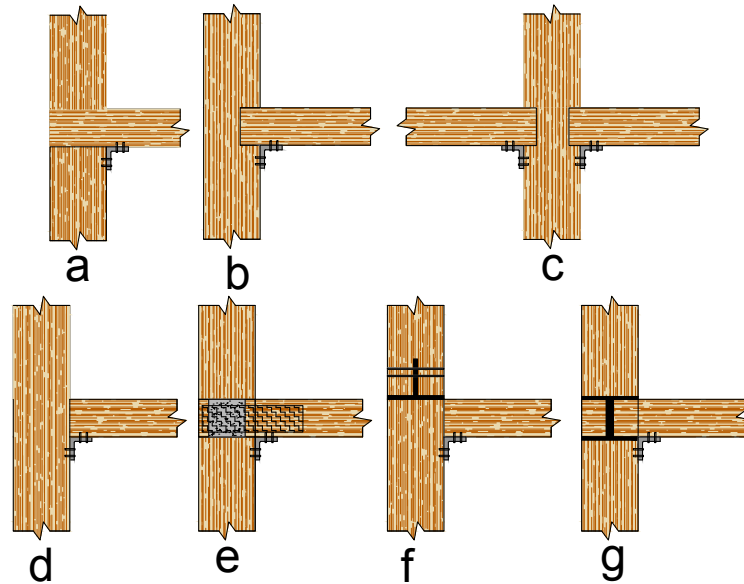
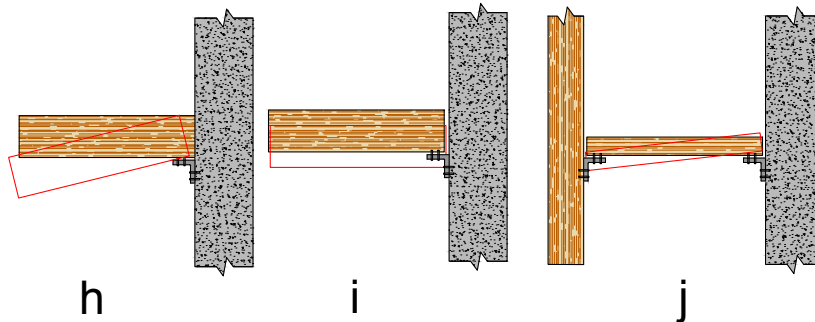




Part-1



Part-2



# Numerical study of connections in a hybrid high-rise timber building

Master's thesis in Master Program Structural Engineering and building technology

Hosamaden Hrh

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MASTER'S THESIS ACEX30 2024

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Gothenburg, Sweden 2024

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Cover: The deformation occurs in timber columns for different types of connections in hybrid high-rise timber buildings.

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## Abstract

When looking at newly constructed buildings worldwide, it is clear that timber has become an important construction material. Many timber buildings have been constructed using advanced technology, creating environmentally friendly structures that also prioritize aesthetic design.

However, when using timber in buildings, several aspects need to be considered, such as the difference in the behavior of materials in hybrid buildings. Timber typically has a lower stiffness than concrete or steel.

This master's thesis focuses on the total deformation of timber columns loaded parallel to the grain and how the type of connection can affect this deformation. Different types of connections are addressed, and the thesis explores how these deformations in timber columns can affect the validation of the connection type between the timber beam/slab and the concrete core.

The study was conducted to determine the total deformation in a high-rise building consisting of 10 floors. Deformations were also studied as the number of floors increased to 20 and 30.

This study analyzes the structural performance of four types of column connections, CBC (column-beam-column), CNC (column-notch-column), CPC (column-pillar-column), and CPPC (column-penetrated plate-column)—in hybrid high-rise timber buildings using Finite Element Analysis (FEA). It models these connections under various loading conditions with realistic material properties and load scenarios.

The findings show that all connection types have significant strength and stiffness, with CPC connections performing the best in deformation resistance. Key factors influencing performance include dimensions, number of floors, load amount, and material type. The study highlights timber's potential as a sustainable construction material for urban environments and suggests future research should focus on experimental validation and innovative connection techniques.

**Keywords:** Timber, connections, high-rise, deformation, column, core, hybrid, notch, pillar.



# Preface

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With this master thesis, we have completed our time at the Chalmers University of Technology and are proud to leave with a degree in structural engineering, fond memories, and friends that will last a lifetime.

Hosamaden Hrh, Khodor Qaraoush, Gothenburg, June 2024



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# List of Symbols

$A$	Area of the cross-section [mm <sup>2</sup> ]
$E$	Elastic modulus [Pa]
$E_1$	Elastic modulus in the principal material direction 1 [Pa]
$E_2$	Elastic modulus in the principal material direction 2 [Pa]
$E_3$	Elastic modulus in the principal material direction 3 [Pa]
$E_{0,\text{mean,fin}}$	Mean value of modulus of elasticity (MOE) [Pa]
$E_{0,\text{mean}}$	Mean modulus of elasticity parallel to the grain or principal material direction [Pa]
$E_{90,\text{mean}}$	Mean modulus of elasticity perpendicular to the grain or principal material direction [Pa]
$F$	Applied load [N]
$G_k$	Characteristic value for permanent load [N]
$G_{12}$	Shear modulus in the plane formed by directions 1 and 2 [Pa]
$G_{13}$	Shear modulus in the plane formed by directions 1 and 3 [Pa]
$G_{23}$	Shear modulus in the plane formed by directions 2 and 3 [Pa]
$L$	Length of the specimen [mm]
$N$	Internal force [N]
$P_1$	External force in the first node [N]
$P_2$	External force in the second node [N]
$Q_d$	Design value for load acting on element [N]
$Q_k$	Characteristic value for variable load [N]
$\delta$	Deformation in the spring [mm]
$\gamma_{g,SLS}$	Partial safety factor for permanent load in SLS [-]
$\gamma_{q,SLS}$	Partial safety factor for variable load in SLS [-]
$\kappa$	Stiffness of the material [N/mm]
$\mathbf{K}^e$	Stiffness matrix [N/mm]
$\mathbf{a}^e$	Element displacement vector [mm]
$\mathbf{f}^e$	External force vector [N]
$\nu$	Poisson ratio [-]
$\nu_{12}$	Poisson's ratio for transverse strain in direction 2 when stressed in direction 1 [-]
$\nu_{13}$	Poisson's ratio for transverse strain in direction 3 when stressed in direction 1 [-]
$\nu_{23}$	Poisson's ratio for transverse strain in direction 3 when stressed in direction 2 [-]
$\psi_0$	Factor for combination value of a variable load [-]
$\psi_1$	Factor for frequent value of a variable load [-]

$\psi_2$	Factor for quasi-permanent value of a variable load [-]
$\psi_2$	Factor for the quasi-permanent value of a variable load [-]
$\sigma$	Stress in the cross-section [Pa]
$\sigma_{c,0,d}$	Design compressive stress in timber [Pa]
$\sigma_{c,0}$	Compression stress, parallel to grain [Pa]
$\sigma_m$	Bending moment stress in timber [Pa]
$\sigma_{t,0}$	Tension stress, parallel to grain [Pa]
$f_{c,d}$	Design compressive strength, parallel to grain [Pa]
$f_{m,d}$	Design bending strength of timber [Pa]
$f_{t,d}$	Design tension strength of timber, parallel to grain [Pa]
$k_c$	Strength related reduction factor [-]
$k_{\text{def}}$	Factor accounting for moisture effects on deformation [-]
$u_1$	Displacement in the first node [mm]
$u_2$	Displacement in the second node [mm]

# List of Acronyms

CLT	Cross laminated timber
EWP	Engineered wood product
Glulam	Glued laminated timber
LVL	Laminated veneer lumber
SLS	Serviceability limit state
ULS	Ultimate limit state
CBC1	Column to beam connection - Case1
CBC2	Column to beam connection - Case2
CPC	Column plate connection
CNC	Notch column connection
CPPC	Column penetrated plate connection
MOE	Module of elasticity
FSP	Fiber saturation point
MC	Moisture content
RH	Relative humidity
RC	Reinforced concrete
CC	Column-to-column connection
PP	Panel to Panel connection
BC	Beam to column connection
BB	Beam to beam connection



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# 1

## Introduction

In this master thesis, the study will go deep into the fascinating world of high-rise timber buildings, and the main focus, particularly on the connections within these structures. Through a detailed numerical study, the study will aim to show the complexities in the connections system when these are linked together with different parts of the structure.

The connections between timber elements play a critical role in ensuring the stability and safety of the building. This study will employ some advanced numerical simulations and analysis techniques to study and investigate various aspects of these connections in different scenarios.

Ultimately, this research aims to optimize and enhancement of connection designs in high-rise timber buildings, this will lead to pushing the limitation of timber construction to make it more stable and safe.

### 1.1 Background

The interest in using timber as a primary building material in the construction industry has significantly increased, both locally and globally. This heightened interest can be attributed to several factors. Firstly, timber is seen as a more economical choice, providing cost-effective solutions for construction projects. Additionally, there is a growing emphasis on sustainability, and timber is considered a more environmentally friendly option, contributing to eco-friendly building practices.

Recently, high-rise timber buildings trend started to grow in the world. In timber building, since the deformations under compression perpendicular to the grain are larger than the deformations under compression parallel to the grain (Jockwer et al., 2021). However, in high-rise timber buildings, the deformation under compression parallel to the grain must be checked to ensure more durability and functionality of the designed connections.

Moreover, the demand for high-rise buildings is increasing in urban areas. To address this need and establish timber as a viable solution for such structures, the concept of hybrid structures has emerged. Hybrid structures combine the strengths of different materials, particularly timber, steel, and concrete, to create buildings that are not only environmentally sustainable but also capable of meeting the structural demands of taller constructions.

## 1.2 Problem description

When integrating timber and concrete, many challenges arise since the concrete and timber respond in different ways to applied loads. For example, in the long-term duration of vertical loads, the deformations result of creep and shrinkage will significantly differ for these two materials when they are subjected to the same magnitude of loads and weather conditions (temperature and relative humidity).

To understand the impact of vertical load on the connection areas, such as the connection area between columns, various types of connection categories need to be considered, including adhesive, bolted, dowel, and notch connections. In this study, several types of column-to-column connections will be evaluated to assess the magnitude of vertical displacement.

Furthermore, it is important to consider the varying degrees of deformation between timber and concrete when designing the connection between these two materials, particularly in the connection between core-to-timber beams and core-to-CLT panels. Figure 1.1 illustrates several connections that will be further studied in the project.

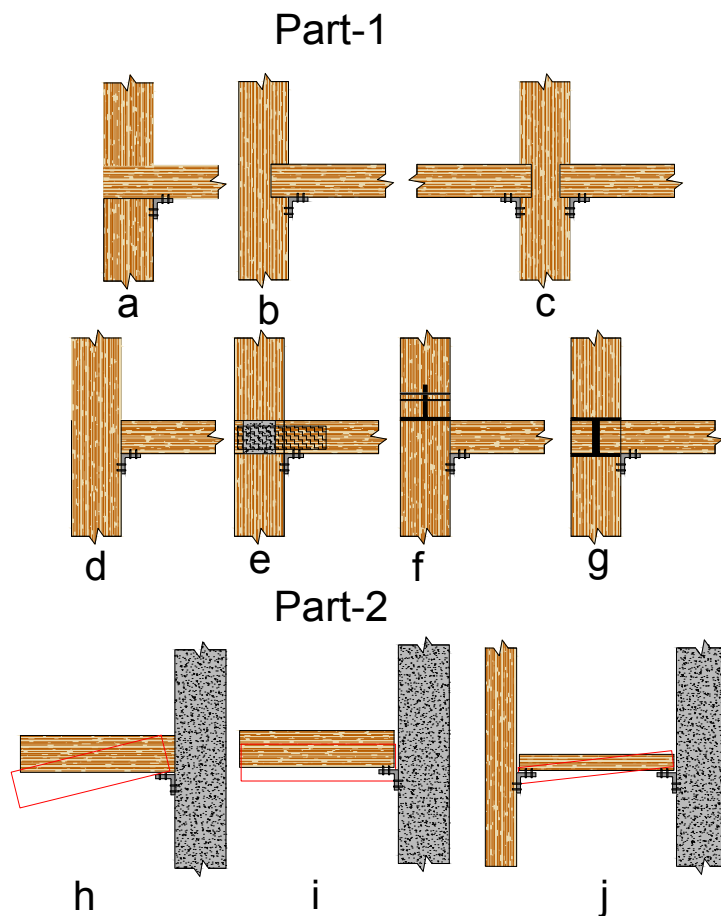


Figure 1.1: Some type of connections

### 1.3 Aim and objectives

This study will primarily focus on the vertical deformation of a column when it is subjected to compression parallel to the grain. The research will also explore the long-term impact of the connection and how the type of connection can influence the overall deformation of the structural system. Furthermore, Matlab and Abaqus FEM program will be used to conduct a detailed analysis of the chosen connection and its influence on the structure's deformation.

In conclusion, the study aims to provide insights into connecting beams and slabs with the core while addressing differences in deformation between columns and the core, all while maintaining the stability and safety of the building.

### 1.4 Methods

The tasks outlined in this master's thesis encompass the following stages:

- Presenting and explaining the findings derived from prior studies on the performance of diverse materials and connections within a hybrid timber building.
- Examination of the effect of loading parallel to the grain on the magnitude of deformation.
- providing a numerical study for different types of connections using Matlab.
- Simulation study using Abaqus FEM to understand the connection behavior under loading.

### 1.5 Limitations

The fictitious building dimensions are  $20m \times 20m$  with a concrete core in the center and the building consists of 10 floors. The building is located in Gothenburg, Sweden. The main users of the building are office workers.

Timber components such as columns, and beams are verified in the ultimate limit state (ULS) and serviceability limit state (SLS), the effect of dynamic deformations has been overlooked. The connections will be studied only under compressive stress. The study is based on the requirements and regulations followed by the Swedish Standards Institute (Swedish Standards Institute, 2010).



# 2

## Construction material

Since this thesis focuses on the connections in Hybrid-structure of timber and concrete, this chapter of the project introduces both material, and material properties, and provides the theory phenomena behind the different responses for these materials. In addition, the effect of applying force on the behavior of the material.

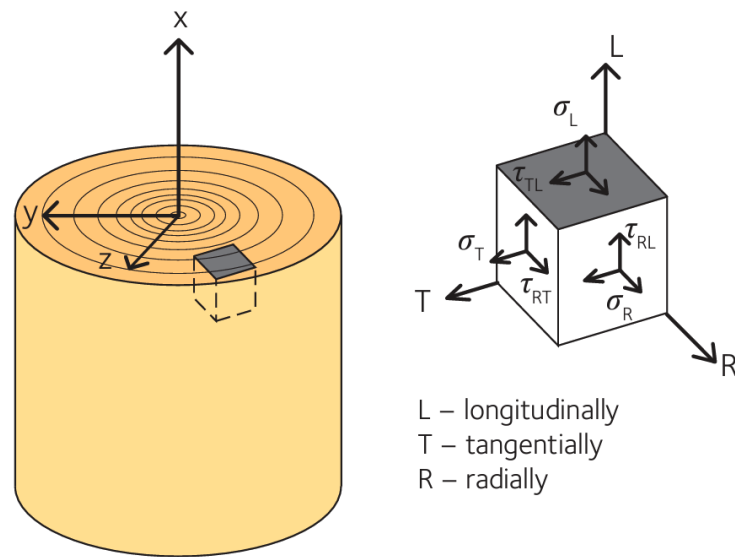
### 2.1 Timber

Timber has been used for a long time in building construction as a major building material, since it is renewable, and has unique environmental and economic benefits compared to other types of building materials concrete and steel. Timber is naturally formed in an ecological cycle that absorbs carbon dioxide (CO<sub>2</sub>) from the air. In addition to these unique benefits, timber is considered a strong building material relative to its weight, making it suitable for construction. Nowadays the use of timber to build large multi-story buildings in growth (Svenskt Trä, 2024).

#### 2.1.1 Timber physical properties

Timber is an anisotropic material which means its properties vary in different directions. Where timber has three different directions which are Longitudinal (L), Tangential, (T), and Radial (R) directions, these these directions are shown in Figure 2.1. Since the difference in behavior in the radial and tangential directions are disregarded the directions of timber specimens are expressed in two ways, parallel or longitudinal to the grain.

Moisture(u) is one of the external factors that can affect the properties of timber, the moisture in timber is always dependent on the moisture content MC of the surrounding air (Swedish Wood, 2022). One often used concept is fiber saturation point (FSP), defined as the MC in timber specimens when the cell wall is filled with water but the cell cavities are still empty. Basically, If the MC is reduced, timber shrinks, but if it increases, timber swells. Moreover, the density of timber is a fundamental physical property of timber. The density of timber is influenced by its moisture content (MC) and increases as the MC of timber increases.



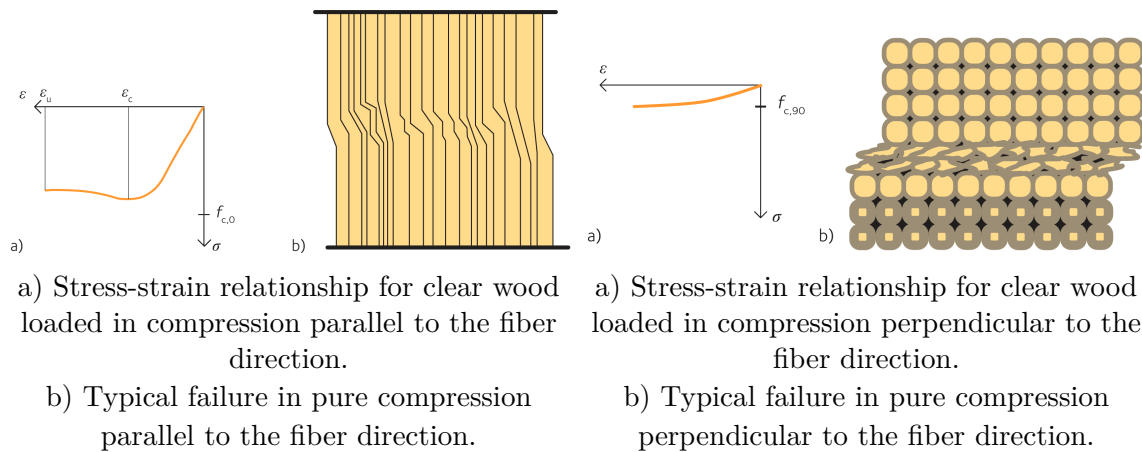
**Figure 2.1:** Longitudinal, tangential, and radial direction of wood (Swedish Wood, 2022a).

For timber, the effects of the natural characteristics such as knots, spiral grain angle, etc., will be large and largely decide the specimen's properties and behavior. Then, to describe the real behavior of timber, 12 constants are needed, modulus of elasticity (MOE), shear modulus ( $G$ ), and Poisson's ratio ( $\nu$ ) in the three directions. But because of disregarding the differences in L and R directions, these constants can be reduced to six in parallel and perpendicular directions.

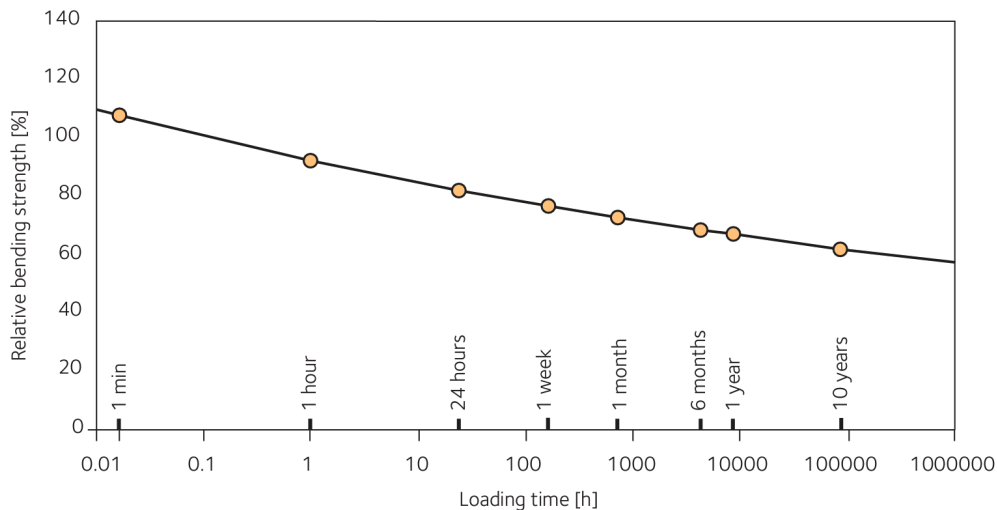
### 2.1.2 Timber mechanical properties

Many factors can influence the strength and stiffness of timber specimens. For instance, the way of loading perpendicular or parallel to the grain directions, compression, or tension. For instance, in the case of loading parallel to the fiber's direction, timber is significantly stronger than in the case of loading perpendicular to the fibers, see Figure 2.2 and Figure 2.3.

Moisture influences the strength of timber too, when the moisture content (MC) of timber is lower, its strength and stiffness are higher. Another factor that also affects the strength of wood is time. Tests show that the bending strength decreases with increasing loading time as shown in Figure 2.3. Additionally, the strength and stiffness of timber are influenced by factors such as the size of the specimen, temperature, and long-term deformations.



**Figure 2.2:** Compression parallel and perpendicular to the grain (Swedish Wood, 2022a).

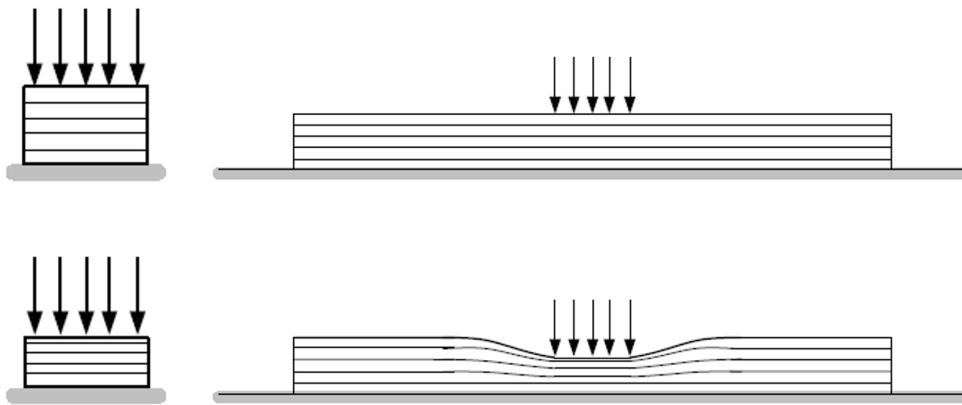


The relationship between relative bending strength and loading time

**Figure 2.3:** Loading time (Swedish Wood, 2022a).

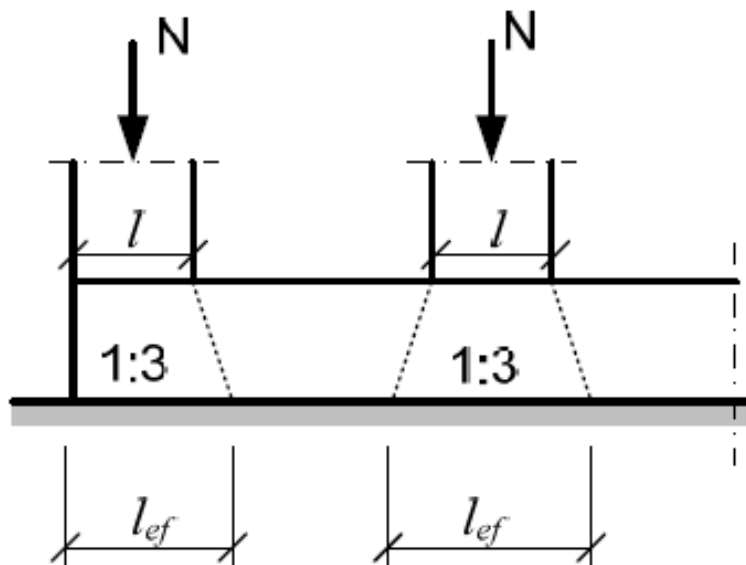
### 2.1.3 Timber behavior under loading

The strength of timber specimen subjected to a compression load perpendicular to the grain is low, in the case of small timber specimen as shown in Figure 2.4. However, when a timber component, such as a beam, is loaded perpendicular to the grain, there is an increase in strength. This occurs because the grain along the timber component acts as a unified unit, collectively resisting the pressure. This phenomenon is known as the stamping pressure effect (Al-Emrani et al., 2011).



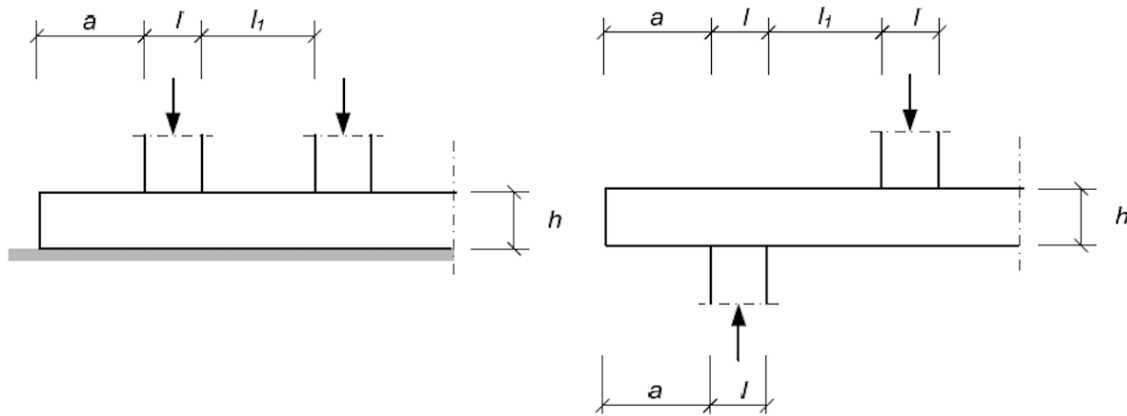
**Figure 2.4:** Timber specimen loaded in compression perpendicular to the grain (Al-Emrani et al., 2011).

The stamping pressure effect describes the load spreading out over a larger area. It is assumed that the force spreads at a ratio of 1:3. The stamping effect is illustrated in Figure 2.5.



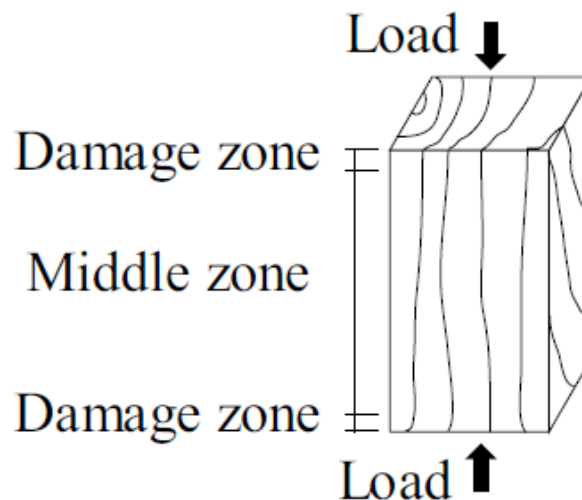
**Figure 2.5:** The stamping pressure effect and force spreads ratio (Al-Emrani et al., 2011).

Therefore, the contact area which is loaded perpendicular to the grain  $A_{ef}$ , should be determined taking into account an effective length parallel to the grain, where the actual length of the area is  $l$ , which means the length of the effective area should be increased by 30 mm on each side, but not more than  $(a, l$  or  $l/2)$  see Figure 2.6.



**Figure 2.6:** Continuous support (left) and discrete supports (right) (Al-Emrani et al., 2011).

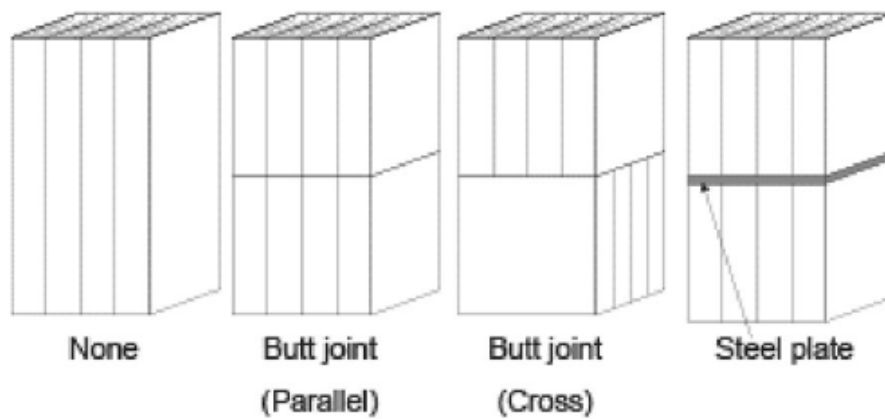
When a glulam specimen is subjected to a load parallel to the grain, it will exhibit three distinct zones: a damage zone at the top, a middle zone, and another damage zone at the bottom. These zones are illustrated in Figure 2.7 (Totsuka et al., 2022). The main difference in these zones is the change in modulus of elasticity (MOE) as it decreases in the damage zones.



**Figure 2.7:** Explanation of the damage and middle zone (Totsuka et al., 2022).

According to the experiment, the results show that the damage zone excited near the loading plates and the joints, and the length of the damage zone is independent of the type of joint e.g. butt joint (parallel/cross) or steel plate, see Figure 2.8.

However, the results show that the length of the damage zone is affected by several factors such as the width of the cross-section and it increases if the width increases. Moreover, the length of the damage zone depends on the roughness of the contact surface and increases if the contact surface area increases. Moreover, the length of the damage zone for wood-to-wood joints is larger than for wood-to-steel joints.



