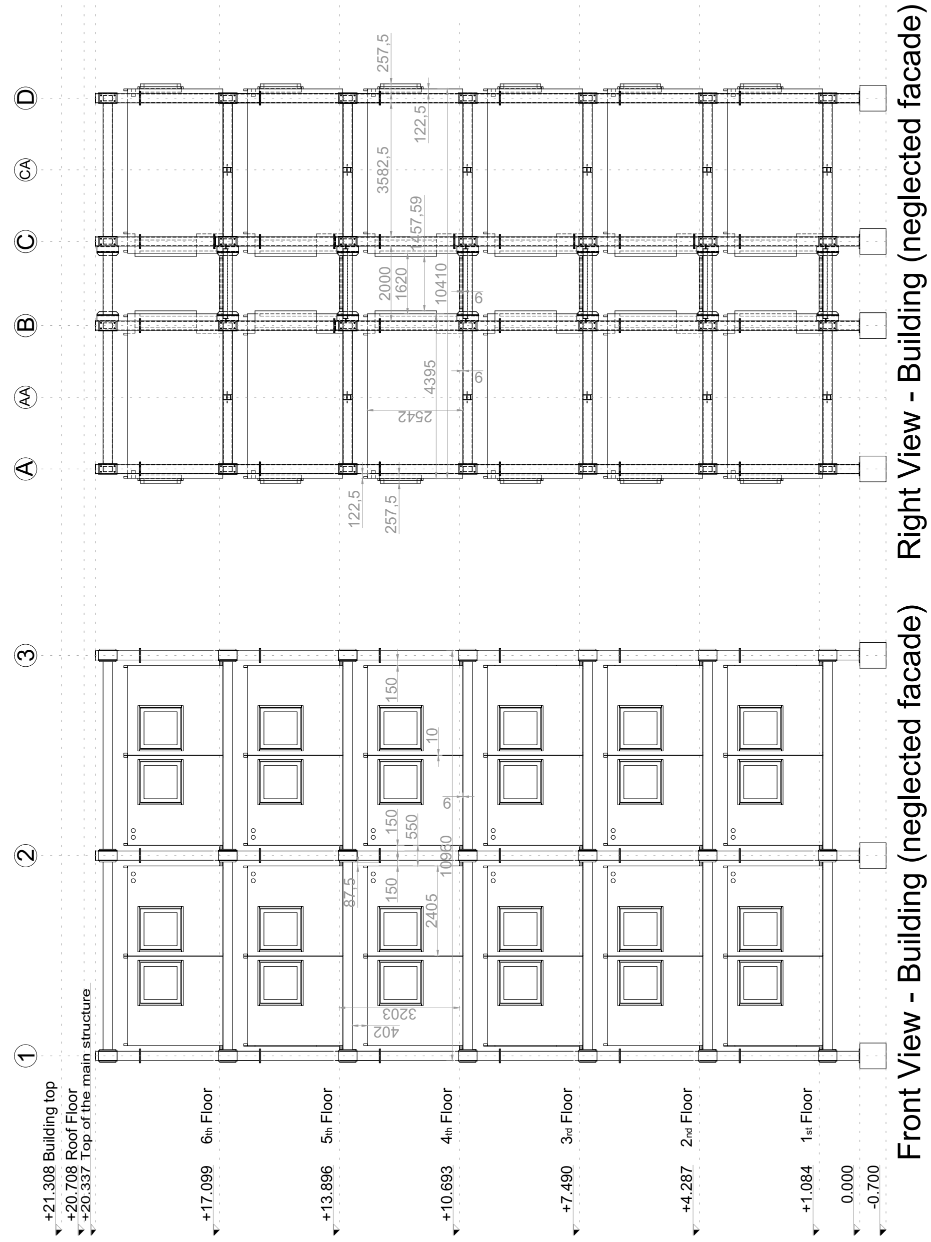


Figure A.4: Structural front and right view of the building

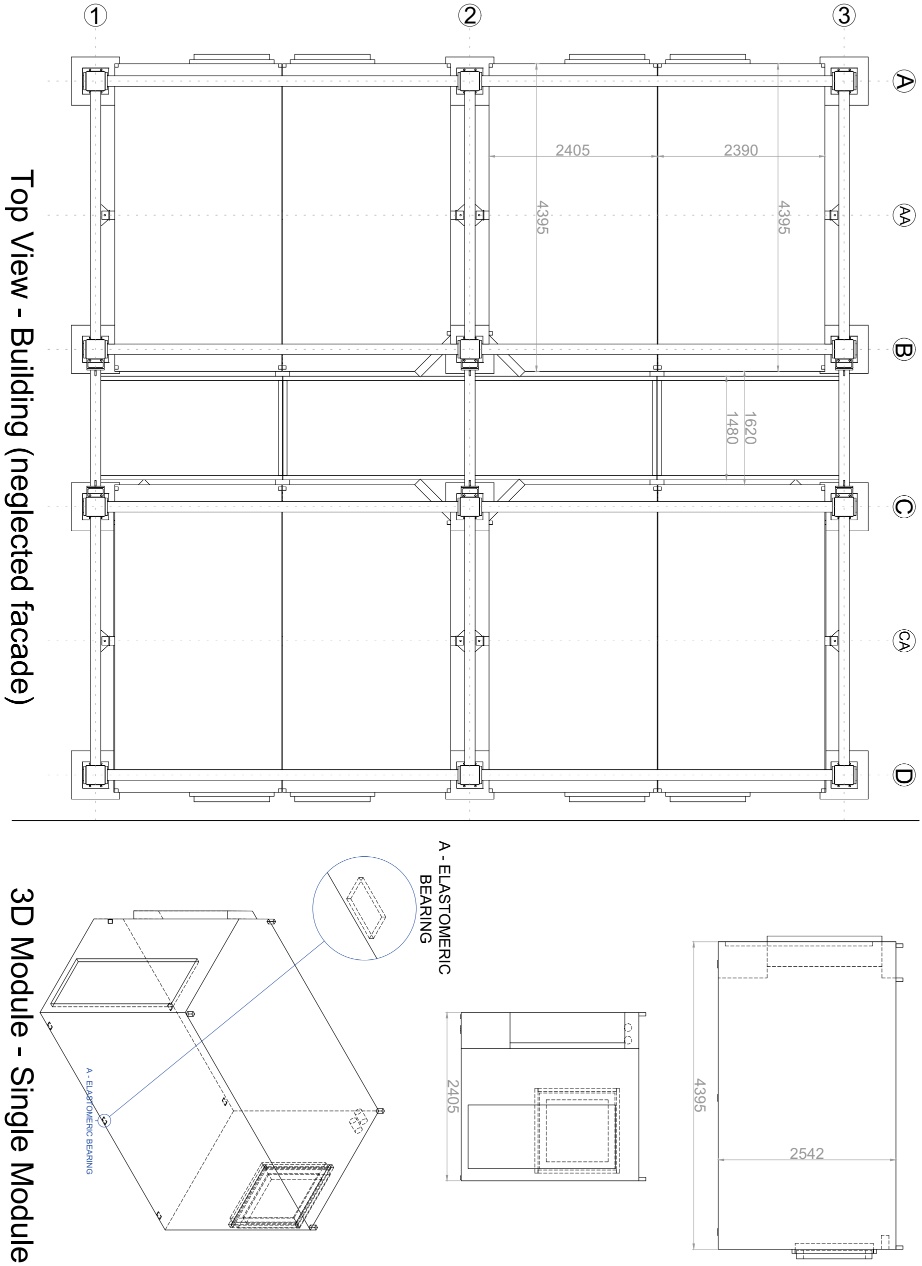


Figure A.5: Plan of the 3D modules in the framed structure

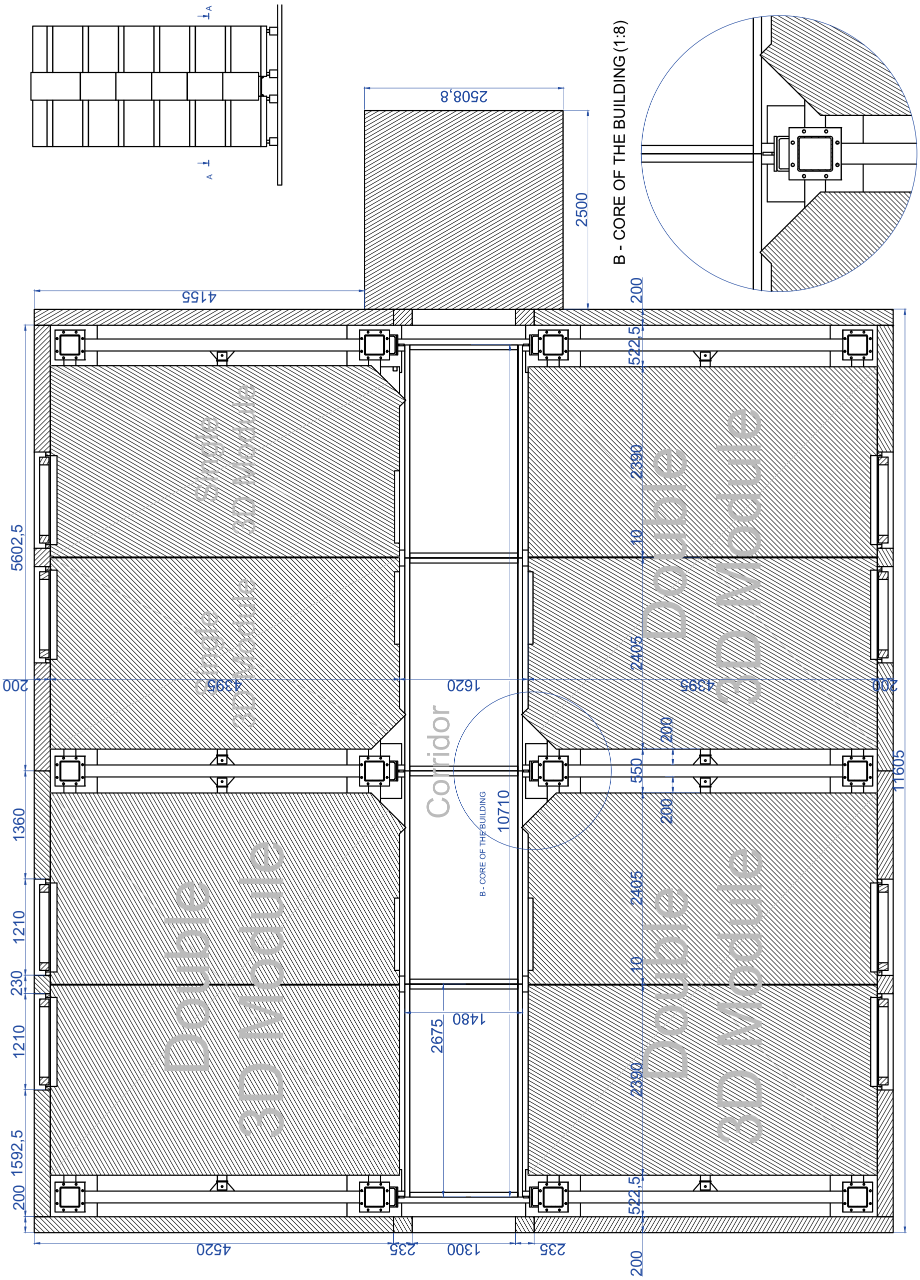


Figure A.6: Generic plan of the building

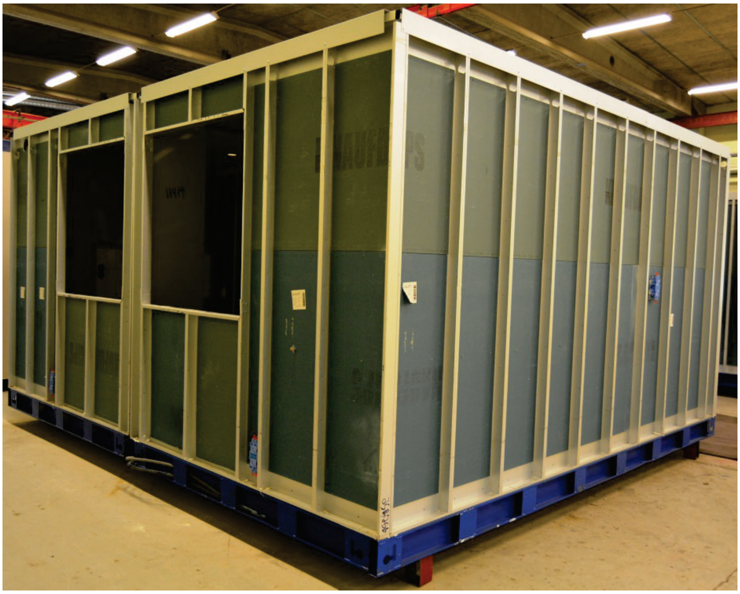


Figure A.7: Construction of 3D Module – 2 x 3D Modules together [27]

Figure A.8: Final 3D Module – 2 x 3D Modules together [27]

Figure A.9: Final 3D module (double 3D module) – Perspective inside [27]

Figure A.10: Final 3D module (double 3D module) – Perspective inside [27]

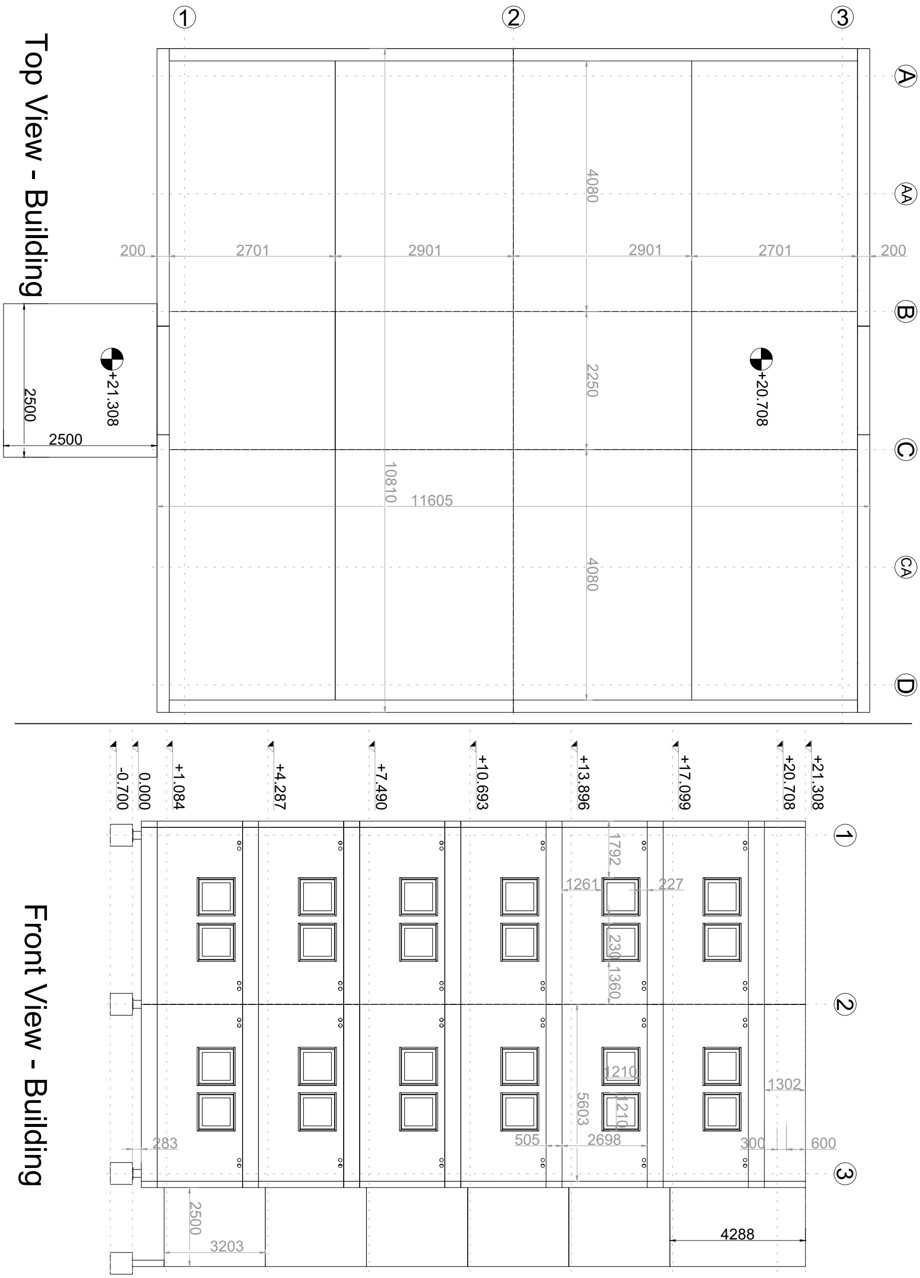


Figure A.11: Top and Front View – Claddings

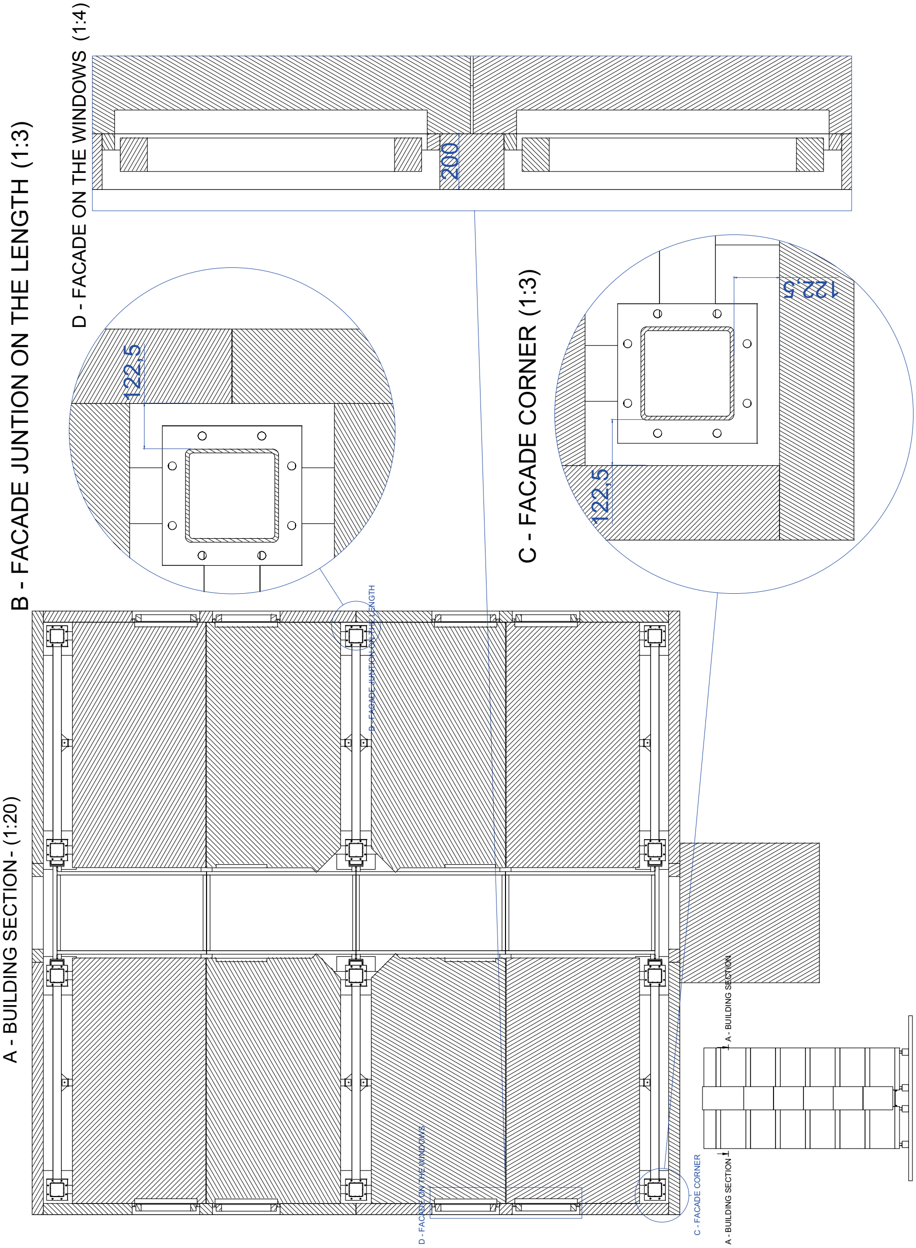


Figure A.12: Details of the façade – requirements for installation

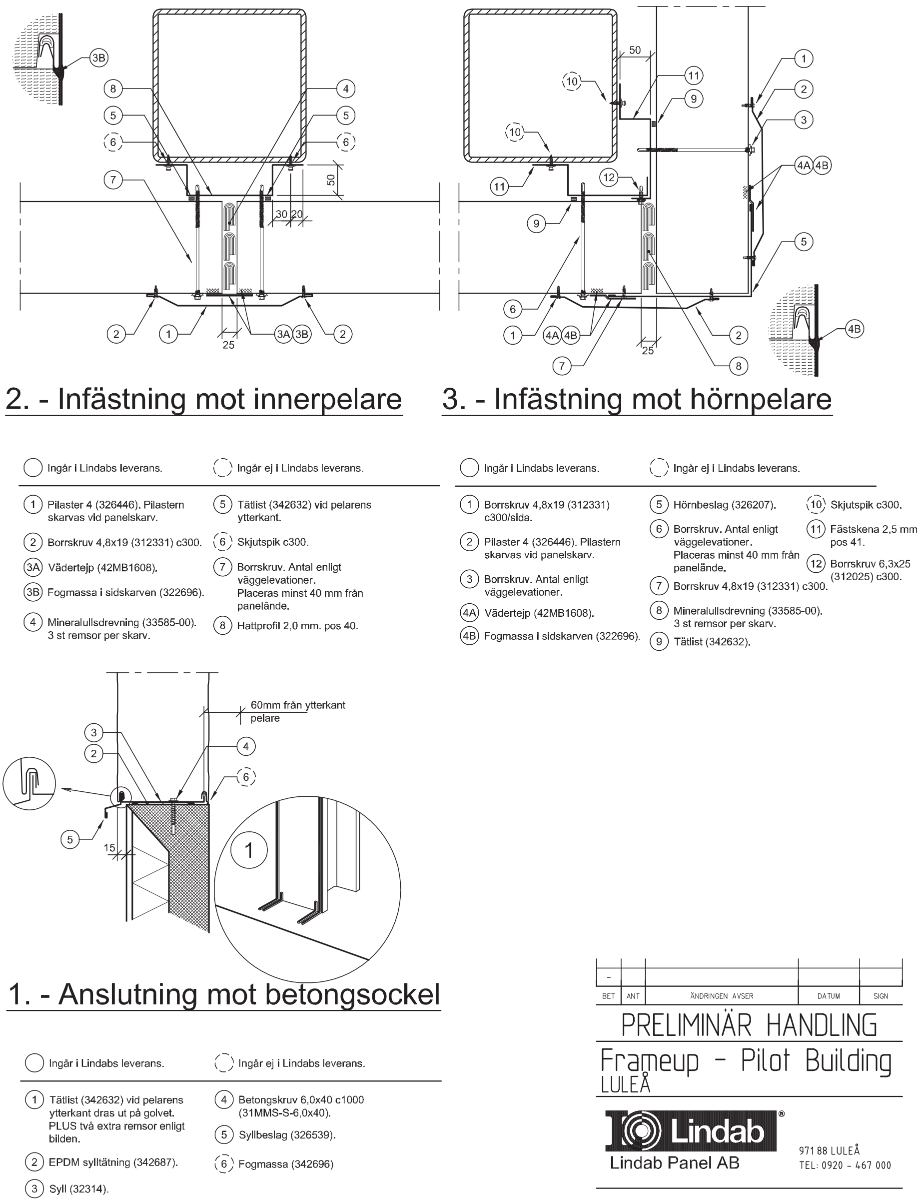


Figure A.13: Façade - extract of details provided by LindAB [28]