**Figure 2.8:** Joints types (Totsuka et al., 2022).

### 2.1.4 Different types of timber

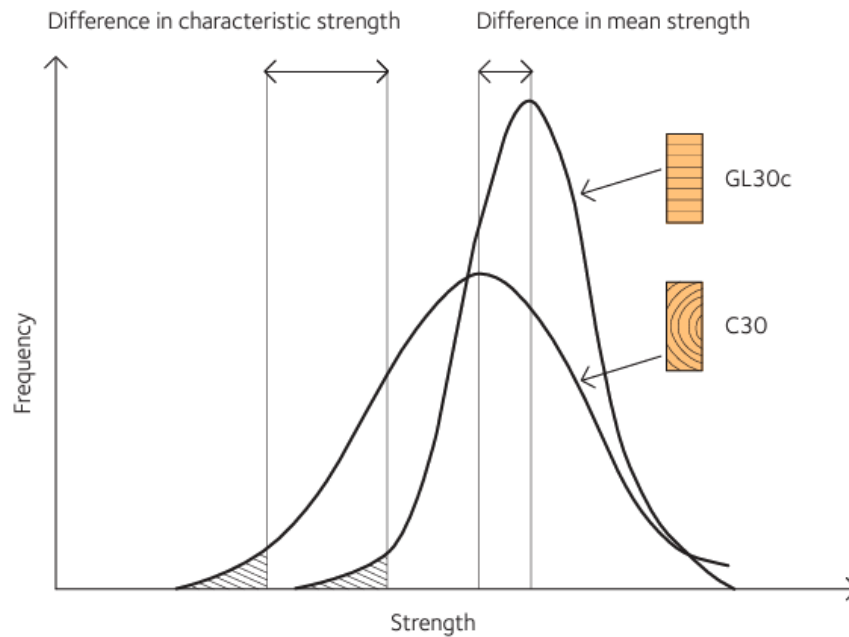
Various types of timber products will be addressed and briefly explained. Each type has unique properties and applications, making them suitable for different construction needs. For instance,

- Glued laminated timber.
- Cross-laminated timber – CLT.
- Laminated veneer lumber – LVL.
- Plywood.

#### 2.1.4.1 Glued laminated timber

Glulam is known as one of the oldest types of Engineered wood products (EWP) that is made by gluing many layers of laminated timber. Firstly, the layers are sawed and dried, and then by using adhesive, the layers are glued together. Secondly, the glued laminated layers are put in a press under special temperature and pressure for a certain time to get the finished product.

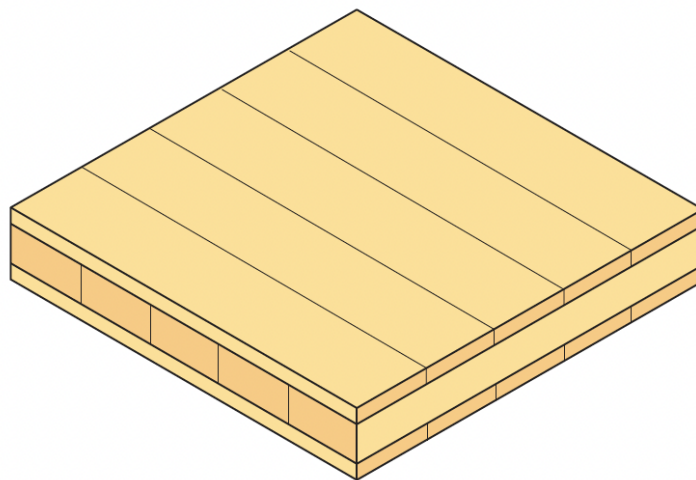
Glued laminated timber, commonly known as glulam, stands out as an exceptional engineering wood product renowned for its strength, stability, and versatility when compared to solid timber. Glulam possesses the remarkable capacity to bear heavy loads and span considerable distances. Figure 2.9 shows the difference in strength between glulam and solid timber (Swedish Wood, 2022a).



**Figure 2.9:** Distribution function for the strength of glulam beams and structural timber (Swedish Wood, 2022a).

#### 2.1.4.2 Cross-laminated timber – CLT

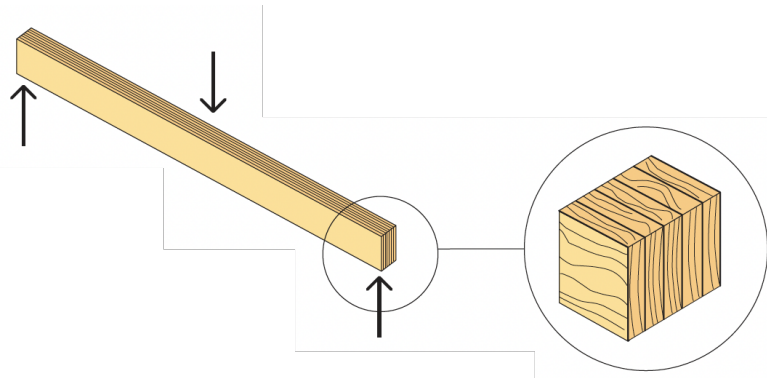
Cross-laminated timber (CLT) is constructed using layers of wood panels that are perpendicular to each other. These CLT panels are commonly used as load-bearing vertical and horizontal elements, such as walls or floor diaphragms. Each layer consists of boards placed perpendicular to those in the layer below 2.10. CLT can be manufactured with 3, 5, 7, or more layers, with varying thicknesses. An odd number of layers provides better strength for CLT (Swedish Wood, 2022a).



**Figure 2.10:** Cross-laminated timber – CLT (Swedish Wood, 2022a).

### 2.1.4.3 Laminated veneer lumber – LVL

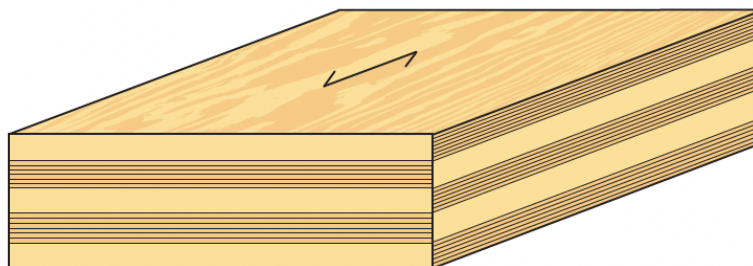
Laminated Veneer Lumber (LVL) is created by gluing together veneer sheets, resulting in high bending, compression, and tension strength due to removing defects before production. LVL can be oriented with fibers in the same direction or perpendicular, depending on the type. The gluing process creates a highly reliable structural element with low variability through defect elimination. For a visual example of LVL, see Figure 2.11 (Swedish Wood, 2022a).



**Figure 2.11:** Laminated veneer lumber – LVL (Swedish Wood, 2022a)

### 2.1.4.4 Plywood

Plywood is similar to LVL but with all, veneers placed perpendicular to each other. The number of veneers is always odd means the fiber direction of the outer layers is always in the same direction, 2.12. This kind of building material has exceptional strength, durability, and resistance to warping. It is common to add some additional material in the top and bottom layers to give plywood resistance to water and fire (Swedish Wood, 2022a).



**Figure 2.12:** Plywood (Swedish Wood, 2022a)

## 2.2 Concrete

The most used building material in the world is concrete. It is used to build bridges, tunnels, roads, railways, houses, and buildings. Some advantages of concrete are strong, cheap, easy to use and handle and it can be used as a prefabricated element or as cast on-site. Buildings that were built in concrete a long time ago do not need much maintenance, this makes concrete a good material choice to minimize the cost of maintenance and reparations (Al-Emrani et al., 2019).

Concrete is a mixture of cement, aggregates, water, and admixtures. Admixtures play a crucial role in modifying the properties of concrete to achieve desired characteristics (Al-Emrani et al., 2019). While concrete has a high compressive strength, its tension strength is only a tenth of the compressive strength. The mixture ratio of the concrete paste makes it classified into different strength classes ranging from C12/15 to C90/105. In this classification, the first number represents the characteristic compressive cylinder strength in  $MPa$ , while the second number represents the characteristic cube strength in  $MPa$  (Al-Emrani et al., 2019).

Because the tensile strength of concrete is low. Therefore, it is natural that concrete cracks if it is subjected to tensile forces. Regarding the structure behavior and the importance of preventing cracks in a structure, concrete can have several types e.g., plain concrete, reinforced concrete, and prestressed concrete (Engström, 2014a).

Cracks can occur due to various factors including drying shrinkage, temperature changes, applied loads, and chemical reactions. To address these concerns, careful attention is given to the formulation of concrete mix designs, which involve the inclusion of reinforcements, control joints, and meticulous curing techniques to effectively manage shrinkage and control the occurrence of cracks.

In addition, concrete will deform when it is stressed. This type of deformation which is stress-dependent can be divided into immediate elastic deformation and creep deformation. Creep deformation increases with time until the final creep value reaches after a long time. This long-term behavior of concrete is influenced by factors such as its composition, curing conditions, temperature, and moisture (Engström, 2014b).



# 3

## Constructions

In this chapter, a brief background about the several types of structural systems in timber used in hybrid structures of timber and concrete will be provided. Moreover, different types of connections will be discussed in this section.

### 3.1 Structural system in timber

There are various timber construction techniques and structural timber systems. Where the project's condition, such as span, load, project size, and completion requirements, determine which type of this system is most suitable (Bergkvist and Fröbel, 2020).

The several types of structural systems are frame systems, in-situ construction, pre-fabricated element systems, column and beam systems, and modular Systems.

In this thesis, the structural system of beams and columns will be studied to check its functionality and durability regarding the long-term deformation (Bergkvist and Fröbel, 2020).

#### 3.1.1 Beam-column system

For 100 years ago the beam-column systems existed as glued laminated timber constructions (GLT) but have rarely been seen as a specific timber construction system (Swedish Wood, 2016). The system consists of a grid of Beams and columns that are designed to resist the vertical loads acting on the structure.

Where the lateral load in case of wind or seismic action is resisted by diagonal bracing or shear wall/ RC core, see Figure 3.2.

This setup increases the thermal capacity of the whole building and improves its energy efficiency. Nowadays, several complete beam-column systems are also available on the market, as prefabricated elements with specific sizes and mechanical properties.



**Figure 3.1:** Beam-column structure system (Robertson et al., 2012)

#### 3.1.2 Panel-system

This type of structural system is prevalent for all types of wooden houses, including single and multi-family houses as well as office buildings (Svenskt Trä, 2024). The load-bearing structure system comprises traditional beams, CLT, or cassette construction, and wall and floor elements. They are usually fully or partially insulated.

The construction process for this type of structural system requires on-site lifting, such as a crane, to lift and mount the elements in place. The system should be able to handle weights of up to three tons. There are many advantages of using a panel system such as the construction time on site being significantly reduced. For multi-story buildings that have long construction times, special weather protection needs to be provided and which is available on the market.



**Figure 3.2:** Panel-system (Lesprom Network, 2023).

### 3.1.3 Modular system

Modular elements are an innovative building solution comprising several rooms or parts of the building (Svenskt Trä, 2024). These self-supported volumes consist of walls, floors, and roofs made of panel elements connected to other volumes. The elements are highly completed and include all types of installations see Figure 3.3.

Cross-laminated timber (CLT) products are often used in this system. The size of these modular elements is limited to transportation. One of the significant advantages of using this system is that over 80 percent of the work is done indoors, which can reduce on-site construction time to 20-30 percent.

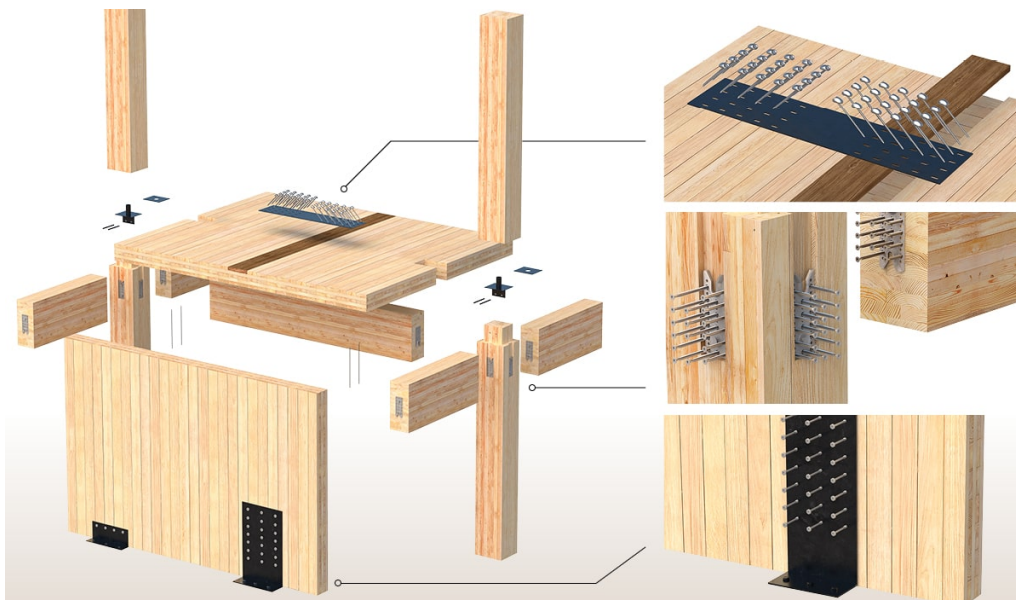


**Figure 3.3:** Modular system (Schrammen Architekten BDA, 2023).

## 3.2 Connections

The structural system of a building consists of various components, including columns, beams, and wall panels, all of which are interconnected. It is essential to ensure that these connections are durable, robust, and long-lasting to support the overall structure during its service life. It is also important to determine which connection system would be best suited for a specific application.

For instance, in timber structures, connections must be designed to carry loads in tension, compression, and bending. Several types of connections are used, depending on the components being connected, such as Beam to Beam (BB), Beam to Column (BC), Column to Column (CC), and Panel to Panel (PP), see Figure 3.4. This section will discuss different types of connections used today.



**Figure 3.4:** A general explanation of several connections in the building ((MTC Solutions, 2023))

In Figure 3.4, there's an illustration detailing how beams are connected to columns and how provisions are made for continuity to the next column above.

### 3.2.1 Connection type (BB/BC)

Generally, there are two ways to connect timber elements in a structured system such as adhesive or mechanical (Fairham, 2019). This focuses more on the mechanical types of connections between two beams or columns to Beams used in timber structures today.

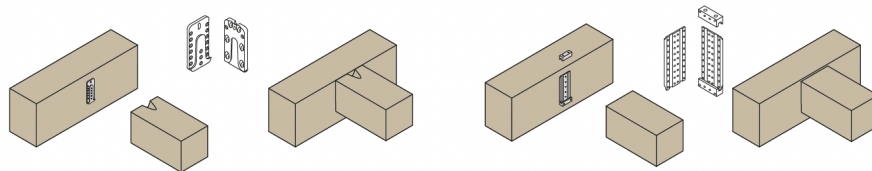
#### 3.2.1.1 Hook connector (BB/BC)

The hook connector is a mechanical connection system with a high degree of prefabrication (Pozzi, 2019). It is composed of two distinct parts that are already connected

to the two elements. These parts are designed such that they can be easily interlocked creating a strong connection which is then generally secured using a single fastener that locks the direction opposite to the insertion, see Figure 3.5.

On the left, is the UV-T type connection, while on the right is the MEGANT type connection. These connections offer several advantages, such as being nearly hidden, making them an excellent choice for fire safety. Additionally, both types of connection systems provide movement locks in all directions. However, there are also some disadvantages to consider. One of them is that these connections require a significant number of fasteners to secure the system, which can be costly.

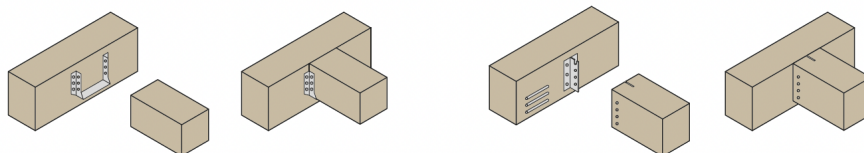
The UV-T connection is comparatively rigid and can resist shear forces up to  $65\text{ kN}$ , making it suitable for small temporary structures. In contrast, the MEGANT connection can withstand up to  $400\text{ kN}$  when employing the largest connectors. The main advantage of this connection system is related to the fast installation and the possibility of easy disassembly which makes this system especially suitable for temporary structures.



**Figure 3.5:** Hook connector-left UV-T/ right MEGANT (Pozzi, 2019).

### 3.2.1.2 Metallic hanger (BB/BC)

The metallic hanger is a commonly used connection system in engineered timber structures (Pozzi, 2019). The brackets are L-shaped with holes on the two wings to accommodate the fasteners which secure the connection to the elements, see Figure 3.6. Since the panel elements of these structures must bear both shear and tensile forces different brackets are designed for these two purposes long vertical ones for tensile forces and low horizontal ones for shear forces. These brackets are usually connected through nails, but screws are also used if there is a need of having a reversible connection.



**Figure 3.6:** Metallic hanger (Pozzi, 2019).

## 3.2.2 Connection type (CC)

Continuity in structural elements, such as columns, is important to distributing loads effectively. Continuity can be achieved through various methods. In timber

construction, particularly in high-rise buildings and heavy loads, column-column connections play a crucial role in ensuring structural safety.

#### 3.2.2.1 Post connector

The first type of connection involves a cross plate attached to one element with bolts or screws and penetrating the second element with a horizontally oriented dowel (Pozzi, 2019). This connection system restricts movement in all directions and is relatively stiff, but the fasteners may split if placed perpendicular to the load. It is easy to assemble and disassemble.

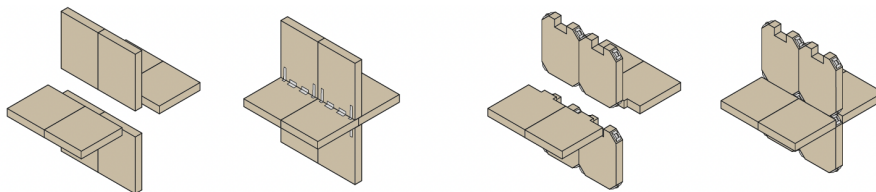
The second type of connection is a circular plug attached to both elements (Pozzi, 2019). This connection type also restricts movement in all directions and is considered relatively stiff, but attention must be paid to the interlocking steel element during the design. Additionally, it is considered a very easy connection to assemble and disassemble, see Figure 3.7.



**Figure 3.7:** Post connector- Cross (Left) circular (Right) (Pozzi, 2019).

#### 3.2.3 Panel connection (P)

The connection system is assumed to be stiff since specific bracket systems are designed to handle both shear and tensile stress (Pozzi, 2019). The connection system is locked for all movements in all directions. It is relatively easy to assemble and disassemble, requiring simple tools and minimal worker instructions, see Figure 3.8.



**Figure 3.8:** Brackets(left) and X-RAD(Right) (Pozzi, 2019).

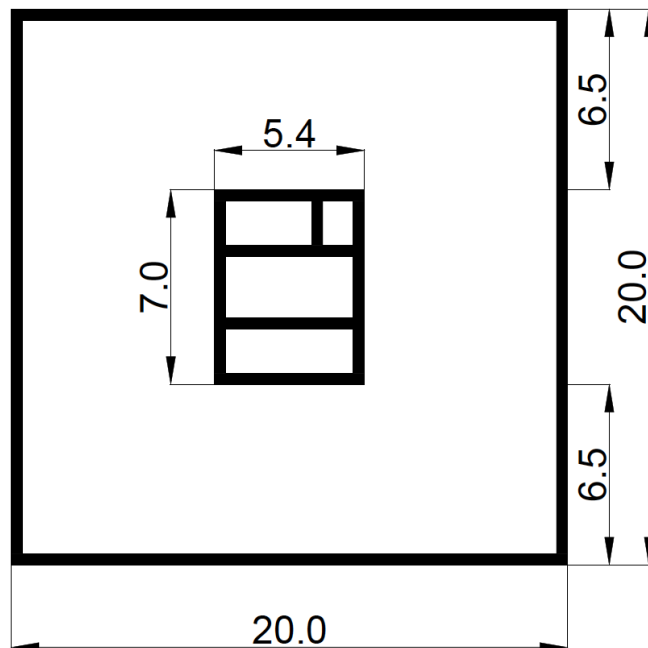
# 4

## Design of beam and column

In this chapter of the project, a fictitious office building is to be studied. The structural system of the building is to be provided. The different types of loads and load combinations will be addressed for both cases in the ultimate limit state (ULS) to optimize the final preliminary sizing of timber members, and service limit state (SLS) to optimize the long-term effect on the timber members.

### 4.1 The case study building

The fictional high-rise office building is located in Gothenburg, Sweden. It has a square footprint of 20 meters by 20 meters and a height of 3 meters on each floor. The building has a standard urban design with a flat roof made of concrete, which adds more mass to the overall structure. The total number of floors for the building can vary between 10, 20, and 30, depending on the scenario. In each case, all floors have the same layout see Figure 4.1.



**Figure 4.1:** Floor plan

### 4.1.1 Structural system/components

The building's structural system is composed of a beam-column system with a concrete core at the center, as shown in Figure 4.2. The columns will be distributed along the building's facade, with beams spanning between them. Each column will span over two stories and have a length of 6 meters. Cross-laminated timber (CLT) panels will be distributed perpendicular to the columns and core. These panels will be supported by the beams and central core through mechanical connections or adhesive.

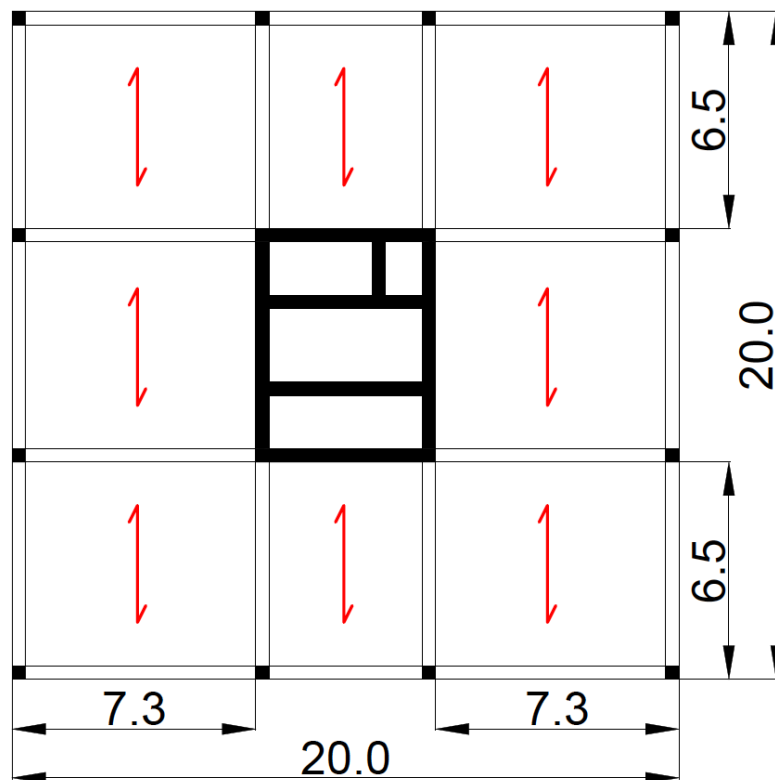


Figure 4.2: Structural system

## 4.2 Material properties

The columns and beams are made of glued laminated timber GL30c. The floors are constructed using CLT panels C24, while the roof is made of concrete C30/37.

Various types of connections need to be used depending on the type of timber member that needs to be connected, such as beam-to-beam, column-to-column, and panel connections.

However, this study will only examine the connections between vertical elements and the core-timber connection. The materials properties of interest to be studied here are shown in Table 4.1 and 4.2, and these properties are given in Eurocode (Swedish Standards Institute, 2010).

**Table 4.1:** Timber properties

	<b>Glulam GL30c</b>	<b>CLT C24</b>
$f_{c,0,k}$ [MPa]	24.5	21
$f_{c,90,k}$ [MPa]	2.5	2.0
$f_{m,k}$ [MPa]	30	24
$E_{t,0,mean}$ [MPa]	11 000	11 000
$E_{0,mean}$ [MPa]	13 000	11 000
$E_{90,mean}$ [MPa]	300	370
$\rho_{t,k}$ [kg/m <sup>3</sup> ]	390	350

**Table 4.2:** Concrete properties

<b>Class</b>	<b>C30/37</b>
$f_{ck}$ [MPa]	30
$E_{cm}$ [MPa]	33 000
$\rho_c$ [kg/m <sup>3</sup> ]	2 400

### 4.3 SLS

Serviceability Limit State (SLS) is a state where the structure can no longer fulfill its intended functionality criteria during its service life (Al-Emrani et al., 2019). In this state, the long-term behavior of a structure is governed by design.

Therefore, deflection, which is evaluated over time, is critical for the SLS state. The design load is calculated according to the equation 4.2. (Swedish Standards Institute, 2010).

$$Q_d = \sum_{j \geq 1} \gamma_{g,SLS,j} * G_{k,j} + \gamma_{q,SLS} * Q_{k,1} + \sum_{i > 1} \gamma_{q,SLS} * \psi_{0,i} * Q_{k,i} \quad (4.1)$$

$$Q_d = \sum_{j \geq 1} \gamma_{g,SLS,j} * G_{k,j} + \sum_{i > 1} \gamma_{q,SLS} * \psi_{2,i} * Q_{k,i} \quad (4.2)$$

where,

$Q_d$	design value for load acting on element [N].
$G_k$	characteristic value for permanent load [N].
$Q_k$	characteristic value for variable load [N].
$\psi_0$	factor for combination value of a variable load [-].
$\psi_2$	factor for the quasi-permanent value of a variable load [-].
$\gamma_{g,SLS}$	partial safety factor for permanent load in SLS [-]. = 1.0
$\gamma_{q,SLS}$	partial safety factor for variable load in SLS [-]. = 1.0

## 4.4 ULS

When a structural member can no longer bear the load and is about to collapse, it is known as the Ultimate Limit State (ULS). To verify this state, various checks such as compression stress, tension stress, bending, and buckling need to be conducted. For timber components, these different checks should fulfill certain criteria, according to Eurocode and applicable annexes.

The load combination for ULS is calculated according to the equation 4.3 (Swedish Standards Institute, 2010). ULS is verified by load-resistant capacity in compression, tension, bending, and buckling.

$\sigma_{c,0} \leq f_{c,d}$	Check of compressive strength capacity parallel to grain.
$\sigma_{t,0} \leq f_{t,d}$	Check of tensile strength capacity parallel to grain.
$\sigma_m \leq f_{m,d}$	Check of bending capacity.
$\sigma_{c,0,d} \leq k_c \times f_{c,d}$	Check of buckling parallel to grain.

where,

$\sigma_{c,0}$	compression stress, parallel to grain [Pa].
$\sigma_{t,0}$	tension stress, parallel to grain [Pa].
$\sigma_m$	bending moment stress in timber [Pa].
$\sigma_{c,0,d}$	design compressive stress in timber [Pa].
$f_{c,d}$	design compressive strength, parallel to grain [Pa].
$f_{t,d}$	design tension strength of timber, parallel to grain [Pa].
$f_{m,d}$	design bending strength of timber [Pa].
$k_c$	strength related reduction factor [-].

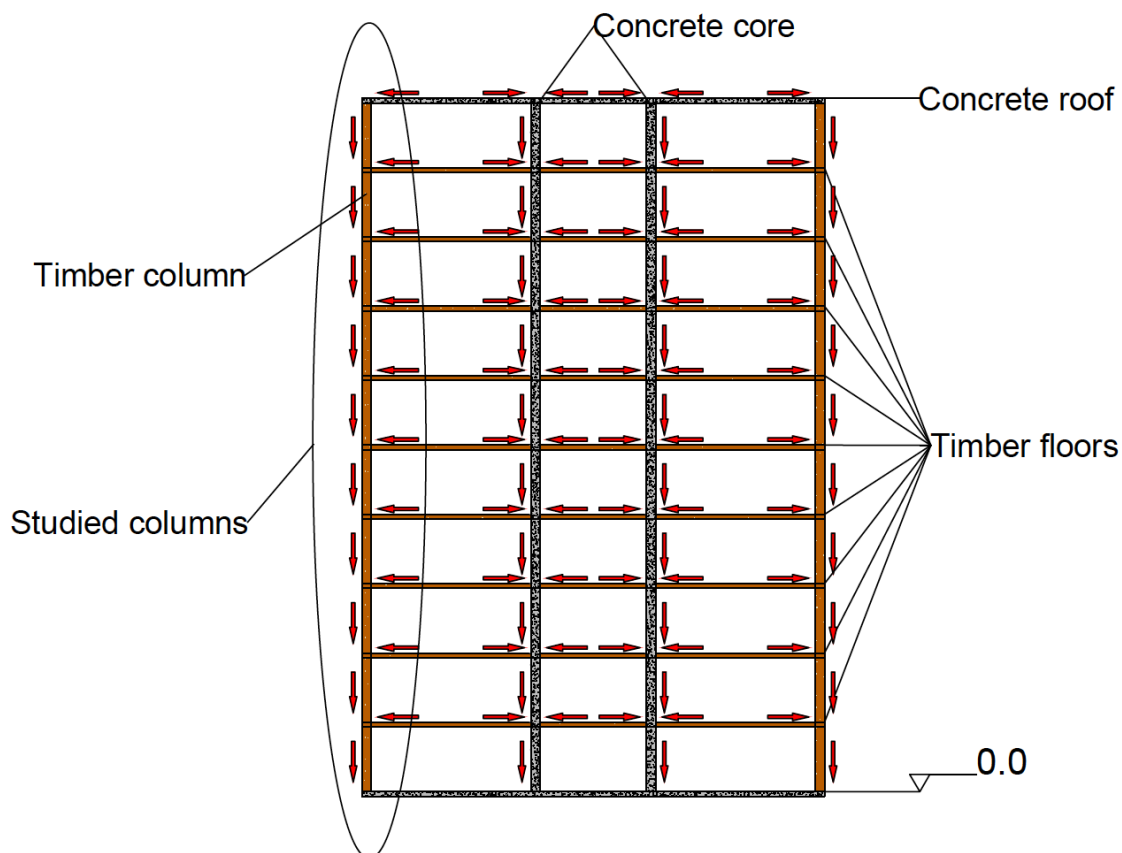
$$Q_d = \sum_{j \geq 1} \gamma_{g,ULS,j} * G_{k,j} + \gamma_{q,ULS} * Q_{k,1} + \sum_{i > 1} \gamma_{q,ULS} * \psi_{0,i} * Q_{k,i} \quad (4.3)$$

## 4.5 Loads

The studied building will be subjected to different types of loads throughout its lifetime. These loads can be categorized into two types, permanent loads and variable loads. In the design process, the size of the timber members should be defined to carry these loads in the ultimate limit state (ULS).

### 4.5.1 Load path

Within a building, the vertical load path refers to the path of the structural load that transfers from the top of the building to the foundation, where the structural load, in the end, is dispersed into the ground. For instance, the surface load acting on the CLT panels on each floor transfers to the beams and by the connections to the vertical components, which are columns, to the foundations see Figure 4.3.



**Figure 4.3:** Load path in the whole building

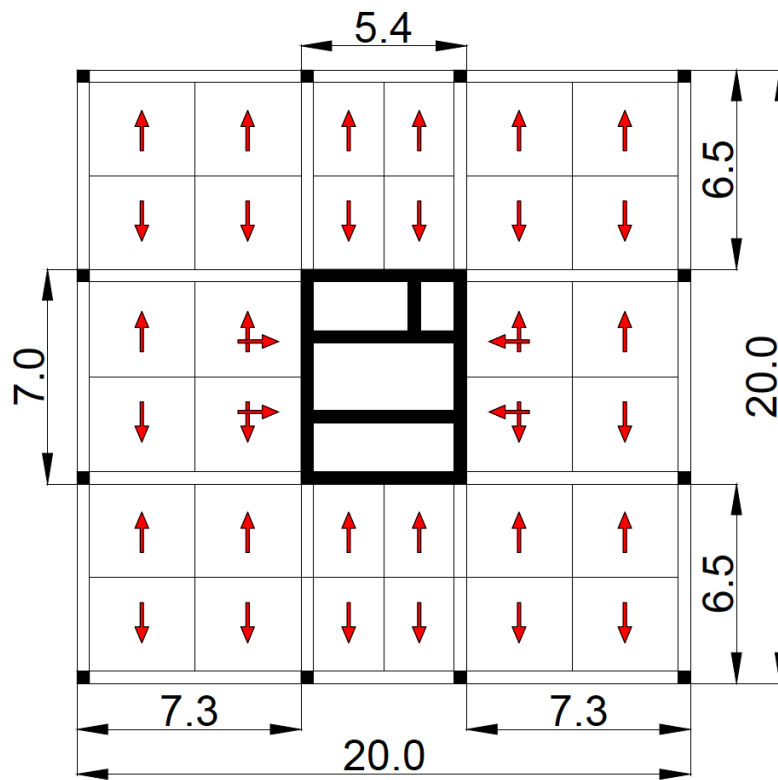


Figure 4.4: Load dividings lines

### 4.5.2 Permanent load

Permanent loads, also known as dead loads, refer to the loads that vary very little over the lifetime of a structure (Al-Emrani et al., 2019). They include the self-weight of timber components, concrete roof and core elements, and installations. Table 4.3 shows the self-weight of each component.

The column self-weight is based on a 30x30 column dimension, which is used for preliminary sizing and may change in further calculations depending on the number of floors. The self-weight of CLT panels is estimated according to the material guide for CLT (martinsons, 2022), while the concrete roof element is estimated according to (Svensk Betong, nd). core element's self-weights are estimated based on their respective densities and dimensions.

**Table 4.3:** Permanent load

Type	[kN/m <sup>2</sup> ]	[kN]
Installations	0.3	7.4
Column	11.48	1.0
Beam	27.93	2.3
Slab	1.24	0.3
Roof	1.2	0.9

### 4.5.3 Variable load

Variable loads, which are also known as live loads, can change in both location and magnitude within a building over time. These loads include snow load, wind load, partition walls, and office areas. It is highly unlikely for all variable loads to act with full amplitude at the same time, which is why load reduction factors need to be used when calculating load combinations for SLS and ULS, see subsections 4.3 and 4.4 for more details.

**Table 4.4:** Variable load

Type	[kN/m <sup>2</sup> ]	[kN]
Office	2.5	55.797
Partition walls	0.5	12.319
Snow	1.2	29.656
Wind	1.3	-

#### 4.5.4 Load combination

According to the Eurocode, permanent and variable loads should be multiplied by specific factors to ensure the building remains safe and reliable over its intended life. The factors are shown in Table 4.5. These values are the values previously suggested by European Construction Standards (Boverket, 2011).

**Table 4.5:** Variable loads and recommended values for  $\psi_i$ -factors

Type	Loads [kN/m <sup>2</sup> ]	$\Psi_0$	$\Psi_1$	$\Psi_2$
Construction	1.0	0.7	0.5	0.3
Office areas	2.5	0.7	0.5	0.3
Partition walls	0.5	0.7	0.5	0.3
Snow	1.2	0.6	0.3	0.1
Wind	-	0.3	0.2	0

After performing calculations, the forces affecting the column under study were determined in three cases, ULS, short-term SLS, and long-term SLS. These results are shown in Table 4.6.

**Table 4.6:** The total applied loads on columns with the difference in number of floors

Floor no.	ULS[KN]	SLS(short-term) [KN]	SLS(long-term) [KN]
10	988	674	310
20	2 067	1 411	657
30	3 095	2 111	966

## 4.6 Preliminary sizing of members

Ultimate Limit State (ULS) is used to determine the dimensions of timber members such as columns and beams during the preliminary sizing of a structural system. The preliminary sizing is done in three stages for 10, 20, and 30 floors respectively. Several checks have been performed for each stage. Table 4.7 shows the result of the primary design.

For columns, compression and buckling checks have been carried out. Verification of combined compression and bending with/without lateral torsional buckling has been done for comparison around the weak axis, as shown in Table 4.7. For beams,

bending and shear checks have also been performed, as shown in Table 4.7. For more details about the preliminary sizing, see Appendix C.

**Table 4.7:** The primary design of the beam and column

Floor no.	Beam GL30c [mm]		Column GL30c [mm]	
	Width	Height	Width	Height
10	300	550	300	300
20	300	550	400	450
30	300	550	500	500



# 5

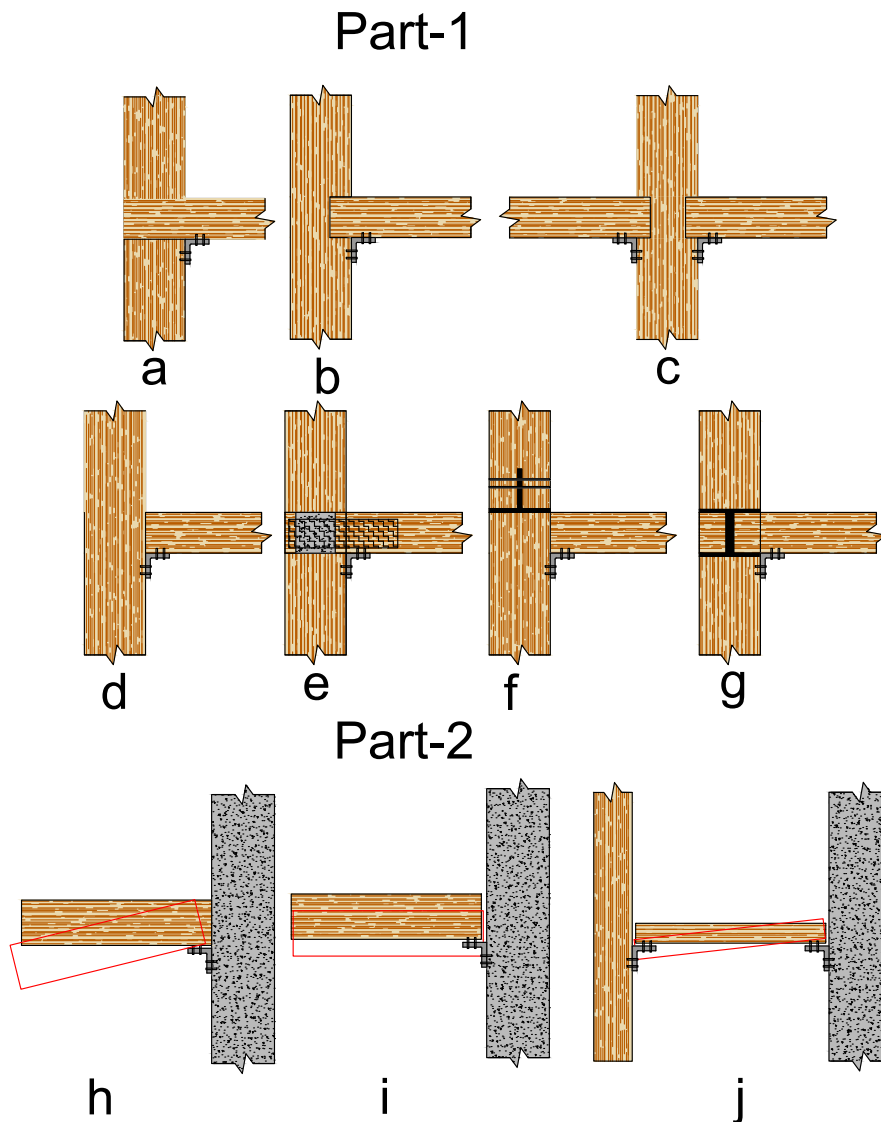
## Vertical deformations

In tall mass timber buildings, the vertical load is carried by the vertical components such as columns and the concrete core. The connection type between these vertical elements plays a significant role in this type of displacement. For instance, the column-to-column connection, beam-to-column connection, and beam/slab-to-concrete core connection all affect the magnitude of the vertical displacement. To quantify the amplitude of the vertical displacement in the chosen structural system, several types of deformations cover this phenomenon (Council, 2024).

- Column axial shortening.
- Column creep.
- Column, beam shrinkage.
- Beam crushing perpendicular to the grain.
- Settlement at connections.

In this chapter, the study will focus on examining the behavior of different types of column-to-column connections under compressive stress parallel to the grain. That will be done with both short-term and long-term effects. Specifically, the focus will be on the connections between columns in the first part of this chapter, as well as between beams and the core or concrete wall within the core in the second part.

The study will be conducted in multiple scenarios based on the different numbers of floors 10, 20, and 30 floors to address the difference in vertical displacement for the most loaded column represented in the previous chapter. moreover, study different types of connections between columns, see Figure 5.1



**Figure 5.1:** Several connections types

## 5.1 Long-term effect

When it comes to the planning and design of timber high-rise buildings, it's essential to consider more than just load-bearing under ULS (ultimate limit state) for vertical timber components like columns and walls (Jockwer et al., 2021). Ensuring that these components and their connections meet the criteria for SLS (serviceability limit state) is equally crucial.

When a timber component is under stress for a prolonged period, it undergoes creep deformation, which increases the magnitude of displacement. According to Eurocode 5, the MOE in the long-term effect should be calculated by dividing it with a factor of  $1 + k_{def}$  as illustrated in the equation 5.1. The  $k_{def}$  factor is determined in the Eurocode based on the climate class 1,2 and 3.

$$E_{0,mean,fin} = \frac{E_{0,mean}}{1 + k_{def}} \quad (5.1)$$

Where,

$E_{0,mean}$	The mean value of modulus of elasticity (MOE).
$E_{0,mean,fin}$	The mean value of modulus of elasticity (MOE).
$k_{def}$	Account for moisture effects on deformation.

Based on the input data and for simplicity, the glulam timber service class 1 has a value of  $k_{def}$  of 0.60 (Swedish Wood, 2022b). Therefore, the new value of MOE of elasticity needs to be recalculated using equation 5.1. This change in MOE will decrease the stiffness of timber over time, leading to increased vertical displacement in timber columns. The long-term load combination for SLS will be used to calculate building displacement over its lifetime.

The shrinkage in timber refers to the reduction in size or volume of wood as it loses moisture. This natural process occurs during drying, causing the timber to contract along its grain. Shrinkage affects the dimensional stability of wood, influencing construction quality.

## 5.2 Effect of axial loading parallel to the grain

As discussed in section 2.1.3, when a timber column is subjected to a compression load parallel to the grain, it will be divided into three zones - the top damage zone, middle zone, and bottom damage zone - depending on the type of joints between the columns. This means that the behavior of a single column will change along its length due to the variation in the magnitude of the MOE. For this reason, the length of the damaged zone in this study was chosen to be a fixed value of 5 mm based on expert experiments and research (Brabec et al., 2015).

The modulus of elasticity (MOE) in the damage zone will be lower compared to the MOE in the mid-zone of the column, as the modulus of elasticity in the damage zone is 3-6 times less than that of the mid-zone. The stiffness of each spring in the damaged area indicates the change in the modulus of elasticity (Brabec et al., 2015).

## 5.3 Spring function in Matlab

As stated earlier, the Matlab Calfem package will be employed to compute the vertical displacement of columns and their connections by utilizing a spring system. The underlying principle behind this function is based on the relationship between the spring's ability to resist the compression or tension force in its local direction, as defined by equation 5.2 (Dahlblom and Olsson, 2010).

The deformation of the spring is calculated by the equation 5.3, where  $u_1$  and  $u_2$  represent the magnitude of displacement for each node of the spring element, see Figure 5.2. The spring element equation system is represented in equation 5.5, by using this equation the displacement vector  $\mathbf{a}^e$  will be calculated.

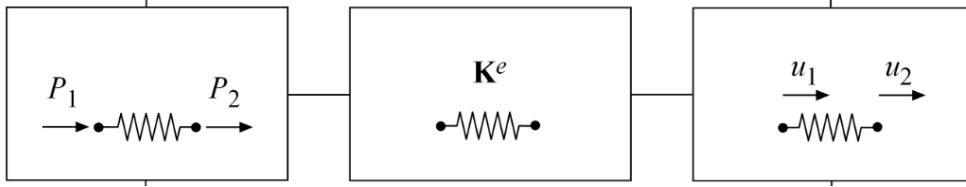


Figure 5.2: Spring element

$$N = \kappa \cdot \delta \quad (5.2)$$

$$\delta = u_2 - u_1 \quad (5.3)$$

$$N = \kappa \cdot (u_2 - u_1) \quad (5.4)$$

$$\mathbf{K}^e \cdot \mathbf{a}^e = \mathbf{f}^e \quad (5.5)$$

$$\mathbf{K}^e = \begin{bmatrix} k & -k \\ -k & k \end{bmatrix} \quad (5.6)$$

$$\mathbf{a}^e = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad (5.7)$$

$$\mathbf{f}^e = \begin{bmatrix} P_1 \\ P_2 \end{bmatrix} \quad (5.8)$$

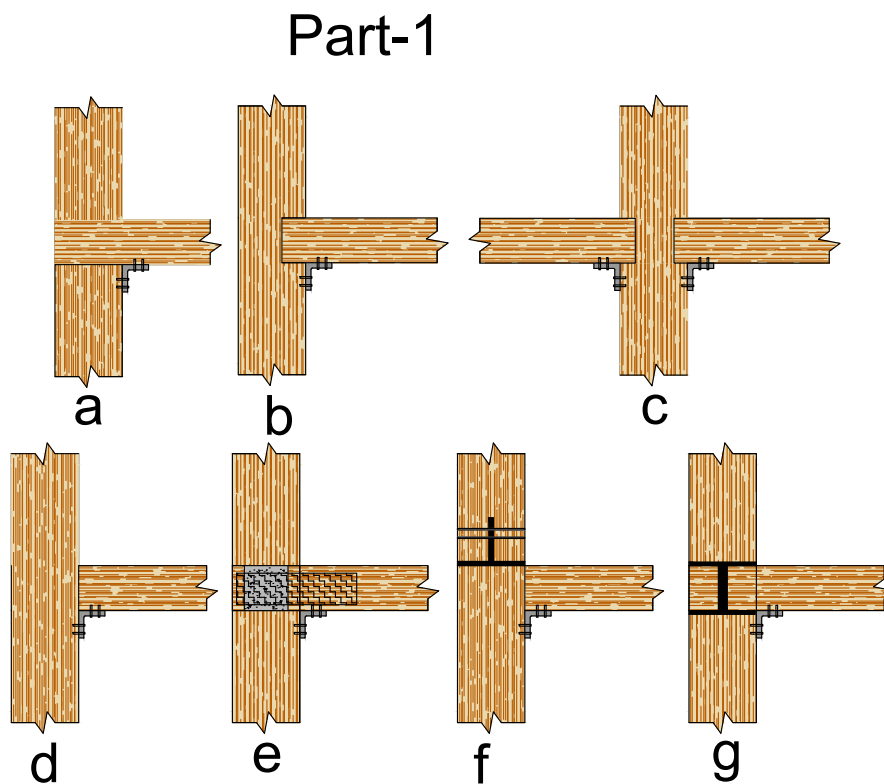
$$\begin{bmatrix} k & -k \\ -k & k \end{bmatrix} \cdot \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} P_1 \\ P_2 \end{bmatrix} \quad (5.9)$$

where,

- $N$  Internal force [N]
- $P_1$  External force in the first node [N]
- $P_2$  External force in the second node [N]
- $\kappa$  Spring Stiffness. [N/mm]
- $\delta$  Deformation in the spring [mm]
- $u_1$  Displacement in the first node [mm]
- $u_2$  The displacement in the second [mm]
- $\mathbf{a}^e$  Element displacement vector [mm]
- $\mathbf{f}^e$  external force vector [N]
- $\mathbf{K}^e$  stiffness matrix [N/mm]

## 5.4 First scenario (10 Floors)

The first scenario shows the different types of connections analyzed where the number of stories is fixed to 10 in the long-term. The different types of connection are shown in Figure 5.3. In the study, the calculation is based on Matlab and Abaqus. For each type of connection, the displacement is calculated in the column and the connection itself. There is no change in the material of the timber column and the only change is the connection and how it is located in the structure system.



**Figure 5.3:** Several connections types

There are many kinds of connections used to connect columns. However, this study focuses on the number of connections.

- CBC** (column-beam-column)
- CNC** (column-notch-column)
- CPC** (column-pillar-column)
- CPPC** (column-penetrated plate-column)

### 5.4.1 Column-beam-column (CBC)

This type of connection will be discussed to highlight the effect of loading perpendicular to the grain. In the first case (CBC1), there will not consider the damage effect due to the axial loading perpendicular to the grain for the beam and parallel to the grain for the column, while the other case (CBC2) will consider the damage zones in both column and beam.

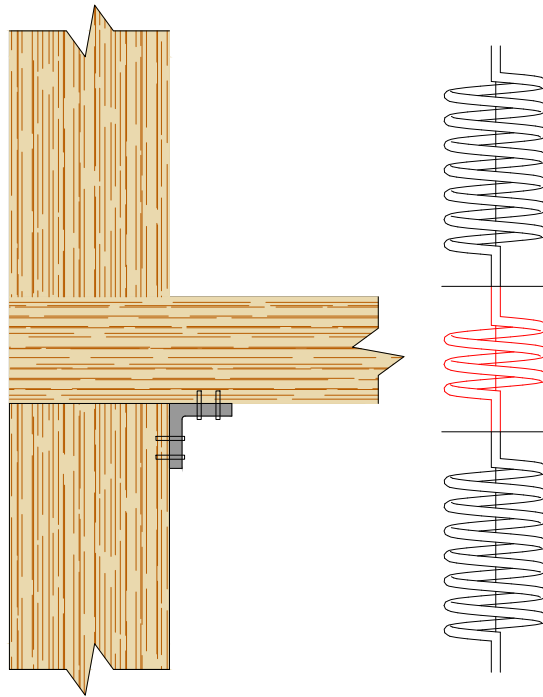
#### 5.4.1.1 Case one CBC1

In case one CBC1, the Glulam column GL30c is found on one floor with a height of 3 m and loaded parallel to the grain. In contrast, the beam is GL30c and loaded perpendicular to the grain, for more details on the material properties and dimensions represented in Table 5.1.

**Table 5.1:** Properties of Beams and Columns (CBC1)

	Column(GL30c)	Beam(GL30c)
<i>Length</i> – [m]	3	7.3
<i>Width</i> – [m]	0.3	0.3
<i>Height</i> – [m]	0.3	0.55
$E_{0,mean}$ – [MPa]	13 000	13 000
$E_{90,mean}$ – [MPa]	300	300
<i>Density</i> – $\rho_{mean}$ – [kg/m <sup>3</sup> ]	430	430

As shown in Figure 5.4, the spring system consists of various elements, with each color denoting a specific component such as black for columns and red for beams. It is worth noting that the stiffness of the springs varies since they have different magnitudes of the modulus of elasticity (MOE). For instance, the GL30c column has a modulus of elasticity(MOE) of 13000 MPa in compression parallel to the grain. In comparison, the GL30c beam has a modulus of elasticity of 300 MPa in compression perpendicular to the grain.



**Figure 5.4:** Spring system CBC1

This difference in (MOE) affects the spring system, as springs with different magnitudes of stiffness are used. The stiffness of a spring is calculated using the equation 5.10 and represented in Table 5.2 (Dahlblom and Olsson, 2010).

$$\kappa = \frac{E_{0,mean,fin} \cdot A}{L} \quad (5.10)$$

where:

- $\kappa$  Stiffness of the material [N/m]
- $E$  Elastic modulus [MPa]
- $A$  Area of the cross-section [mm<sup>2</sup>]
- $L$  Length of the specimen [mm]

**Table 5.2:** CBC1

Type	Area [mm <sup>2</sup> ]	Stiffness $\kappa$ [N/mm]	Length [mm]
Column	300×300	2.438 e+05	3 000
Beam	300×300	3.125 e+04	550
Column	300×300	2.438 e+05	3 000

5.4.1.2 Case two CBC2

In case two CBC2, compression perpendicular to the grain in the beam can cause crushing in the fibers at the top and bottom of the beam 5.5, and lead to more displacement. This is discussed in more detail in Section 2.1.3. In the column, the damage zone will occur in the interface area between the beam and column, with a depth of 5 mm.

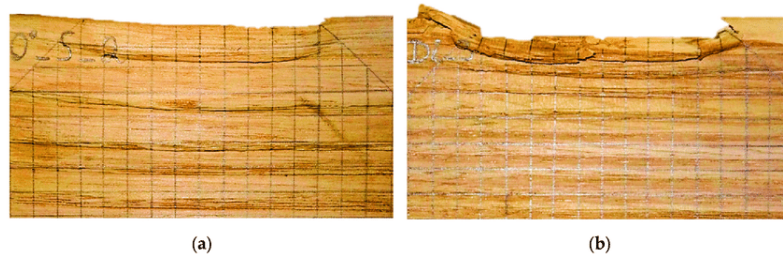


Figure 5.5: Crushing in grain

The spring system will consist of more spring elements that can describe the material stiffness reduction along the connection in the vertical direction, see Figure 5.7.

As shown in Figure 5.6, a spring represents each sub-zone. For example,  $M_c$  represents the middle zone of the column,  $D_{c,2}$  represents the bottom damage zone of the column, and  $D_{b,2}$  represents the top damage zone for the beam (crushing area).  $M_b$  represents the mid-zone of the beam and  $D_{b,2}$  represents the bottom damage zone of the beam (crushing area). Cross-section area, stiffness, and length of each sub-zone are calculated according to equation 5.10 and presented in Table 5.3.

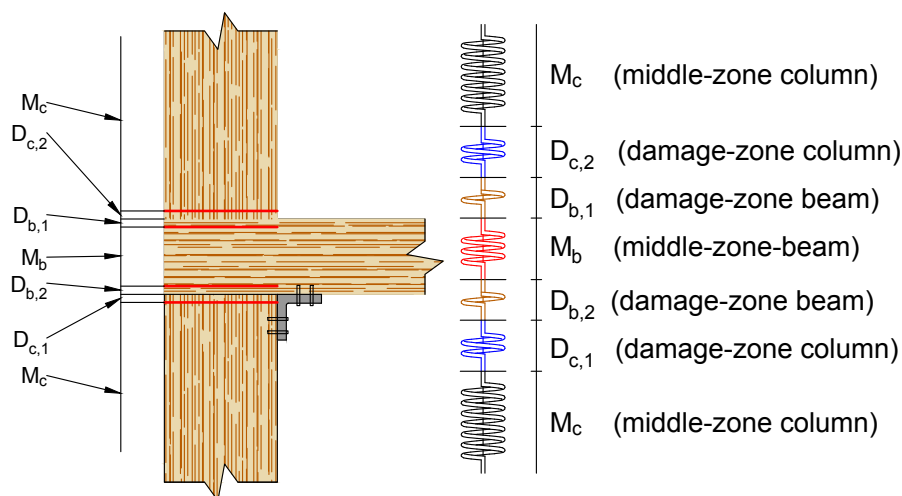


Figure 5.6: Spring system CBC2

**Table 5.3:** CBC2

Type	Area [ $mm^2$ ]	Stiffness $\kappa$ [ $N/mm$ ]	Length [ $mm$ ]
Middle-zone column	300×300	2.445 e+05	2.99
Damage zone column	300×300	4.875 e+07	0.005
Damage zone beam	300×300	1.125 e+06	0.005
Middle-zone beam	300×300	3.125 e+04	0.540
Damage zone beam	300×300	1.125 e+06	0.005
Damage zone column	300×300	4.875 e+07	0.005
Middle-zone column	300×300	2.445 e+05	2.99

#### 5.4.1.3 Implementation in Matlab

The two types of connection CBC1 and CBC2 will be provided in Matlab. The studies will consider the impact of vertical load when it is applied both perpendicular (beam) and parallel (column). The number of floors is 10 and the same material properties and geometry are used for both cases.

In the first case, the CBC1 connection was implemented without accounting for any of the sub-zones. The displacement is calculated using the spring system which is presented in Figure 5.7, Detail D. The spring system consists of two different springs one for the column and one for the beam.

There are a total of 20 springs along the height of the entire structure in the first scenario, with each spring element having one degree of freedom at each end. The spring element on the bottom floor is fixed on one of its ends. So the spring system can move in the vertical direction to obtain the total displacement of the entire structure, see Figure 5.7, Detail A. Loads of each floor are applied on the end node between the column and beam spring for simplicity, see Figure 5.7 detail D.

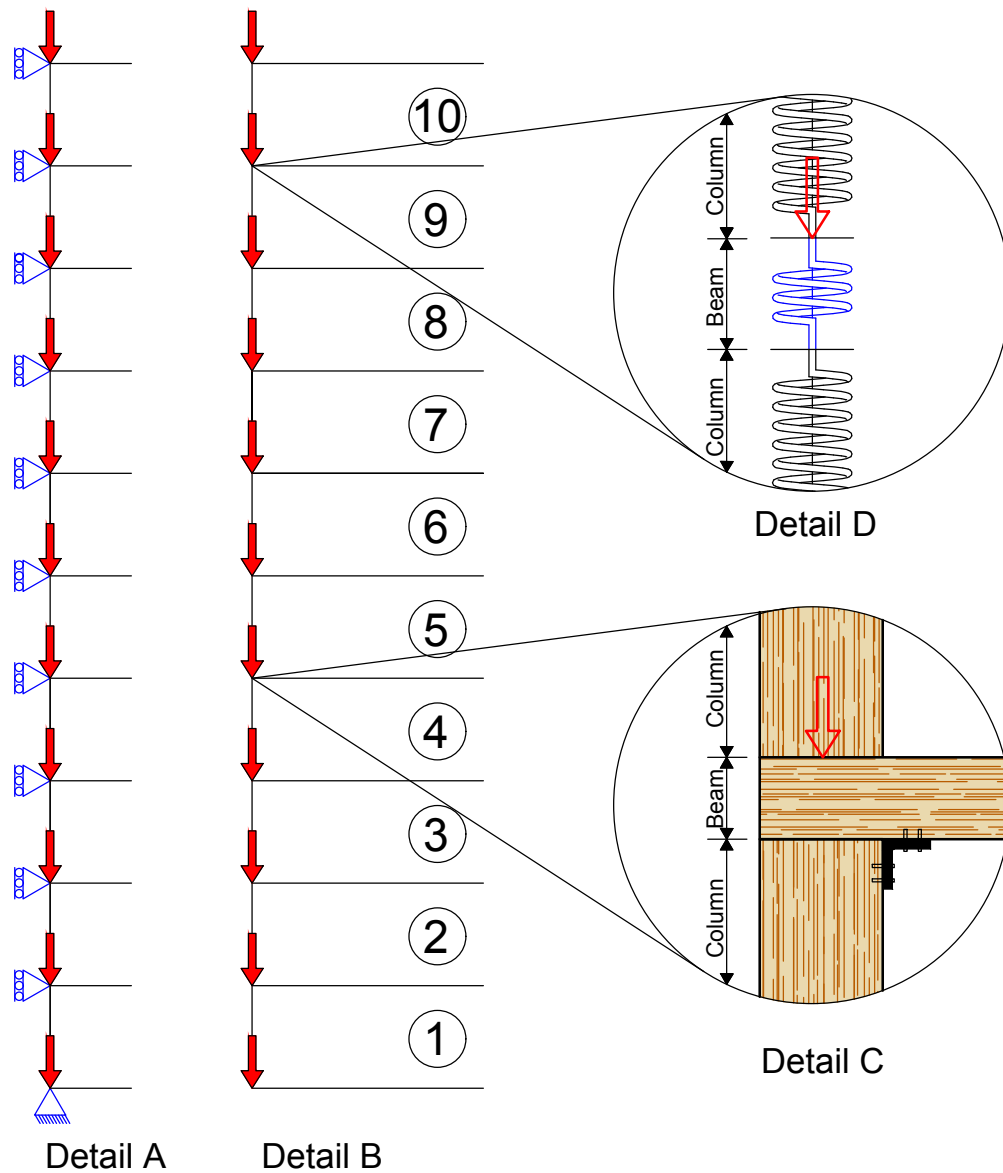


Figure 5.7: CBC1-Detail

For Case Two CBC2, the same application rules as Case One are followed, with the difference being that the number of springs is increased to 57 springs to cover the damage that occurs in the timber along the entire structure system. In this case, the column is divided into three springs, compared to CBC1 which has only one spring. The different springs in each column represent the top damage zone, middle zone, and bottom damage zone, and the same goes for the beam as well, see Figure 5.8 detail D.