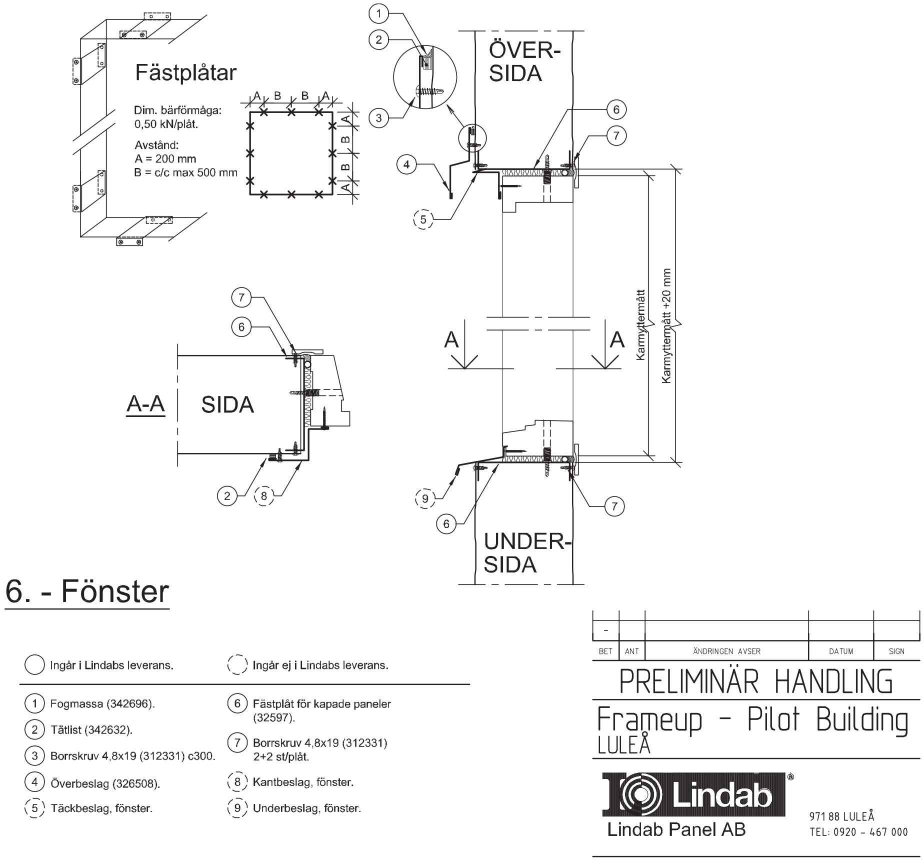


Figure A.14: Façade - extract of the drawings provided by LindAB [28]

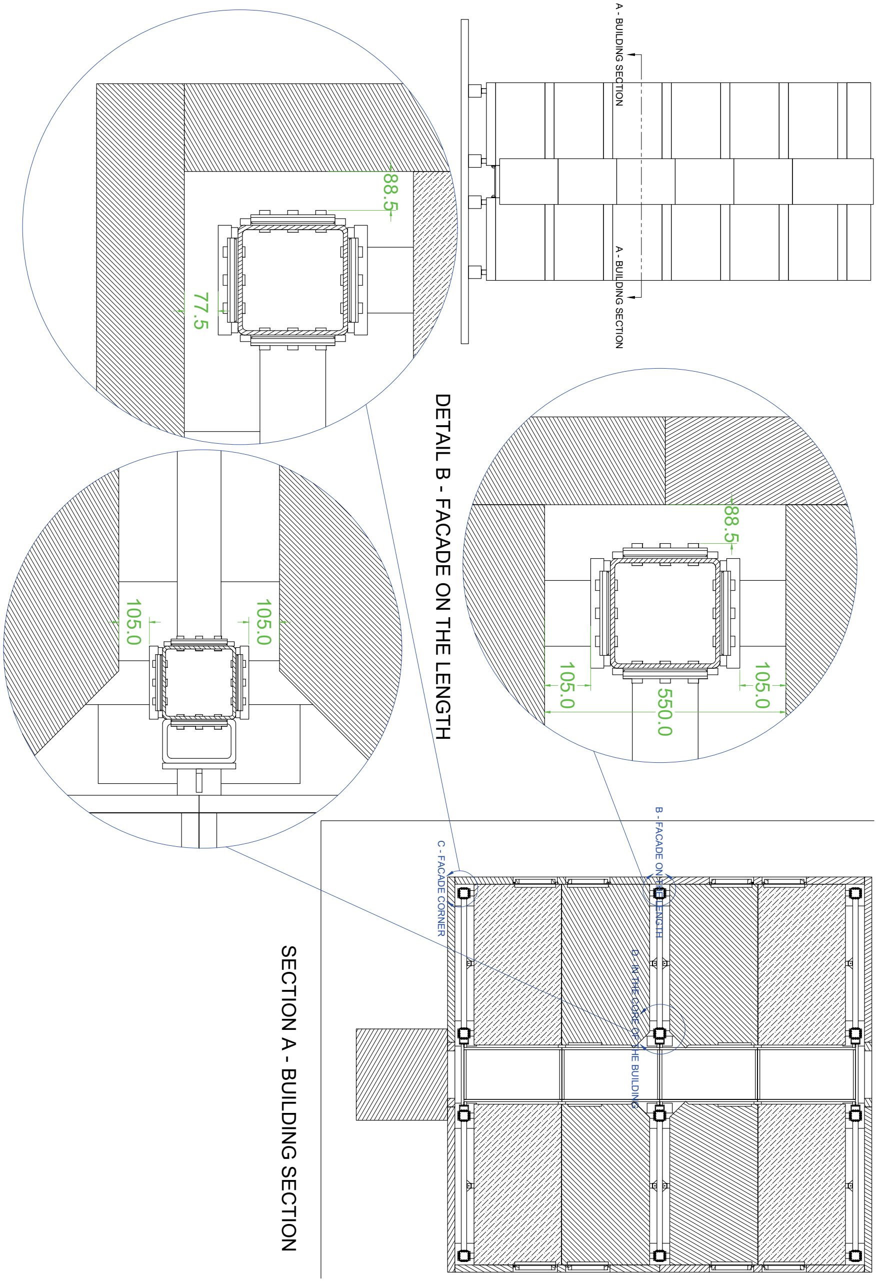


Figure A.15: Details of the façade – solution with Finger Connection

ANNEX B

Description of the components of the Lifting system

The 2D manufacturing drawings hereby considered are a fraction of the whole document submitted to Steel Workshop [41] and extracted here for consultation.