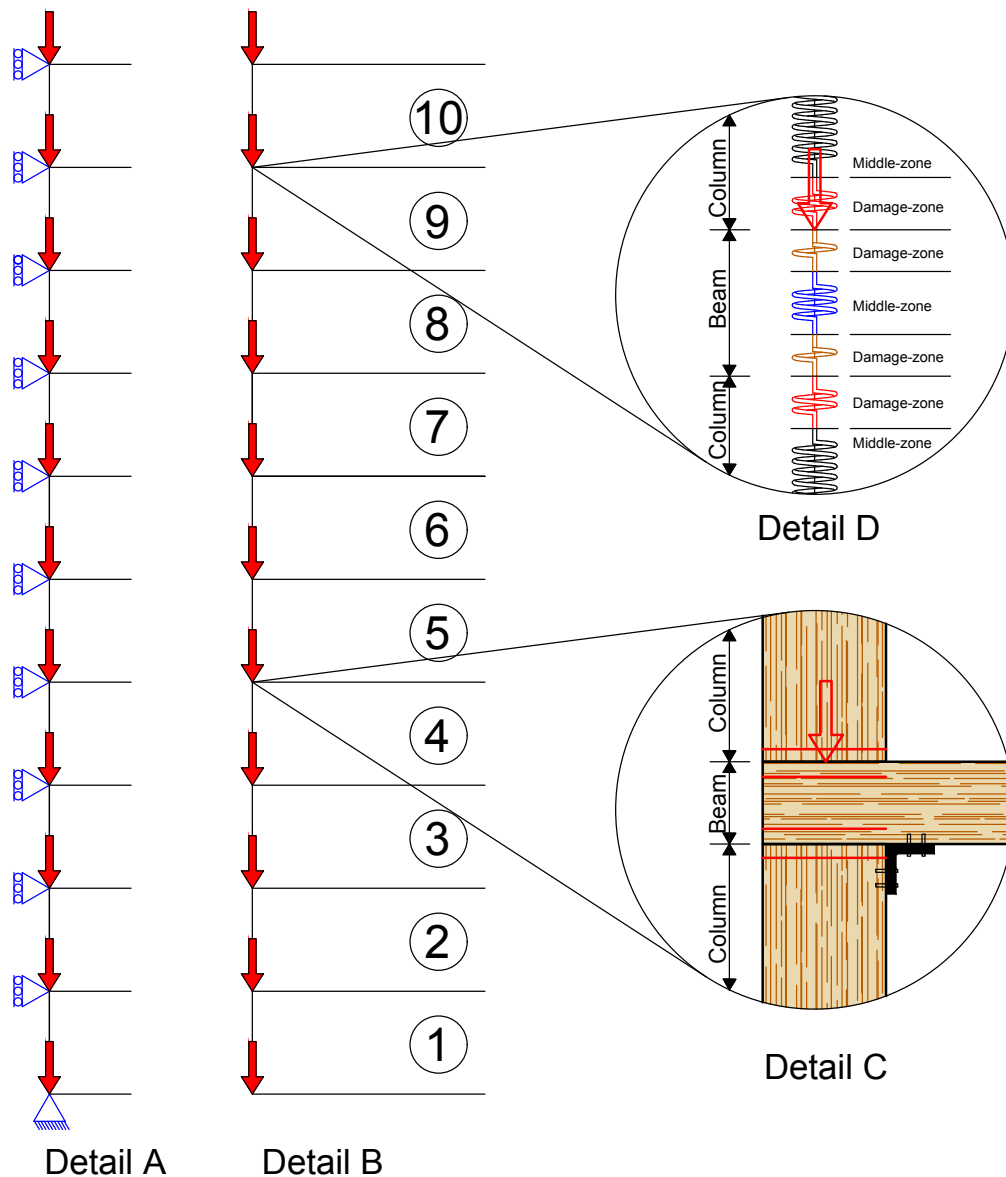
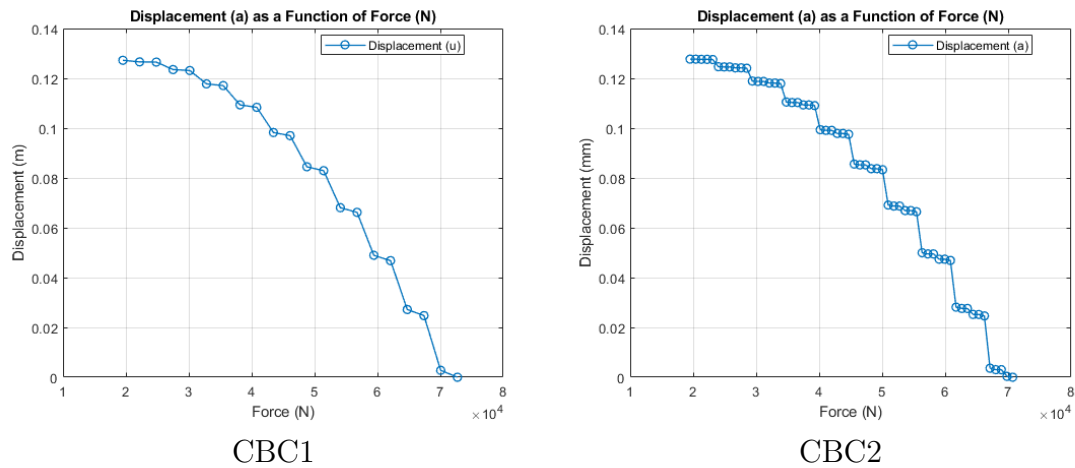


Figure 5.8: CBC2-Detail

#### 5.4.1.4 Result

The two cases, CBC1 and CBC2, are defined in Matlab for the inter structure with 10 floors. As mentioned, this stage aims to address the effect of loading both perpendicular and parallel to the grain, as well as to check how much the displacement magnitude will differ if we consider the damage zone that occurs in the column and the crushing zone that takes place in the beam due to loading perpendicular to the grain. The results for both cases, as shown in Figure 5.9, do not exhibit a significant difference; in contrast, the results for both cases show the same amount of displacement for the entire structure, as seen in Table 5.4. Further details can be found in Appendix A.1.1 and A.1.2.

## 5. Vertical deformations



**Figure 5.9:** CBC1 and CBC2 Displacement as a function of load

**Table 5.4:** CBC1,CBC2-Displacement per floor

CBC1,CBC2 Displacement		
Floor no.	CBC1[mm]	CBC2[mm]
column floor 10	127.2	127.7
column floor 9	126.5	127.6
column floor 8	123.1	124.2
column floor 7	117.1	118.1
column floor 6	108.4	109.3
column floor 5	97.0	97.9
column floor 4	83.0	83.7
column floor 3	66.2	66.9
column floor 2	46.2	47.4
column floor 1	24.7	25.2
Basement	0	0

It could be that the result of the damage zone length, which is assumed to be 5 mm in this paper based on some experiments, does not affect the overall outcome.

However, the total vertical displacement for this type of connection still exhibits a magnitude of vertical displacement, which is 127.7 mm on the top floor. This should be considered in the design stage of the connection type for a tall timber structure. To clarify the results, displacement in both cases CBC1 and CBC2 are plotted concerning the number of floors in Figure 5.10.

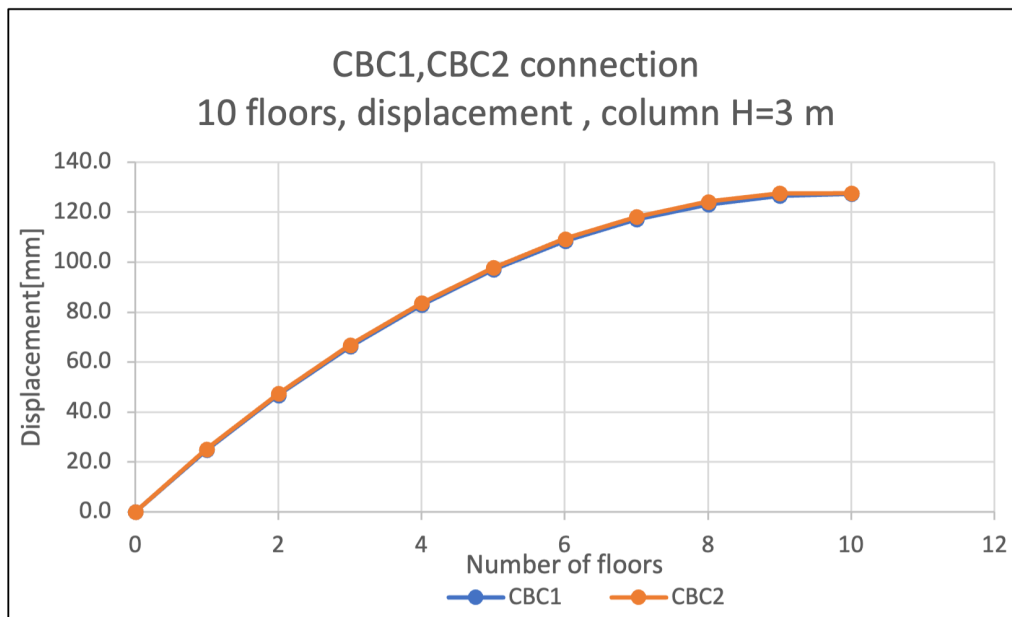
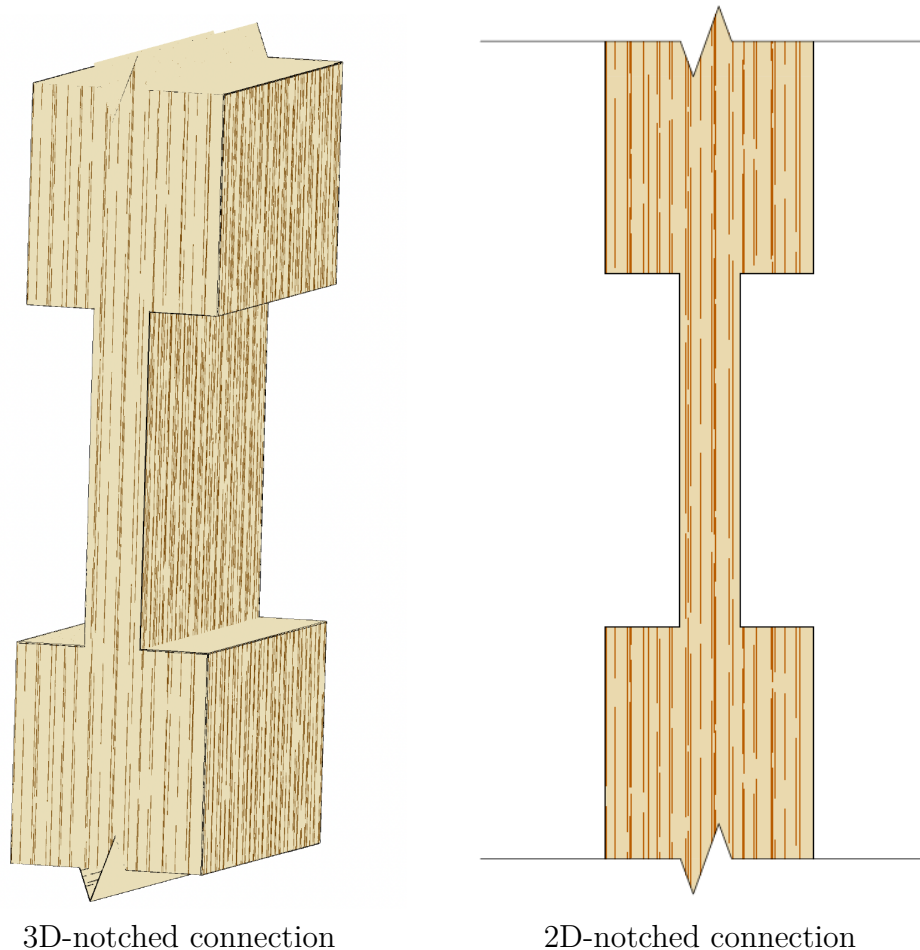


Figure 5.10: CBC1,CBC2 Displacement per floor no.

### 5.4.2 Notched connection CNC

The connection to be discussed here is a notch column. The column will be 6 meters in height and have notches on both sides, allowing beams to bear on the notches to serve as a connection. The purpose of choosing this type of connection is to prevent damage that may occur in the joint area, known as the damage zone. The geometry and size of this connection are illustrated in Figure 5.11.



**Figure 5.11:** Notched connection

Figure 5.11 shows that the cross-section area of the column will vary in the notch meaning that the stiffness of the columns will also change according to the equation 5.2. As shown in Figure 5.11 in the 3D model the beams on both left and right can be placed in the notch part of the column.

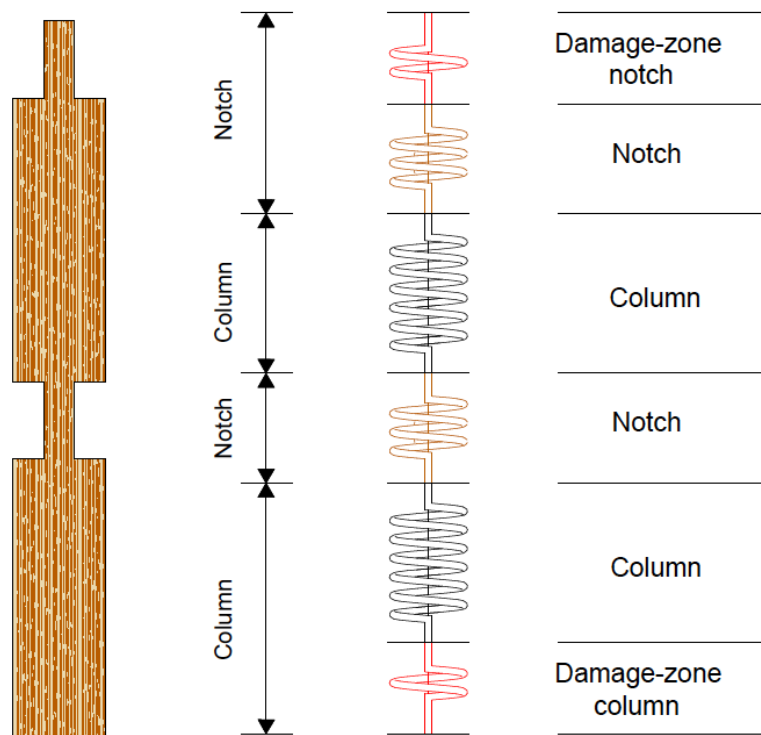
#### 5.4.2.1 Spring system

In this type of connection, the spring system of each column consists of five series of springs, with each spring presenting a different behavior of the column along its length. Figure 5.12 shows the damage zone at the top of the notch due to the discontinuity of the column presented with a spring. This area is known as a notch.

The bottom damage zone is presented by a spring with a stiffness of the full cross-sectional area of the column. Above the notch and below it are two springs, and the notch area is presented by one spring. Table 5.5 below presents stiffness, length, and area of each spring.

**Table 5.5:** Notched connection properties

Type	Area [ $mm^2$ ]	Stiffness $\kappa$ [ $N/mm$ ]	Length [ $mm$ ]
damage zone notch	$300 \times 100$	$1.625 \text{ e}+07$	5
notch	$300 \times 100$	$8.125 \text{ e}+05$	300
Top column $A_{total}$	$300 \times 300$	$2.813 \text{ e}+05$	3 000
notch	$300 \times 100$	$8.125 \text{ e}+05$	300
Bottom column $A_{total}$	$300 \times 300$	$2.813 \text{ e}+05$	3 000
damage zone column	$300 \times 100$	$3.250 \text{ e}+07$	5



**Figure 5.12:** Notched connection springs

when the cross-section area of the column is reduced in the notch, that will affect a new stress distribution in the column under and above the notch based on the equation 5.11.

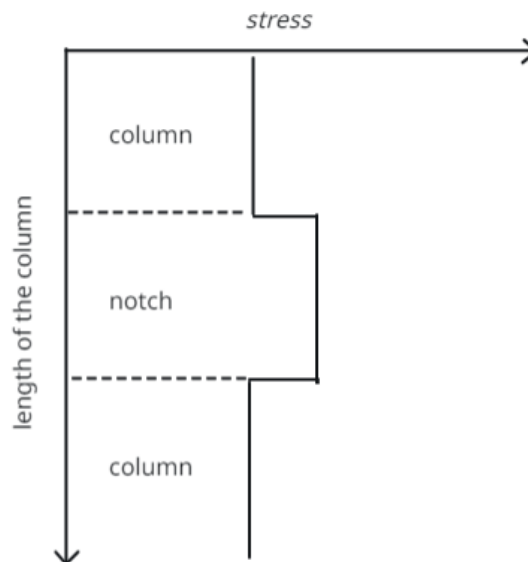
$$\sigma = \frac{F}{A} \quad (5.11)$$

where,

- $A$  Area of the cross-section [mm<sup>2</sup>]
- $F$  applied load [N]
- $\sigma$  stress in the cross-section [MPa]

The stress in a column is generally distributed equally along its length, as long as the cross-sectional area remains the same throughout. However, in a notch joint, the stress increases due to the reduction in the area. This change in stress distribution can cause certain areas of the column, known as "D-regions" to become less effective in resisting vertical loads or compressive stress.

These D-regions typically occur in the corners of the column above and below directly after the notch joint. Therefore, the effective area of the column, known as  $A_{ef}$ , should be reduced accordingly. To further understand this effect on the connection, the FEM program Abaqus is used and more explanation about that will be seen later in subsection 5.4.2.2.



**Figure 5.13:** Stress distribution

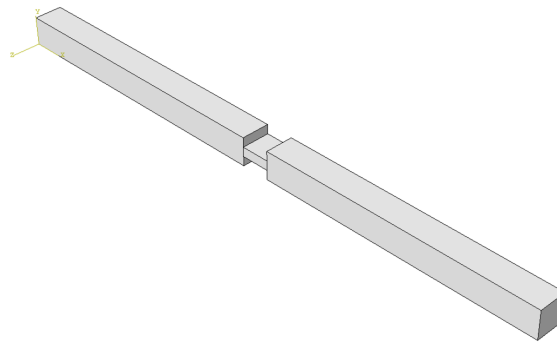
If there is a reduction in the area above and below the notch, the spring system of the connection will need to be adjusted accordingly. This can be achieved by adding springs to represent the reduction of area, which will become  $A_{ef}$ .

### 5.4.2.2 FEM modeling in Abaqus

The purpose of utilizing Abaqus software is to analyze the effective area of the cross-section's column. This area will appear when reducing the area in the notch part. To achieve this, the column with the notch will be modeled, and the effective areas will then be used in Matlab code to refine the results, ensuring they are as realistic as possible.

#### 5.4.2.2.1 Modeling of the elements

In Abaqus, the elements are modeled as solid 3D deformed parts with solid shapes. For the notched connection, a single model is created, featuring two columns with the notch positioned between them. This model is shown in Figure 5.14.



**Figure 5.14:** Notched element

#### 5.4.2.2.2 Material properties

In the modeling, one type of material is used for the timber column and notch. The material is glulam GL30c, and there are four material behaviors, the density of the timber, and the elastic behavior including elastic modulus, Poisson ratio, and shear modulus. This parameter is shown in Table 5.6. Glulam GL30c is an engineering constant material, which means its properties differ significantly in different directions. The study in Abaqus focuses on the elastic behavior of the structure, without considering plastic behavior. Some results from Abaqus will be used in the Matlab code and there the material is studied the elastic behavior only.

**Table 5.6:** Abaqus material properties

Density [kg/m <sup>3</sup> ]						430		
Elastic behavior								
E1 [MPa]	E2 [MPa]	E3 [MPa]	Nu12	Nu13	Nu23	G12 [MPa]	G13 [MPa]	G23 [MPa]
13000	300	300	0.4	0.4	0.4	540	540	54

### 5.4.2.2.3 Interaction

The interaction between interface surface parts of the model simulates the realistic contact between the column and the connection part there are different types of interaction to be close to reality. Some types allow some freedom or movement, while others allow the parts to behave as if they were one part. But here in this connection type the model is made of only one part so that there's no interaction needed.

### 5.4.2.2.4 Boundary conditions

In this case, the boundary condition used in the bottom face of the column under the connection involves displacement and rotation. The boundaries are fixed in all three directions, and no external moments are imposed on them. These boundary conditions were applied from the initial step before any forces were applied to the column.

### 5.4.2.2.5 Load application

The load here is applied as a pressure on the whole cross-section to make the load distributed uniformly at the surface of the column. The amplitude of the load in this model is tabular. The tabular amplitude defines how the magnitude of the load changes at different steps or intervals during the simulation (Manual, 2012). However, in this model, the amplitude remains constant, resulting in the loads being applied in one step. This is because the study focuses on the final state.

When dealing with this amplitude type, a load scale factor can be incorporated. However, because this model lacks inclines, the load scale factor can be disregarded. This approach to load application guarantees that all nodes in the column move uniformly when subjected to the load.

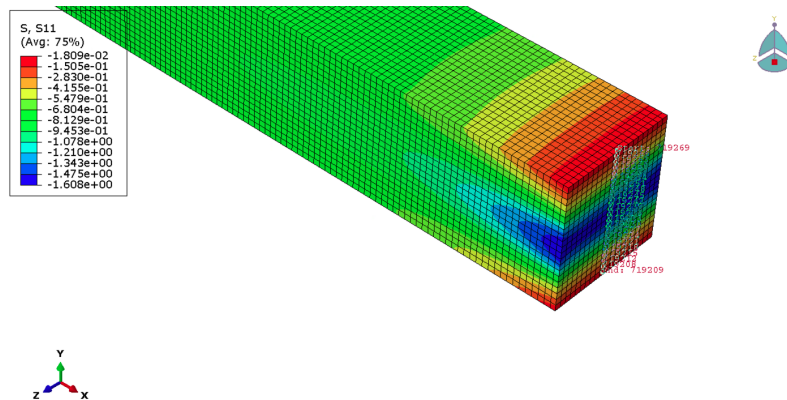
### 5.4.2.2.6 Mesh and convergence study

The mesh element in this model is called C3D20, A 20-node quadratic brick element was used to model the column. The "C" in "C3D20" denotes a "Continuum" element, which means it is suitable for analyzing solid structures. The "3D" signifies its three-dimensional element, while "20" specifies the number of nodes in the element (Manual, 2012).

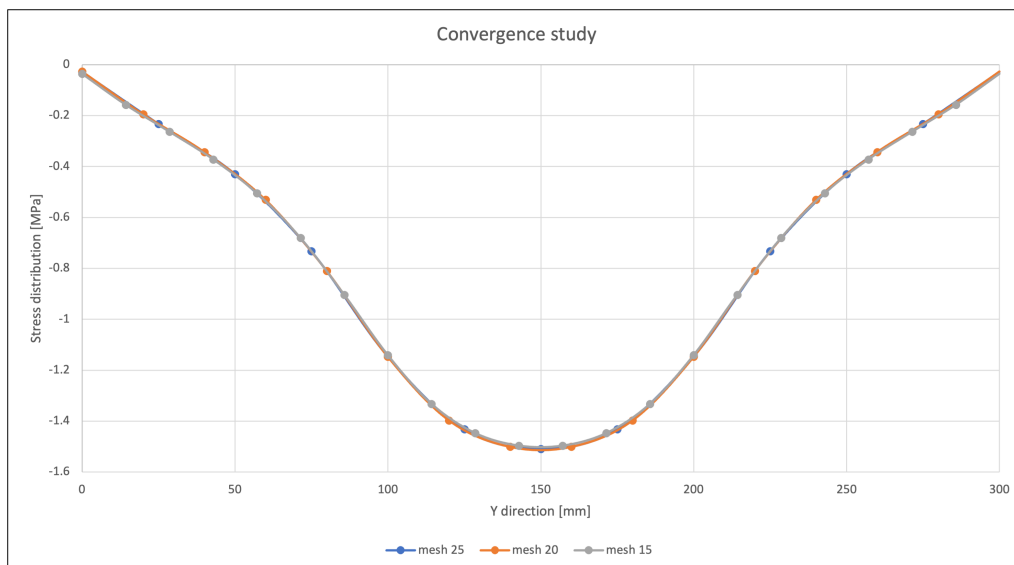
The study involved selecting three different mesh sizes to find the most suitable size of mesh elements, as detailed in Table 5.7. A path was then followed in the y-direction within the column's cross-sectional area, located 200 mm below the notched edge as illustrated in Figure 5.15. This path exposes the entire cross-section to compression stress distribution.

**Table 5.7:** Different mesh size (CNC)

Type	Column	Notched
Mesh-1	25	25
Mesh-2	20	20
Mesh-3	15	15

**Figure 5.15:** Notched path-200

For each mesh size, the stress distribution across the element mesh (type C3D20) was analyzed. The x-y data output for each path and mesh size were plotted using Excel, as shown in Figure 5.16.

**Figure 5.16:** Notch convergence study

The convergence study for these three element sizes revealed no significant difference in stress distribution. Therefore, mesh size 15 is selected for further analysis, as shown in Figure 5.17.

## 5. Vertical deformations

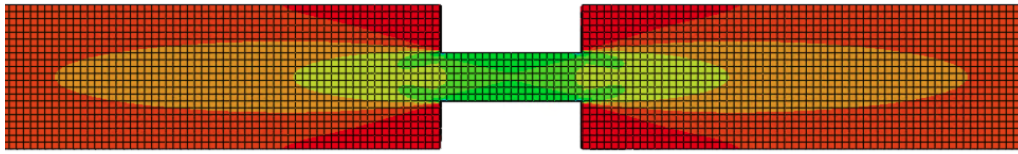


Figure 5.17: Notched mesh size 15

### 5.4.2.2.7 Abaqus results

To evaluate the stress distribution in the column both under and above the notch, and to identify areas where stress is equally or partially distributed, as well as where the stress becomes compressive for the entire cross-section of the column, paths in the y-direction have been examined. These paths are located at distances of 0 mm, 200 mm, 400 mm, and 700 mm from the notched edge. Figure 5.18 shows the stress distribution in each path.

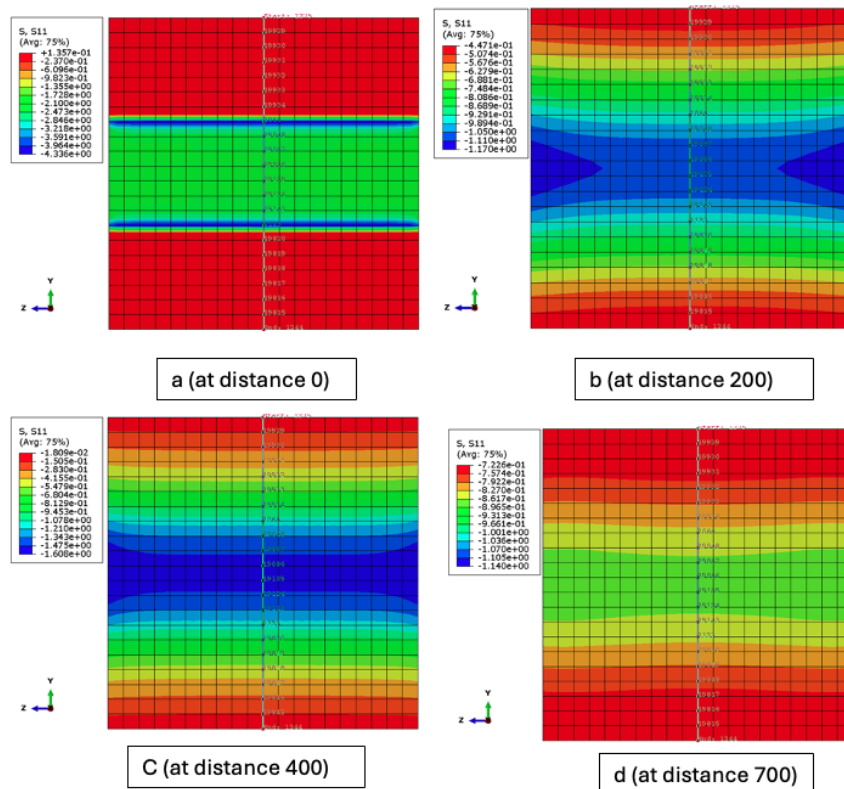


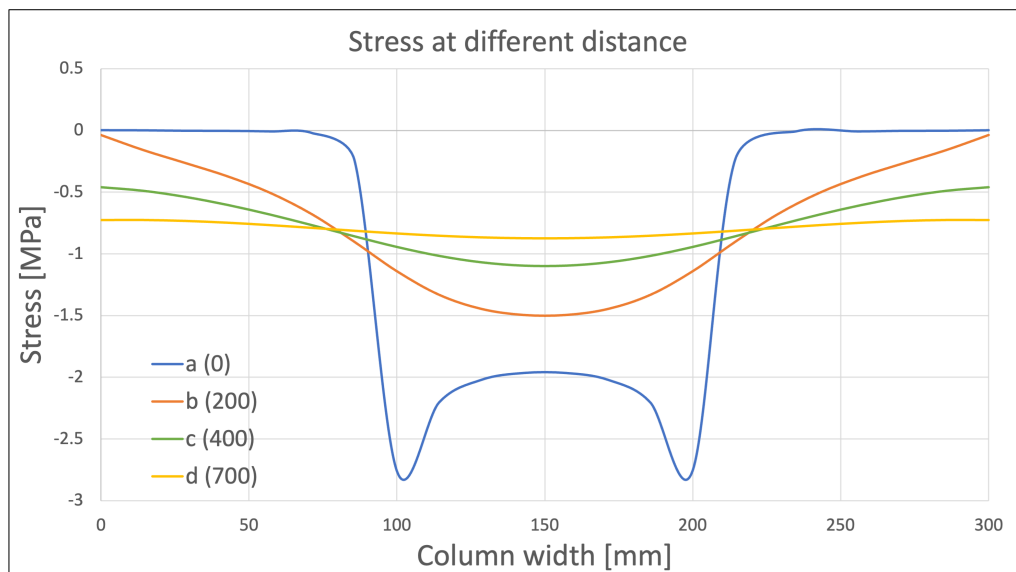
Figure 5.18: Stress distribution at different distance

As shown in Figure 5.18 in the path at a distance 0 from the notched edge directly under the notch, the stress distribution is concentrated under the notch, with no stress observed on the sides of the notch. The stress distribution area begins to increase linearly with the distance from the notch.

It was observed that the part under the notch is supposed to have compressive stress, while the part on the sides is in tension until the distance under the notch reaches 200 mm, where the stress becomes almost purely compressive over the cross-section of the column. This indicates that the entire area of the column resists compressive stress at a distance of 200 mm.

However, to ensure that the stress is fully distributed in the column, two additional paths were taken, one at a distance of 400 mm and the second at a distance of 700 mm. At a distance of 400 mm, the stress is on its way to becoming uniformly distributed, while at a distance of 700 mm, the result shows fully uniformly distributed stress. This means that at this distance, the compressive stress applied on the top of the column reappears throughout the column, see Figure 5.19.

To ensure an even distribution of stress in the column, two additional measurements were taken: one at a distance of 400 mm and the other at 700 mm. At 400 mm, the stress starts to become uniformly distributed, while at 700 mm, the results show a fully uniform stress distribution. This indicates that at 700 mm, the compressive stress applied at the top of the column is distributed throughout the entire column. Figure 5.19 shows more details about the stress distribution in each path.



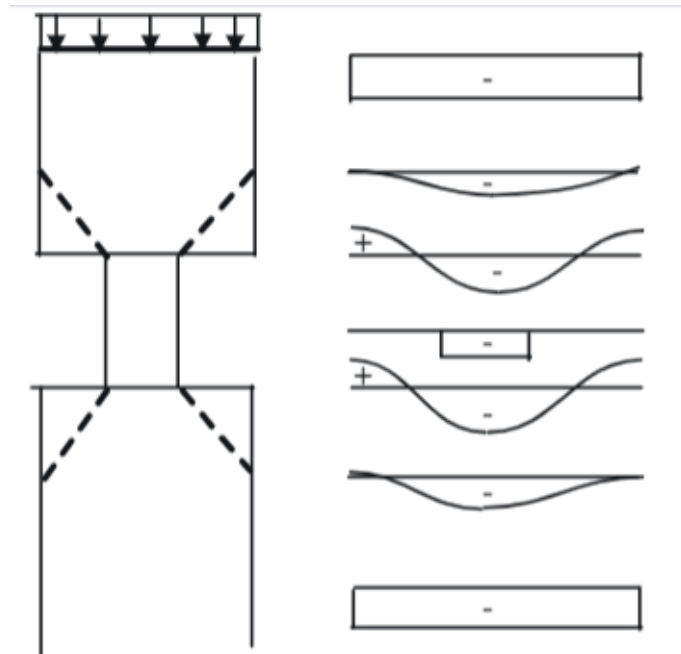
**Figure 5.19:** CNC-Stress at different distance

Therefore, the area of the column under and above the notch needs to be recalculated to estimate the effective area, which will be used later in the calculation of the spring system in Matlab.

#### 5.4.2.3 Implementation in Matlab

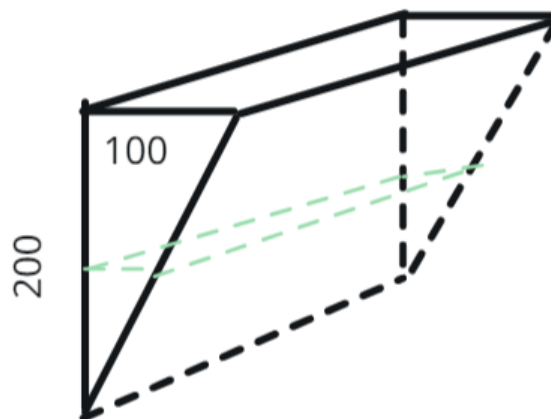
Based on the results from Abaqus, the stress distribution in the column under and above the notch consists of both compression and tension stresses. It is observed that it takes a distance of 200 mm for the stress to become purely compressive, indicating

that the column cross-section is active in resisting compressive loads within this distance 5.20.



**Figure 5.20:** Illustration over the stress

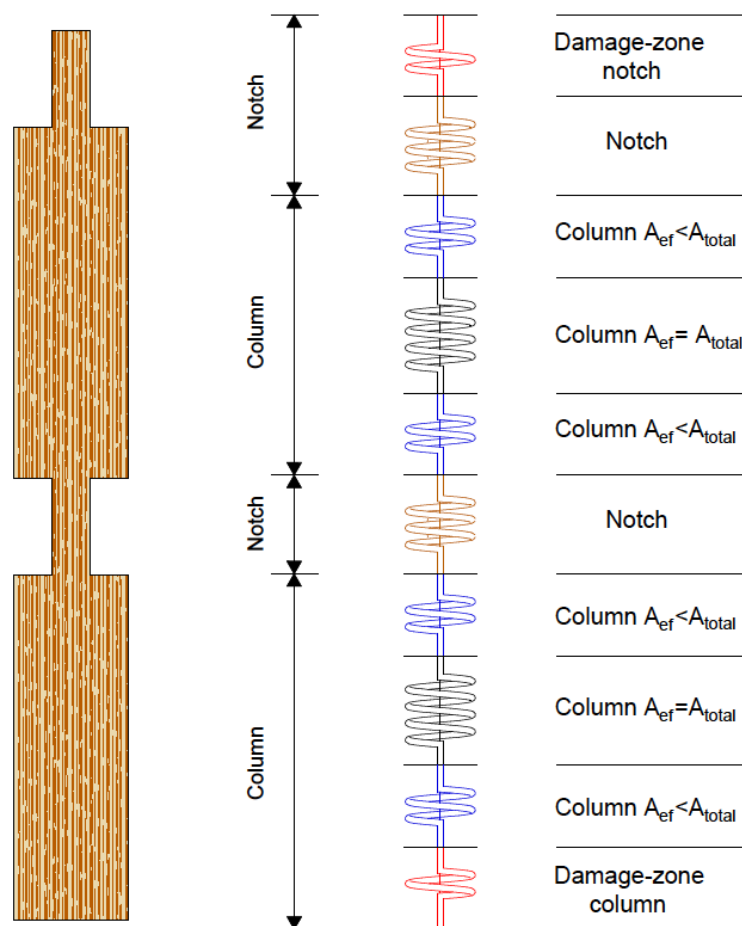
The stress distribution along the length of the column is now to be explained. To include this uneven stress distribution under and above the notch, adjustments need to be made to the spring system shown in Figure 5.12. A new spring will be introduced to cover the phenomenon of this uneven stress distribution. This new spring will have a new area, representing the part of the column that resists compressive stress under and above the notch. This area is depicted in Figure 5.21. To calculate this area, the law of triangles was used to estimate the average area of this region, which will then be subtracted from the total area of the cross-section of the column to obtain the effective area used in the calculation of the stiffness for the new spring.



**Figure 5.21:** Area effective

**Table 5.8:** Notched connection

Type	Area [ $mm^2$ ]	Stiffness $\kappa$ [ $N/mm$ ]	Length [ $mm$ ]
damage zone notch	$300 \times 100$	$1.625 \text{ e}+07$	5
notch	$300 \times 100$	$8.125 \text{ e}+05$	300
Top column $A_{total}$	$300 \times 300$	$2.813 \text{ e}+05$	2 800
Top column $A_{ef}$	$300 \times 300$	$2.438 \text{ e}+06$	200
notch	$300 \times 100$	$8.125 \text{ e}+05$	300
Bottom column $A_{ef}$	$300 \times 300$	$2.438 \text{ e}+06$	200
Bottom column $A_{total}$	$300 \times 300$	$2.813 \text{ e}+05$	2 800
damage zone column	$300 \times 100$	$3.250 \text{ e}+07$	5

**Figure 5.22:** Notched connection springs with consideration of D-region

The number of springs for this connection will now be 50, with 51 degrees of freedom with each spring element having one degree of freedom at each end. The spring

element on the bottom floor is fixed on one of its ends. So the spring system can move in the vertical direction to obtain the total displacement of the entire structure. The load will be applied to the notch spring, assuming that the load is coming from the beam to be placed on the notch.

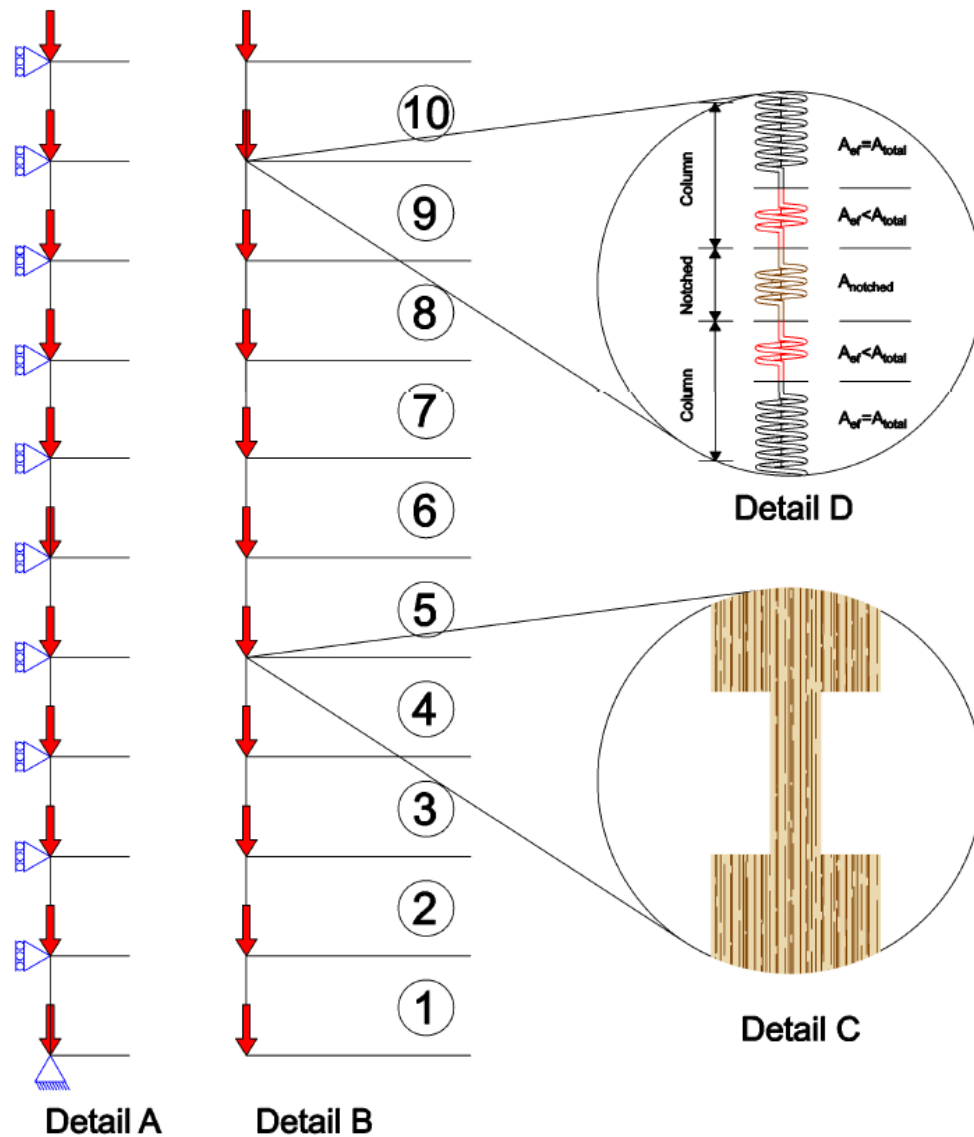
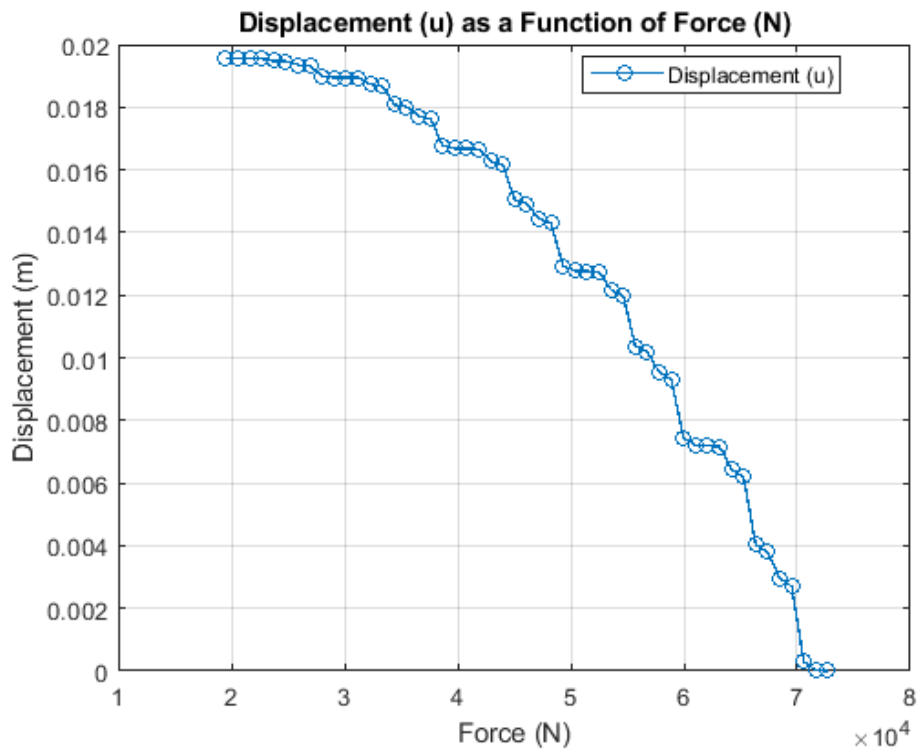


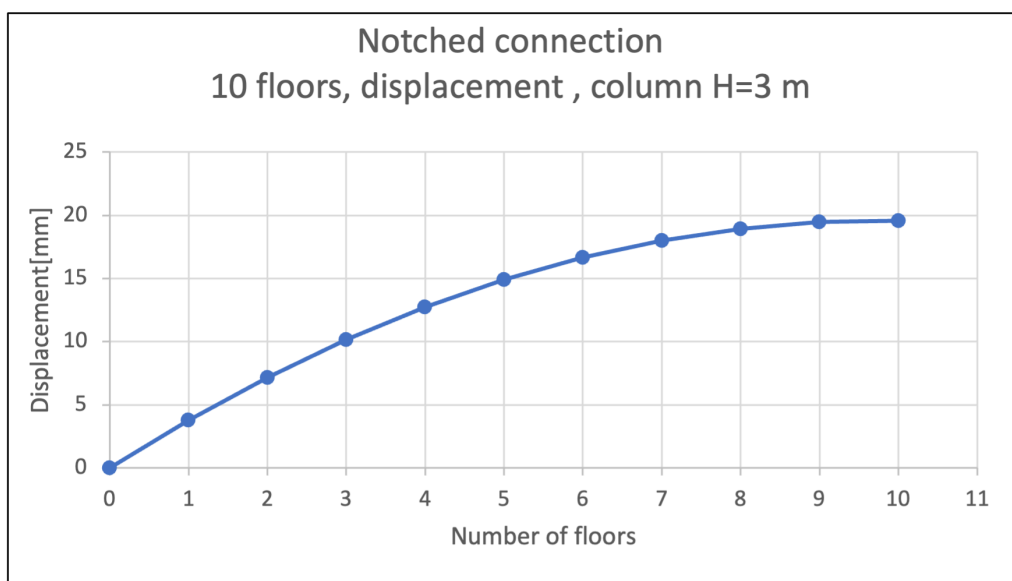
Figure 5.23: CNC-Detail

Figure 5.24 illustrates the displacement as a function of the applied load. The displacement value at the top of the column is the highest, as the bottom floor bears the most load. The total magnitude of displacement at the top of the building is approximately 19.5 mm. It is observed that the amount of displacement in the nodes where the CNC connection is applied is relatively small. This is because the notch has the same modulus as the GL30c column. Further details can be found in Appendix A A.1.3.



**Figure 5.24:** CNC-displacement vs load

The displacement of each column concerning the number of floors has been plotted in Figure 5.25 to demonstrate the magnitude of vertical displacement in each column when using the notch column connection. The result indicates that the total displacement on the top floor of the entire building is 19.5 mm. Table 5.9 represents the magnitude of displacement on each floor. For further details, please refer to Appendix A A.1.3.



**Figure 5.25:** Displacement per floor no.

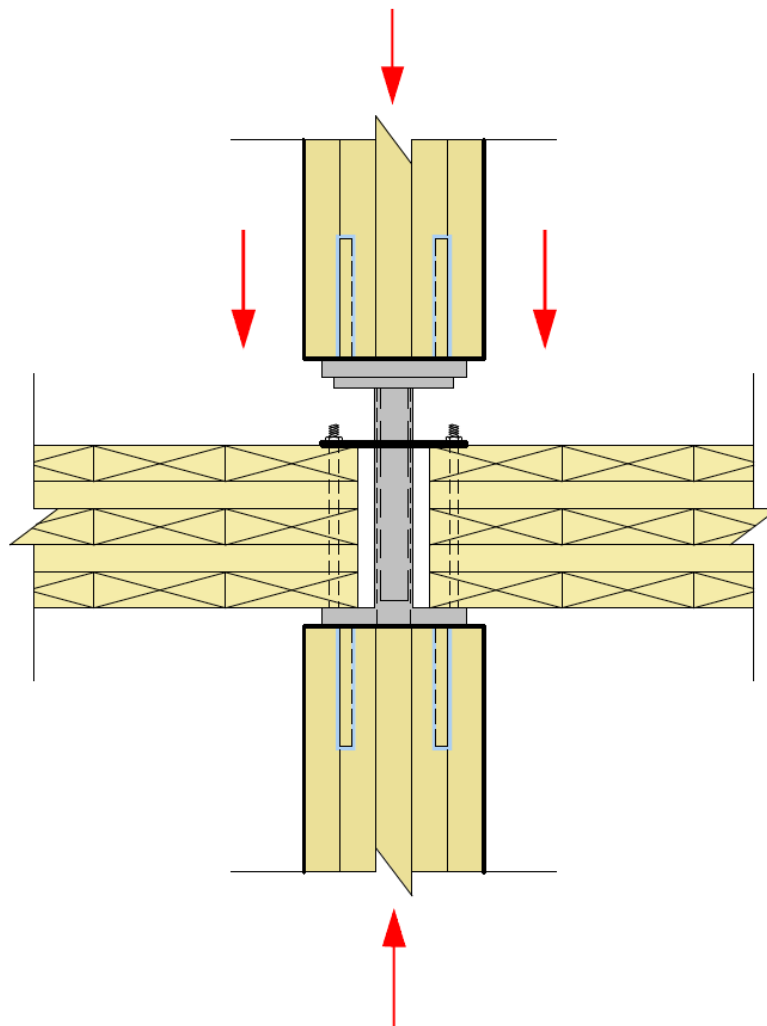
**Table 5.9:** Displacement per floor no.

<b>CNC-Notched connection</b>	
<b>Floor no.</b>	<b>Displacement [mm]</b>
column floor 10	19.6
column floor 9	19.5
column floor 8	18.9
column floor 7	18.0
column floor 6	16.7
column floor 5	14.9
column floor 4	12.7
column floor 3	10.2
column floor 2	7.2
column floor 1	3.8
Basement	0

### 5.4.3 Pillar steel connection (CPC)

The type of connection being discussed is a pillar connection as shown in Figure 5.26. This system permits the construction of buildings employing a column-to-floor configuration, with a column spacing of up to 6.0 meters (Rothoblaas, 2019). The Pillar connection system is ideal for use on columns in the corners or on the perimeter of the structural mesh. The geometry of the connections is designed to fulfill the criteria of transferring the vertical load from the top column and CLT panels to the bottom columns without causing any damage or crouching of the CLT panels.

The simplified model of this connection comprises three main parts. The upper plate is connected to the upper column, while the middle part is a cylinder or a standoff that is welded to the upper and bottom plate. This part should be designed to transfer the vertical load to the bottom column. The bottom plate is connected to the bottom column by fasteners. Steel connection assembly pieces are pre-installed on the bottom of the upper column to simplify the manufacturing process.



**Figure 5.26:** Pillar connection (Rothoblaas, 2019).

## 5. Vertical deformations

The column for this type of connection will be 6 m in height and continuous on two floors. The geometry and material properties of all parts of the connection are defined in table 5.10. the properties of the plate and the cylinder are taken from catalog (Rothoblaas, 2019).

**Table 5.10:** Properties of Beams and Columns

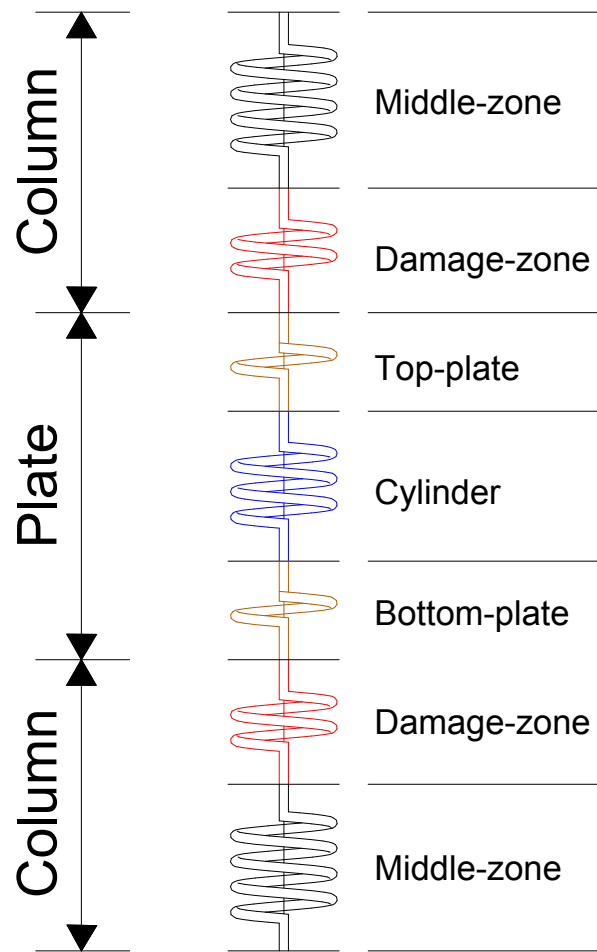
	Column(GL30c)	plate	cylinder
<i>Length</i> – [mm]	300	300	-
<i>Width</i> – [mm]	300	300	-
<i>Height</i> – [mm]	300	20	6 000
<i>Diameter</i> – [mm]	-	-	120
$E_{0,mean}$ – [MPa]	13 000	-	-
$E_{90,mean}$ – [MPa]	300	-	-
$E$ – [MPa]	-	200 000	200 000
<i>Density</i> $\rho_{mean}$ – [kg/m <sup>3</sup> ]	430	7 850	7 850

### 5.4.3.1 Spring system

The structure system for the entire building is simplified by using several springs each spring represents part of the structural system. The figure 5.27 below shows this system. The column is divided into three parts, top damage zone, middle zone, and bottom damage zone. The connection includes three parts, top plate, cylinder, and bottom plate. Each spring is described with special specifications depending on the material of the spring, Table 5.11 shows the properties of each spring in each sub-zone.

**Table 5.11:** CPC connection

Type	Area [mm <sup>2</sup> ]	Stiffness $\kappa$ [N/mm]	Length [mm]
Middle-zone	300×300	1.221 e+05	2 990
Damage zone	300×300	4.875 e+07	5
Top-plate	300×300	9.000 e+08	20
Cylinder	$\pi \times 60^2$	7.540 e+06	300
Bottom-plate	300×300	9.000 e+08	20
Damage zone	300×300	4.875 e+07	5
Middle-zone	300×300	1.221 e+05	2 990



**Figure 5.27:** Spring system CPC

The load will transfer from the top column to the top plate. The cylinder will bear the entire load that comes from the top plate and transfer it to the bottom plate, which will then make its way to the bottom column. The spring has one degree of freedom which presents the vertical displacement.

#### 5.4.3.2 Implementation in Matlab

A total of 27 springs are used to cover the entire building for this type of connection. Since the column is continuous across two floors, the load on each column comes from two floors for the node where the load needs to be applied to obtain accurate displacement regarding this type of connection and this is shown in Figure 5.28, detail D.

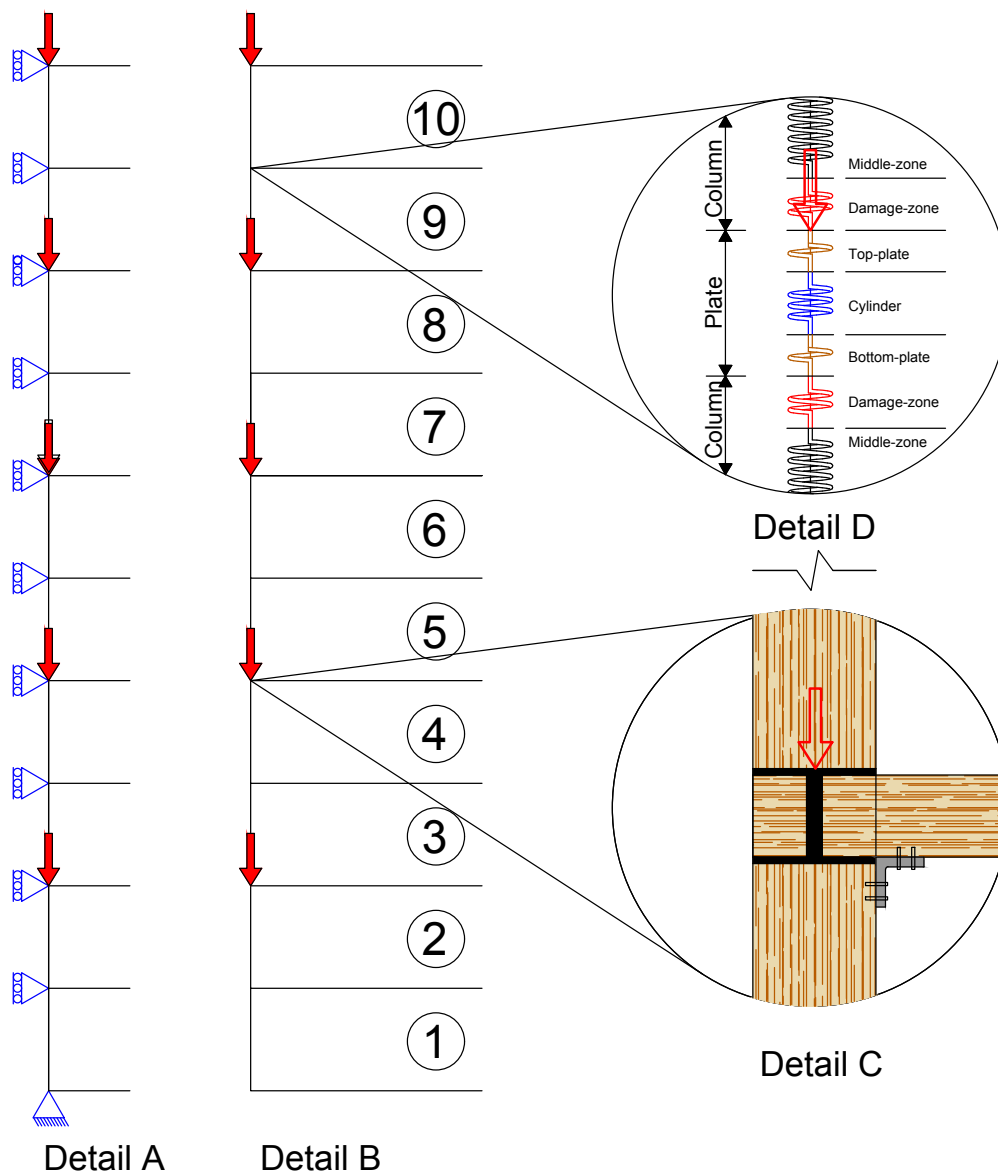
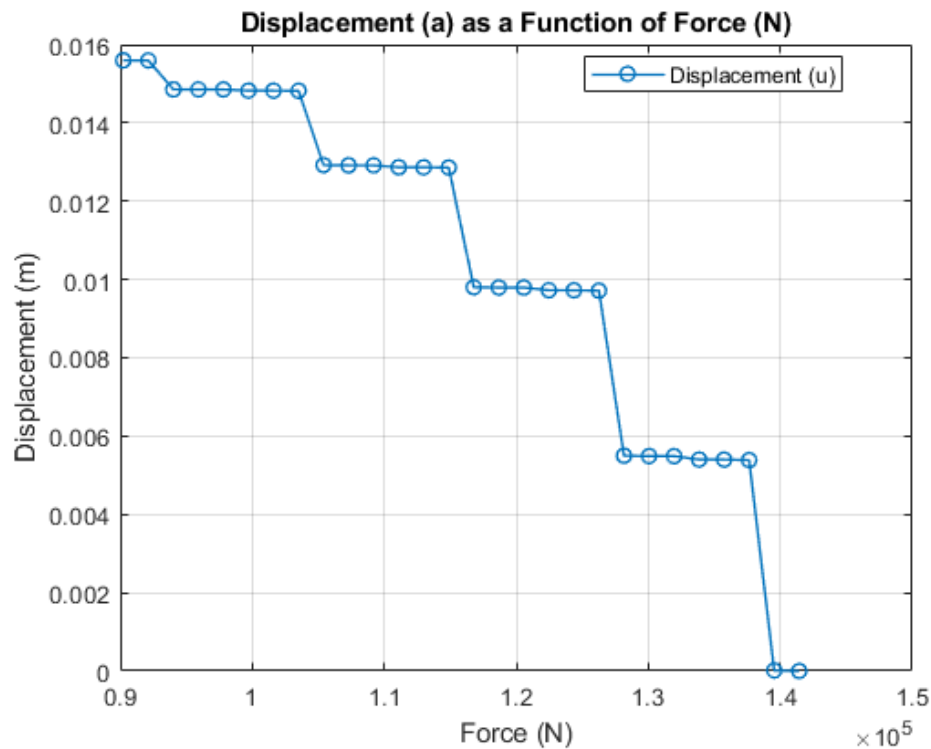


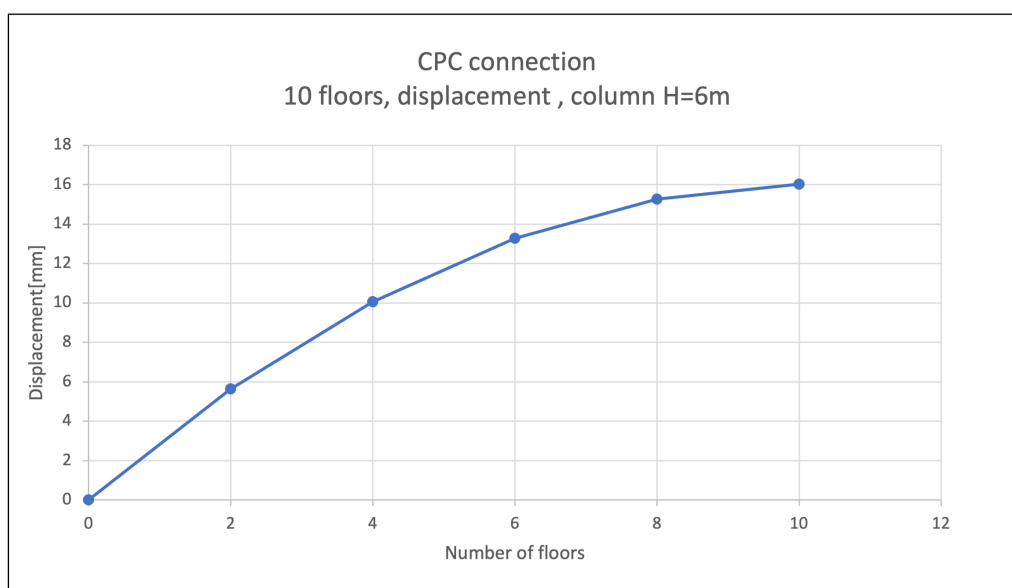
Figure 5.28: Detail-CPC

Figure 5.29 illustrates the displacement as a function of the applied load. The displacement value at the top of the column is the highest, as the bottom floor bears the most load. The total magnitude of displacement at the top of the building is approximately 16 mm. It is observed that the amount of displacement in the nodes where the CPC connection is applied is relatively small and can be neglected. This is because steel has a much higher modulus of elasticity compared to GL30c, which can decrease the deformation of the connection. Further details can be found in Appendix A.1.4.