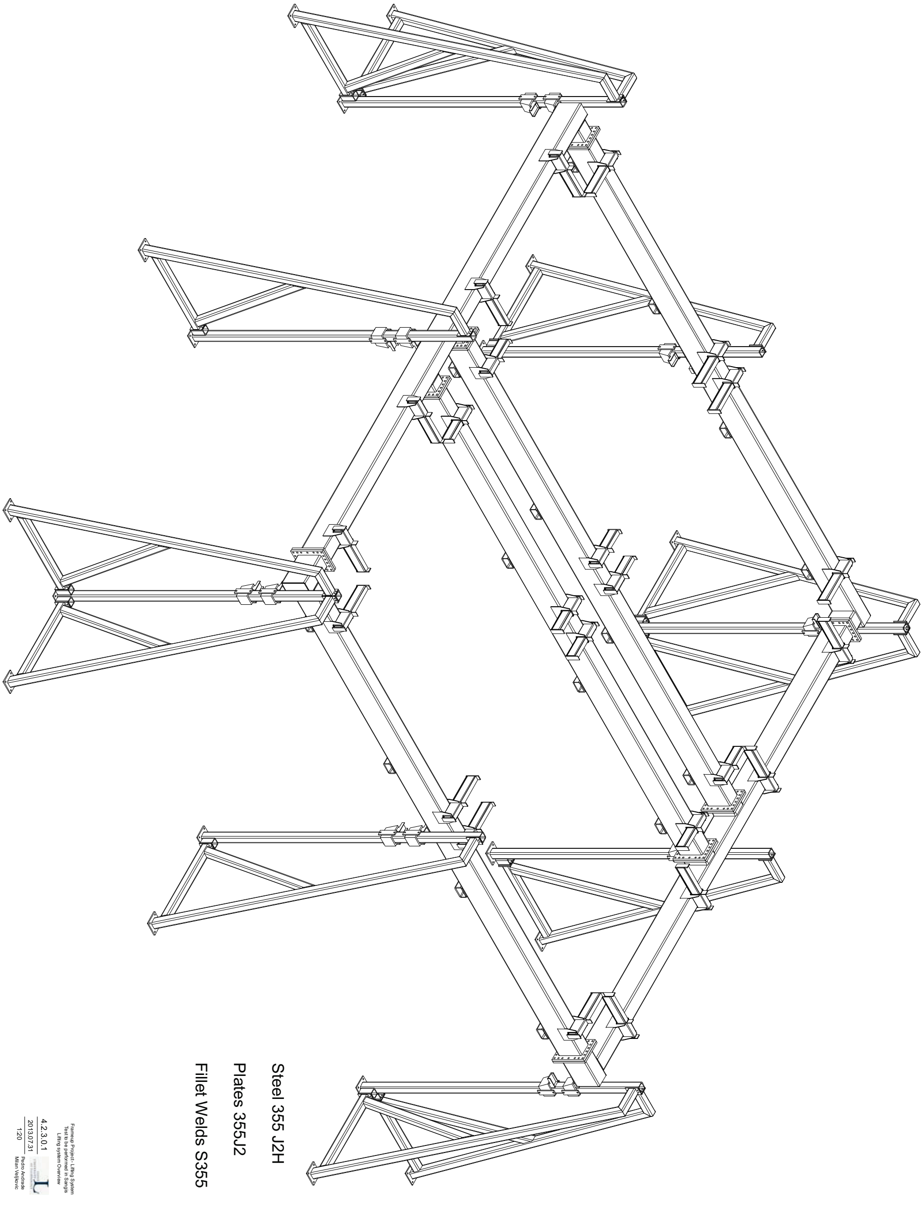


Figure B.1: Perspective of Lifting system

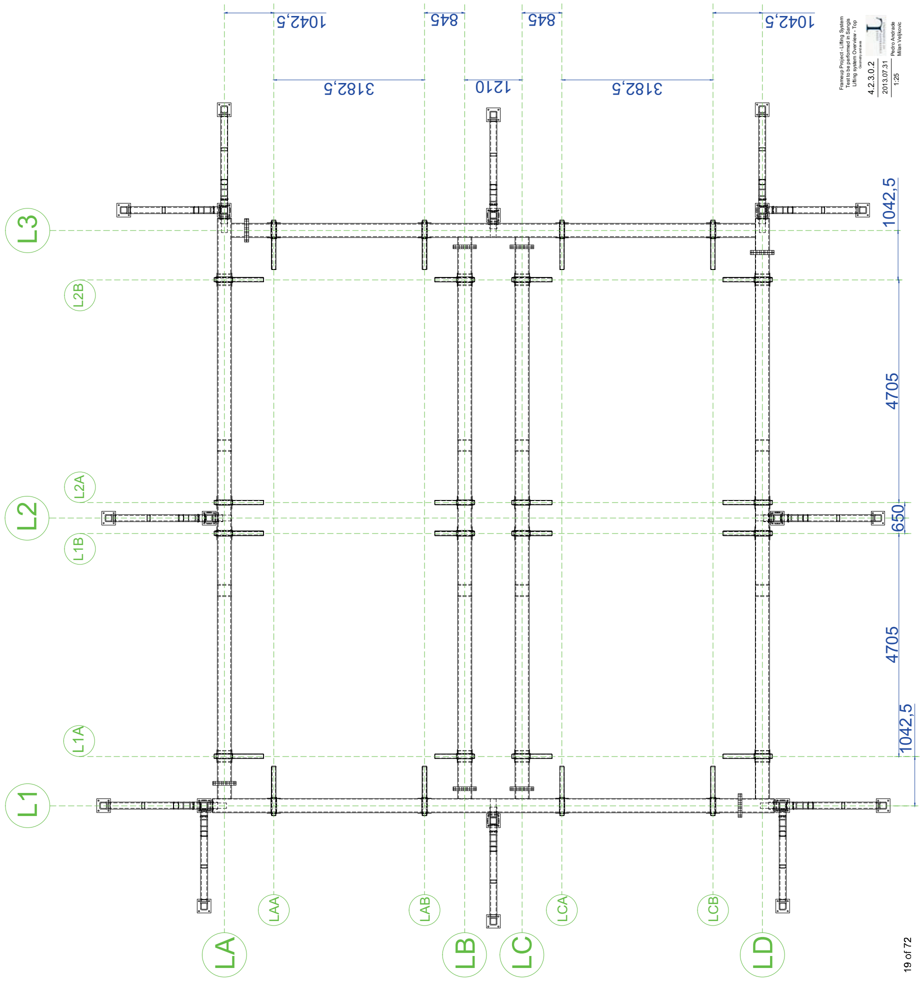


Figure B.2: Upper plan of the Lifting system

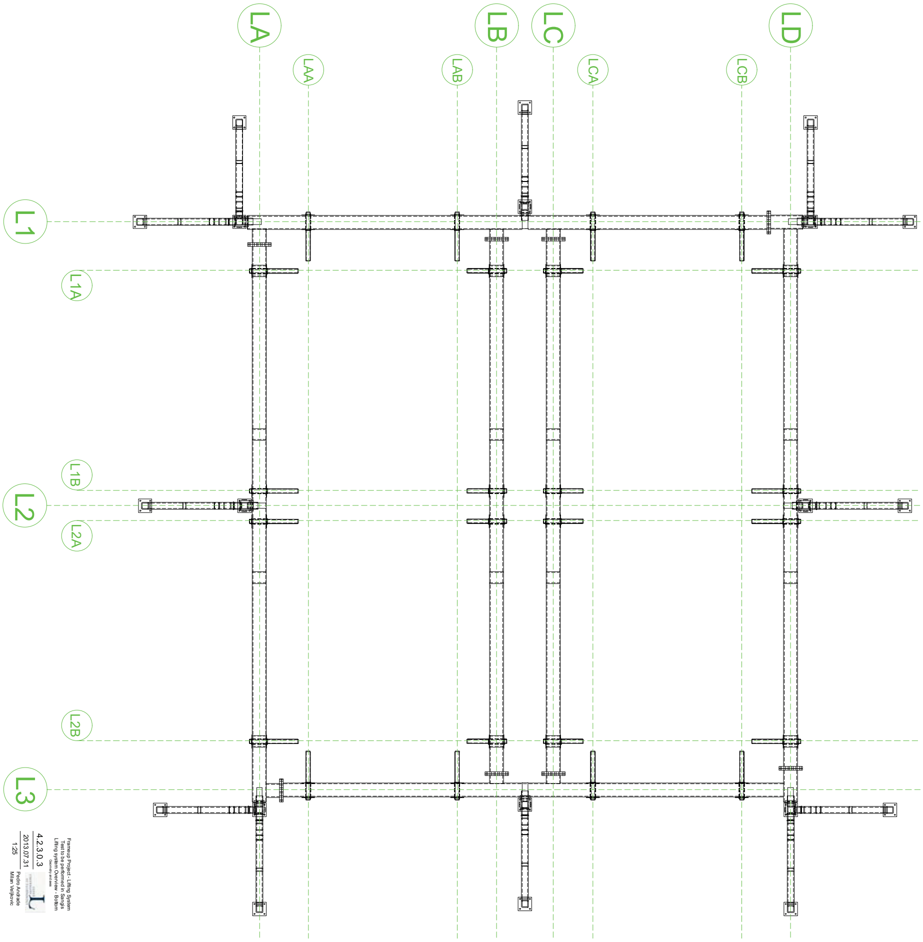


Figure B.3: Lower plan of Lifting system

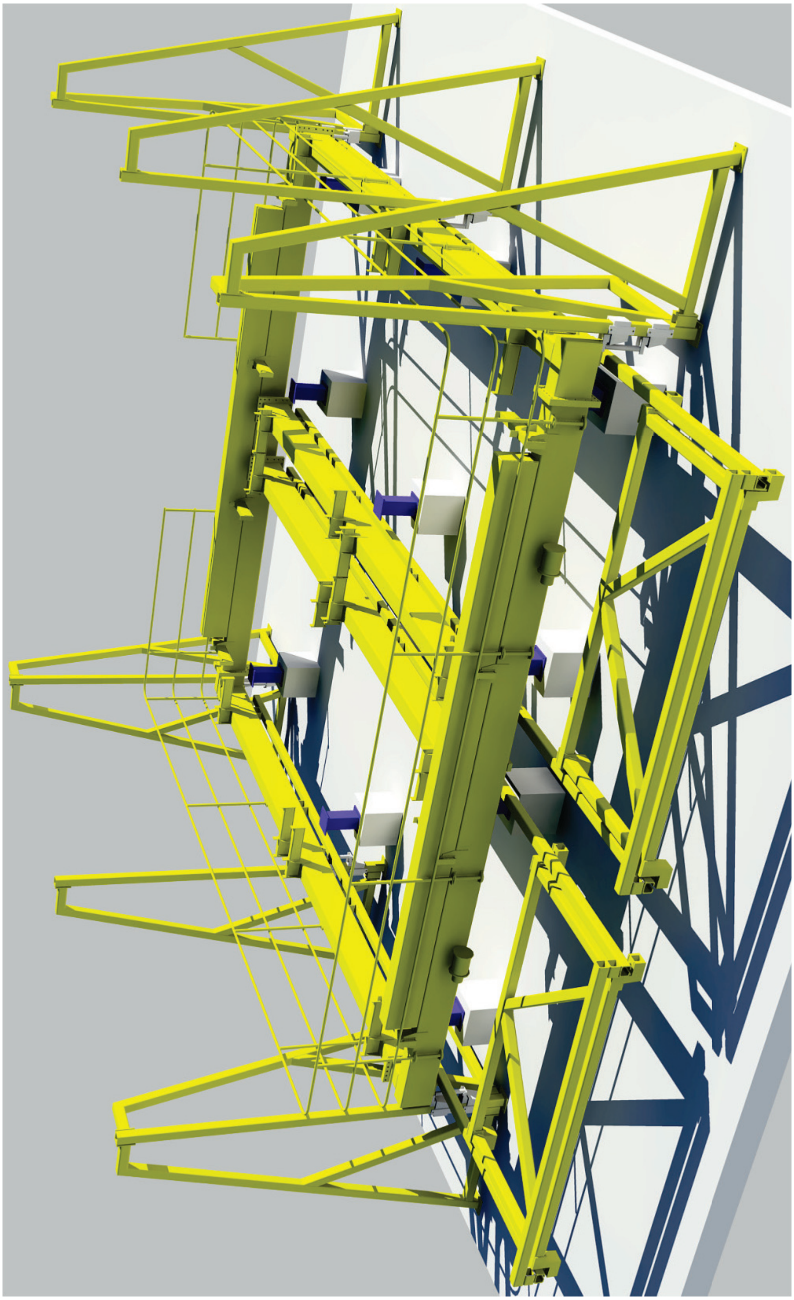


Figure B.4: Lifting system in yellow

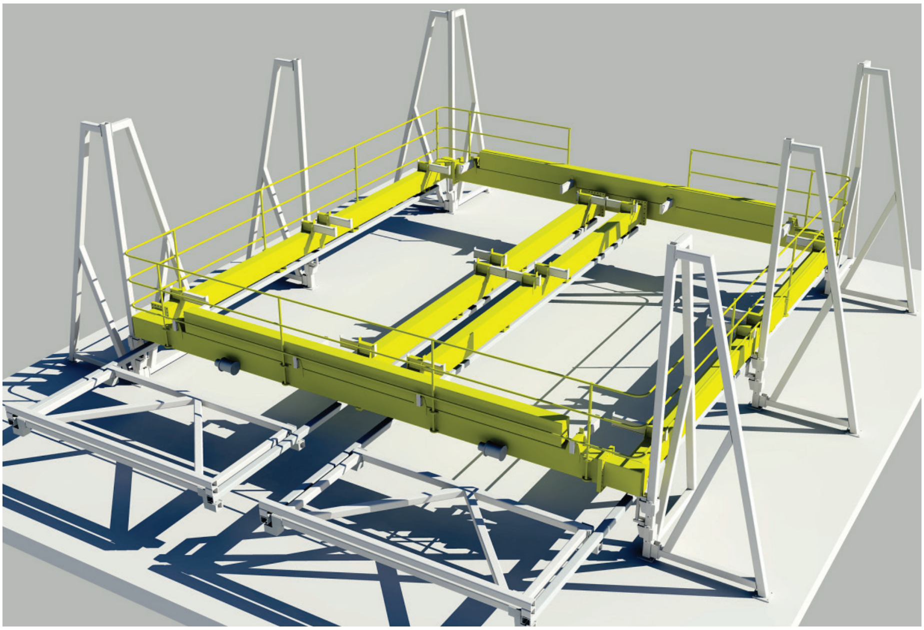


Figure B.5: Highlighted Lifting system's component: grid

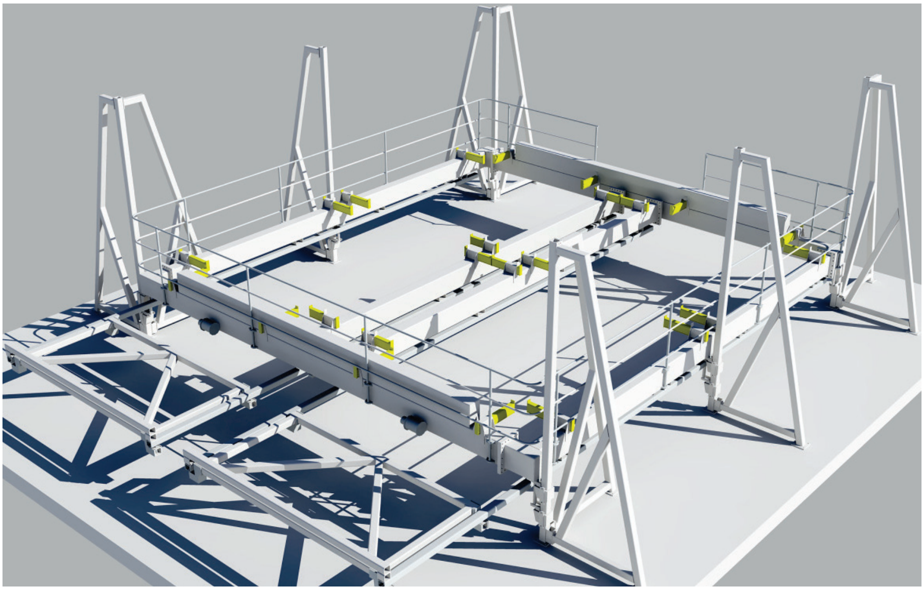


Figure B.6: Highlighted L. System's component: 24 internal cantilevers

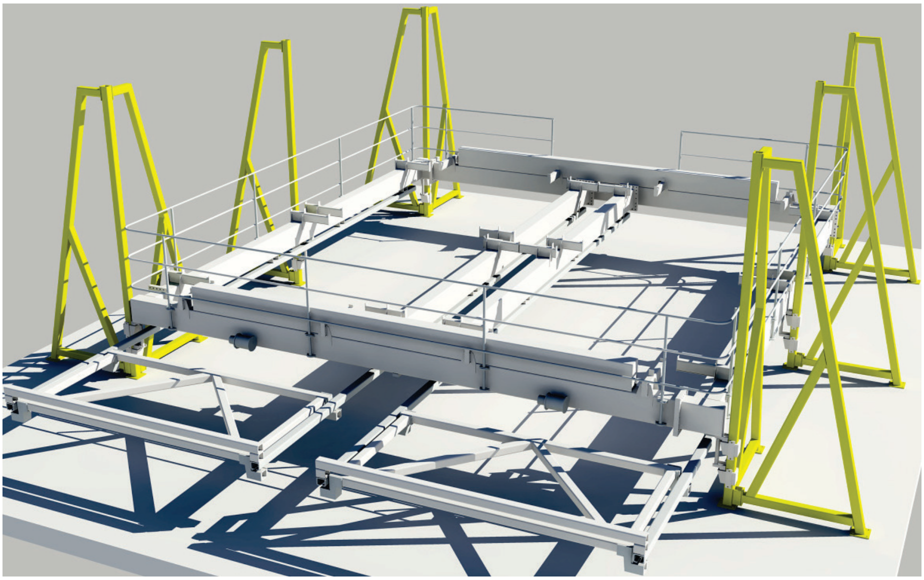


Figure B.7: Highlighted Lifting system's component: 6 Pylons

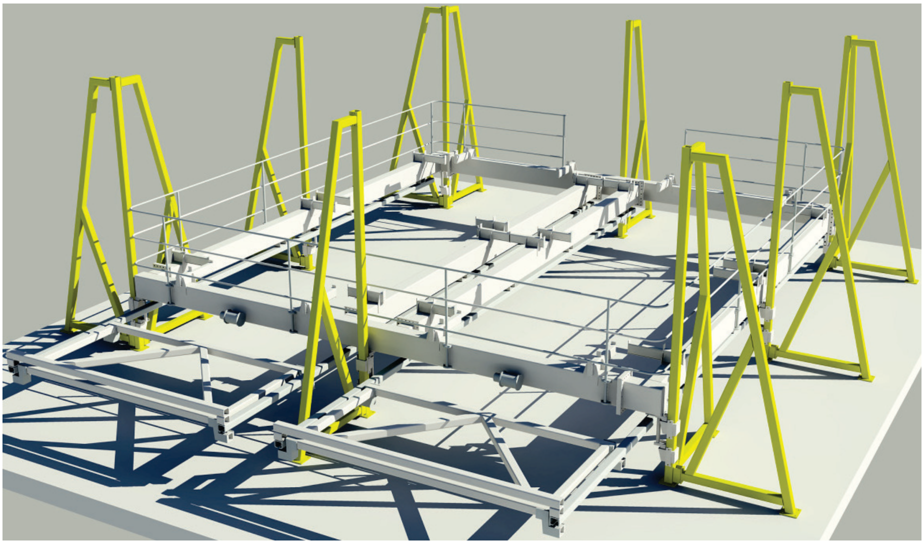


Figure B.8: Highlighted Lifting system's components: 8 Pylons

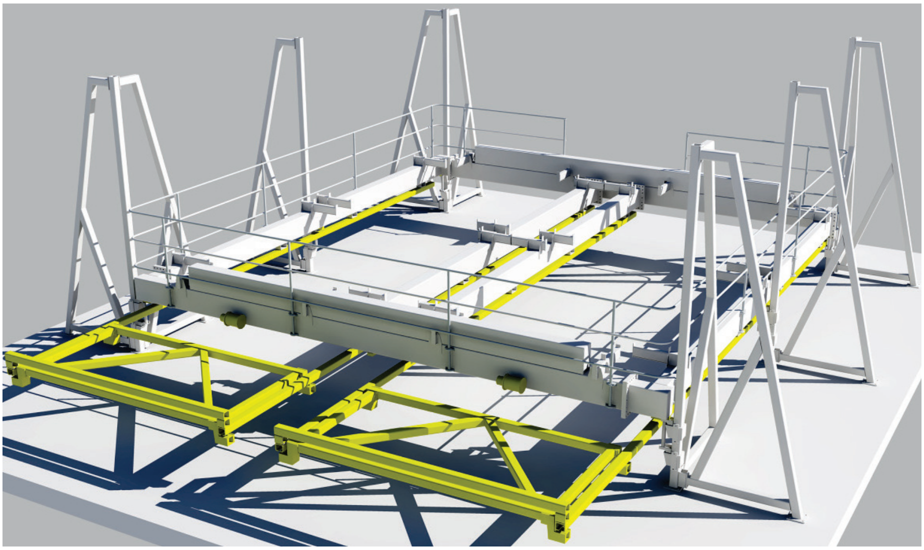


Figure B.9: Illustration of the Lifting system's component: conveyor system

ANNEX C

Structural Design of the Building

Figure C.1: Illustration of the structural view of the 6-story building

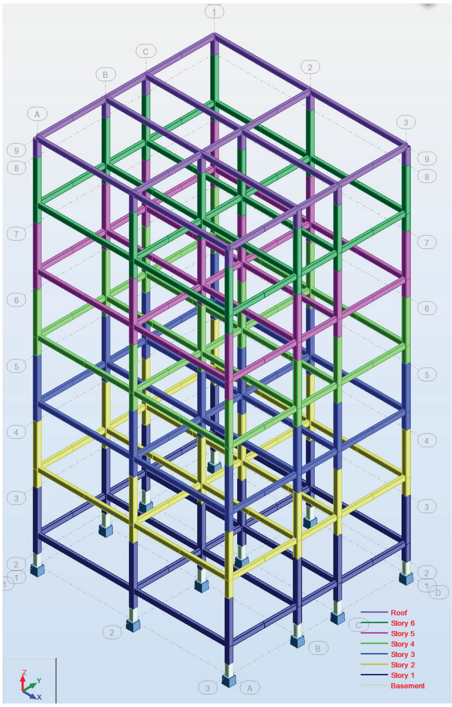


Figure C.2: Division on the levels

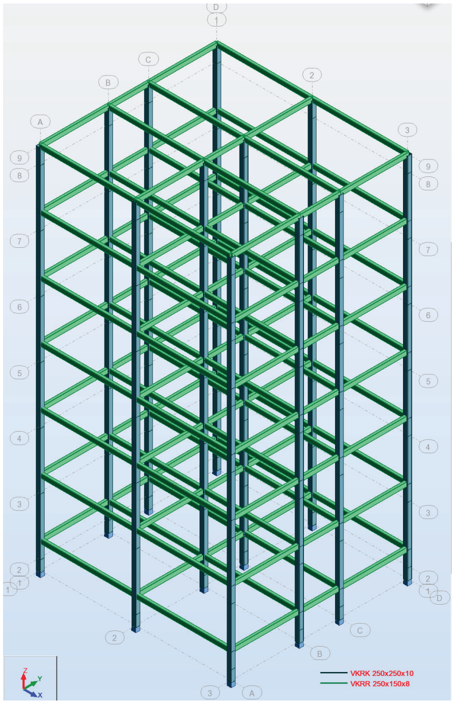


Figure C.3: Division on the profiles

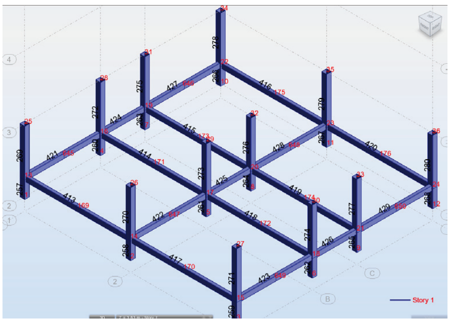


Figure C.4: Modelling of the floor

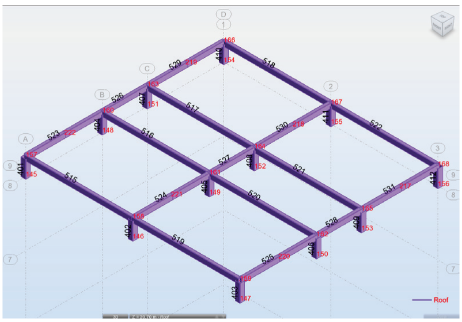


Figure C.5: Modelling of the roof

Table C.1: Self-weights of the building

Self-weight of the steel structure of the building [tons]							
Parts			Elements	SW	Elements	Total	5% more
Lifting system	To lift	Grid	LS1	3.083	1	3.083	3.237
			LS2	3.083	1	3.083	3.237
			LS3	3.067	1	3.067	3.220
			LS4	3.067	1	3.067	3.220
			LS7 and LS8	5.640	1	5.640	5.922
	Total self-weight (to be lifted)					17,940	**18.9**
	Fixed	Pylons	LS5 - bracing	0.765	12	9.176	9.634
			LS6A - for double bracing	0.419	4	1.675	1.759
			LA6B - for single bracing	0.436	4	1.745	1.833
	Total self-weight (not to be lifted)					12,596	**13.3**
	Total self-weight of the Lifting system					30,536	**32.1**
Building	Roof	Modular Frames	Modular frame C1-D1 and A3-B3	0.556	2	1.111	1.167
			Modular frame A1-B1 and C3-D3	0.556	2	1.111	1.167
			Modular frame A2-B2 and C2-D2	0.556	2	1.111	1.167
		Main Beams	Main beams: D1-D2, D2-D3, C1-C2, C2-C3, B1-B2, B2-B3, A1-A2, A2-A3	0.291	8	2.328	2.445
			Main corridors' beams: B2-C2	0.139	1	0.139	0.146
			Main corridors' beams: B1-C, B3-C3	0.139	2	0.279	0.292
		Plates	Element Plate 440x250x30	0.026	8	0.207	0.218
	Total weight of the roof (to be lifted)					6,287	**6.7**
	A Generic Floor	Frames	Modular frame C1-D1 and A3-B3	0.884	2	1.767	1.856
			Modular frame A1-B1 and C3-D3	0.884	2	1.767	1.856
			Modular frame A2-B2 and C2-D2	0.887	2	1.774	1.863
		Main Beams	Main beams: D1-D2, D2-D3, C1-C2, C2-C3, B1-B2, B2-B3, A1-A2, A2-A3	0.291	4	1.164	1.222
			Main corridors' beams: B2-C2	0.293	4	1.174	1.232
			Main corridors' beams: B1-C, B3-C3	0.139	1	0.139	0.146
			Main beams: D1-D2, D2-D3, C1-C2, C2-C3, B1-B2, B2-B3, A1-A2, A2-A3	0.139	2	0.279	0.292
		Auxiliary Beams	Auxiliary modules' beams: AA1-AA2, CA1-CA2, AA2-AA3, CA2-CA3	0.158	4	0.631	0.662
			Auxiliary corridors' beams: C1A-B1A, C2A-B2A	0.032	4	0.130	0.136
		Plates	Element Plate 440x250x30	0.026	8	0.207	0.218
	Total weight of the floor (to be lifted)					9,032	**9.5**
	Basement	Columns	B1 - Column Basement	0.087	12	1.053	1.106
	Total weight of the basement					1.053	**1,2**

Total weight for lifting (grid + cantilevers) (to be lifted)	17.940	**19**
Total self-weight of the full scale test (1 floor + roof + grid) (to be lifted)	33.259	**35**
Total self-weight to erect a 6-story building (5 floors + roof + grid) (to be lifted)	69.386	**73**

Total estimated self-weigh for a 6-story building erection, to be lifted by Lifting system(all structural and non-structural elements)	**330**

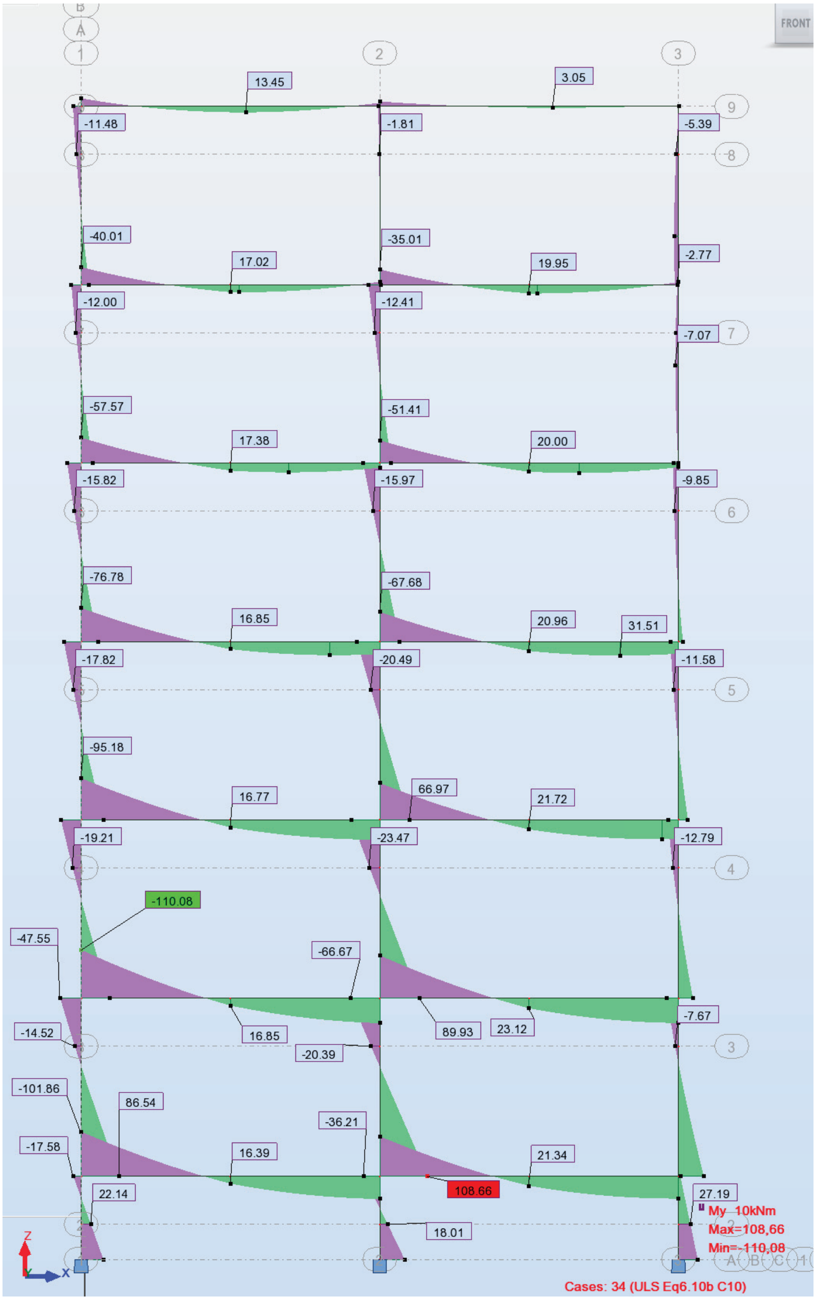


Figure C.6: M_y global extremes diagrams for all combinations – B1-B3 axes

ANNEX D

Structural Design of the Lifting system

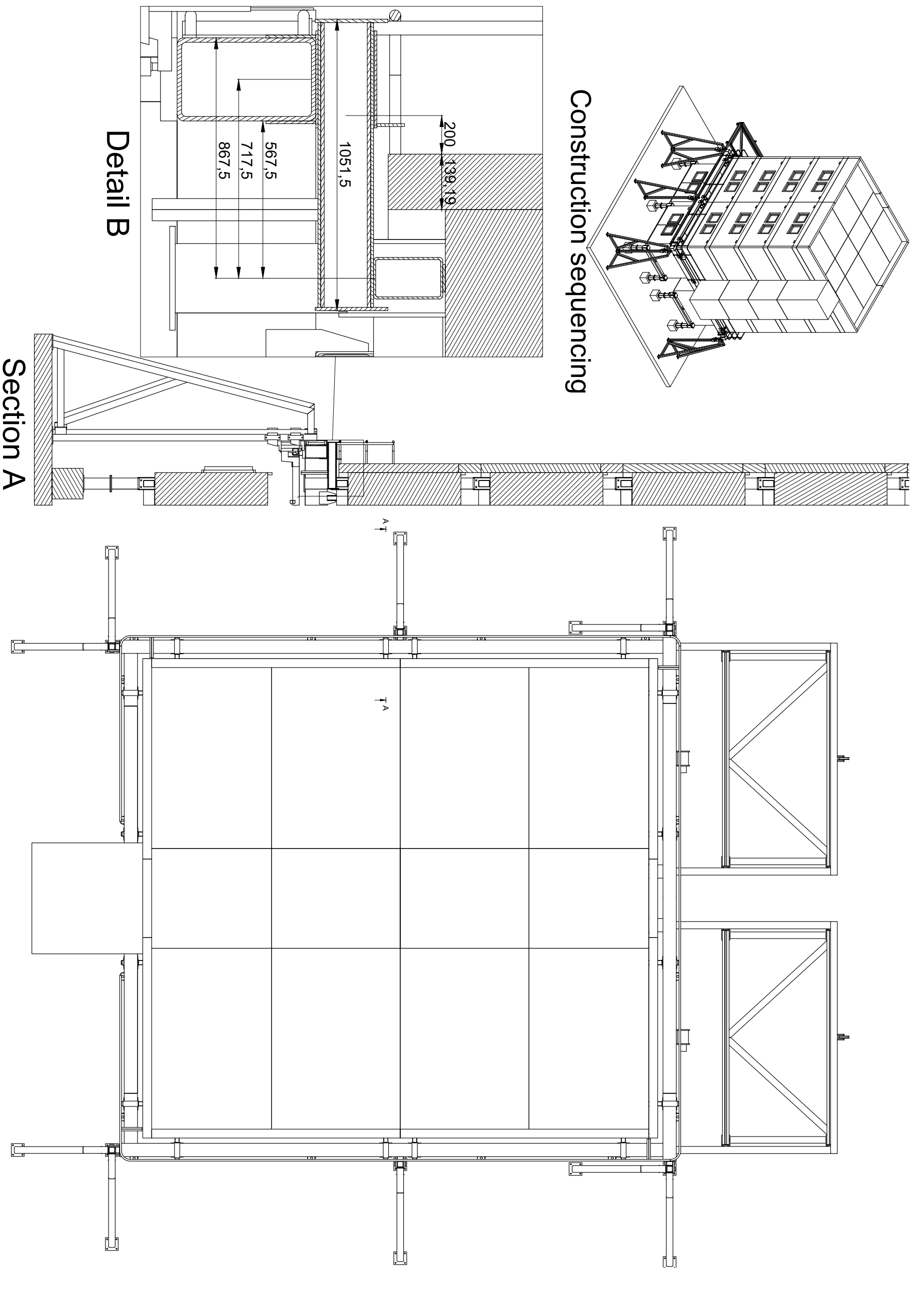


Figure D.1: Overview of the sliding cantilever

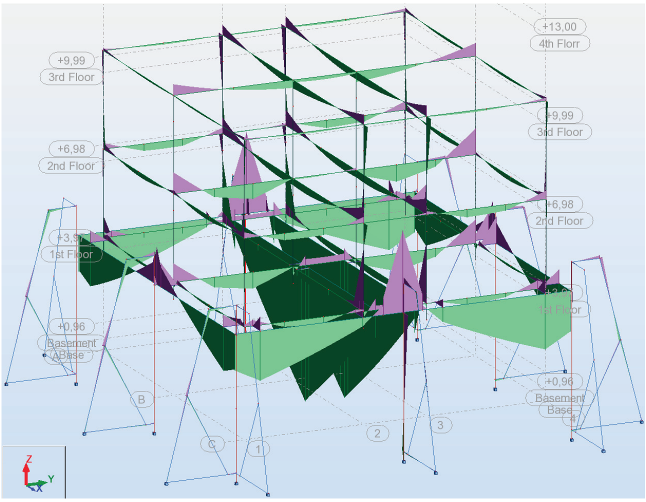


Figure D.2: Overview of the Pilot Building structural modelling, M_y diagrams

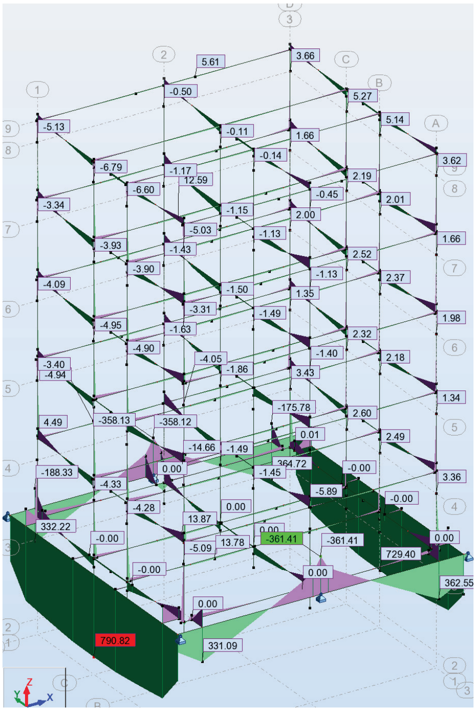


Figure D.3: Overview of six-story building structural modelling, M_y diagrams

ANNEX E

Construction Sequence

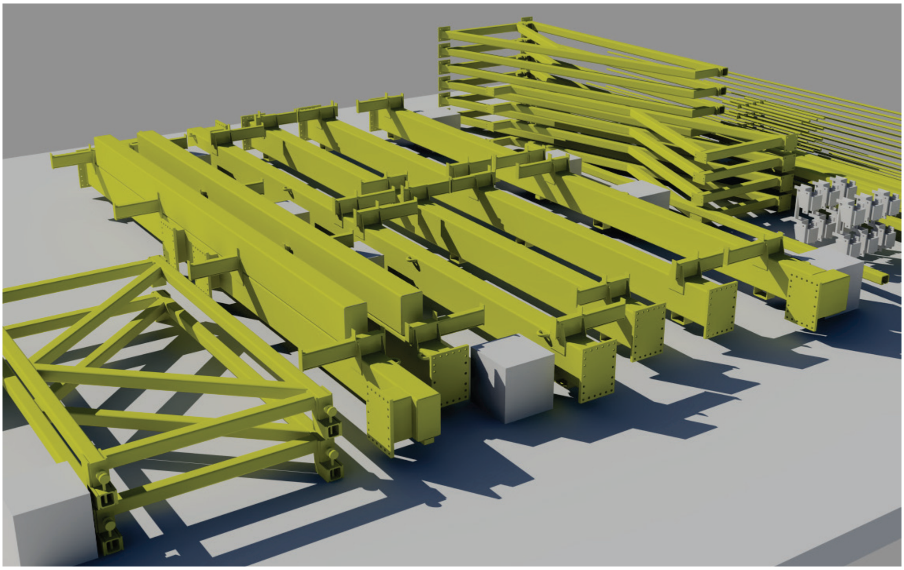


Figure E.1: Lifting system installation [S2]