**Figure 5.29:** CPC-Displacement as a function of load

Figure 5.30 below illustrates the displacement in the floors resulting from the displacement in the entire column connection system. As shown, the largest displacement occurs on the bottom floor, measuring 6 mm, and becomes smaller on the second floor and so on. It is observed that the connection has very low displacement, meaning the displacement mostly occurs in the column itself. For more information on the magnitude of the displacement in the connection, see Appendix A.1.4.



**Figure 5.30:** CPC-Displacement per floor

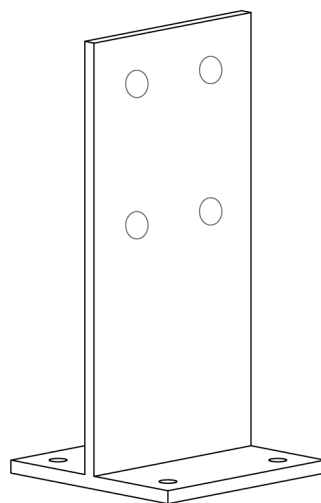
#### 5.4.4 Column-Penetrated plate-Column(CPPC)

This connection type, F70L S235 carbon steel with hot galvanizing, involves a knife plate that passes through the timber in the upper column and is welded to a horizontal plate, which is connected to the bottom column by screw anchors(Rothoblaas, 2019). The knife plate, with holes to be connected to the timber by smooth dowels or bolts, is shown in Figure 5.31.

The knife plate and dowels transmit the vertical load acting on the column to the bottom plate and then to the column below. Screw anchors in the bottom plate handle the shear and bending moment. Since the focus of this project is on the vertical displacement resulting from the vertical load, the screws, and shear forces do not need to be addressed. This type of connection is suitable for use in climate classes 1, 2, and 3. The properties of the bottom plate, knife plate, and column are shown in Table 5.12.

**Table 5.12:** Properties of CPPC connection

	Column(GL30c)	bottom plate	knife plate
<i>Length</i> – [mm]	300	300	300
<i>Width</i> – [mm]	300	300	8
<i>Height</i> – [mm]	3 000	8	500
$E_{0,mean}$ – [MPa]	13 000	-	-
$E_{90,mean}$ – [MPa]	300	-	-
$E$ – [MPa]	-	210 000	210 000
<i>Density</i> $\rho_{mean}$ – [kg/m <sup>3</sup> ]	430	7 850	7 850



**Figure 5.31:** CPPC connection

#### 5.4.4.1 Spring system

The spring system for this type of connection will consist of various springs with different stiffness. For instance, the column will be divided into three springs to account for the damage zone phenomenon that occurs in the joint area between the rough surface of the steel plate and the timber column. The damage zone in the column will be located at the bottom and top of the column. The modulus of elasticity (MOE) for the damage zone will be reduced to 1/3 of the MOE for timber, while the MOE for the Middle-zone will remain constant.

In this connection, the knife plate divides the column into two parts at the bottom one to the right of the Knife plate and the other on the left. Therefore, the spring in this area of the column will have several springs connected in parallel as shown in Figure 5.32. The calculation of the spring stiffness will use equation 5.12. According to equation 2, the stiffness of this spring will increase, making the connection stiffer to handle the vertical displacement.

$$\frac{1}{K} = \frac{1}{\left(\frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_1}\right)} \quad (5.12)$$

where,

- $K$  the equivalent stiffness [N/m]
- $k_1$  the stiffness of the timber part [N/m]
- $k_2$  the stiffness of the knife plate [N/m]

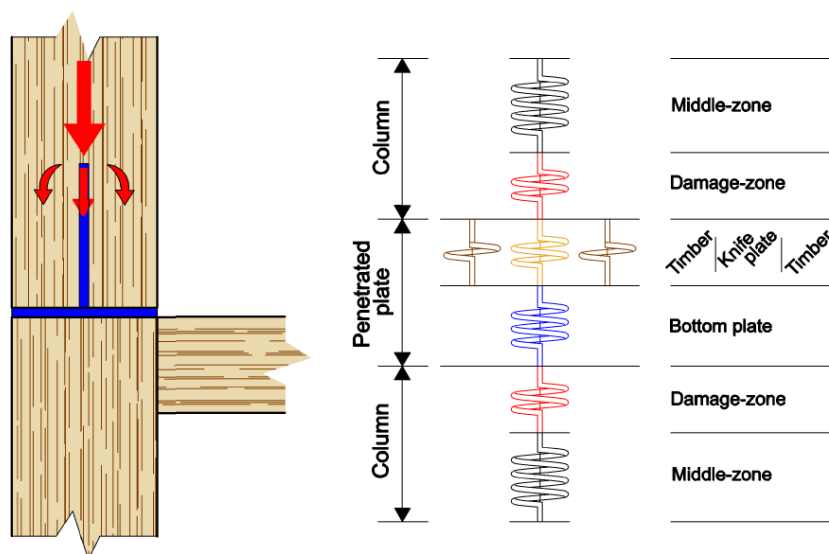


Figure 5.32: Spring system-CPPC

### 5.4.4.2 Implementation in Matlab

A total of 19 elements of springs are defined in Matlab to cover the entire building's column connection system along the height of the building. Three series springs represent the column, and three parallel springs represent the penetrated plate and the timber area on the sides of it. The stiffness for each part was calculated in Matlab with respect to the change in MOE, area, and length of each sub-zone shown in Table 5.13. The load was applied where the connection is located. For instance, the load on floor 10 was added to the load on floor 9 and then applied to the connection node.

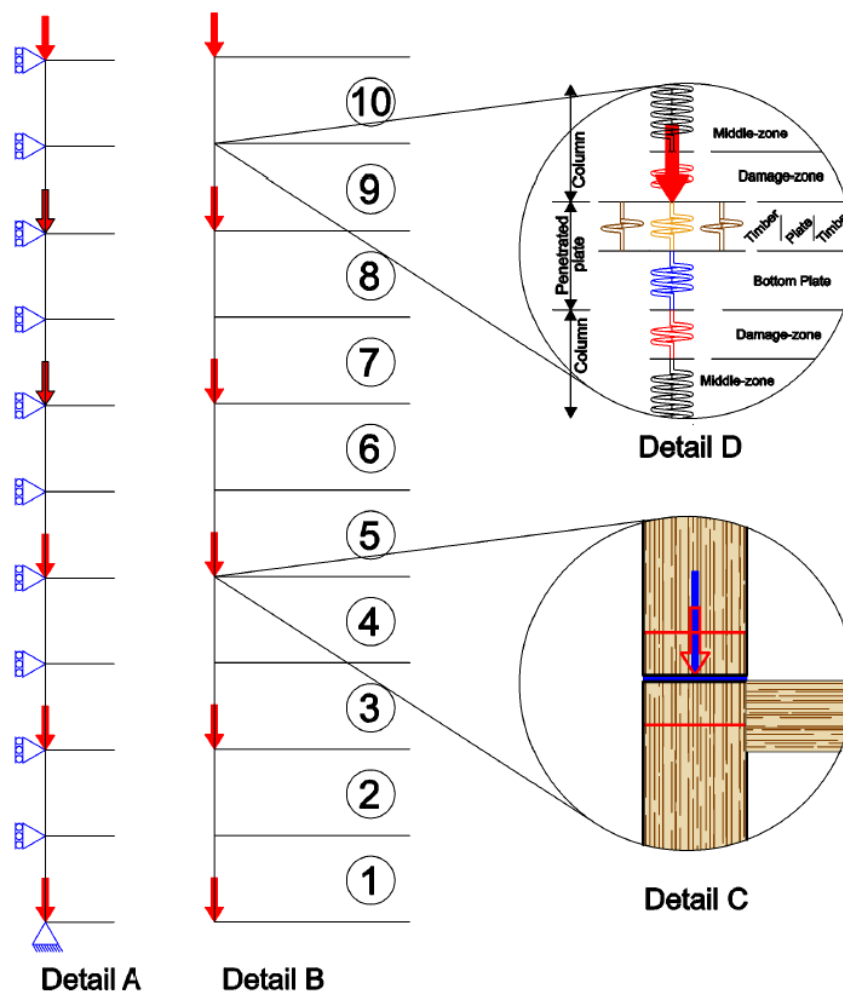


Figure 5.33: Detail-Penetrated plate

**Table 5.13:** CPPC connection

Type	Area [ $mm^2$ ]	Stiffness $\kappa$ [ $N/mm$ ]	Length [ $mm$ ]
Middle-zone	300×300	1.221 e+05	2 990
Timber part	146×500	2.438 e+07	500
Knife plate	300×8	9.600 e+05	500
Bottom plate	300×300	3.600 e+09	8
Damage zone	300×300	4.875 e+07	5
Middle-zone	300×300	1.221 e+05	2 990

The applied load plotted against the displacement is shown in Figure 5.35. As illustrated in Figure 5.35, the total vertical displacement is 18 mm at the top of the column. It is observed that the majority of this displacement comes from the column itself, while the connection has a low value of displacement.

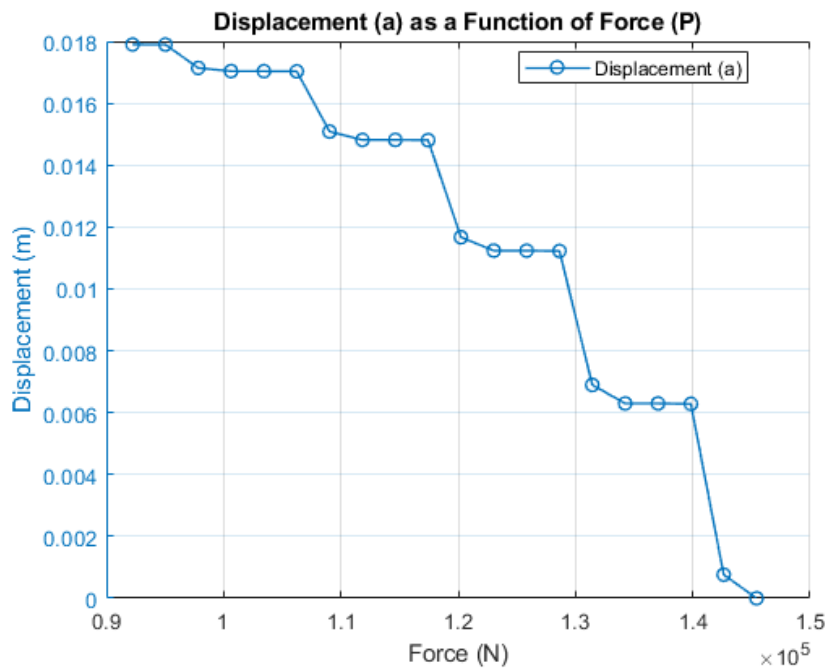
**Figure 5.34:** CPPC-Displacement as a function of load.

Figure 5.35 shows the displacement on each floor and the total displacement. Since the column is continuous over two floors, the first column on the bottom and first floor shows the highest displacement of 6 mm. The value of displacement in the second column decreases, and so on, until reaching a total displacement of 17.4 mm.

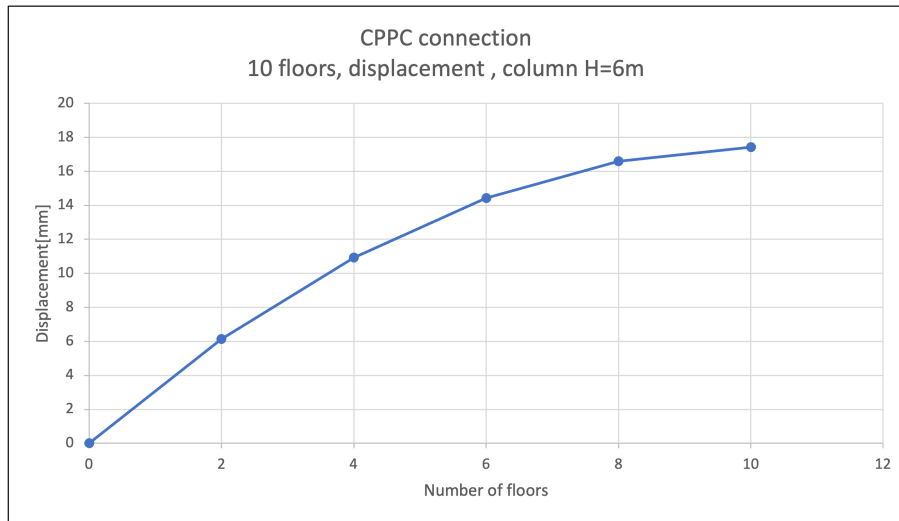


Figure 5.35: CPPC-Displacement per floor no.

### 5.4.5 Discussion

Now, the displacements to the different connection types that have been studied are plotted in Figure 5.36, corresponding to the number of floors, which is fixed at 10 in this stage of work. The difference in the magnitude of displacement shows that the CBC1 and CBC2 connections have the highest magnitude of displacement. In contrast, the notched column connections CNC, CPC, and CPPC show almost the same results. The connection with the least displacement is the CPC connection.

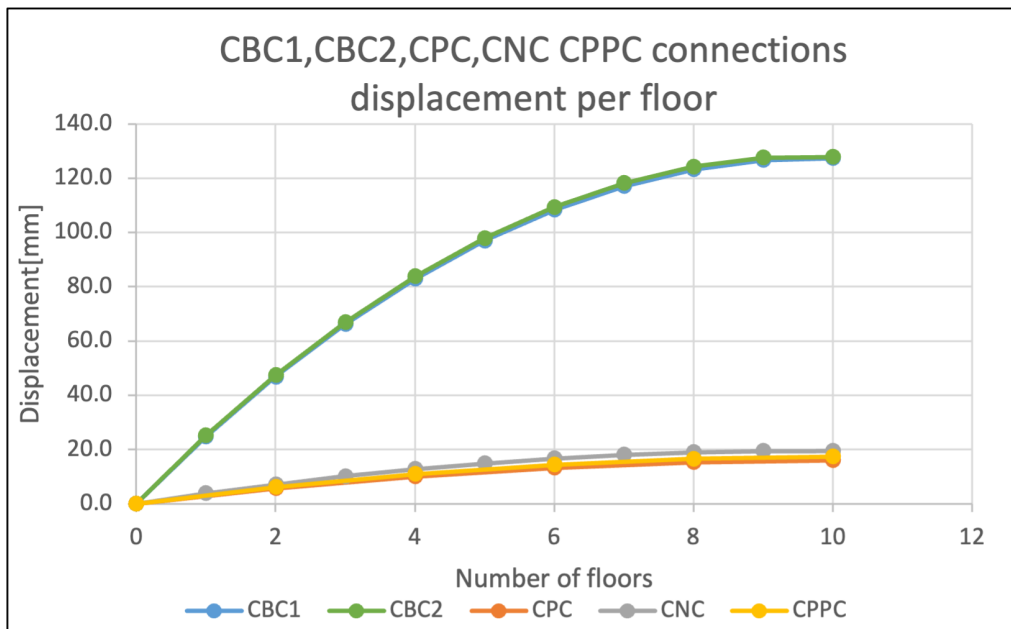


Figure 5.36: Displacement in all connections

## 5.5 Second scenario (20 Floors)

Based on the results shown in the previous section, it was found that the CPC connections have the least amount of vertical displacement. In this scenario, the CPC connection will be studied in more detail and the study will focus on the number of floors will be 20 floors. As a result, the dimensions of the column will change according to the section 4.6 and after checking the column and the dimensions of the column know  $450 \times 400$ . The aim is to evaluate CPC connections and determine the most suitable connection type when the dimensions and thickness of the plate change.

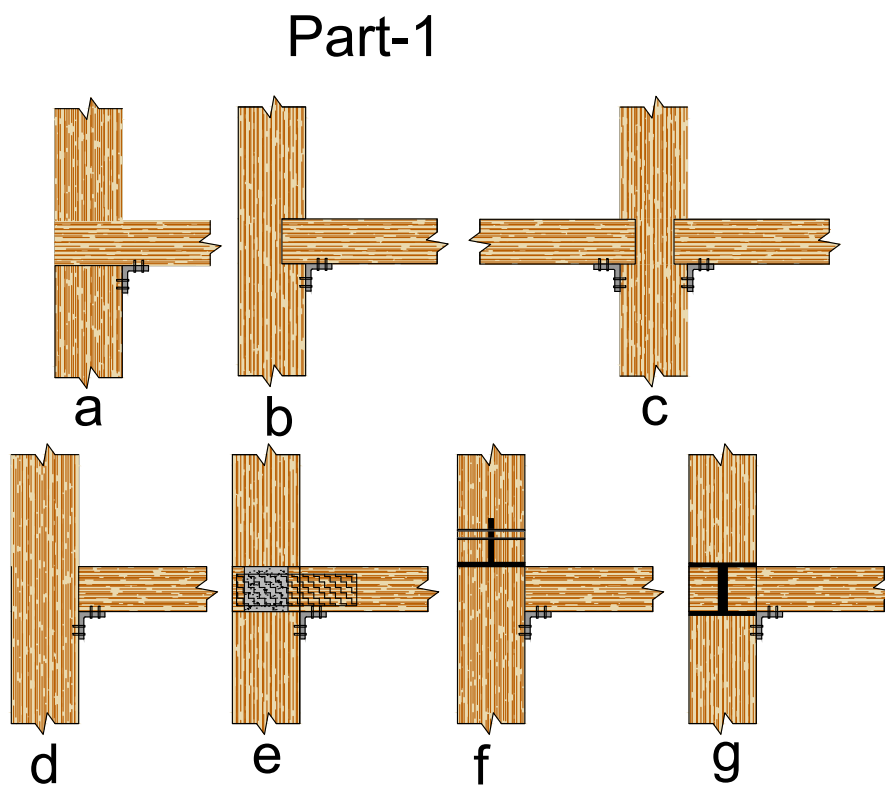


Figure 5.37: Several connections types

### 5.5.1 Column-Plate-Column(CPC)

In the second scenario, the connection type CPC is to be analyzed for a 20-floor building. The preliminary sizing of columns and beams has been revised to consider the additional structural load resulting from the change in the number of floors. Specifically, the column size has been adjusted from  $300 \text{ mm} \times 300 \text{ mm}$  to  $450 \text{ mm} \times 400 \text{ mm}$ . For more details regarding the preliminary sizing, see appendix C. Additionally, this section explores the impact of altering the dimensions of the plate, including length, width, and thickness. The approach for this study is outlined in Figure 5.38.

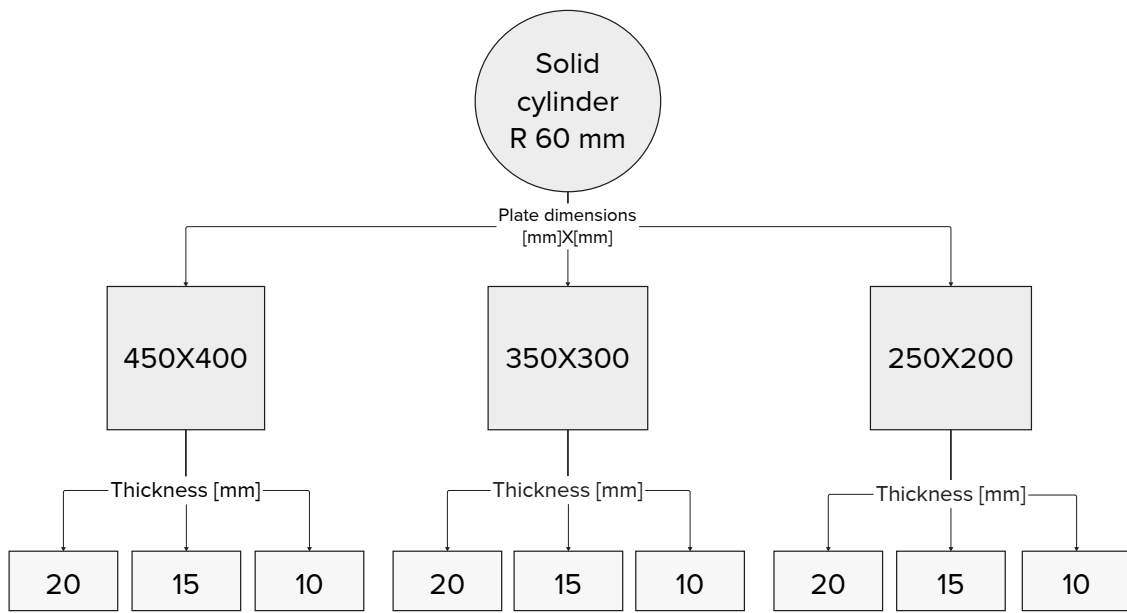


Figure 5.38: Second scenario strategy

### 5.5.1.1 FEM modeling in Abaqus

The purpose of using Abaqus software is to determine the effective area of the cross-section of the column when reducing the plate area in the connection. The connection will be modeled and the model and its properties that are used here will be presented and explained. In this study, the height of the column part is 3000 mm, and the boundary conditions are applied at the bottom, with the load applied at the top of the column part above the connection, Figure 5.39 shows two columns and a connection parts between them.

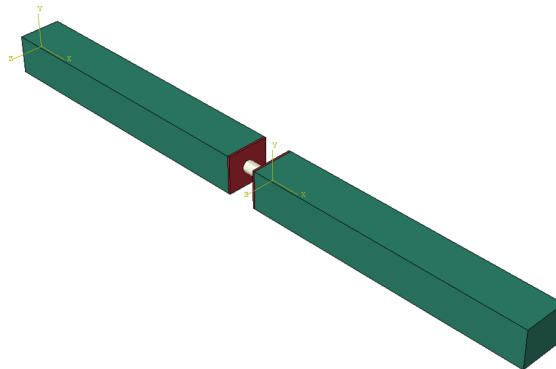


Figure 5.39: CPC parts

#### 5.5.1.1.1 Modeling of the elements

In Abaqus, the elements are modeled as 3D deformed parts with solid shapes. There are three types of parts in this model. The first part is a column made of glulam G130c, the second part is a plate made of steel S355, and the last part is a solid cylinder also made of steel S355.

### 5.5.1.1.2 Material properties

In the model, two types of materials are used, glulam GL30c for the timber columns and steel S355 for the steel parts in the connection. For glulam GL30c material, there are four material behaviors, the density of the timber, and the elastic behavior including elastic modulus, Poisson ratio, and shear modulus. The parameters for these materials are shown in Table 5.14 and 5.15.

Glulam GL30c is an engineering constants material, which means its properties differ significantly in different directions. while S355 in Abaqus is defined as an isotropic material that assumes homogeneity and uniformity in all directions within the material (Manual, 2012). In the model, the plastic behavior was not considered since the elastic behavior of the structure was studied in Matlab. Some results from Abaqus are needed for our Matlab code.

**Table 5.14:** Abaqus material properties (Timber GL30c)

Density [kg/m <sup>3</sup> ]						430		
Elastic behavior (Engineering Constants)								
<b>E1</b> [MPa]	<b>E2</b> [MPa]	<b>E3</b> [MPa]	<b>Nu12</b>	<b>Nu13</b>	<b>Nu23</b>	<b>G12</b> [MPa]	<b>G13</b> [MPa]	<b>G23</b> [MPa]
13 000	300	300	0.4	0.4	0.4	540	540	54

**Table 5.15:** Abaqus material properties (Steel S355)

Density [kg/m <sup>3</sup> ]		7 850	
Elastic behavior (Isotropic)			
Young's modulus [MPa]		Poisson's ratio [-]	
200 000		0.3	

### 5.5.1.1.3 Interaction

The interaction between interface parts of the model makes a kind of simulates the realistic contact between the column and the connection part and between the column and the connection. In the model, there are two kinds of interaction. The first interaction is a tie, which is used between the connection parts this explains the close connection between the parts in the connection. The second one is rigid, which is used between the interface in the column and the connection. The rigid allows some separation between the column and the connection.

#### 5.5.1.1.4 Boundary conditions

The boundary condition applied to the bottom face of the column under the connection involves displacement/rotation type. The boundaries are fixed in all three directions, and no external moments are imposed on them.

#### 5.5.1.1.5 Load application

The load is applied as a pressure over the entire cross-section to ensure uniform distribution across the surface of the column. This method of load application ensures that all nodes in the column experience the same displacement under the applied load. The amplitude of the load in this model is tabular.

The tabular amplitude defines how the magnitude of the load changes at different steps or intervals during the simulation (Manual, 2012). However, in this model, the amplitude remains constant, resulting in the loads being applied in one step. This is because the study focuses on the final state.

When dealing with this amplitude type, a load scale factor can be incorporated. However, because this model lacks inclines, the load scale factor can be disregarded. This approach to load application guarantees that all nodes in the column move uniformly when subjected to the load.

#### 5.5.1.1.6 Mesh and convergence study

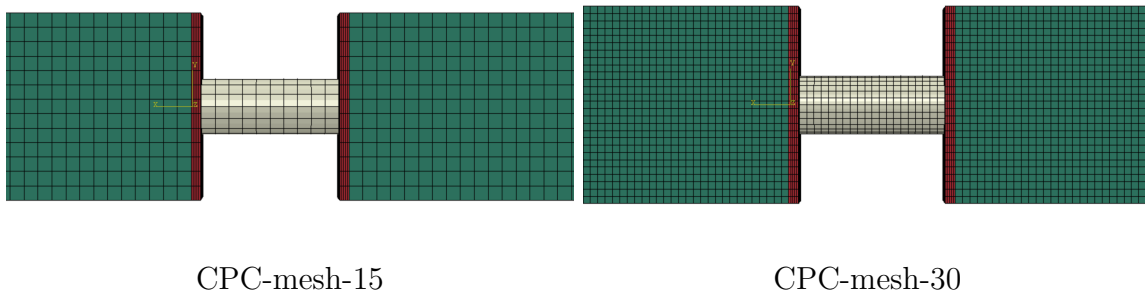
The mesh element in this model is called C3D20, A 20-node quadratic brick element was used to model the column. The "C" in "C3D20" denotes a "Continuum" element, which means it is suitable for analyzing solid structures. The "3D" signifies its three-dimensional element, while "20" specifies the number of nodes in the element (Manual, 2012).

This element type C3D20 is utilized for columns, plates, and cylinders. For the convergence study, two different mesh sizes were evaluated. Table 5.16 displays the mesh size for each part, and Figure 5.40 illustrates the appearance of the two mesh sizes in the modes for the column part containing the connection parts.

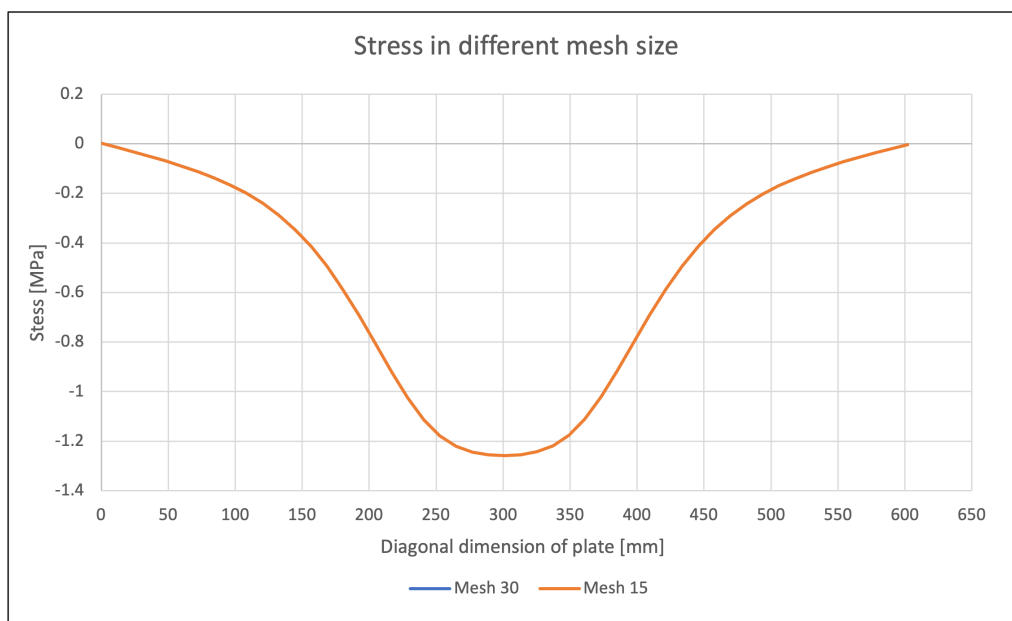
The stress along the path was compared for each mesh size, as shown in Figure 5.41. These two graphs aid in determining the most suitable mesh size to ensure that the results from this study can be effectively applied in future Abaqus simulations.

**Table 5.16:** Different mesh size (CPC)

Type	Column	Plate	Cylinder
Mesh-1	30	30	30
Mesh-2	15	15	15



**Figure 5.40:** CPC-mesh-15,30



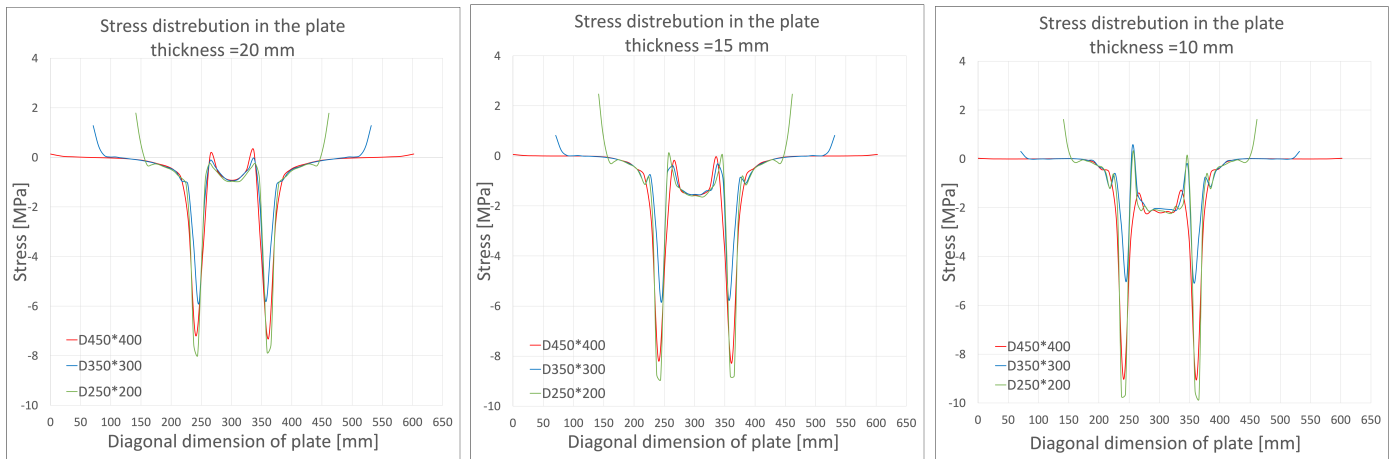
**Figure 5.41:** CPC convergence study

Figure 5.41 shows the mesh sizes 15 and 30 will give almost the same result of stress distribution. As a result, the mesh size 30 that is used in the future calculation is selected for further analysis in the calculations.

#### 5.5.1.1.7 Abaqus results

The primary purpose of studying the connection in Abaqus is to understand how stresses are distributed through the column. This involves modeling the connection detail and analyzing important results from Abaqus to comprehend the stress distribution mechanism. Key results to focus on include the stress in the plate under the cylinder and the stress through the column to determine where the stress will be distributed relatively uniformly.

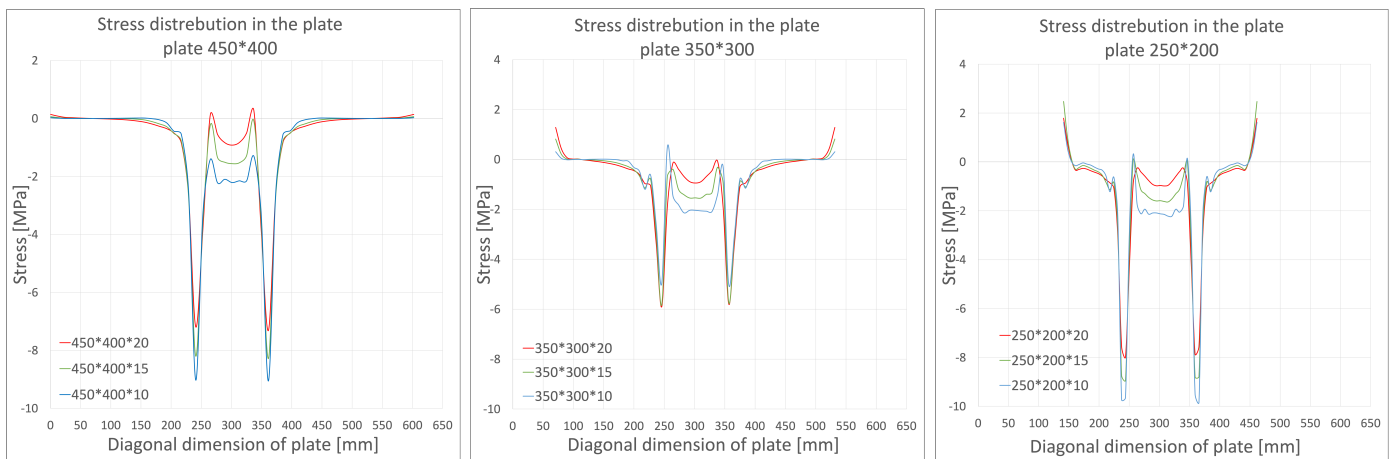
## 5. Vertical deformations



case (a) thickness 20 mm

case (b) thickness 15 mm

case (c) thickness 10 mm



case (d) plate 450 × 400

case (e) plate 350 × 300

case (f) plate 250 × 200

**Figure 5.42:** Stress in plate in different cases

To analyze the stresses in the plate, a path is selected to pass through the middle of the plate's thickness and extend diagonally to capture the full stress distribution effect. The stress distribution results along this path were compared for various plate dimensions and thicknesses, and are plotted in Figure 5.42.

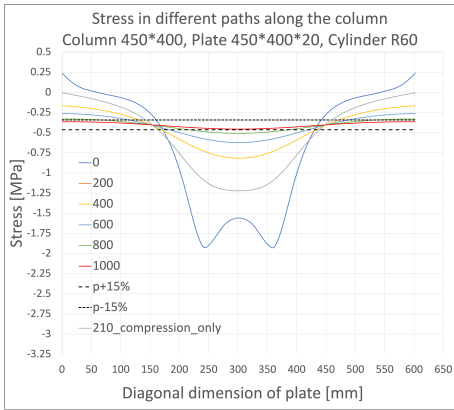
Stress variation occurs in the plate beneath the cylinder before reaching the timber column. Figure 5.42 highlights the stress differences across the studied cases and shows how stress varies with changes in the plate's dimensions and thickness. From Figure 5.42, it is evident that the stress at the perimeter of the cylinder-plate interface is higher than at the center of the cylinder for several reasons.

For instance, the stress concentration at the edges. when a plate presses down on the cylinder the perimeter edges are the first region to come into contact and bear

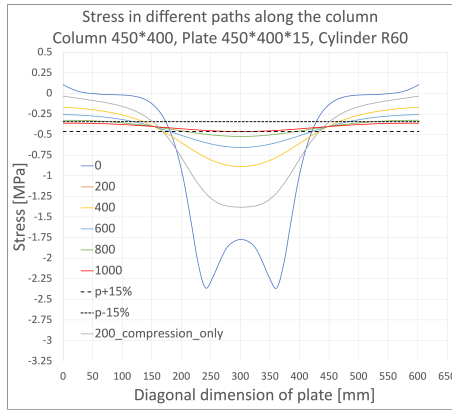
the load and this leads to higher concentrated stress (Pilkey and Pilkey, 2008). On the other hand, the cylinder acts as a boundary that can block the free deformation in the material, and this lead also to higher stress (Beer et al., 2017).

Figure 5.42 cases (a,b, and c) shows the comparison of the stress in the different plate dimensions  $450 \times 400$ ,  $350 \times 300$ , and  $250 \times 200$  with the same thickness the at is taken as diagonal in the plate to show better the difference along the path. It can be noticed that the small plate will exposed to different stresses between compression under the cylinder and tension in the perimeter of the plate, and also will be the same with a change the thickness. However, the tension stress decreases with increasing plate dimensions.

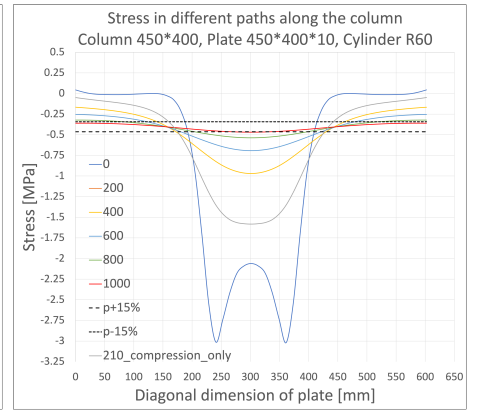
## 5. Vertical deformations



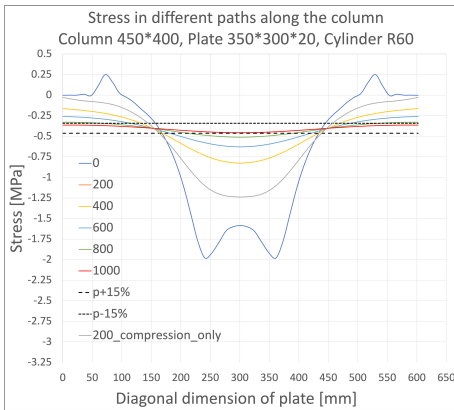
case (a) plate  $450 \times 400 \times 20$



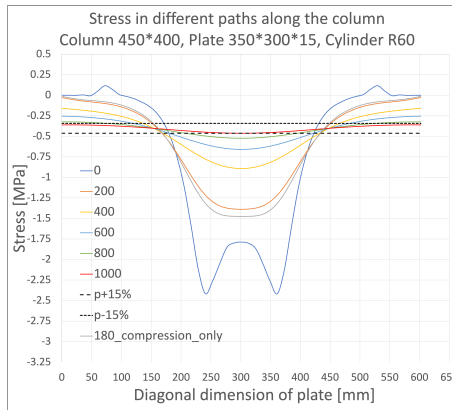
case (b) plate  $450 \times 400 \times 15$



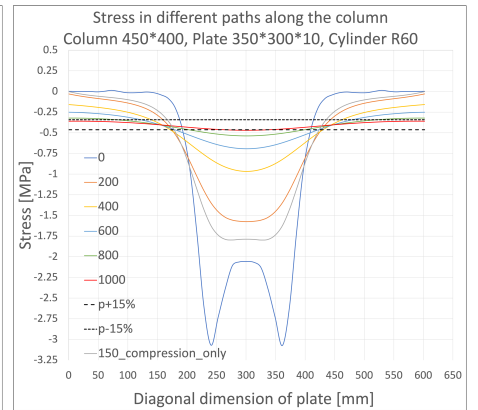
case (c) plate  $450 \times 400 \times 10$



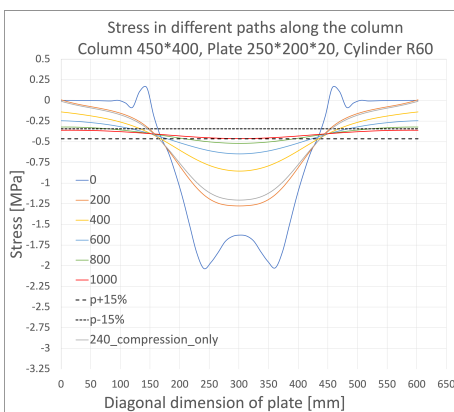
case (d) plate  $350 \times 300 \times 20$



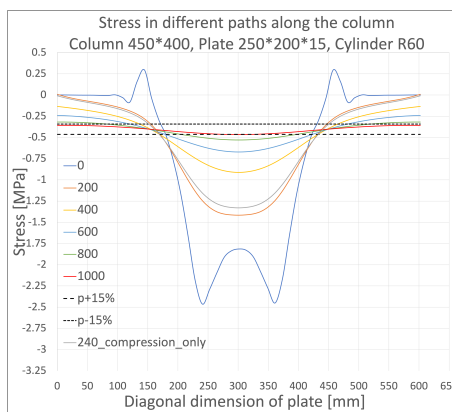
case (e) plate  $350 \times 300 \times 15$



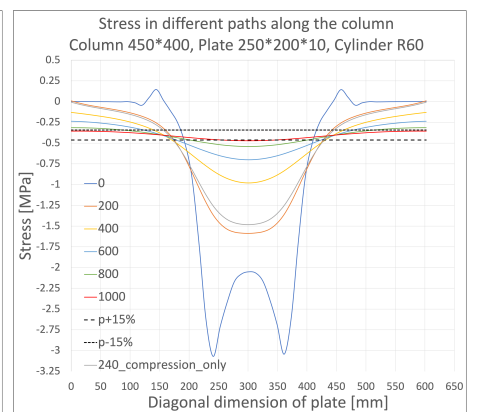
case (f) plate  $350 \times 300 \times 10$



case (g) plate  $250 \times 200 \times 20$



case (h) plate  $250 \times 200 \times 15$



case (I) plate  $250 \times 200 \times 10$

**Figure 5.43:** Stress in column in different cases

To study the stresses in the column, various cases were examined based on the dimensions and thickness of the plate. Measurements were taken every 200 mm along the column to obtain stress data. This analysis helps determine which plate optimizes the performance of the timber column, ensuring that the stress under the plate is distributed more effectively.

The gray curve in all cases in Figure 5.43 shows that the tension in the column will disappear from the cross-section and the compression will dominate on the cross-section in the column under the plate. This situation occurs over a length of almost 200 mm under the plate.

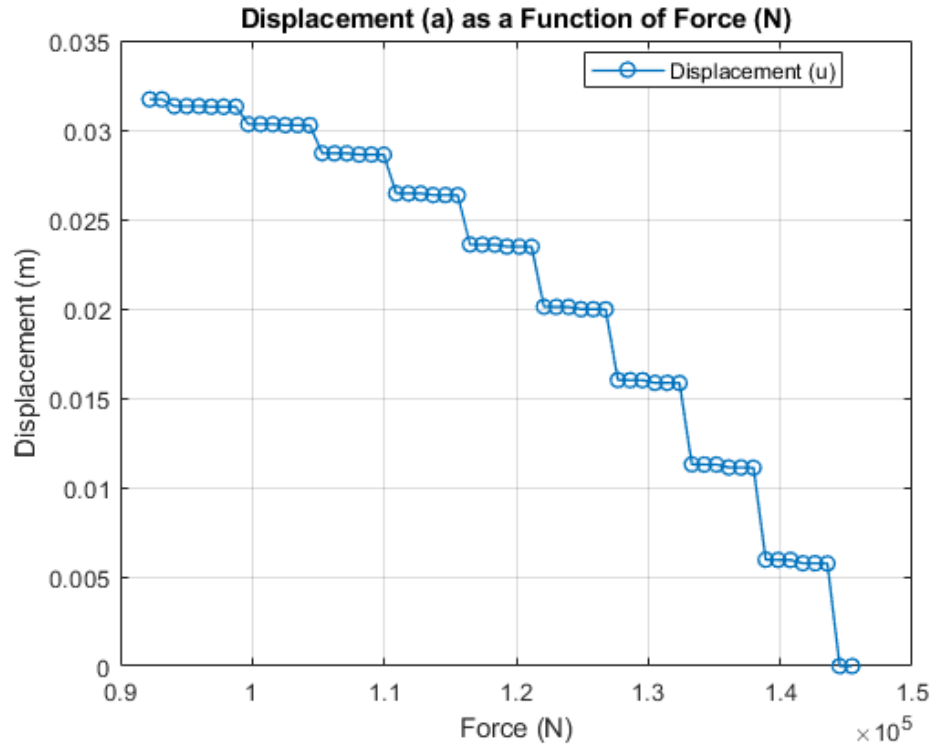
From Figure 5.43 cases (a,b, and c) when the plate dimensions  $450 \times 400$  it can be noticed that when the thickness of the same plate changes, the stress distribution under the plate in the column will take some distribution in the cross-section. This is the same for the different plate dimensions like  $350 \times 300$  or  $250 \times 200$ . Conversely, when the plate has the same thickness as in Figure 5.43 cases (a,d, and g) when the thickness is 20 mm the stress in the column is almost the same if some of the effects ignored from the path 0 mm under the plate, that passes through the column I the interface between the column and the plate.

From the above it can be concluded that the column part under 200 mm will be subjected to the compression on the entire cross-section will contribute to the resistance. On the other side, in the part of the column 200 mm in length under the plate, some parts are exposed to tension or very small compression and this part will be removed from the study in Matlab to give better results close to reality.

The acceptance criteria for variation in pressure distribution, considered reasonably uniform, can vary depending on the engineering context, with the universal acceptance of 10-15% as a small variation (Fleming, 1986). According to that, in all cases in Figure 5.43, it can be noted that the stress distribution variation falls between the application pressure +15% and -15% almost along the path 1000 mm under the plate. However, the stress distribution in all cases in Figure 5.43 becomes almost identical approximately starting from the path 200 mm under the plate.

### 5.5.2 Implementation in Matlab

The spring system 5.28 now needs to extend to cover the entire structure with 20 floors. The number of springs is 57 springs extending along the structure and the same application roles for the case with 10 floors are used. the displacement vs the load of 20 floors are plotted in Figure 5.44.



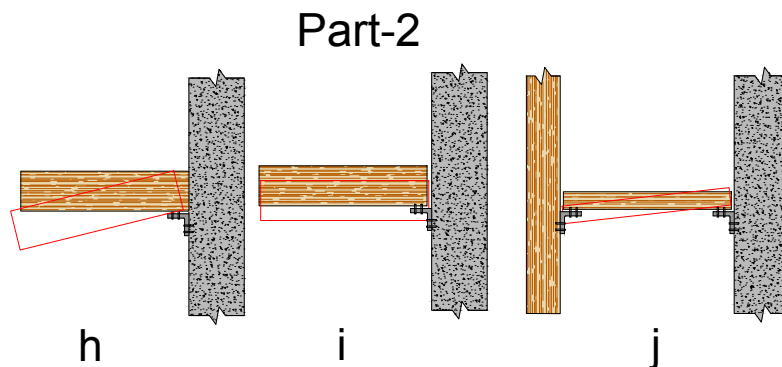
**Figure 5.44:** CPC load VS vertical displacement

Figure 5.44 shows the total displacement of the CPC connection in the case of 20 floors, where the observed magnitude of displacement is 31.7 mm, which is double the value of the displacement in the first scenario. The same connection was also studied for 30 floors, and the result shows 47.5 mm, where the dimensions of the column were modified to accommodate the new structural load, and the spring system in Matlab was adjusted to consider the new conditions.

## 5.6 Timber to concrete connection

The concrete can creep and shrink due to loading over time and also shrink due to surrounding conditions such as moisture and temperature. This long-term effect can cause the concrete to settle. The settlement of the concrete core in a TCC structure should be modified and addressed, as the timber column will also settle due to both long-term and short-term effects.

The magnitude of settlement in these two structural components should be taken into account. Timber settles more than concrete therefore, the type of connection between these two materials should consider this difference. For instance, in an 18-story mass timber building (Brock Commons Tallwood House, Canada), the axial shortening of GLT and PSL columns is managed through several measures (Council, 2018).



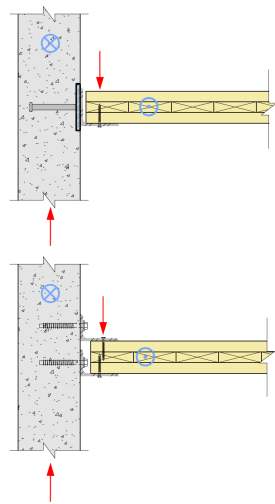
**Figure 5.45:** Timber to concrete connection

- **Steel Shim Plates:** 1.6-mm-thick steel shim plates were added at column-to-column connections on floors 7, 11, and 15 to mitigate shortening and shrinkage.
- **Partial Shimming:** Only 50% of calculated deformations were shimmed to avoid overcompensation, considering variations in the elastic modulus.
- **Mechanical Services Design:** HVAC and mechanical systems were designed to accommodate up to 32 mm of deflection.
- **Ongoing Monitoring:** Permanent sensors embedded in the building are monitored by UBC to track deformations.
- **Concrete Tolerances:** The cast-in-place concrete door and elevator sills have a  $\pm 19$  mm tolerance. Adjustments include sloping the concrete topping or chipping the sills if needed.

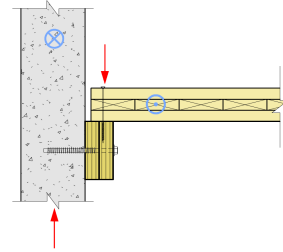
The difference in deformation between the concrete core and timber columns can be managed through various strategies. Additionally, the type of connection plays a significant role in handling this deformation difference. There are many types of connections to join timber beams or CLT panels to concrete (products council, 2021).

## 5. Vertical deformations

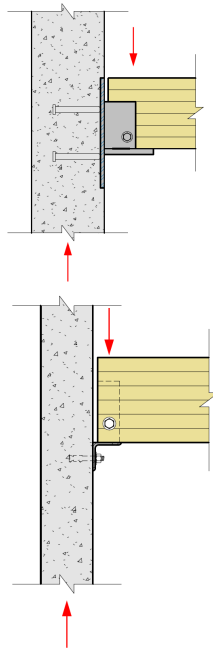
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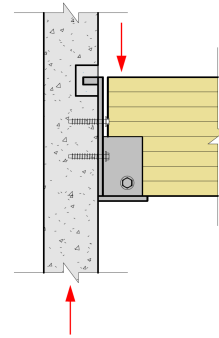
Panel bears at bracket at wall



Beam perpendicular to wall connected to face of wall



Beam perpendicular to wall connected to face of wall



Beam perpendicular to wall connected to face of wall with top bearing

**Figure 5.46:** Timber concrete connections (products council, 2021).

# 6

## Discussion

The assumptions, Matlab implementation, and Abaqus will be discussed in this chapter. The results of different types of connections that have been studied will also be highlighted here.

### 6.1 Assumptions

Starting with the assumptions that have been taken from some experiments and studies regarding the D-zone that occurs in the timber member due to the type of connection, for instance, timber to timber, steel to timber. In this paper, the length of the D-zone was fixed to 5 mm, which may affect the result of the total displacement. This value should be estimated by an experimental study based on the same type of timber product with a different range of specimens to define the more relative value to be used in the calculation. However, in this project, the effect of this length on the damage zone was almost neglected. The reduction of the MOE in the damage zone, which was also based on some experimental studies, should also be estimated by experimental to get an accurate MOE to be used in the calculation to get more reasonable results.

The long-term effect on timber in the form of creep and shrinkage in this project has been covered by using the reduction factor  $k_{def}$  for the MOE according to the EURO code and some experimental studies for simplicity and shortage of time. This effect should be estimated in a parametric study which can cover the change in the condition of temperature and moisture during a period of time to estimate the real factor that can express this effect.

In this project, there was no consideration of the type of construction method, whether it is serial or parallel, while the time of calculation starts from the time the building is finished and it's getting in its service life SLS load combination for the short and long term have been considered. The different types of connections that have been chosen to cover the behavior of timber columns in case of having timber-steel joint or timber-to-timber joint. This also has some consideration regarding the safety, fire resistance, maintenance, and economic aspects, but in this project, the highlighted aspect is the amount of displacement observed by the type of joint or connection.

## 6.2 Matlab implementation

Since the Matlab spring function has been used to address the vertical deformation results, the outcomes depend on how the implementation process has been done in Matlab for each type of connection. The spring function is based on the stiffness of each spring and how this stiffness can affect the magnitude of displacement in each spring. The parameters that influence the stiffness of the spring, according to the spring stiffness equation, are the cross-sectional area, the modulus of elasticity (MOE), and the length of the specimen. The stiffness increases if the area and MOE of the specimen increase and decreases if the length of the specimen increases.

This theory behind the spring function can explain the differences in results for each connection. It is also noted that when the stiffness of a spring is high, the displacement is small, and vice versa. According to the Matlab results for all studied connections, the displacement was entirely dependent on the column, where the connection itself had a very small impact on the total magnitude of the displacement, which can be neglected. This is because, when the steel connection is used, the spring stiffness representing this connection has a MOE that is almost 16 times the MOE of the timber column. Another factor affecting the Matlab outcomes is that the load is applied to specific nodes to match reality as closely as possible.

## 6.3 FEM design Abaqus

The stress distributions in the column were estimated by Abaqus for two connection types notch column and CPC connections. The results obtained from Abaqus may have been affected by the validation of the interactions between the parts of the connection model in the input phase. The output also depended on the different paths taken at each cross-section over the stress distributions. The diagonal path provided more accurate results compared to the path taken across the width of the cross-section. For the CPC connection type, the model studied in Abaqus was simplified, so no bolts or screws were penetrating the plate in the model, as the focus was solely on addressing the stress distribution in the column under compressive stress. This simplification could have affected the obtained results in some way.

## 6.4 Result

Regarding the different types of connections that have been studied in the case of a 10-story building, including CBC1, CBC2, notch column, CP, and CPPC. CBC1 and CBC2 highlighted the effect of loading perpendicular to the grain and parallel to the grain. This type of connection, concerning the displacement result, should be avoided in such high timber buildings or should be improved to achieve an accurate result. It can be improved, for instance, by adding steel rods to the beam and these rods penetrating the top and bottom column so that the compressive stress is transferred through, or by adding a steel I section inside the beam where the connection is to be.

The notched connection gives outstanding results despite the connection type being timber to timber. The idea behind this type of connection is that the column is prefabricated, so the notched part has the same material properties as the whole column. Moreover, the idea of the damage zone can be neglected since the column does not consist of joints from another material such as steel. The size of the notch plays an important role in the results and should be considered carefully in the design process of the column connection.

The CPC and CPPC connections yield almost the same results due to the presence of a steel joint or connection, which can cause an increase in displacement in the joint area due to the high MOE (Modulus of Elasticity) of the steel and the isotropic nature of the material, allowing it to distribute stress equally in all directions. The difference between these two connections is that the CPPC connection type can minimize the effective length of the column by allowing the knife plate to penetrate the column to a depth of 500 mm, making the column stiffer at its end. However, the CPC connection type yielded more accurate results due to the bottom and upper plates helping to mitigate the increase in displacement without making any changes to the column's cross-sectional properties. The different geometries and thicknesses have been studied in Abaqus for this type of connection. The results show that the thickness of the plate plays a significant role in the stress distribution in the column, while the cross-section of the plate has a limited effect.



# 7

## Conclusion

The vertical displacement in the hybrid structure TCC is influenced by many factors. In this project, the focus has been on the type of connection and its influence on the final settlement of the timber column. For concrete, long-term effects such as creep and shrinkage also influence the magnitude of settlement, but in this project, the settlement of the concrete core has not been estimated. The total difference in displacement between the timber and concrete should be taken into account during the design phase of the project.

Manufacturing mistakes, transportation processes, and the installation of the column and assembly of the connection have not been accounted for in the total displacement. These issues can result in an amount of displacement that needs to be considered during the calculation of the deformation.

### 7.1 Design Recommendation

Some recommendations are to be taken into account during the design phase for such a situation.

- The validation of EWP and its strength class has a significant role in timber displacement.
- The length of the column has a high impact on the timber displacement.
- The cross-section area of the column influences the magnitude of displacement.
- Types of joints, timber to timber or timber to steel, should be calculated differently.
- The thickness of the steel plate used in a connection plays an important role in the stress distribution in the column.
- The strength class of the concrete should be estimated with consideration to the differences in settlement of the timber and concrete, meaning a higher strength class of concrete results in less settlement.

### 7.2 Further studies

This project requires further studies to ensure that the vertical displacement value obtained here is accurate and reasonable. For instance, an experimental study based on the type of connection is needed to determine the length of the "D" zone in the joint area. A parametric study for environmental conditions such as temperature and moisture over a long period for the region where the building will stand is necessary to estimate their impact on the structure.