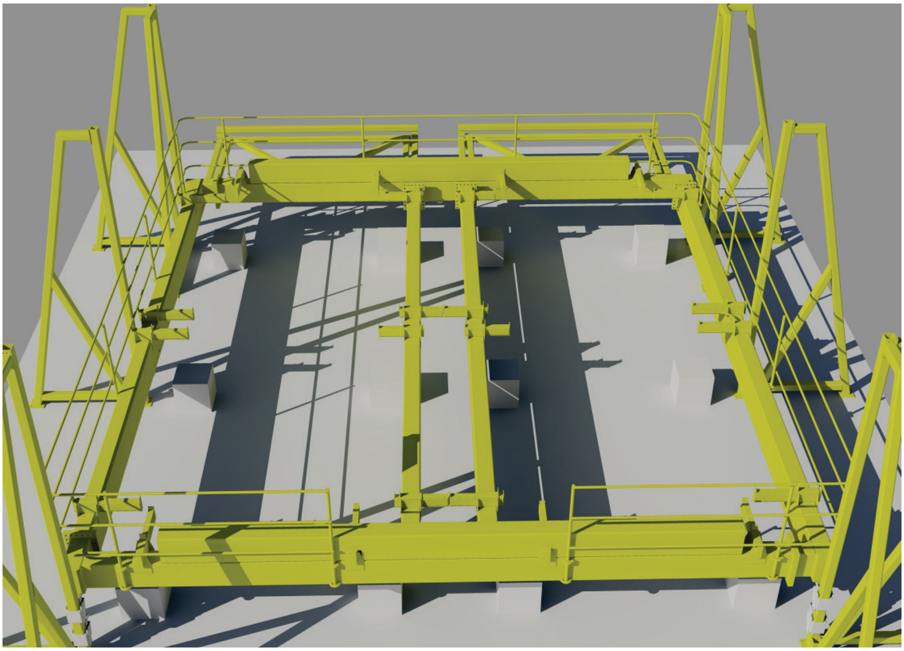


Figure E.2: Lifting system installation [S2]

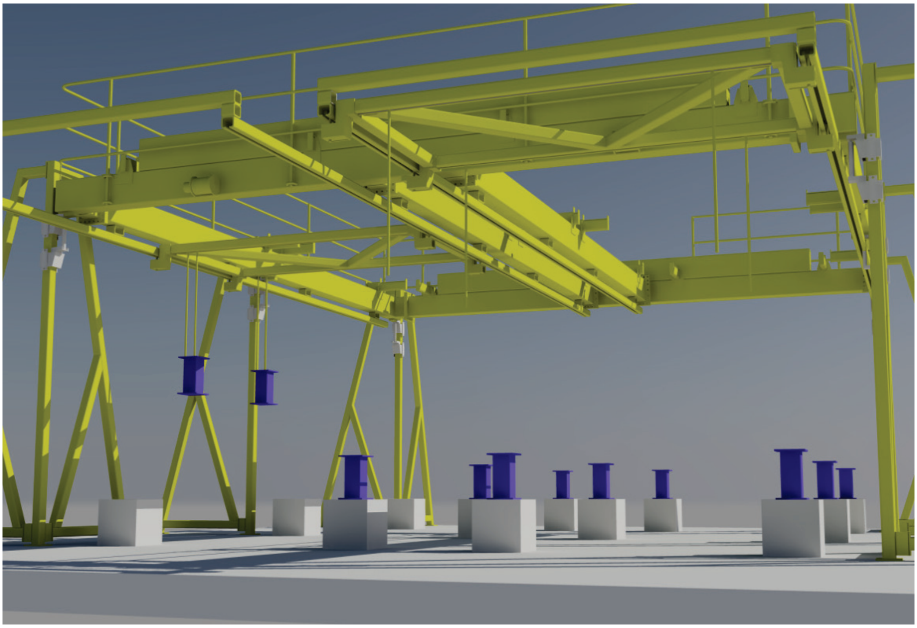


Figure E.3: Lifting system installation [S2]

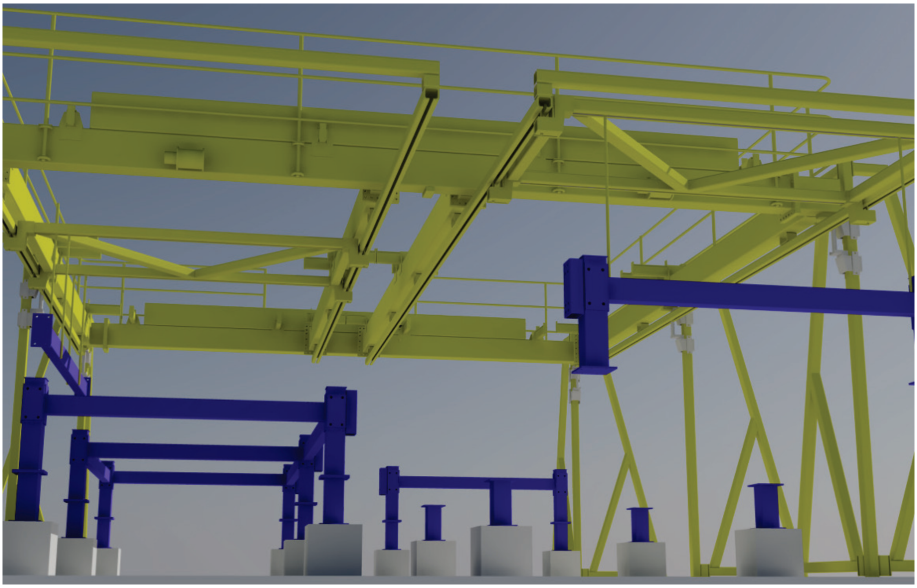


Figure E.4: Assembling of roof structure [S3]

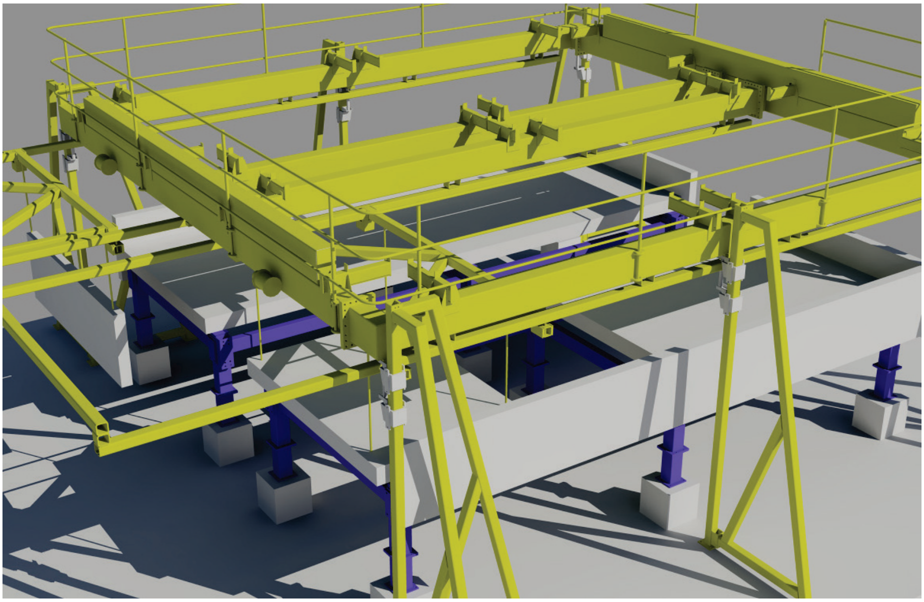


Figure E.5: Assembling of roof structure and claddings [S3]

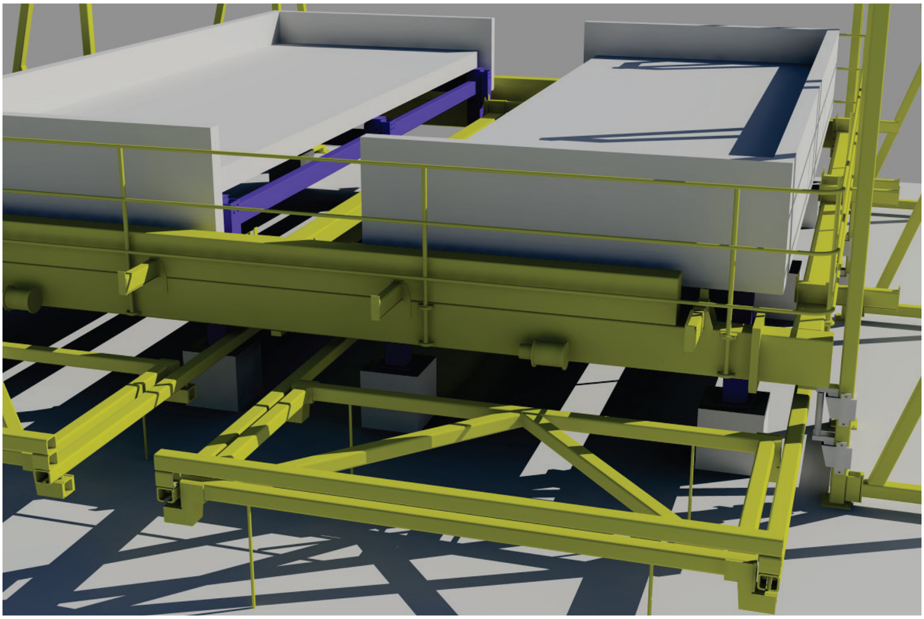


Figure E.6: Assembling of roof structure and claddings [S3]

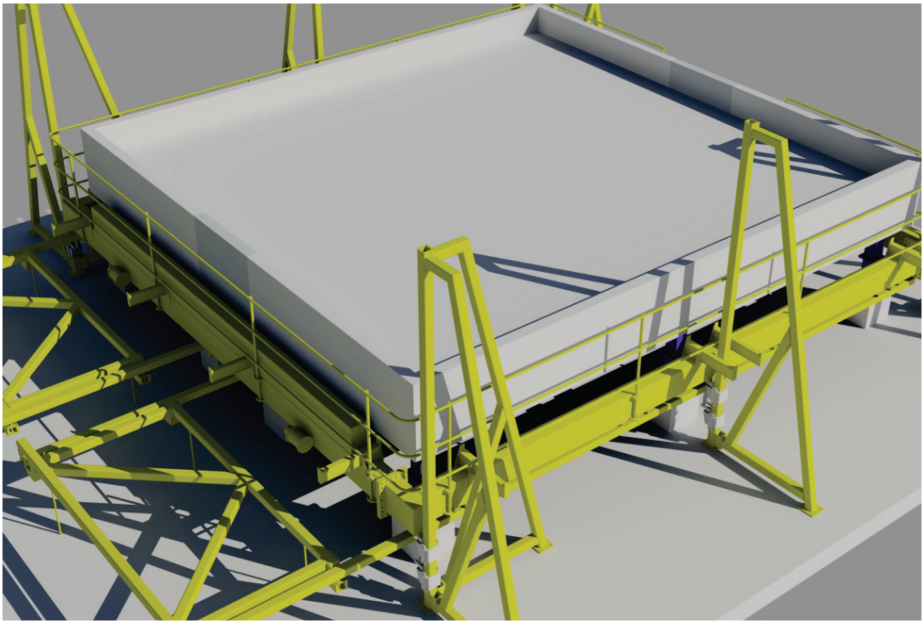


Figure E.7: Assembling of roof structure and claddings [S3]

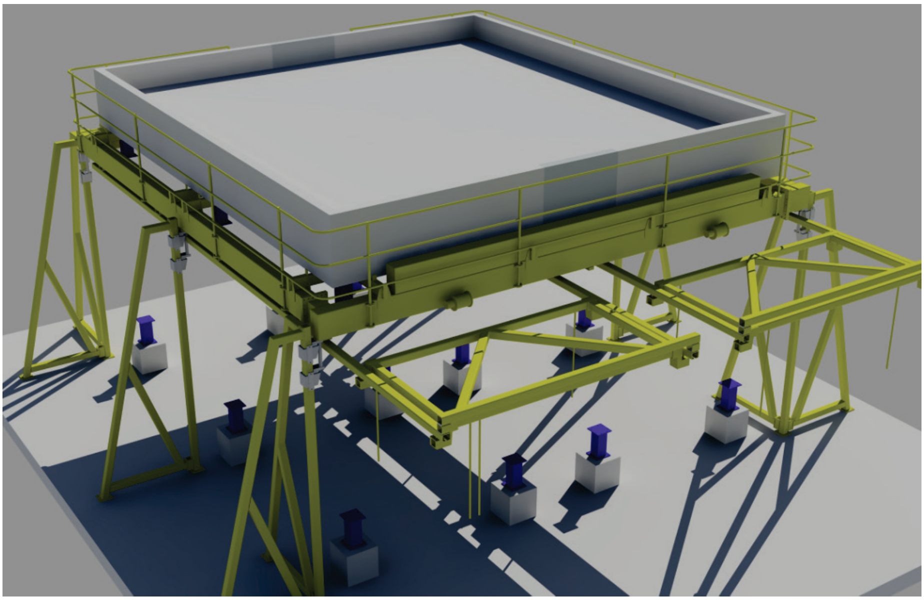


Figure E.8: Lifting the building [Routine 1: R1.D]

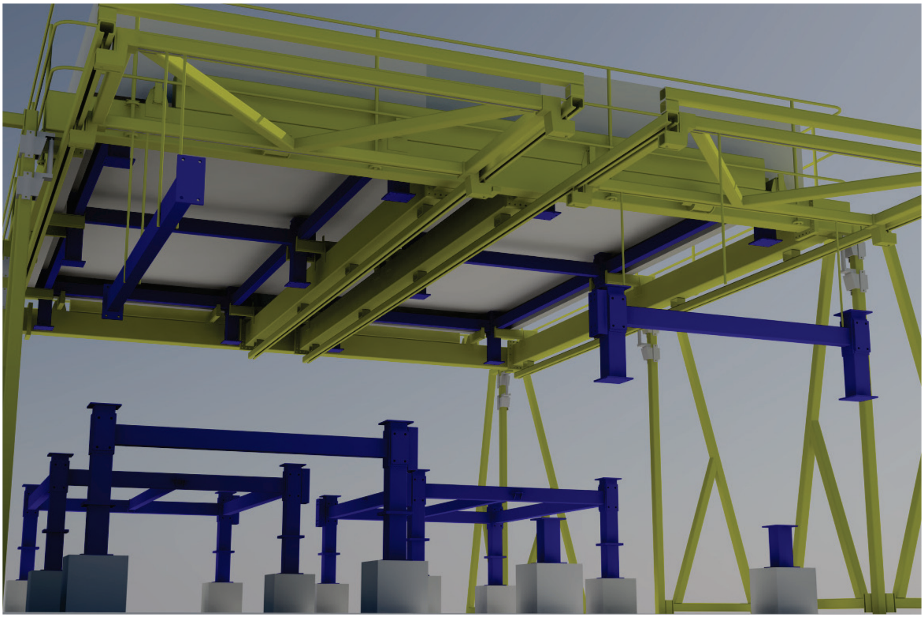


Figure E.9: Assembling of the floor below [Routine 2: R2C]

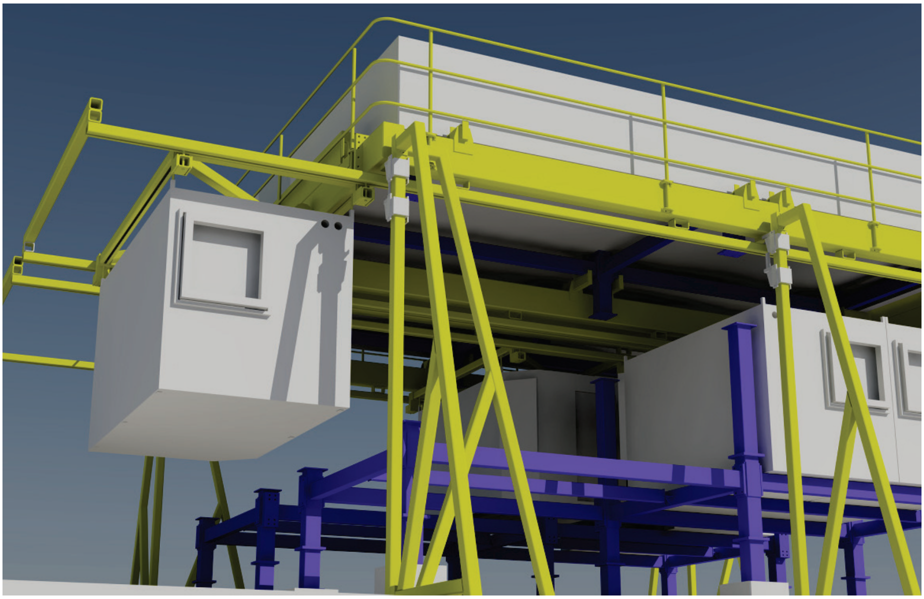


Figure E.10: Assembling of the floor below [Routine 2: R2H]

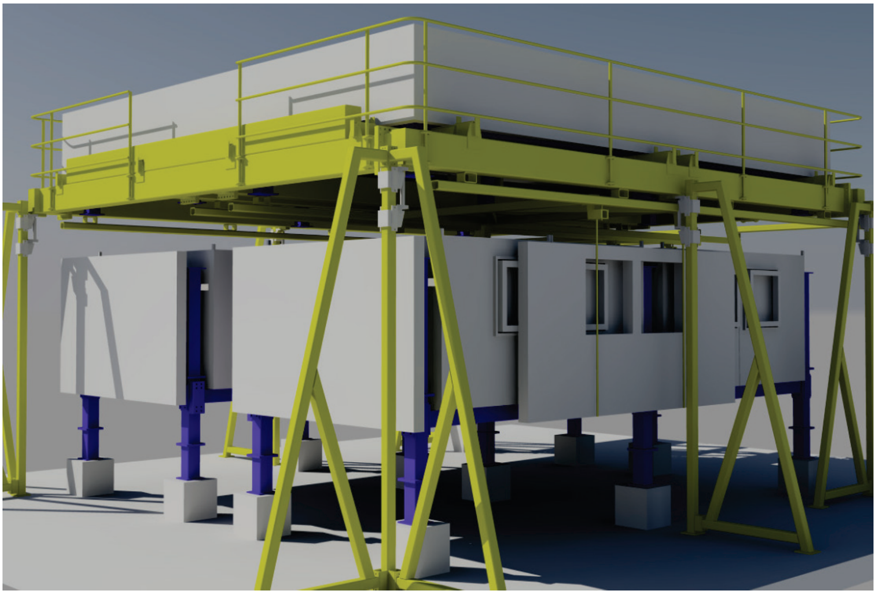


Figure E.11: Assembling of the panels [Routine 2: R2.J]

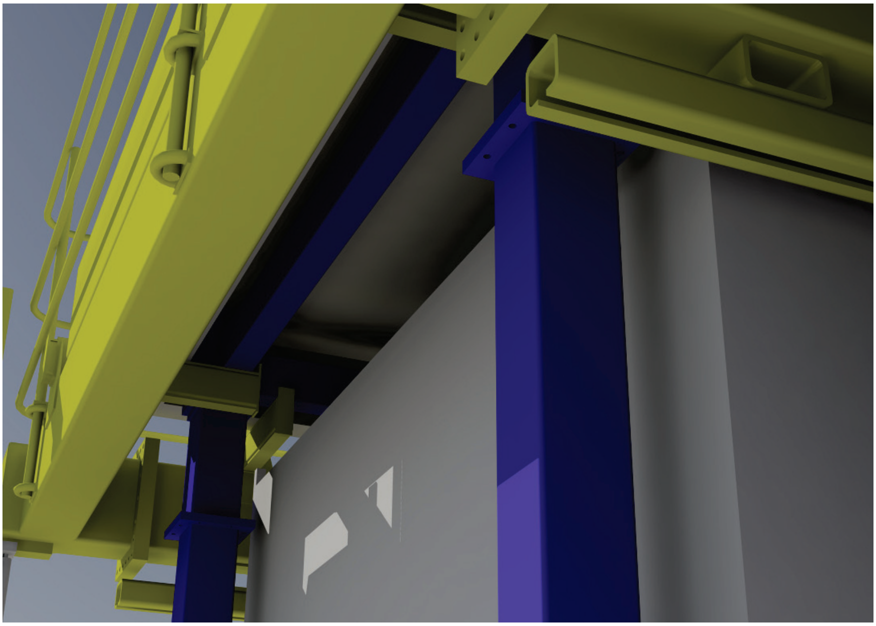


Figure E.12: Connecting building with the floor below [Routine 3:R3.A]

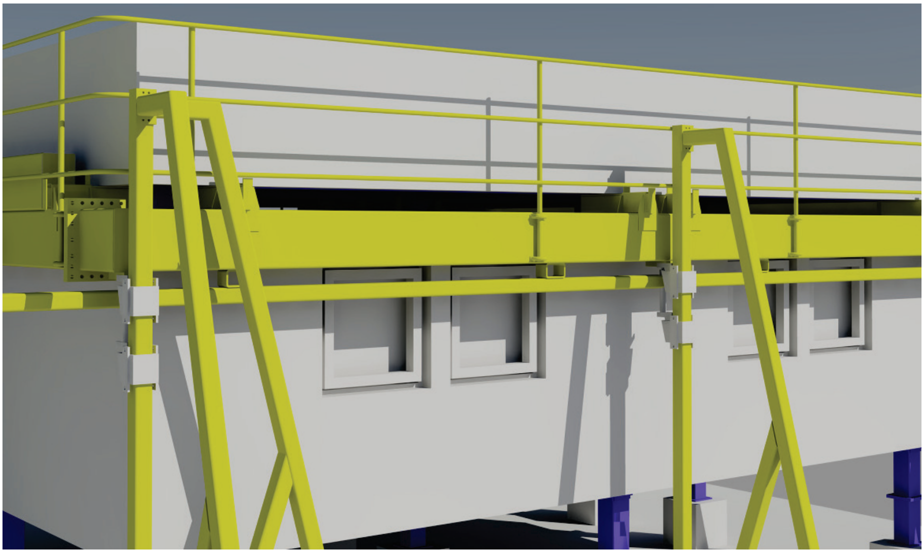


Figure E.13: Connecting building with the floor below [Routine 3: R3.B]

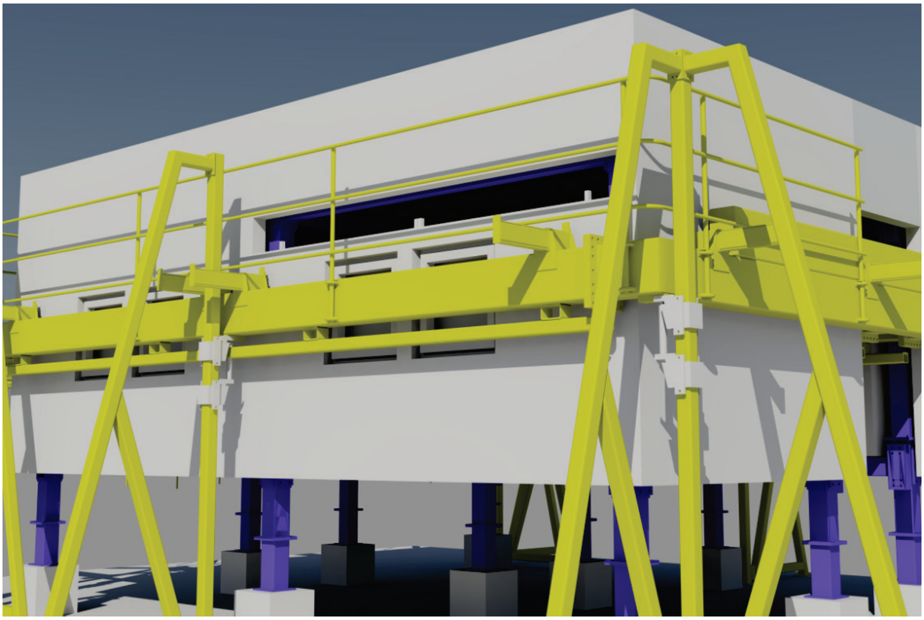


Figure E.14: The grid is free to move [Routine 3: R3.F]

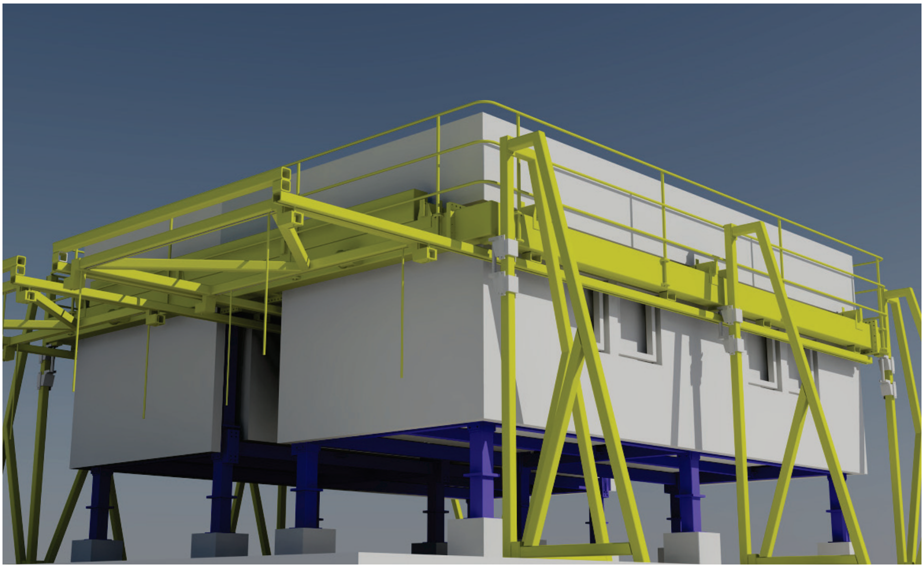


Figure E.15: Assembling of the transitions panels [Routine 3: R3.F]

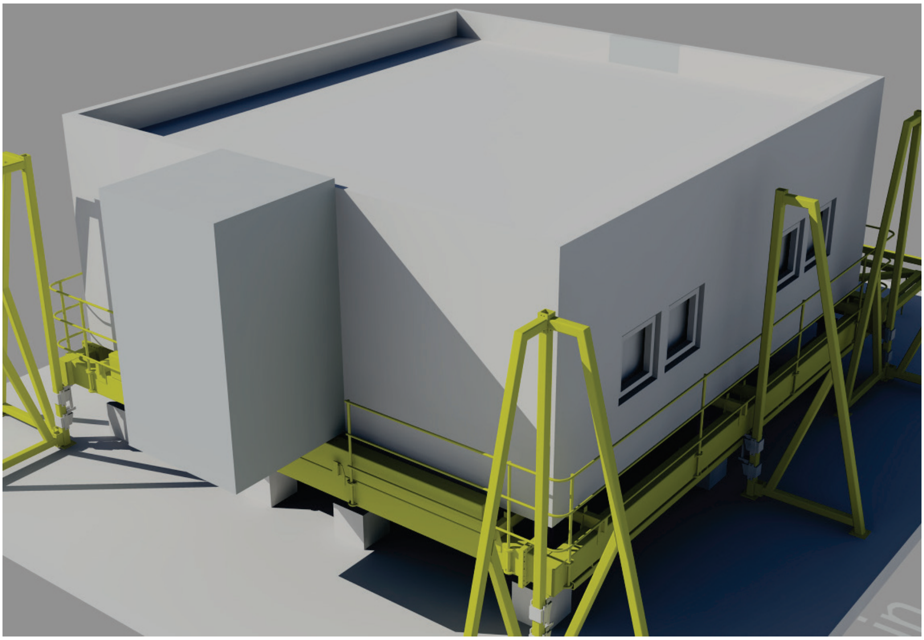


Figure E.16: Grid position before lifting the building [Routine 1: R1.C]

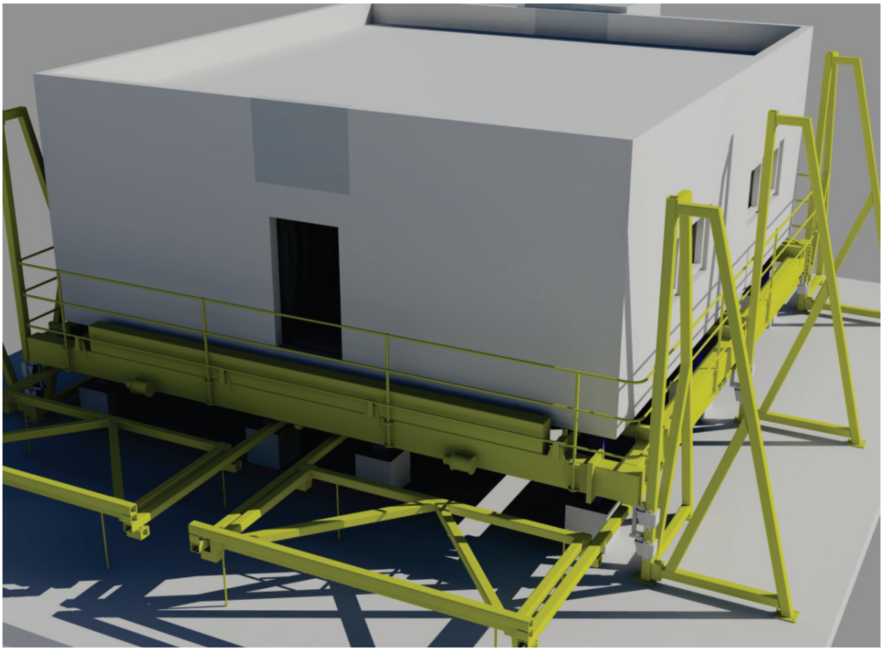


Figure E.17: Grid position before lifting the building [Routine 1: R1.C]

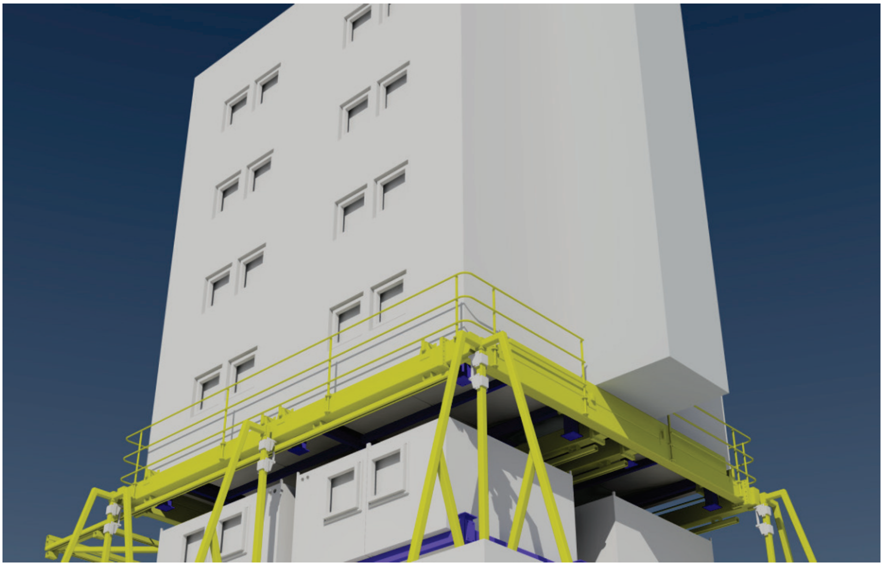


Figure E.18: Assembly of last floor [Routine 2: R2.I]

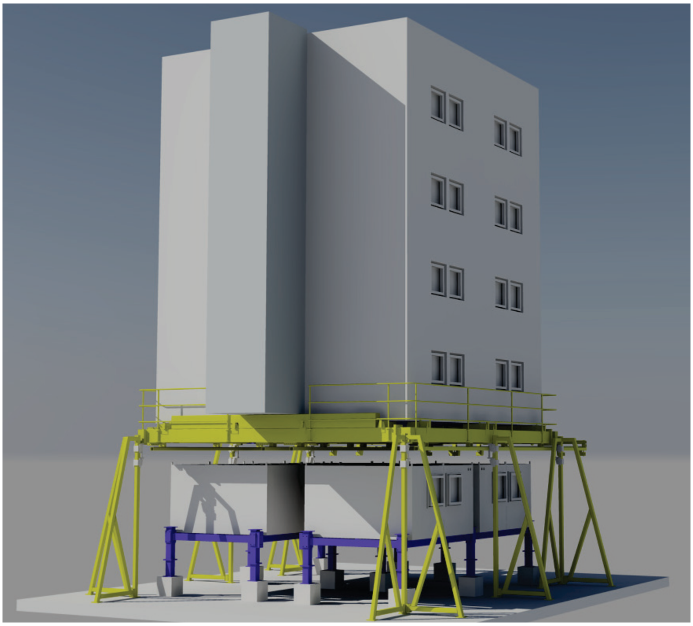


Figure E.19: Assembling of last floor [Routine 2: R2.I]

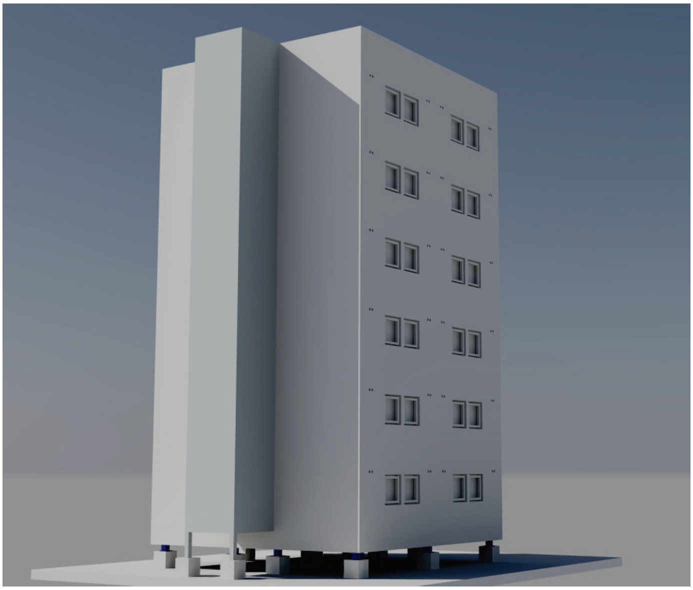


Figure E.20: Final building [S7]

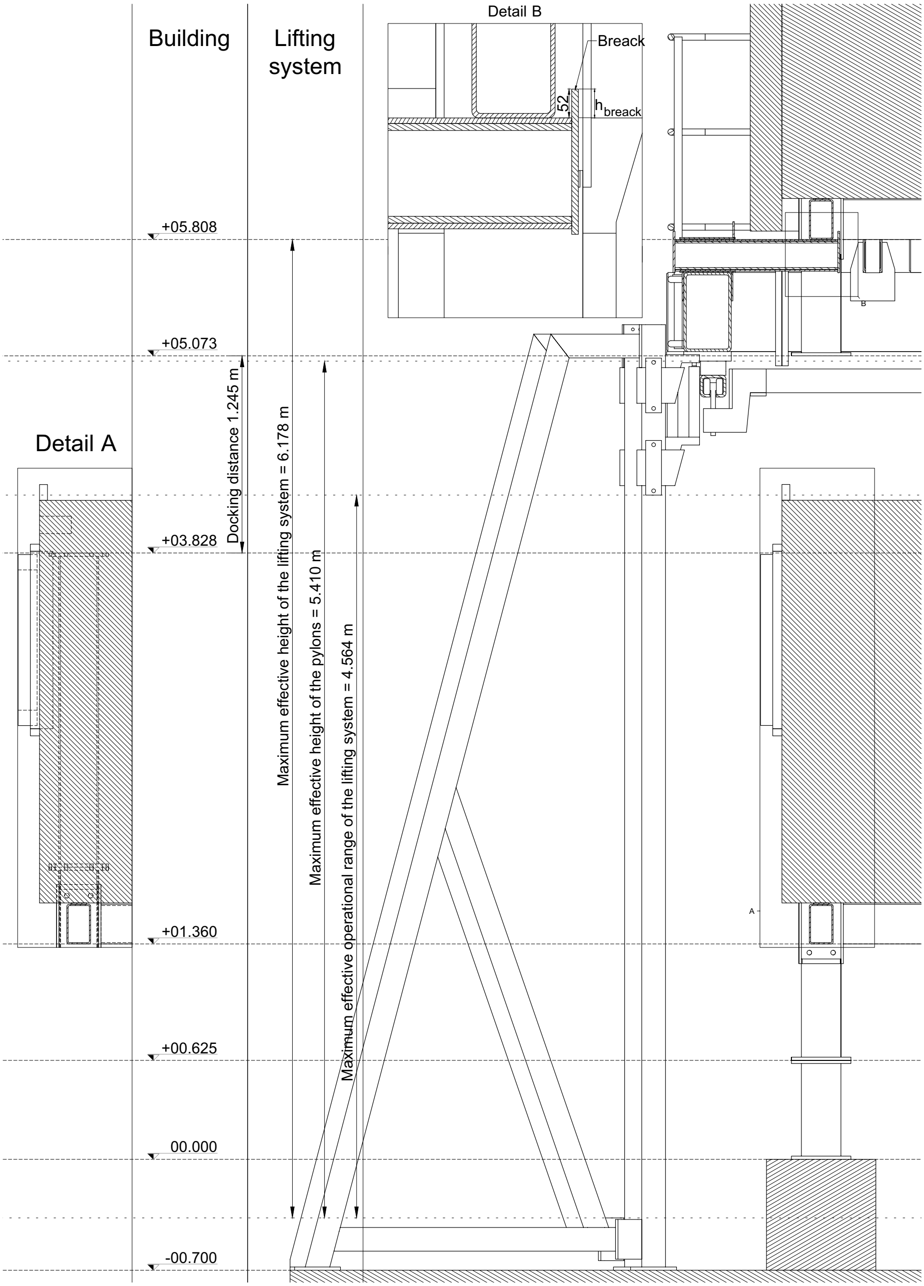


Figure E.21: Lifting system: heights of operational steps

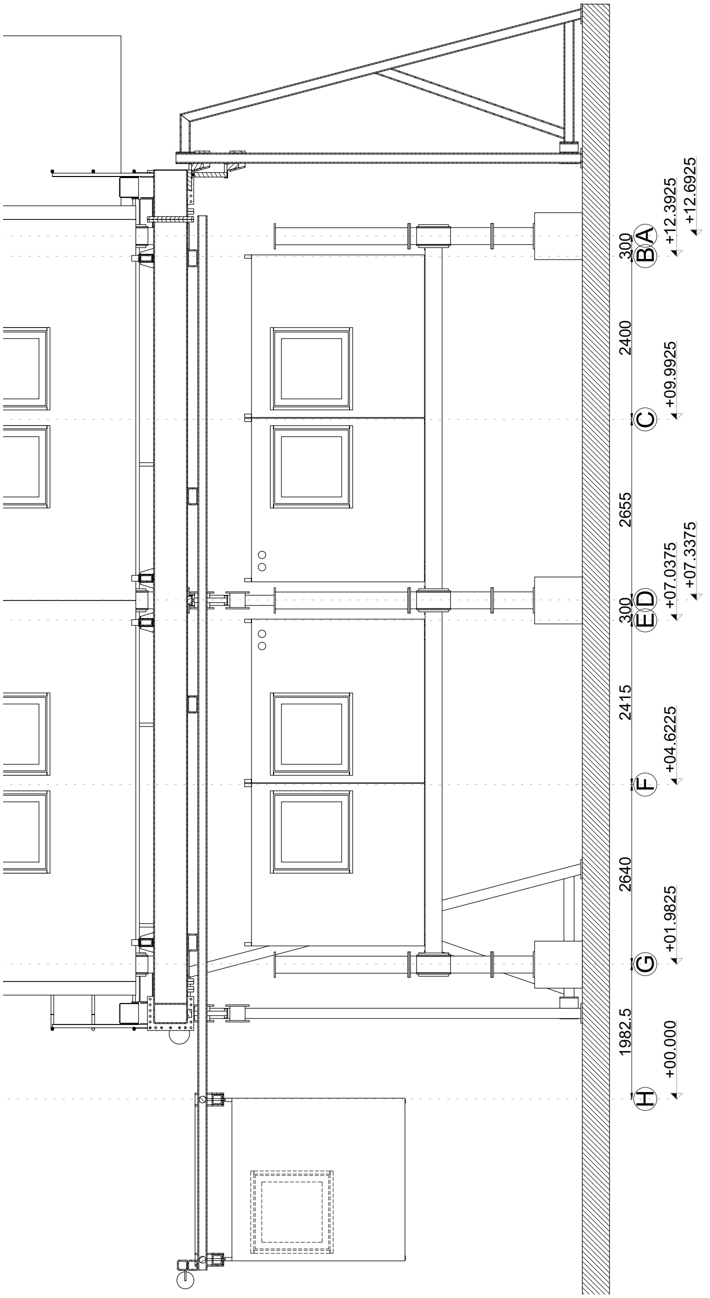


Figure E.22: Lifting system: heights of operational steps

ANNEX F

Description of the Full Scale Test

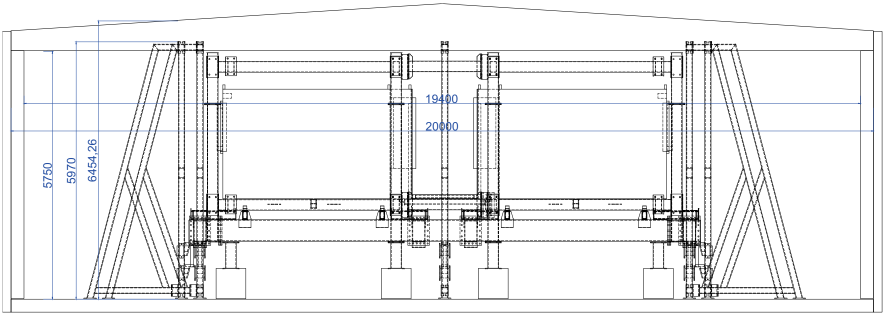


Figure F.1: Section of Sangis' warehouse – constrains for test setup

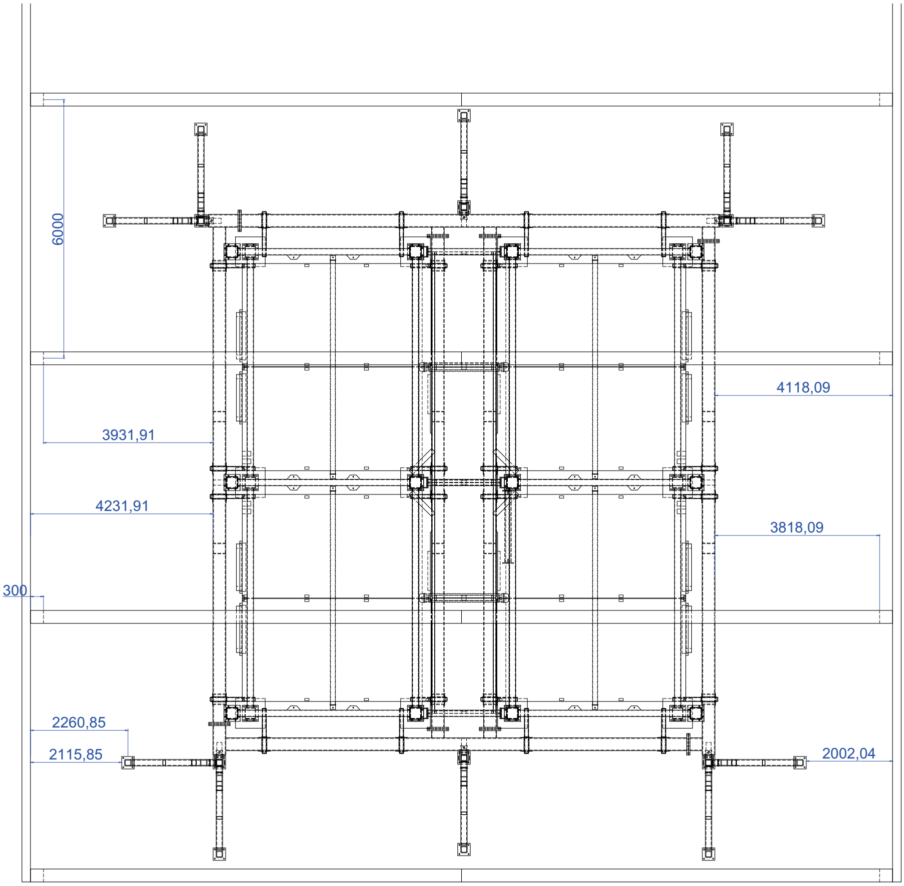


Figure F.2: Plan of Sangis' warehouse – constrains for test setup

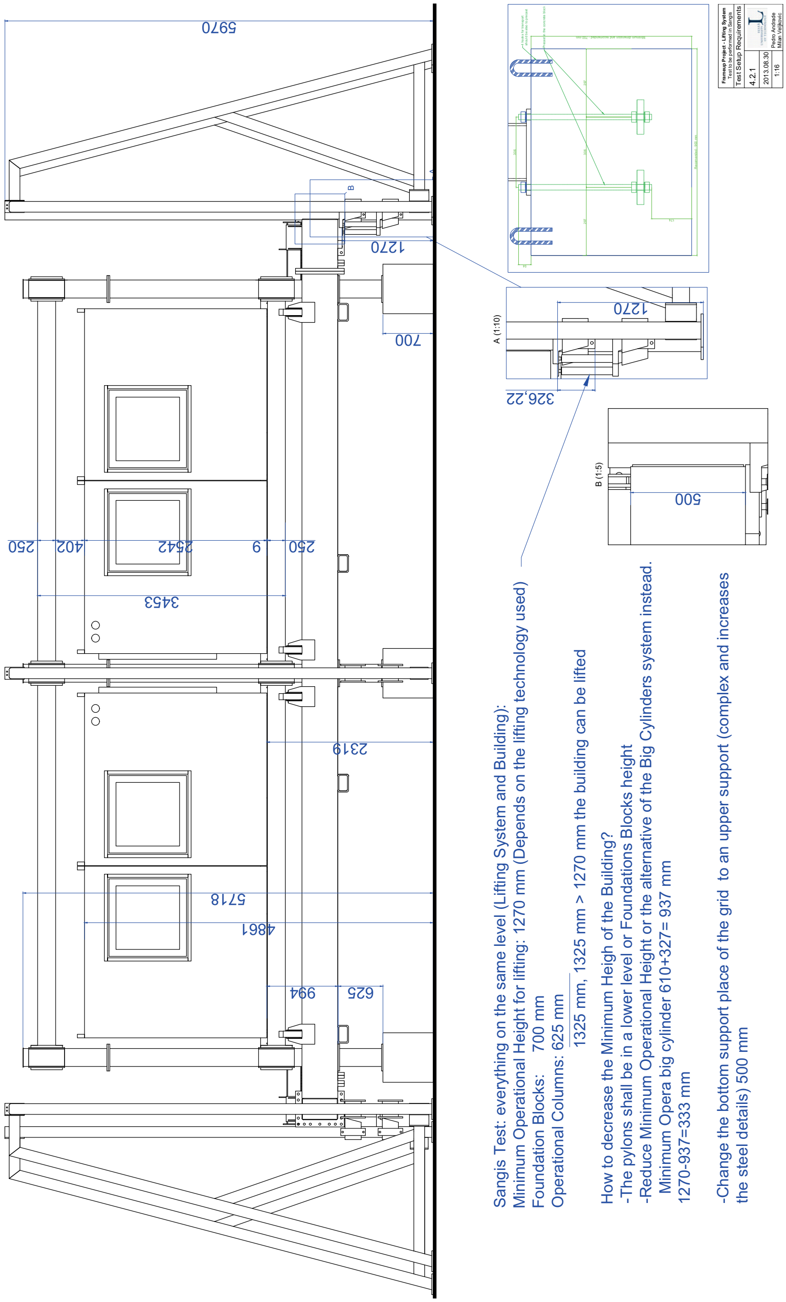


Figure F.3: Sketch of the full scale test requirements

Figure F.4: Full scale test – installation of the Lifting system

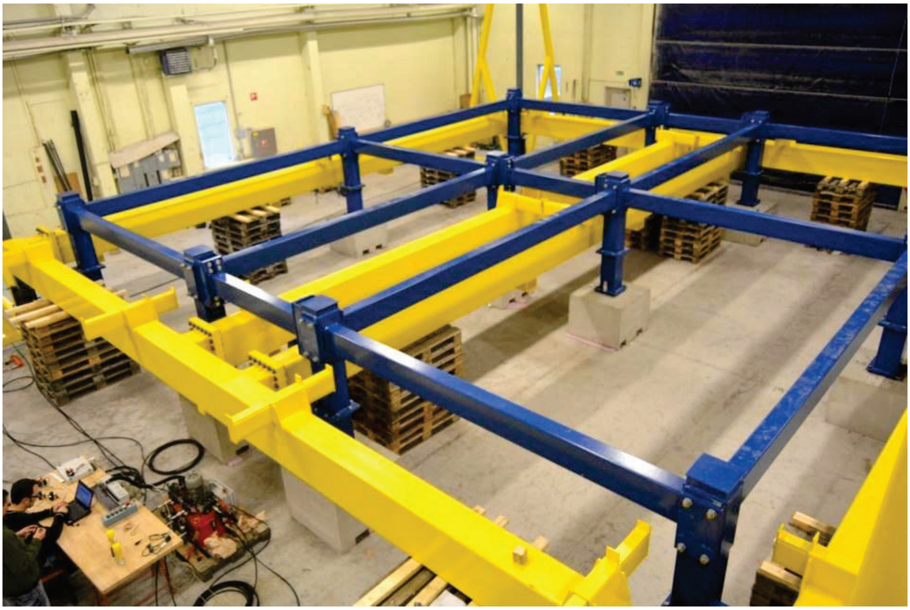


Figure F.5: Full scale test – initial phase

Figure F.6: Full scale test – assembling phase

Figure F.7: Full scale test – start of the lifting phase

ANNEX G

Finger Connection Drawings

(Column Splice with 8 mm horizontal gap)

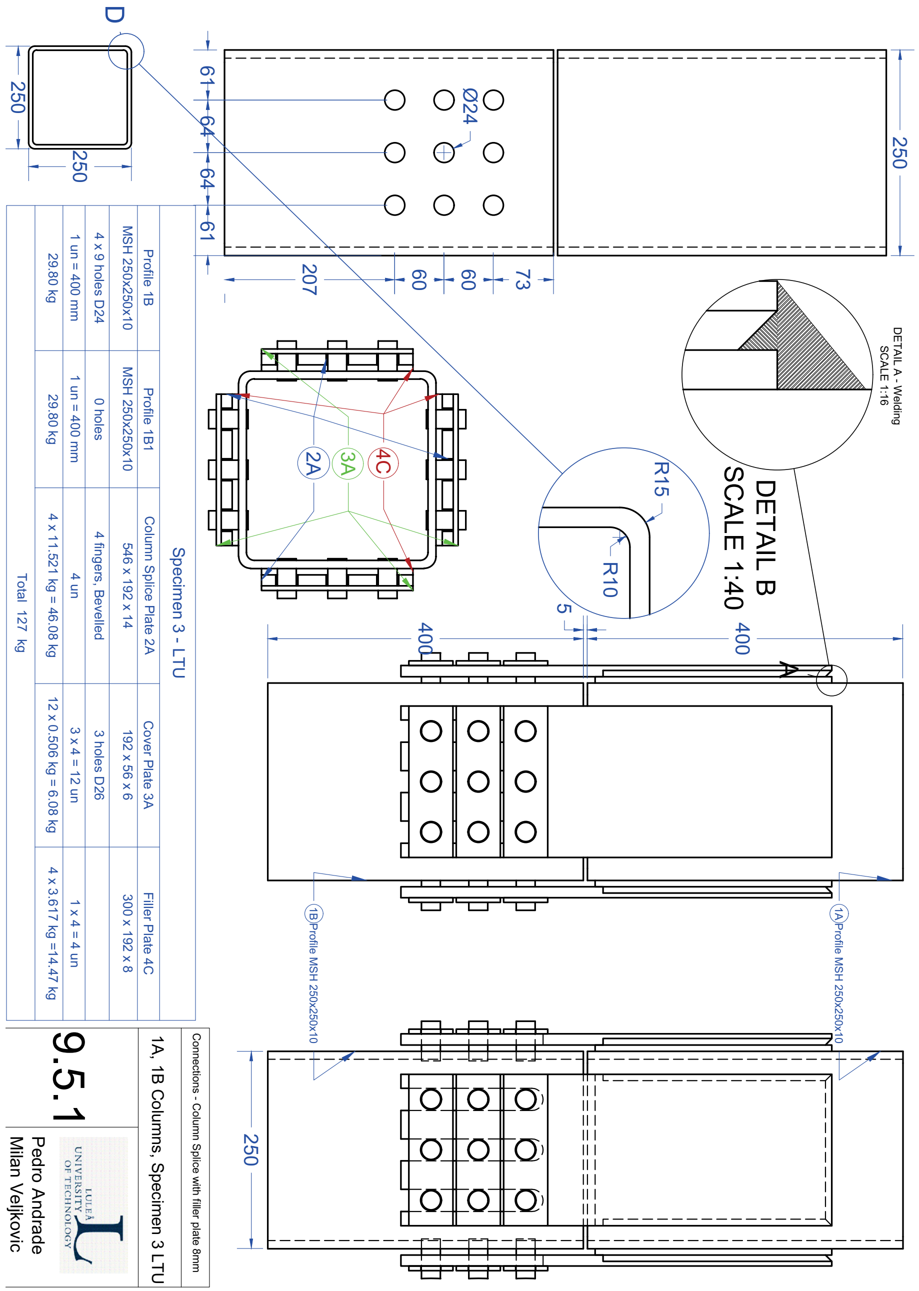


Figure G.1: Production drawings of the Column-splice

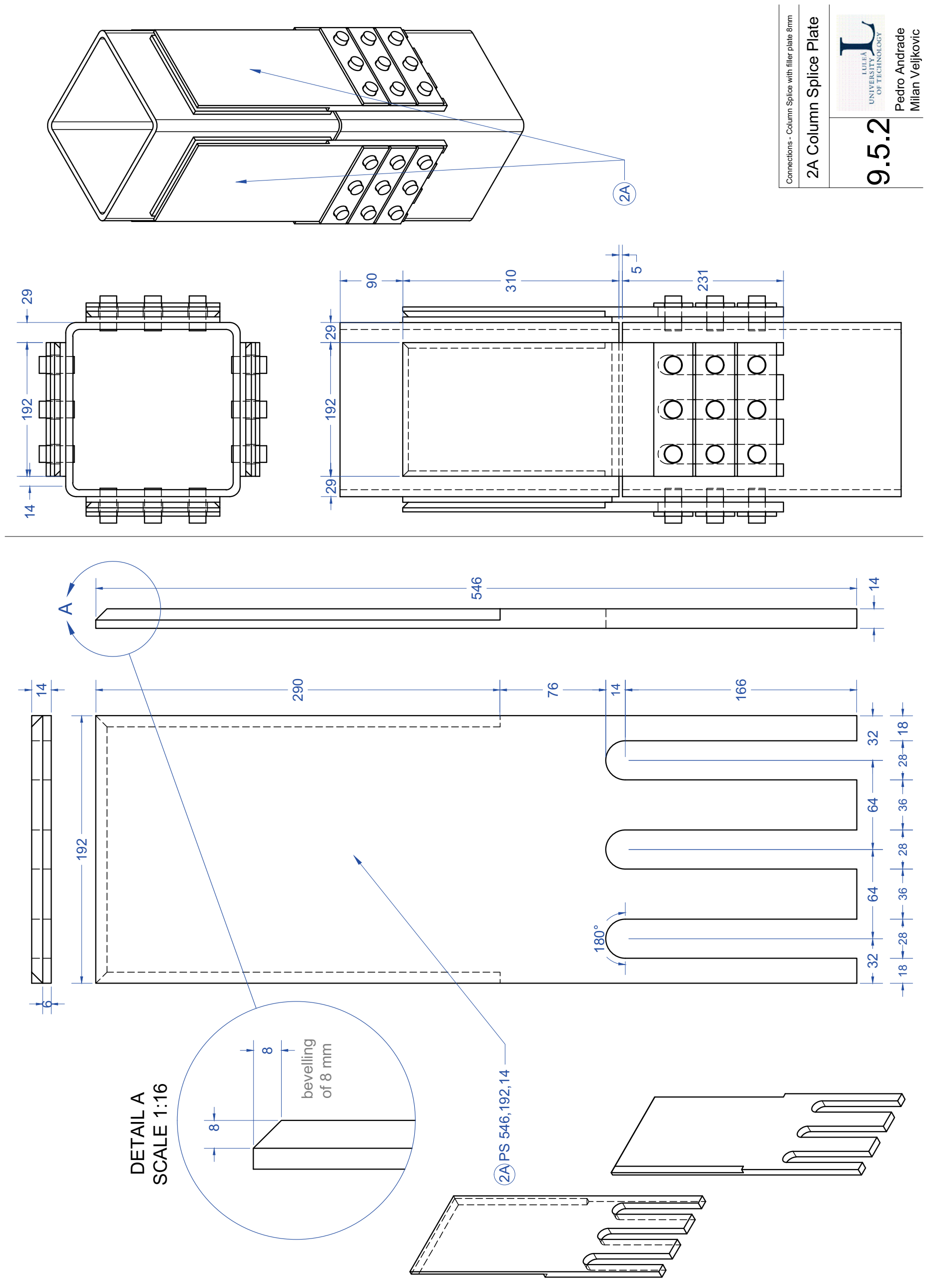


Figure G.2: Production drawings of the Column-splice – Finger Plate

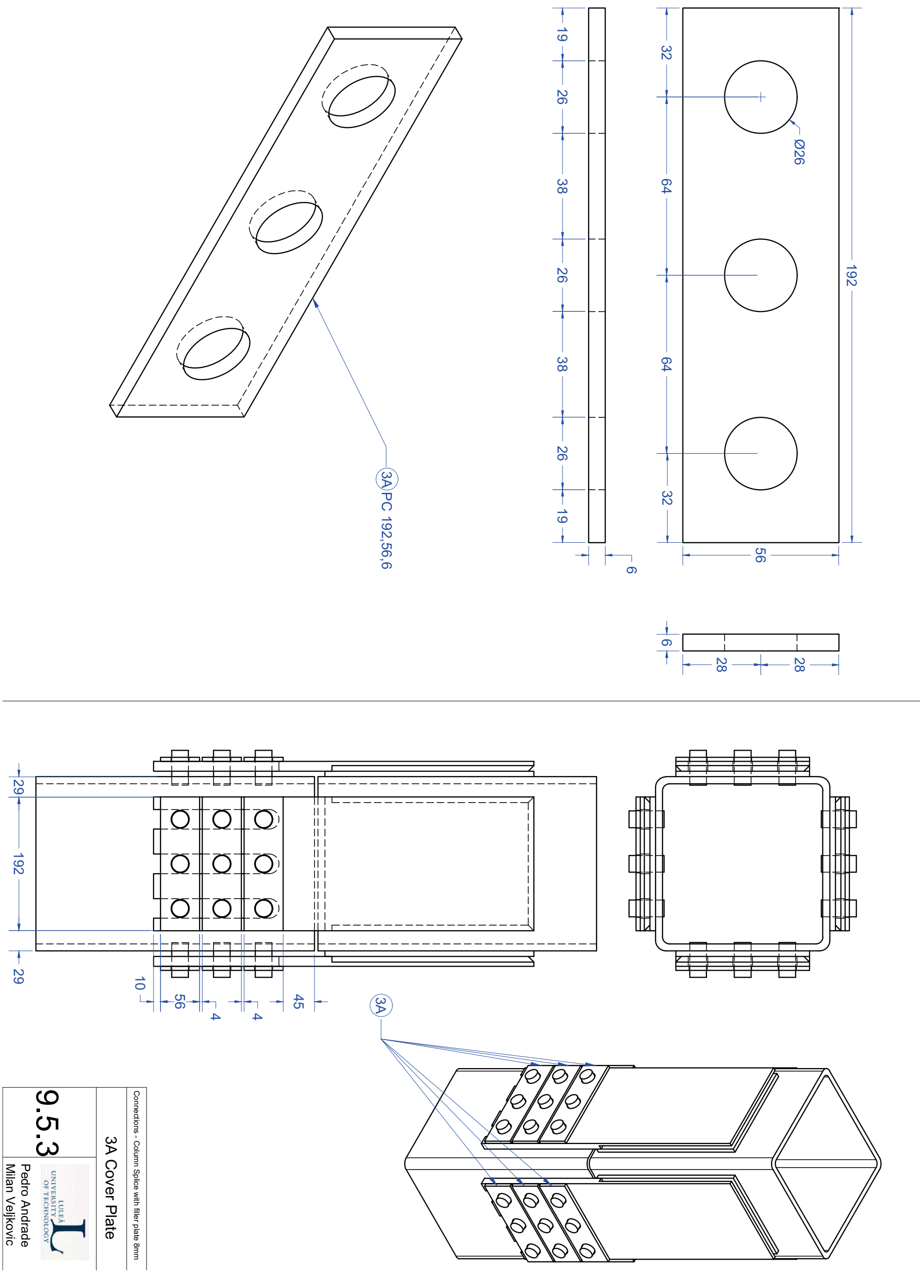


Figure G.3: Production drawings of the Column-splice – Cover Plate

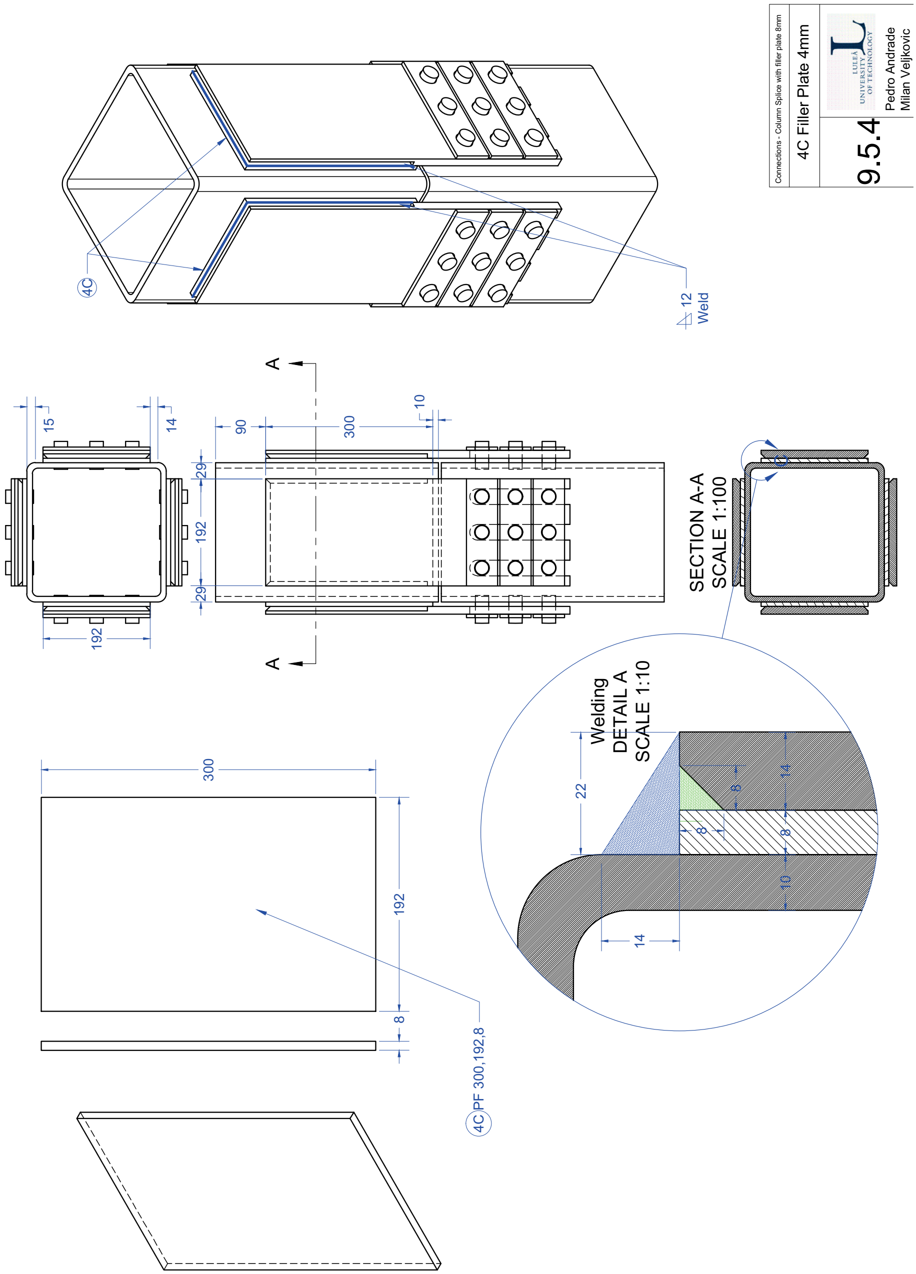


Figure G.4: Production drawings of the Column-splice – Filler Plate

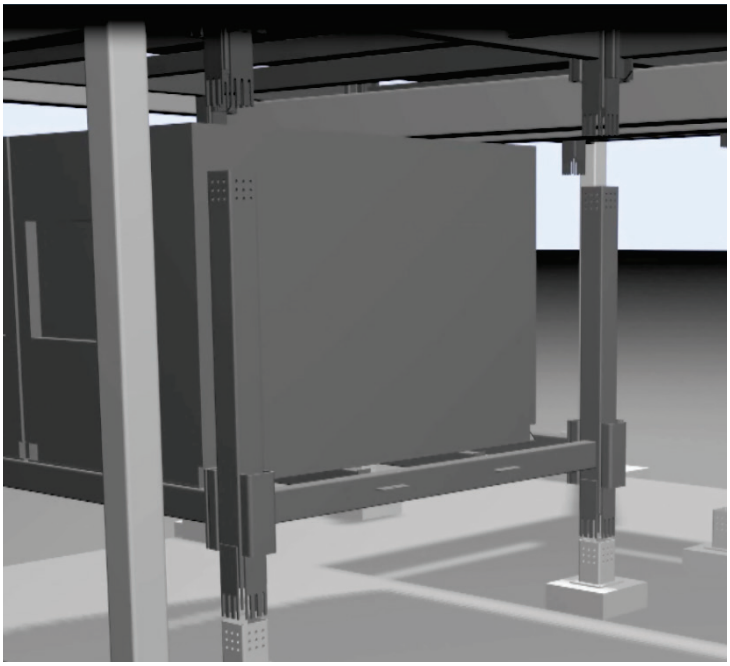


Figure G.5: Snapshot during the animated execution process, [4:05] [29]

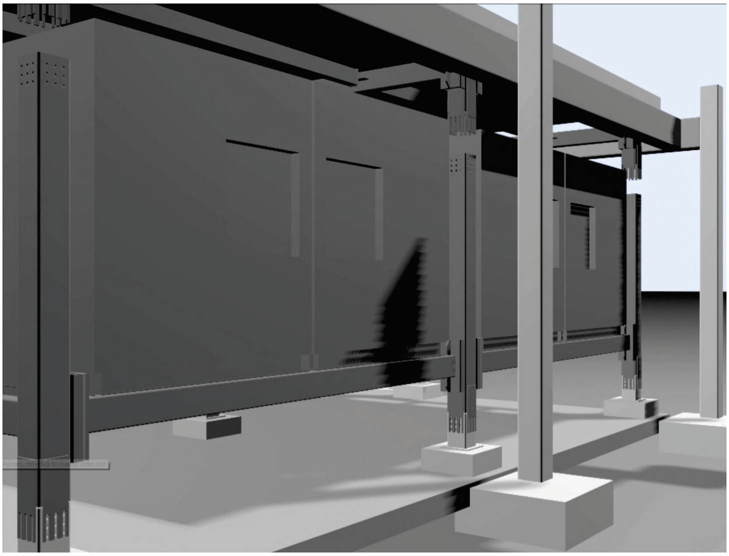


Figure G.6: Snapshot during the animated execution process, [4:33] [29]

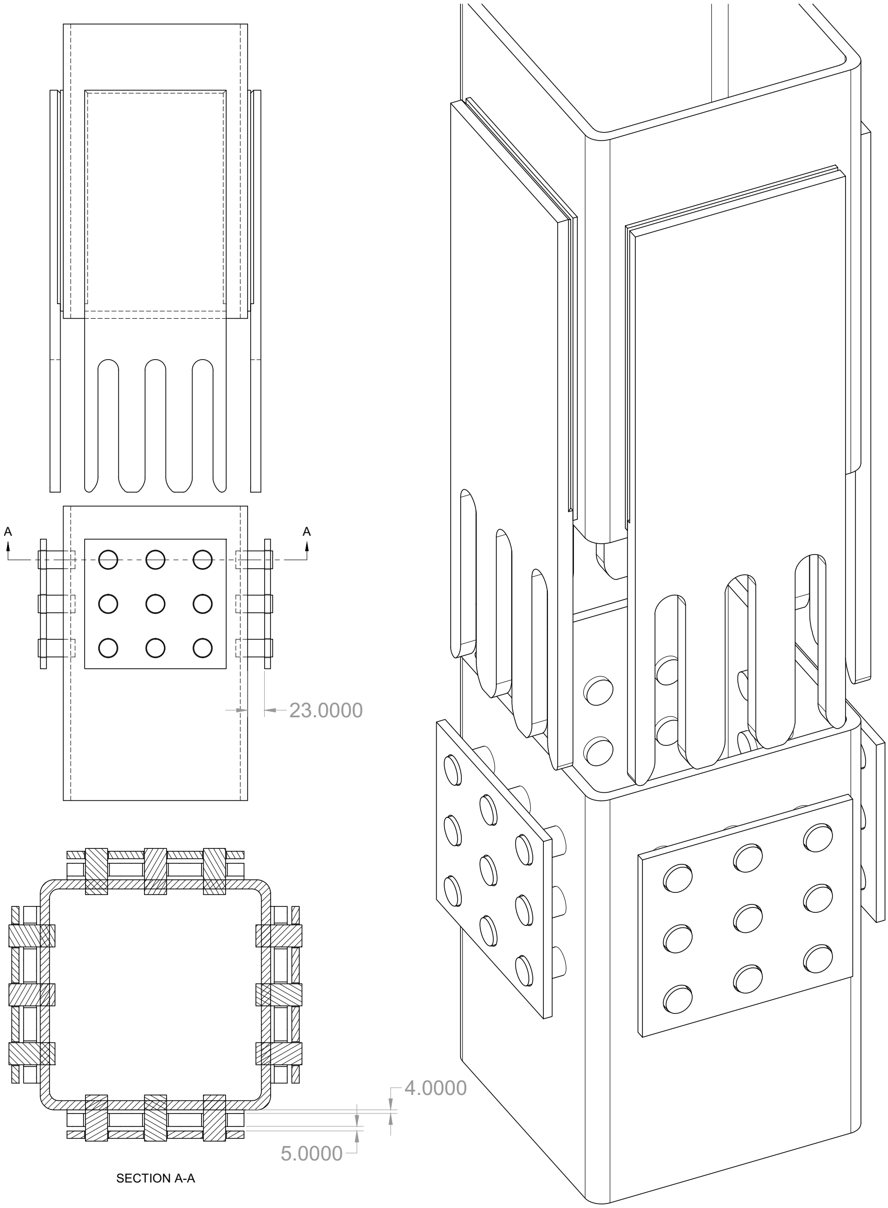


Figure G.7: Proposal for Finger Connection concept update

ANNEX H

Finger Connection Laboratory Preparation and Tests

(Column Splice with 8 mm horizontal gap)

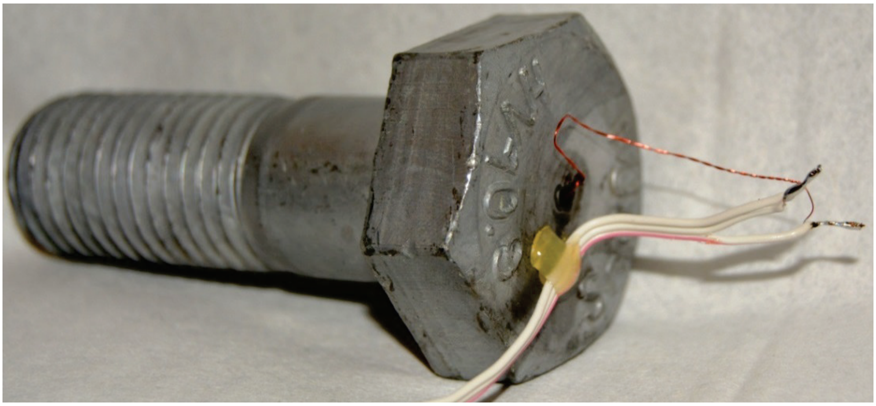


Figure H.0.1: Experimental bolts setup

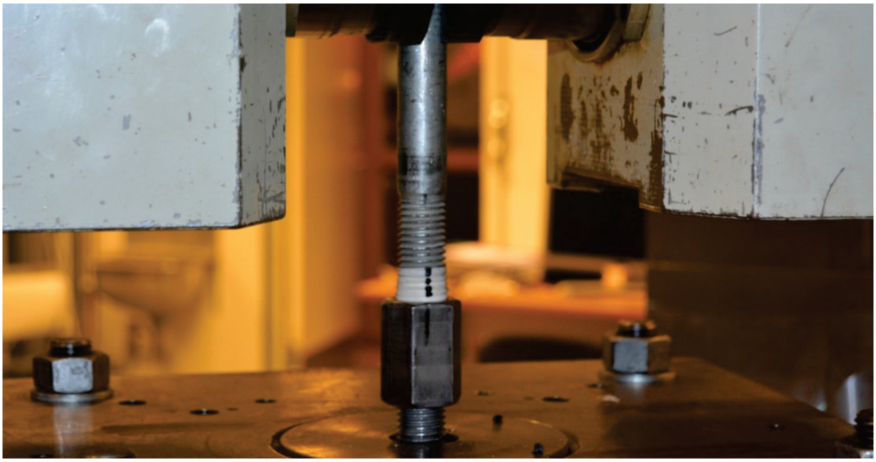


Figure H.0.2: Calibration of bolts

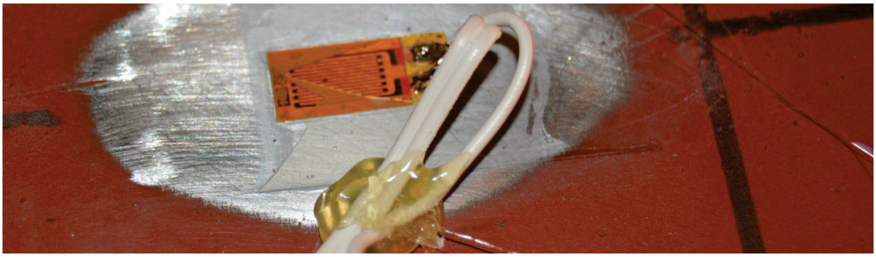
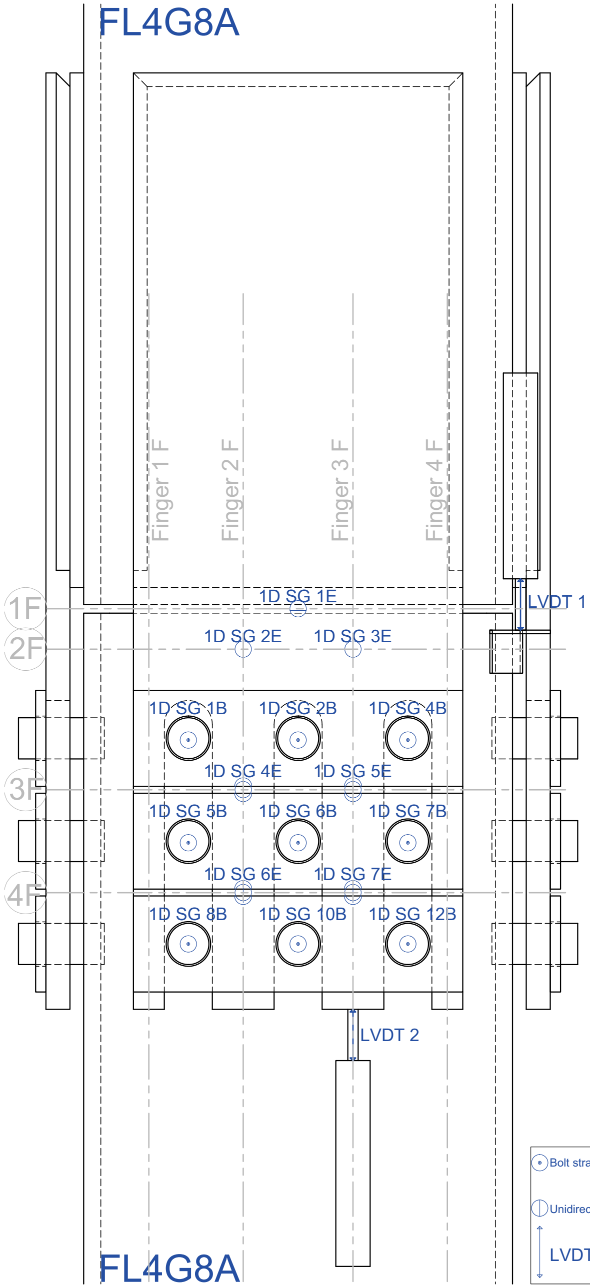
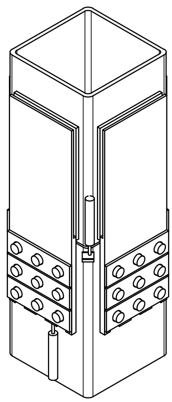


Figure H.3: Strain Gauge installed in Finger Plate



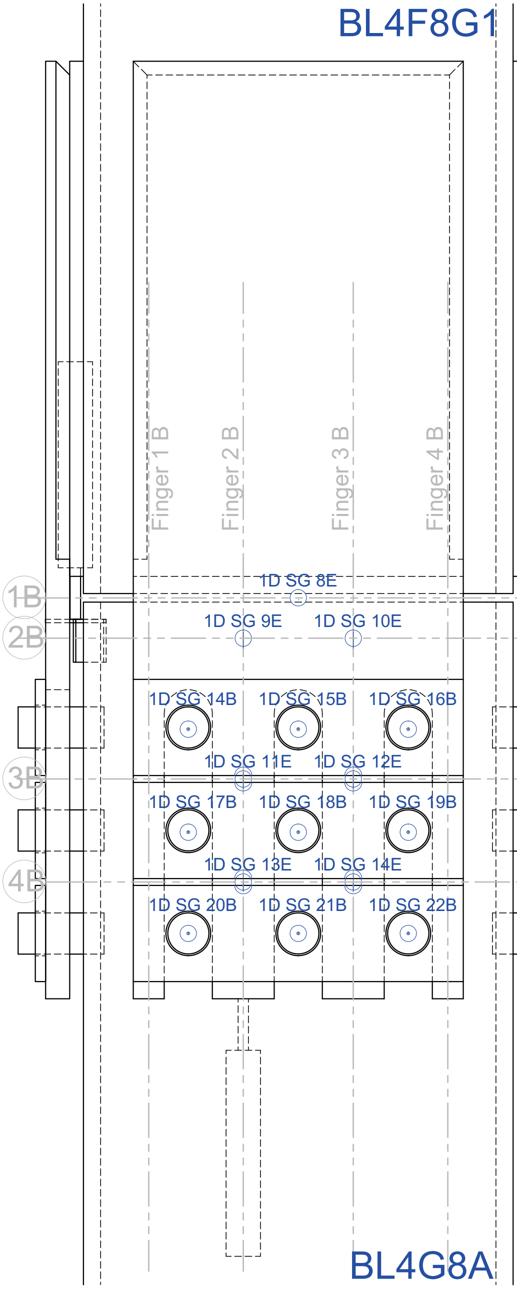


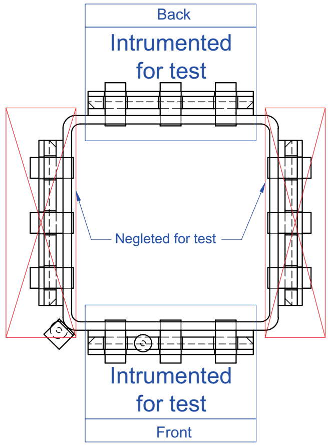
Test Terminology		Document. Terminology
Ch.	Front	
Face Strain Gauges		
1	1D SG 1E	F SG 1-1
2	1D SG 2E	F SG 2-1
3	1D SG 3E	F SG 2-2
4	1D SG 4E	F SG 3-1
5	1D SG 5E	F SG 3-2
6	1D SG 6E	F SG 4-1
7	1D SG 7E	F SG 4-2
Bolts Strain Gauges		
8	1D SG 1B	F Bolt 1-1
9	1D SG 2B	F Bolt 1-2
10	1D SG 4B	F Bolt 1-3
11	1D SG 5B	F Bolt 2-1
12	1D SG 6B	F Bolt 2-2
13	1D SG 7B	F Bolt 2-3
14	1D SG 8B	F Bolt 3-1
15	1D SG 10B	F Bolt 3-2
16	1D SG 12B	F Bolt 3-3
17	LVDT1	
18	LVDT2	

Bolt strain gauge
Unidirectional strain gauge
LVDT n

Front, Lower and Upper profile, specimen
4 Plates and Gap 8mm - Replicate A
Experiments Setup
Installation of Strain Gauges and LVDT
9.5.5.1
LULEÅ UNIVERSITY OF TECHNOLOGY
Pedro Andrade
Milan Veljkovic

Figure H.4: Schematic arrangement of test setup, front view





Test Terminology		Document. Terminology
Ch.	Back	
	Face Strain gauges	
19	1D SG 8E	B SG 1-1
20	1D SG 9E	B SG 2-1
21	1D SG 10E	B SG 2-2
22	1D SG 11E	B SG 3-1
23	1D SG 12E	B SG 3-2
24	1D SG 13E	B SG 4-1
25	1D SG 14E	B SG 4-2
	Bolts Strain Gauges	
26	1D SG 14B	B Bolt 1-1
27	1D SG 15B	B Bolt 1-2
28	1D SG 16B	B Bolt 1-3
29	1D SG 17B	B Bolt 2-1
30	1D SG 18B	B Bolt 2-2
31	1D SG 19B	B Bolt 2-3
32	1D SG 20B	B Bolt 3-1
33	1D SG 21B	B Bolt 3-2
34	1D SG 22B	B Bolt 3-3

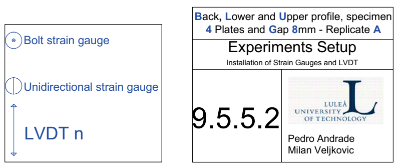
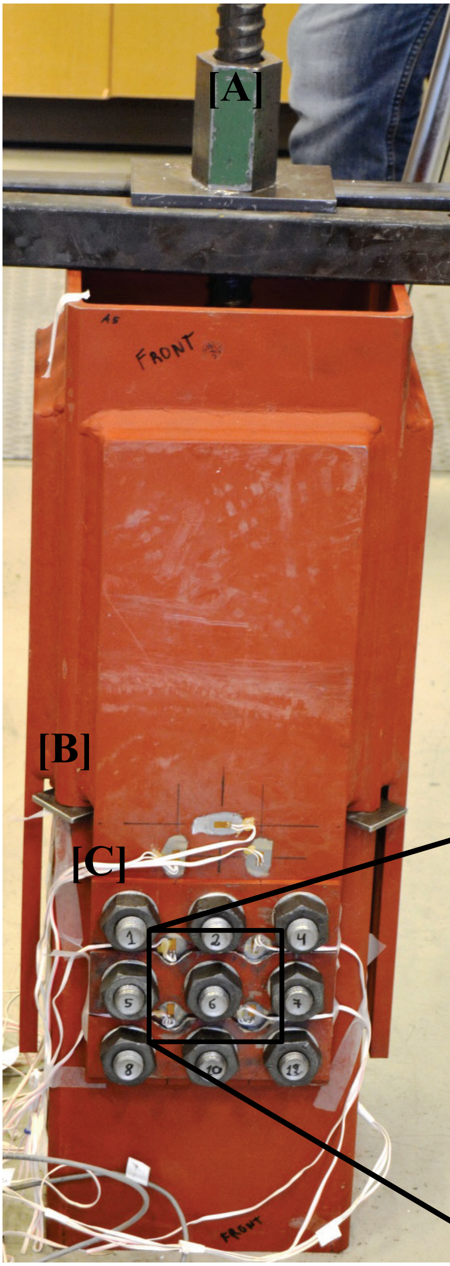


Figure H.5: Schematic arrangement of test setup, back view



To prevent the movement, a **rod [A]** going through the profile's core, clamps members against the ground.

In between profiles, **small plates [B]**, strategically placed, transmits the vertical forces, whereas insures clearance for the future 5 mm vertical gap.

The Strain Gauges (SG) **cables [C]**, are tied together to relieve wrench movements from any kind of constraints.

It is considered a **notch [D]** on Cover plates which permits to accommodate the SG without compromising its functions.

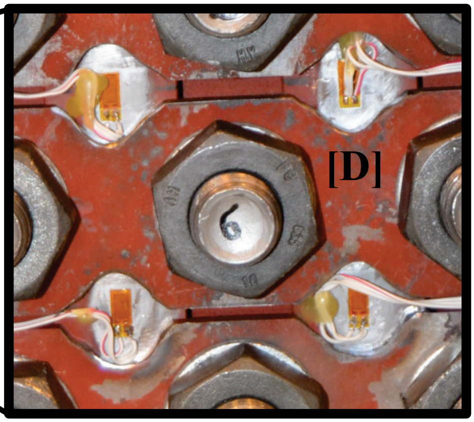


Figure H.6: Setup detail for Assembling Phase

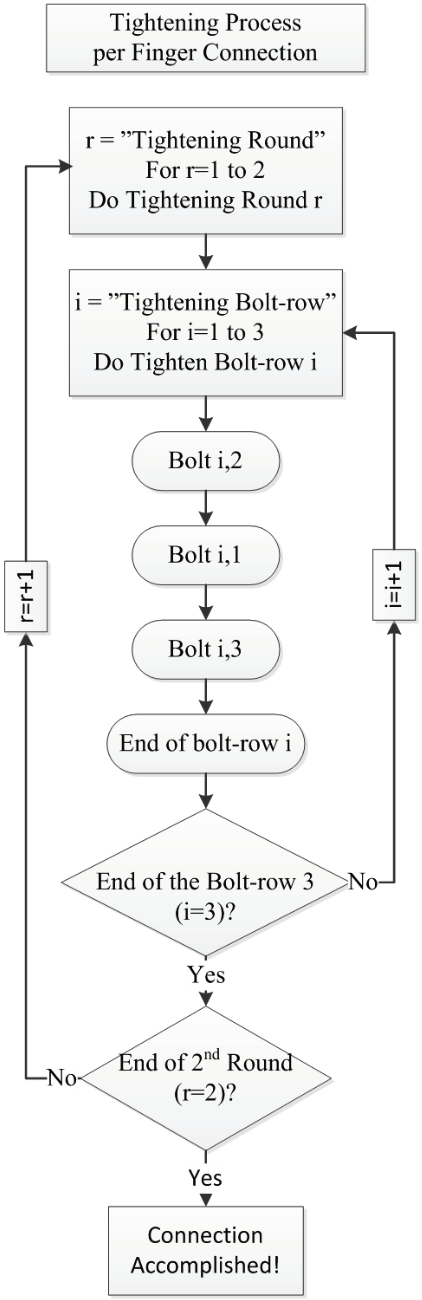


Figure H.7: Flowchart of the Tightening Process

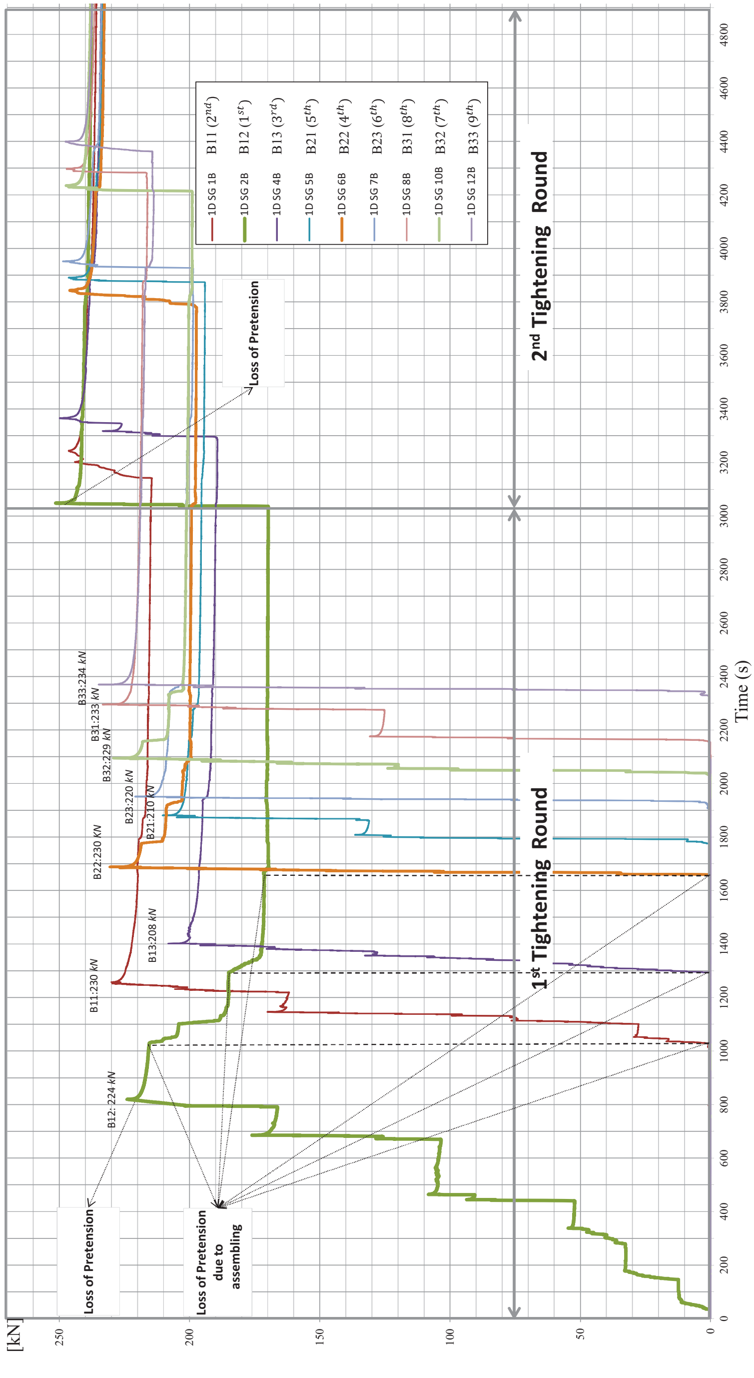


Figure H.8: Loss of pretension assessment within Assembly Phase, focus on the front Bolt B_{12}

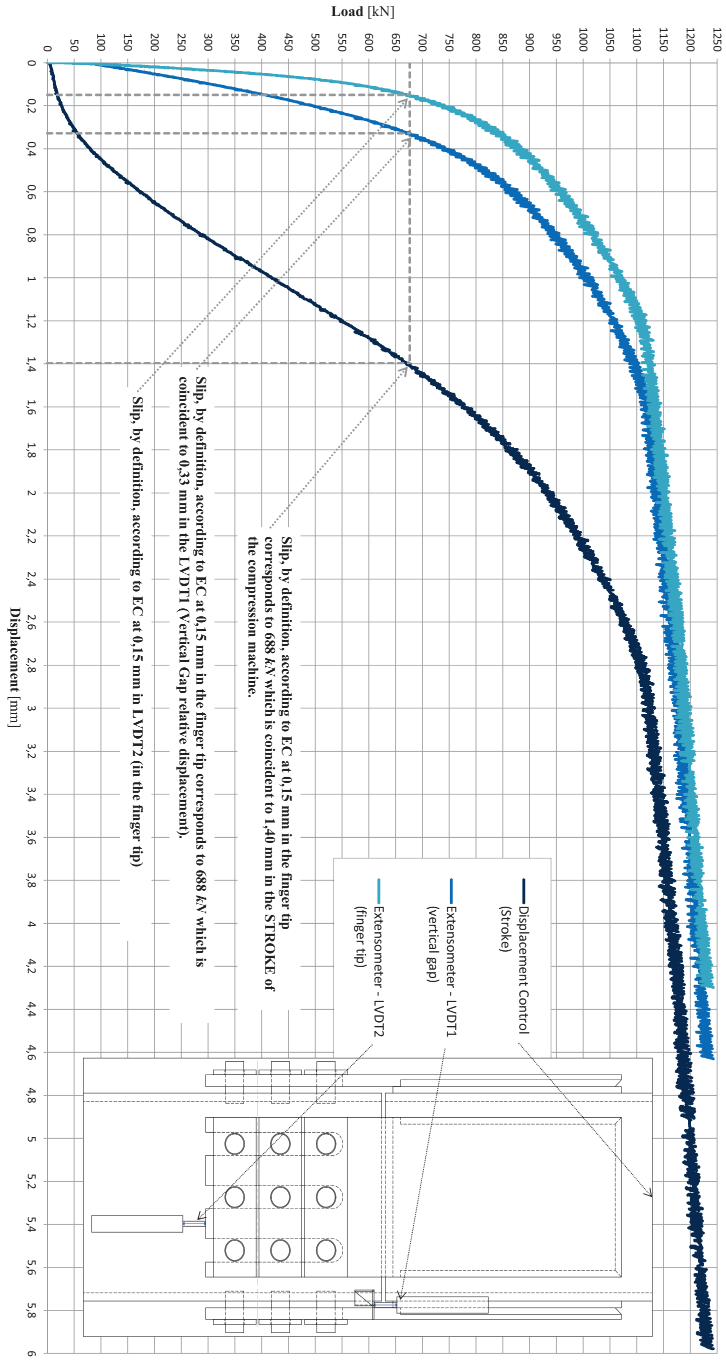


Figure H.9: Load – Displacement Curve

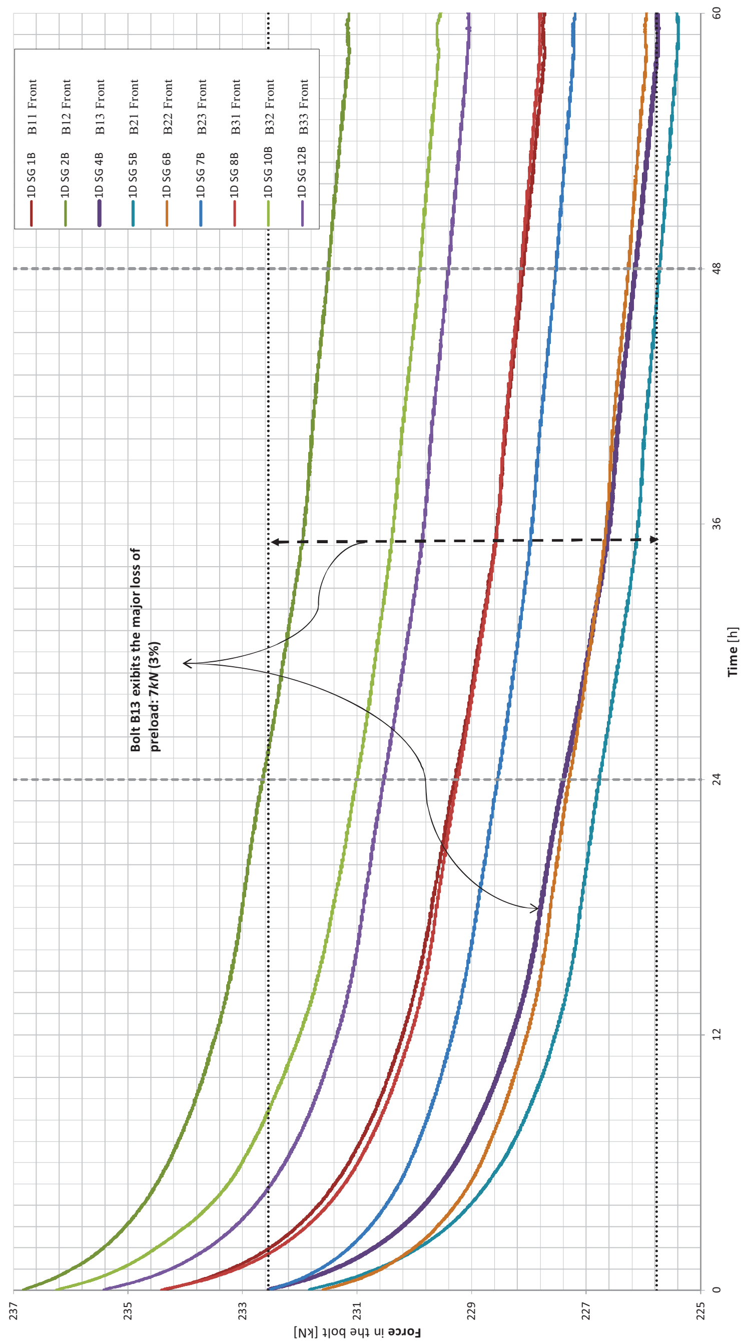


Figure H.10: Loss of preload during 60 hours

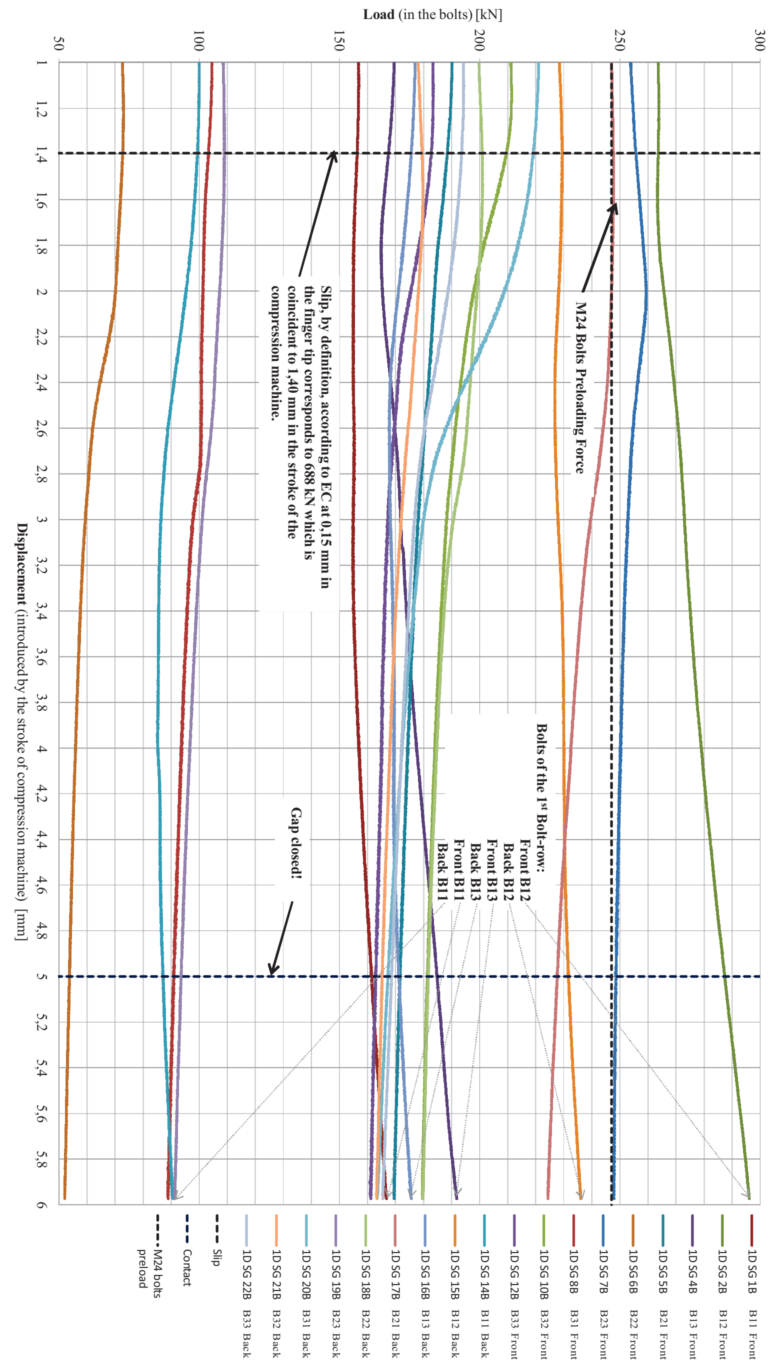


Figure H.11: Bolts preloading force along the compression test

ANNEX I

Finger Connection Modelling

(Column Splice with 8 mm horizontal gap)

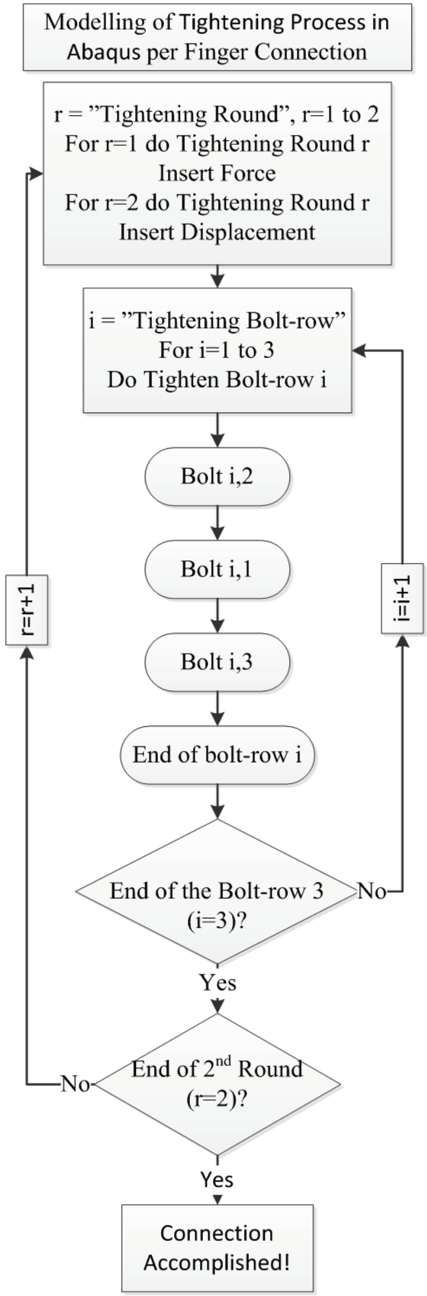


Figure I.1: Flowchart of the tightening modelling

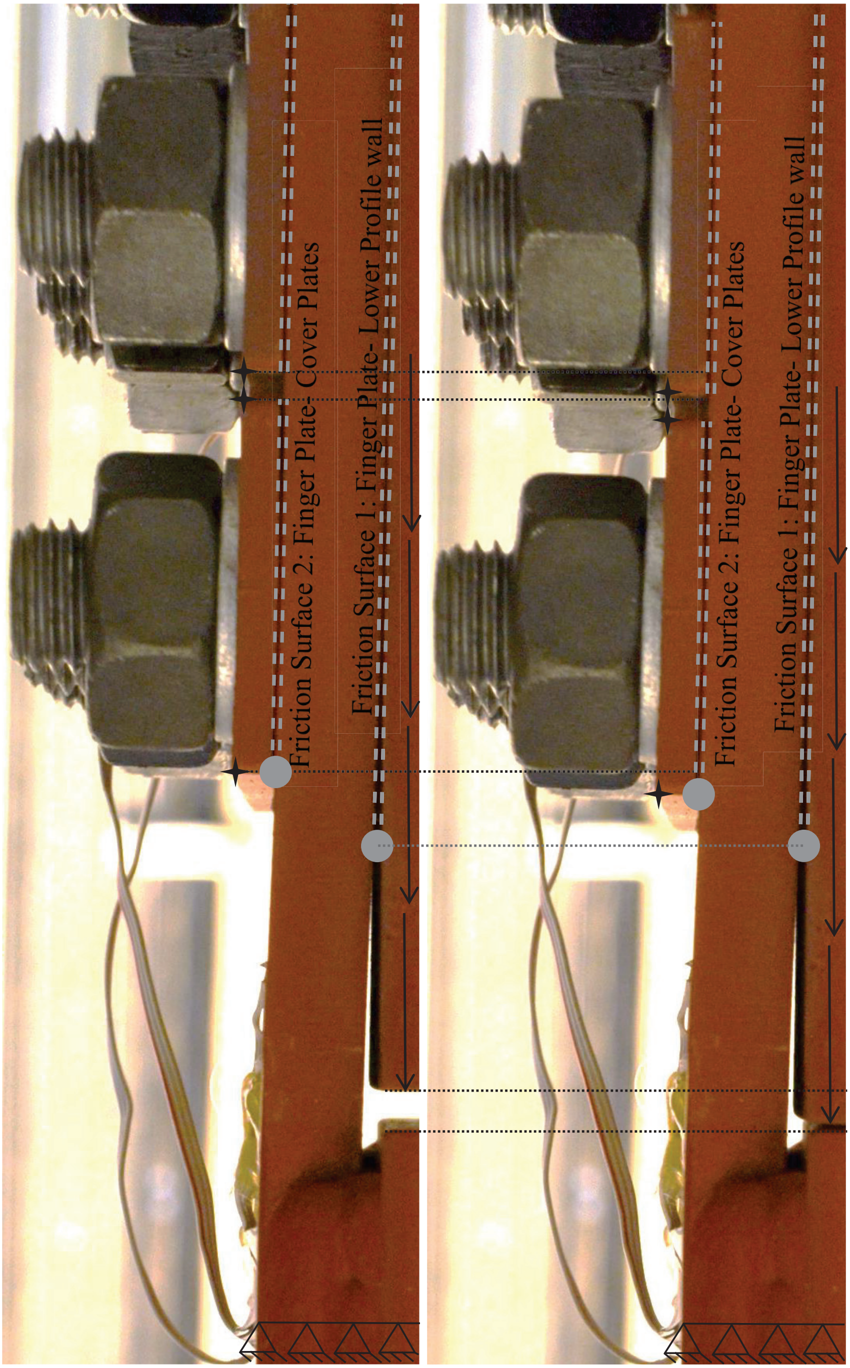


Figure I.2: Pictures of the 4mm gap Slip Test – Identification of the two friction surfaces [43]

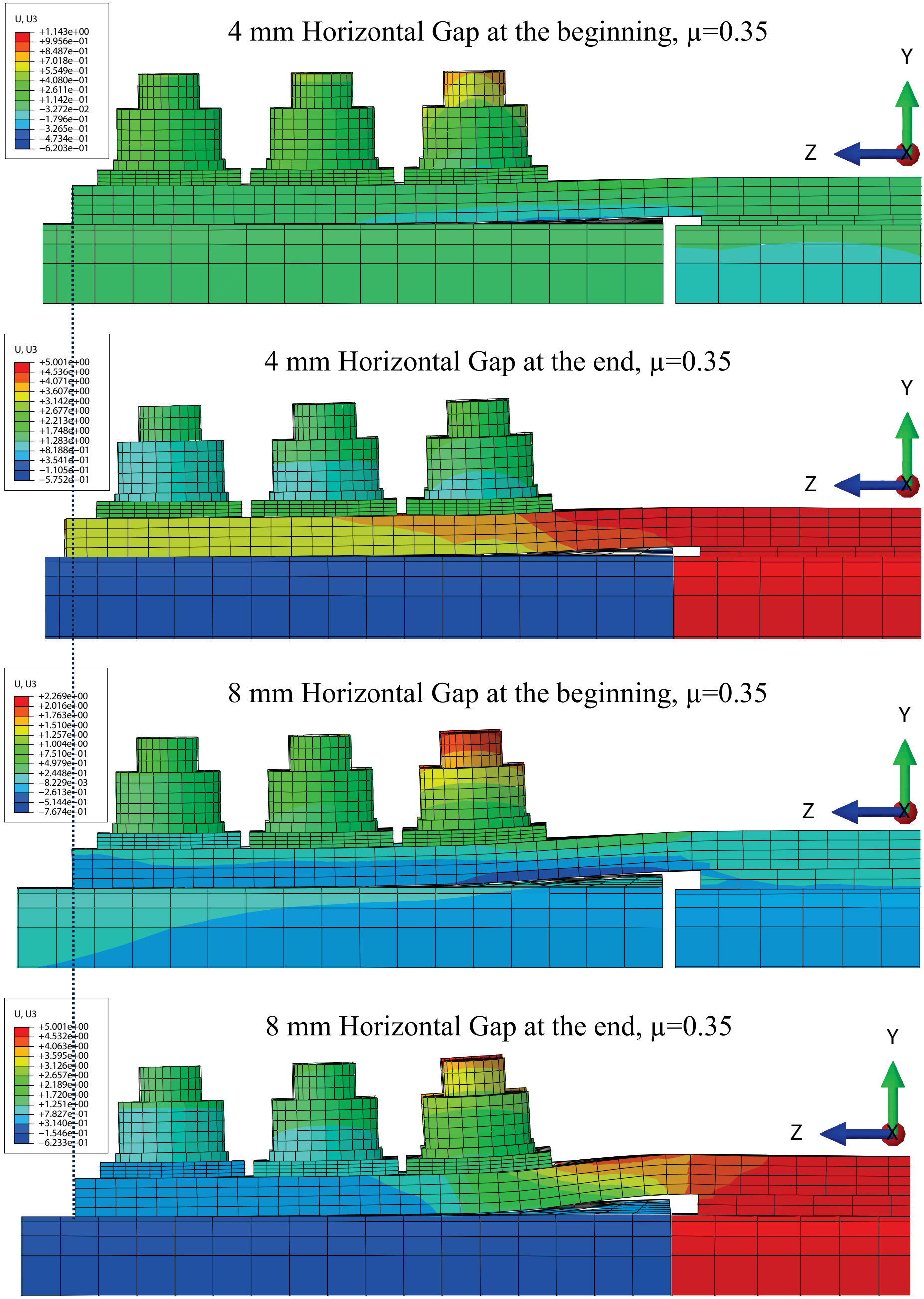


Figure I.3: Model of 4 and 8 mm – z displacements at start and at the end

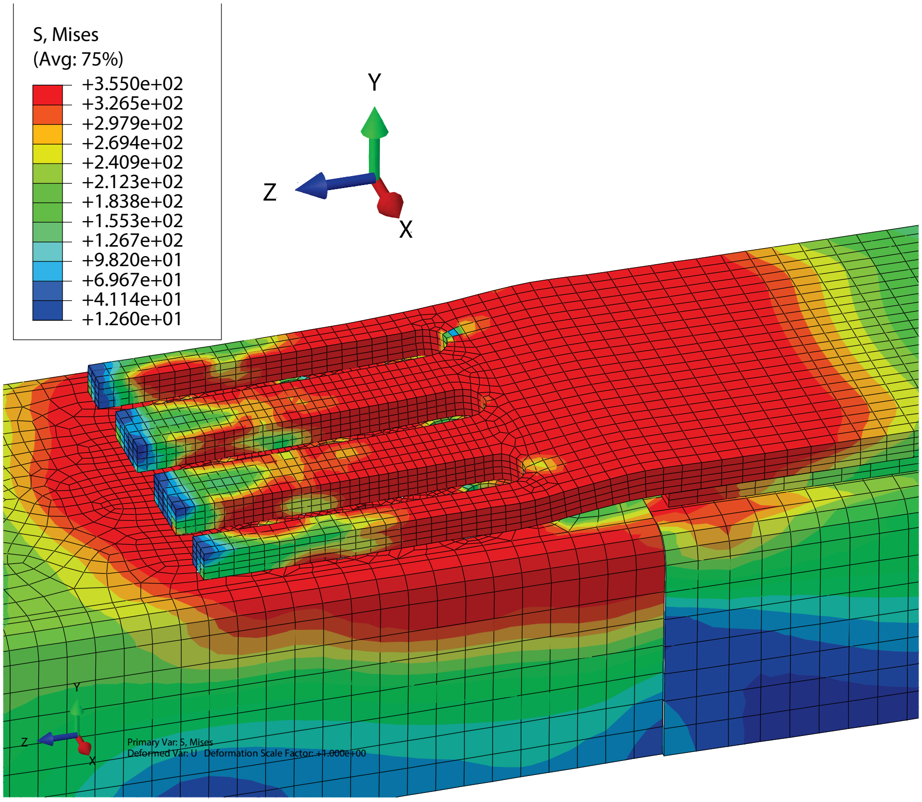


Figure I.4: Model of 8 mm – stresses at the limit of the yield stress $3.550e^{+02}$

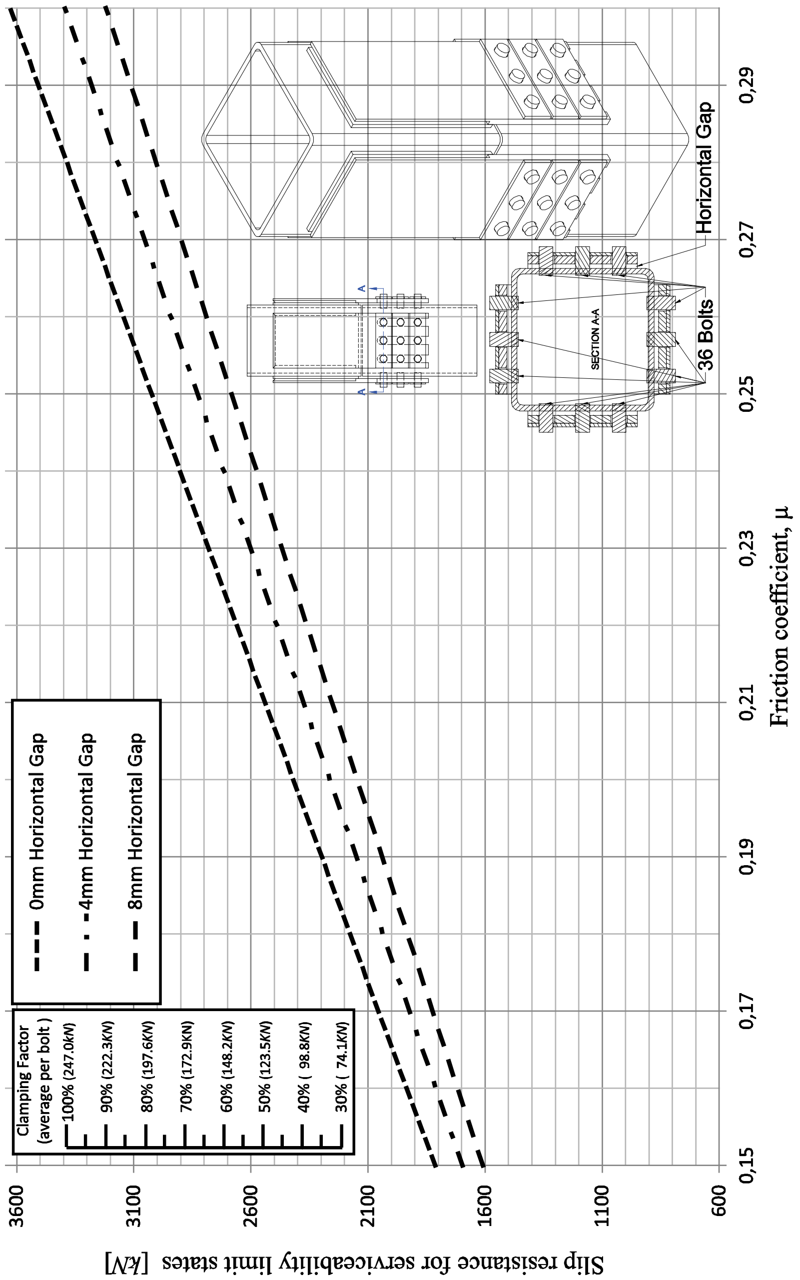


Figure I.5: Nomograph for expedite design of the Finger connection