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# A

## Appendix 1

## A.1 10 floors

### A.1.1 CBC1 connection

**Table A.1:** Displacement per spring

CBC1	Displacement [mm]	Load [kN]
a1	127.2	19.5
a2	126.6	
a3	126.5	72.5
a4	123.5	
a5	123.1	72.5
a6	117.8	
a7	117.1	72.5
a8	109.3	
a9	108.4	72.5
a10	98.2	
a11	97.0	72.5
a12	84.5	
a13	82.9	72.5
a14	68.1	
a15	66.2	72.5
a16	49.0	
a17	46.8	72.5
a18	27.2	
a19	24.7	72.5
a20	2.8	
a21	0.0	

**Table A.2:** Displacement per floor no.

	Displacement [mm]	Load [kN]	No. Floor
column floor 10	127.2	19.5	10
column floor 9	126.5	72.5	9
column floor 8	123.1	72.5	8
column floor 7	117.1	72.5	7
column floor 6	108.4	72.5	6
column floor 5	97.0	72.5	5
column floor 4	82.9	72.5	4
column floor 3	66.2	72.5	3
column floor 2	46.8	72.5	2
column floor 1	24.7	72.5	1
	0.0	72.5	0

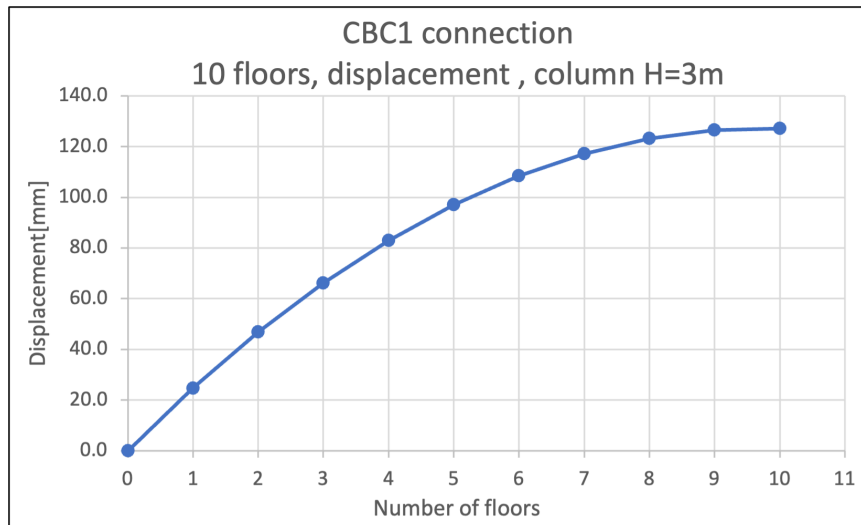


Figure A.1: Displacement per floor no.



---

```

% Define element degrees of freedom matrix (Edof)
Edof = [1, 1, 2 % Element degrees of freedom relate to nodes
2, 2, 3
3, 3, 4
4, 4, 5
5, 5, 6
6, 6, 7
7, 7, 8
8, 8, 9
9, 9, 10
10, 10, 11
11, 11, 12
12, 12, 13
13, 13, 14
14, 14, 15
15, 15, 16
16, 16, 17
17, 17, 18
18, 18, 19
19, 19, 20
20, 20, 21];
% Boundary conditions needs to be specified in "solveq"
% Define boundary condition matrix (bc) relate to nodes freedom
bc = [21, 0];

% Get dimensions of problem
nel = 20; %Calculate number of elements
(nel)
ndof = 21; %number of dofs (ndof)

% Define vector with applied loads (load_vector)
load_vector=[p1 p2 p3 p4 p5 p6 p7 p8 p9 p10];

% Define vector with locations of applies loads (load_position)
load_position=[(nel-19) (nel-17) (nel-15) (nel-13) (nel-11) (nel-9)
(nel-7) (nel-5) (nel-3) (nel-1)];

% Preallocate matrices and vectors
K = zeros(ndof);
for iel=1:nel
    Ke=springle(Ep(iel));
    K(Edof(iel,2:end),
    Edof(iel,2:end))=K(Edof(iel,2:end),Edof(iel,2:end))+Ke; % Assembled
    stiffness matrix
end

% Global load vector
f =zeros(ndof, 1);

% Apply nodal loads
% Tasks: Insert the load_vector in the fl vector in the positions
specified by load_position

```

---

---

```

for i = 1:length(load_position)
    f(load_position(i)) = f(load_position(i)) + load_vector(i);
end
% f(load_position) = f(load_position) + load_vector;    % Assembled
% load vector

% Solving the system
u=solveq(K,f,bc);          % Obtaining the translations for the DOF

% Results
fprintf('\nDisplacements:\n');
fprintf('a%1u = %7.4f mm\n', [(1:ndof)', u*1000]); % Printing the
% displacements in mm (conversion by a*1000)

% Define the range for the x-axis based on the load_vector
x_range = linspace(min(load_vector), max(load_vector), numel(u));

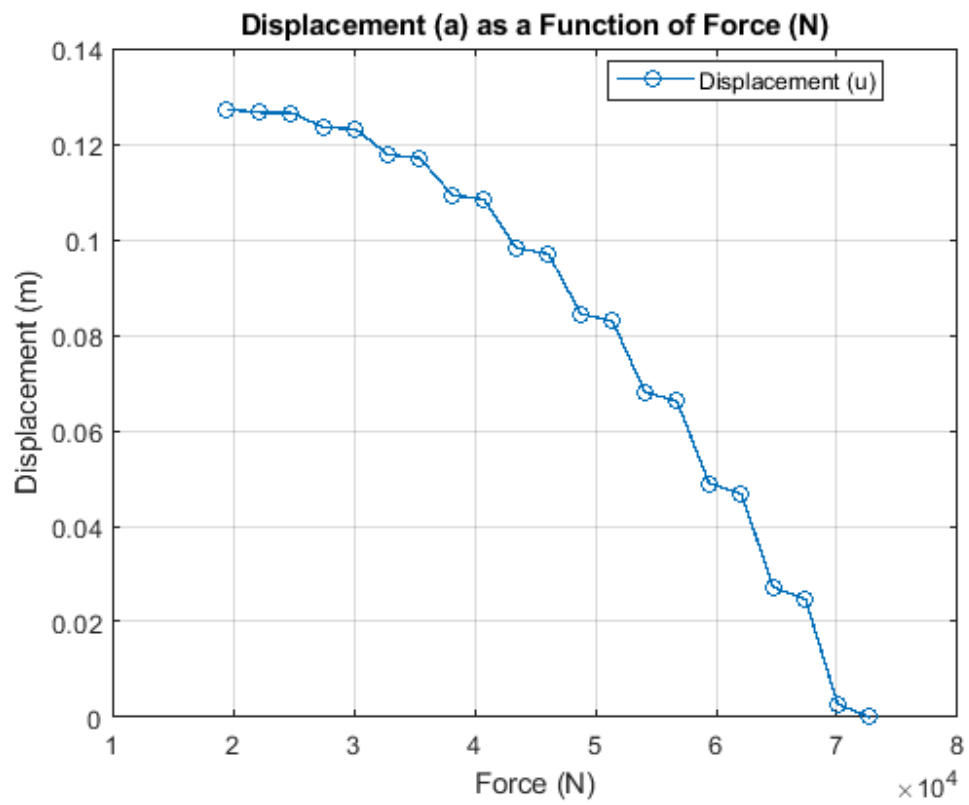
% Plot displacement (a) as a function of force (P)
plot(x_range, u, '-o', 'LineWidth', 1);
xlabel('Force (N)');
ylabel('Displacement (m)');
title('Displacement (a) as a Function of Force (N)');
grid on;
legend('Displacement (u)', 'Location', 'best');

```

```

Displacements:
a1 = 127.2399 mm
a2 = 126.6039 mm
a3 = 126.5239 mm
a4 = 123.5178 mm
a5 = 123.1394 mm
a6 = 117.7632 mm
a7 = 117.0865 mm
a8 = 109.3402 mm
a9 = 108.3652 mm
a10 = 98.2488 mm
a11 = 96.9754 mm
a12 = 84.4889 mm
a13 = 82.9172 mm
a14 = 68.0606 mm
a15 = 66.1905 mm
a16 = 48.9639 mm
a17 = 46.7955 mm
a18 = 27.1987 mm
a19 = 24.7319 mm
a20 = 2.7651 mm
a21 = 0.0000 mm

```



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## A.1.2 CBC2 connection

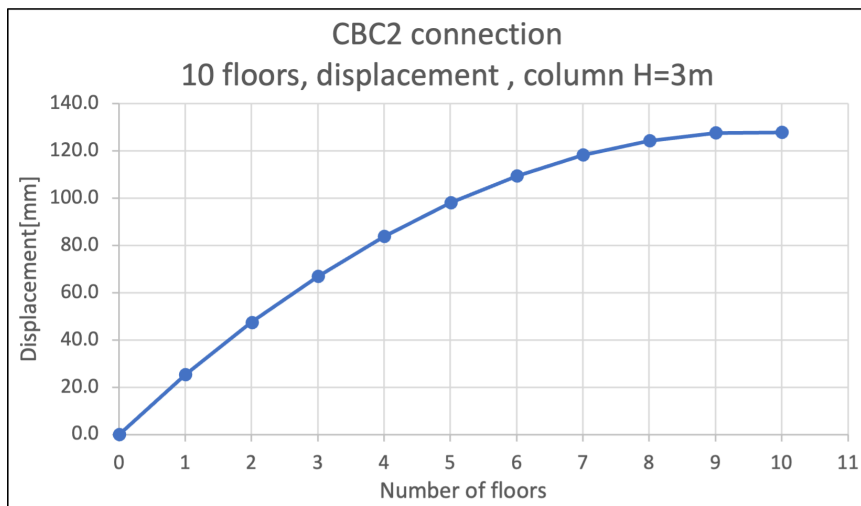
**Table A.3:** Displacement per spring

CBC2	Displacement [mm]	Load [kN]
a1	127.7	19.5
a2	127.7	
a3	127.6	
a4	127.6	72.5
a5	127.5	
a6	124.7	
a7	124.6	
a8	124.6	
a9	124.2	
a10	124.2	72.5
a11	124.1	
a12	118.9	
a13	118.8	
a14	118.8	
a15	118.1	
a16	118.1	72.5
a17	117.9	
a18	110.5	
a19	110.3	
a20	110.3	
a21	109.3	
a22	109.3	72.5
a23	109.1	
a24	99.4	
a25	99.1	
a26	99.1	
a27	97.9	
a28	97.9	72.5
a29	97.5	

CBC2	Displacement [mm]	Load [kN]
a30	85.6	
a31	85.3	
a32	85.2	
a33	83.7	
a34	83.7	72.5
a35	83.3	
a36	69.1	
a37	68.7	
a38	68.7	
a39	66.9	
a40	66.9	72.5
a41	66.4	
a42	50.0	
a43	49.5	
a44	49.5	
a45	47.4	
a46	47.4	72.5
a47	46.9	
a48	28.1	
a49	27.6	
a50	27.6	
a51	25.2	
a52	25.2	72.5
a53	24.6	
a54	3.6	
a55	3.0	
a56	3.0	
a57	0.3	
a58	0.0	

**Table A.4:** Displacement per floor no.

	Displacement [mm]	Load [kN]	No. Floor
column floor 10	127.7	19.500	10
column floor 9	127.6	72.500	9
column floor 8	124.2	72.500	8
column floor 7	118.1	72.500	7
column floor 6	109.3	72.500	6
column floor 5	97.9	72.500	5
column floor 4	83.7	72.500	4
column floor 3	66.9	72.500	3
column floor 2	47.4	72.500	2
column floor 1	25.2	72.500	1
	0.0	72.500	0

**Figure A.2:** Displacement per floor no.

```

clc
clear all
close all

```

## Problem description%%

case 2 CBC2 10 floors, (column\_beam\_column)connection column H=3.1 Problem geometry :o--/\|\|/--  
o--/\|\|/--o--/\|\|/--o Analysis model

```

%a_1          a_2          a_3          a_4          [Degrees of freedom]
% o--/\|\|/--o--/\|\|/--o--/\|\|/--o
%   -(1)->      -(2)->      -(3)->          [Elements]
%       k1=N/m      k2=N/m      k3=N/m
% End of problem description

```

## Problem input

```

% Constants
L_column      = 3;                %length of the column[m]
Lc_Damge      = 0.005;            % length of the Damage
    zone in column[m]
Lc_middle     = L_column - 2.*Lc_Damge; % length of the middel
    zone in the column[m]
L_beam        = 0.55;            % the hoght of the beam
    [m]
Lb_Damge      = 0.005;            %the estimated length of
    the beam crushing zone[m]
Lb_middle     = L_beam -2*Lb_Damge; % length of the beam
    middel zone [m]
A_column      = 0.3*0.3;          % area of the
    column[m^2]
Ac_Damge      = 0.3*0.3;          % area of the Damage zone
    in the column[m^2]
Ac_midel     = 0.3*0.3;          % the arae of the column
    middel zone [m^2]
A_beam        = 0.3*0.3;          %the arae of the
    beam[m^2]
Ab_Damge      = 0.3*Lb_Damge;     % the damge zone arae of
    the beam[m^2]
E_column      = (1.3*10^10)/(1+0.6); %MOE fo the column [N/
    m^2]
E_beam        = (3*10^8)/(1+0.6); %MOE for the beam [N/
    m^2]

% stiffnesses
K_Mc          = A_column*E_column/Lc_middle; %stiffness midel zone
    column [N/m]
K_Dc          = (A_column*(1/3)*(E_column))/Lc_Damge;%stiffness damage zone
    column [N/m]
K_Mb          = A_beam*E_beam/Lb_middle;    %stiffness midel zone
    beam [N/m]

```

---

```

K_Db    = A_beam *(1/3)*(E_beam)/Lb_Damage;    %stiffness damage zone
beam [N/m]

% Define element properties column vector (Ep)

Ep = [K_Dc;K_Mc;K_Dc;K_Db;K_Mb;K_Db;
      K_Dc;K_Mc;K_Dc;K_Db;K_Mb;K_Db;
      K_Dc;K_Mc;K_Dc;K_Db;K_Mb;K_Db;
      K_Dc;K_Mc;K_Dc;K_Db;K_Mb;K_Db;
      K_Dc;K_Mc;K_Dc;K_Db;K_Mb;K_Db;
      K_Dc;K_Mc;K_Dc;K_Db;K_Mb;K_Db;
      K_Dc;K_Mc;K_Dc;K_Db;K_Mb;K_Db;
      K_Dc;K_Mc;K_Dc;K_Db;K_Mb;K_Db;
      K_Dc;K_Mc;K_Dc;K_Db;K_Mb;K_Db;
      K_Dc;K_Mc;K_Dc;K_Db;K_Mb;K_Db;
      K_Dc;K_Mc;K_Dc];

% loads
p1=19.513*10^+3;    % [N]
p2=70.719*10^+3;    % [N]
p3=70.719*10^+3;    % [N]
p4=70.719*10^+3;    % [N]
p5=70.719*10^+3;    % [N]
p6=70.719*10^+3;    % [N]
p7=70.719*10^+3;    % [N]
p8=70.719*10^+3;    % [N]
p9=70.719*10^+3;    % [N]
p10=70.719*10^+3;    % [N]
% % Problem mesh

Edof = [1, 1, 2;    % Element degrees of freedom relate to
        nodes
        2, 2, 3;
        3, 3, 4;
        4, 4, 5;
        5, 5, 6;
        6, 6, 7;
        7, 7, 8;
        8, 8, 9;
        9, 9, 10;
        10, 10, 11;
        11, 11, 12;
        12, 12, 13;
        13, 13, 14;
        14, 14, 15;
        15, 15, 16;
        16, 16, 17;
        17, 17, 18;
        18, 18, 19;
        19, 19, 20;
        20, 20, 21;
        21, 21, 22;
        22, 22, 23;
        23, 23, 24;

```

---

---

```

24, 24, 25;
25, 25, 26;
26, 26, 27;
27, 27, 28;
28, 28, 29;
29, 29, 30;
30, 30, 31;
31, 31, 32;
32, 32, 33;
33, 33, 34;
34, 34, 35;
35, 35, 36;
36, 36, 37;
37, 37, 38;
38, 38, 39;
39, 39, 40;
40, 40, 41;
41, 41, 42;
42, 42, 43;
43, 43, 44;
44, 44, 45;
45, 45, 46;
46, 46, 47;
47, 47, 48;
48, 48, 49;
49, 49, 50;
50, 50, 51;
51, 51, 52;
52, 52, 53;
53, 53, 54;
54, 54, 55;
55, 55, 56;
56, 56, 57;
57, 57, 58];

% Boundary conditions needs to be specified in "solveq"
% Define boundary condition matrix (bc) relate to nodes freedom
bc = [58, 0];

% Get dimensions of problem
nel = 57; %Calculate number of elements
(nel)
ndof = 58; %number of dofs (ndof)

% Define vector with applied loads (load_vector)
load_vector=[p1 p2 p3 p4 p5 p6 p7 p8 p9 p10];

% Define vector with locations of applied loads (load_position)
load_position=[(ndof-57) (nel-53) (nel-47) (nel-41) (nel-35) (nel-29)
(nel-23) (nel-17) (nel-11) (nel-5)];

% Preallocate matrices and vectors
K = zeros(ndof);

```

---

---

```

for iel=1:nel
    Ke=springle(Ep(iel));
    K(Edof(iel,2:end),
    Edof(iel,2:end))=K(Edof(iel,2:end),Edof(iel,2:end))+Ke; % Assembled
    stiffness matrix
end

% Global load vector
f =zeros(ndof, 1);

% Apply nodal loads
% Tasks: Insert the load_vector in the fl vector in the positions
% specified by load_position
for i = 1:length(load_position)
    f(load_position(i)) = f(load_position(i)) + load_vector(i);
end
% f(load_position) = f(load_position) + load_vector; % Assembled
load vector

% Solving the system
a=solveq(K,f,bc); % Obtaining the translations for the DOF
for iel= 1:nel
a(iel)= a(iel)+0.002/6;
end

% Results
fprintf('\nDisplacements:\n');
fprintf('a%1u = %7.4f mm\n', [(1:ndof)', a*1000]'); % Printing the
displacements in mm (conversion by a*1000)

% Define the range for the x-axis based on the load_vector
x_range = linspace(min(load_vector), max(load_vector), numel(a));

% Plot displacement (a) as a function of force (P)
plot(x_range, a, '-o', 'LineWidth', 1);
xlabel('Force (N)');
ylabel('Displacement (mm)');
title('Displacement (a) as a Function of Force (N)');
grid on;
legend('Displacement (a)', 'Location', 'best');

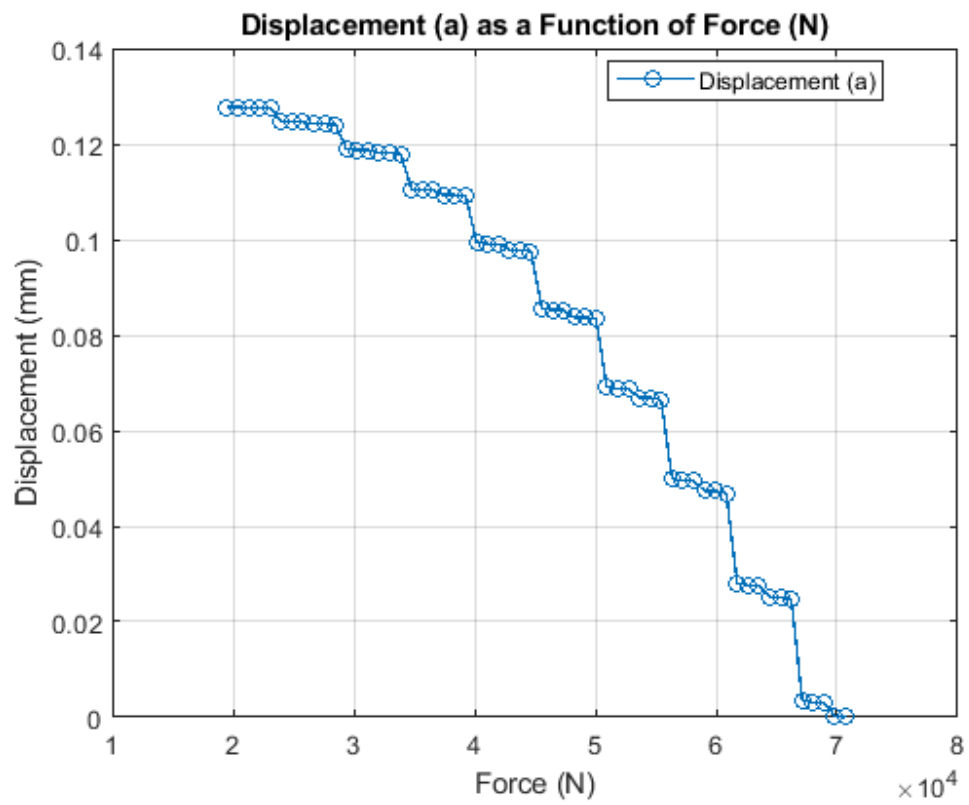
Displacements:
a1 = 127.7069 mm
a2 = 127.7065 mm
a3 = 127.6267 mm
a4 = 127.6263 mm
a5 = 127.5461 mm
a6 = 124.6587 mm
a7 = 124.5785 mm
a8 = 124.5766 mm
a9 = 124.2077 mm
a10 = 124.2058 mm

```

---

---

a11 = 124.0627 mm  
a12 = 118.9123 mm  
a13 = 118.7692 mm  
a14 = 118.7659 mm  
a15 = 118.1078 mm  
a16 = 118.1045 mm  
a17 = 117.8986 mm  
a18 = 110.4852 mm  
a19 = 110.2792 mm  
a20 = 110.2745 mm  
a21 = 109.3272 mm  
a22 = 109.3225 mm  
a23 = 109.0537 mm  
a24 = 99.3772 mm  
a25 = 99.1084 mm  
a26 = 99.1022 mm  
a27 = 97.8658 mm  
a28 = 97.8596 mm  
a29 = 97.5279 mm  
a30 = 85.5885 mm  
a31 = 85.2568 mm  
a32 = 85.2492 mm  
a33 = 83.7236 mm  
a34 = 83.7159 mm  
a35 = 83.3214 mm  
a36 = 69.1190 mm  
a37 = 68.7244 mm  
a38 = 68.7153 mm  
a39 = 66.9006 mm  
a40 = 66.8915 mm  
a41 = 66.4341 mm  
a42 = 49.9686 mm  
a43 = 49.5112 mm  
a44 = 49.5007 mm  
a45 = 47.3968 mm  
a46 = 47.3862 mm  
a47 = 46.8660 mm  
a48 = 28.1375 mm  
a49 = 27.6173 mm  
a50 = 27.6053 mm  
a51 = 25.2122 mm  
a52 = 25.2002 mm  
a53 = 24.6171 mm  
a54 = 3.6256 mm  
a55 = 3.0425 mm  
a56 = 3.0290 mm  
a57 = 0.3468 mm  
a58 = 0.0000 mm



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### A.1.3 CNC connection

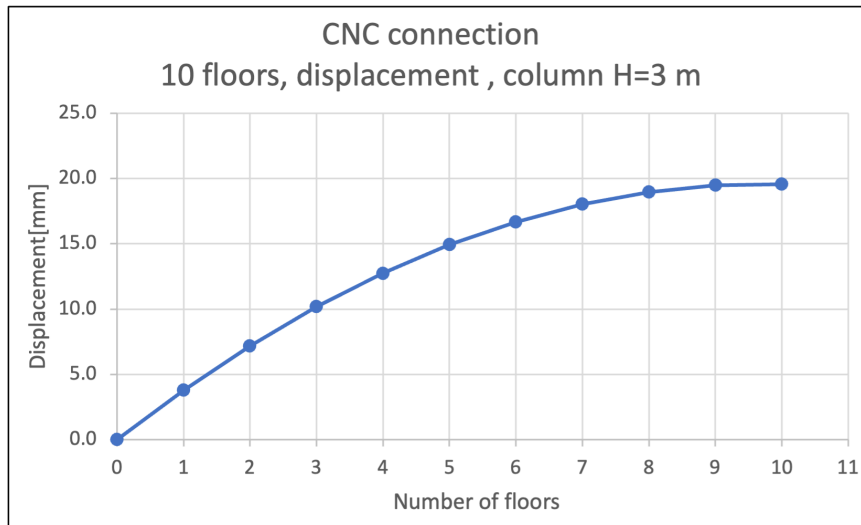
Table A.5: Displacement per spring

CNC	Displacement [mm]	Load [kN]
a1	19.6	
a2	19.6	
a3	19.6	19.5
a4	19.5	
a5	19.5	
a6	19.5	72.5
a7	19.4	
a8	19.3	
a9	19.0	
a10	19.0	
a11	18.9	
a12	18.9	72.5
a13	18.7	
a14	18.7	
a15	18.1	
a16	18.0	72.5
a17	17.7	
a18	17.6	
a19	16.8	
a20	16.7	
a21	16.7	
a22	16.7	72.5
a23	16.3	
a24	16.2	
a25	15.0	

CNC	Displacement [mm]	Load [kN]
a26	14.9	72.5
a27	14.5	
a28	14.3	
a29	12.9	
a30	12.8	
a31	12.8	
a32	12.7	72.5
a33	12.2	
a34	12.0	
a35	10.4	
a36	10.2	72.5
a37	9.5	
a38	9.3	
a39	7.4	
a40	7.2	
a41	7.2	
a42	7.2	72.5
a43	6.4	
a44	6.2	
a45	4.0	
a46	3.8	72.5
a47	3.0	
a48	2.7	
a49	0.3	
a50	0.0	
a51	0.0	

Table A.6: Displacement per floor no.

	Displacement [mm]	Load [kN]	No. Floor
column floor 10	19.6	19.5	10
column floor 9	19.5	72.5	9
column floor 8	18.9	72.5	8
column floor 7	18.0	72.5	7
column floor 6	16.7	72.5	6
column floor 5	14.9	72.5	5
column floor 4	12.7	72.5	4
column floor 3	10.2	72.5	3
column floor 2	7.2	72.5	2
column floor 1	3.8	72.5	1
	0.0	72.5	0



**Figure A.3:** Displacement per floor no.

```

clc
clear all
close all

```

## Problem description%%

case 1 10 floors, (notch connection) column H=6 m Problem geometry :o--\|\|/\|--o--\|\|/\|--o--\|\|/\|--o  
 Analysis model

```

%a_1          a_2          a_3          a_4          [Degrees of freedom]
% o--\|\|/\|/\|--o--\|\|/\|/\|--o--\|\|/\|/\|--o
%   -(1)->      -(2)->      -(3)->          [Elements]
%       k1=N/m      k2=N/m      k3=N/m
% End of problem description

```

### Constants

```

L_middle = 2.6; %length of the column without notch[m]
L_column_notch = 0.3; % length of the notch [m]
L_damage= 0.005 ; % length of the damage zone [m]
L_effective= 0.2; % length of the effective area[m]
A_column= 0.3*0.3; % column area[m^2]
A_damage_n = 0.3*0.1; % Area of the damage zone at notch
[m^2]
A_damage_c= 0.3*0.2; % Area of the damage zone at column
[m^2]
A_column_notch = 0.1*0.3; % Area of column notch [m^2]
A_effective= 0.2*0.3; % Effective Area of column [m^2]

E_column = (1.3*10^10)/(1+0.6); %MOE of the column under long-term[N/
mm^2]
E_damage = E_column/3; %MOE of Damage zone[N/mm^2]
E_column_notch = E_column ; %MOE of column notch[N/mm^2]
E_effective = E_column; %MOE of effective part[N/mm^2]
E_middel = E_column ; %MOE of part above and done the notch[N/
mm^2]

% stiffnesses
K_D_n= A_damage_n*E_damage/L_damage; %stiffness of the damage-zone notch
[N/m]
K_D_c= A_damage_c*E_damage/L_damage; %stiffness of the damage-zone
column[N/m]
K_effective= A_effective*E_effective/L_effective;%stiffness of the
effective-zone [N/m]
K_middel1 = A_column*E_middel /L_middle; %stiffness of the middel
part [N/m]
K_column_notch = A_column_notch*E_column_notch/
L_column_notch; %stiffness of the notch [N/m]

% Problem mesh
% Define element properties column vector (Ep)
Ep = [K_D_n;K_column_notch; K_effective;K_middel1;
      K_effective;K_column_notch;K_effective;K_middel1;

```

---

```

K_effective;K_D_c; K_D_n;K_column_notch;
K_effective;K_middle1;K_effective;K_column_notch;
K_effective;K_middle1;K_effective;K_D_c;
K_D_n;K_column_notch;K_effective;K_middle1;
K_effective;K_column_notch;K_effective;K_middle1;
K_effective;K_D_c;K_D_n;K_column_notch;K_effective;K_middle1;
K_effective;K_column_notch;K_effective;K_middle1;
K_effective;K_D_c;K_D_n;K_column_notch;K_effective;K_middle1;

K_effective;K_column_notch;K_effective;K_middle1;K_effective;K_D_c];

% loads
p1=19.513*10^+3; % [N]
p2=72.719*10^+3; % [N]
p3=72.719*10^+3; % [N]
p4=72.719*10^+3; % [N]
p5=72.719*10^+3; % [N]
p6=72.719*10^+3; % [N]
p7=72.719*10^+3; % [N]
p8=72.719*10^+3; % [N]
p9=72.719*10^+3; % [N]
p10=72.719*10^+3; % [N]

Edof = [1, 1, 2 % Element degrees of freedom relate to nodes
2, 2, 3
3, 3, 4
4, 4, 5
5, 5, 6
6, 6, 7
7, 7, 8
8, 8, 9
9, 9, 10
10, 10, 11
11, 11, 12
12, 12, 13
13, 13, 14
14, 14, 15
15, 15, 16
16, 16, 17
17, 17, 18
18, 18, 19
19, 19, 20
20, 20, 21
21, 21, 22
22, 22, 23
23, 23, 24
24, 24, 25
25, 25, 26
26, 26, 27
27, 27, 28
28, 28, 29
29, 29, 30
30, 30, 31

```

---

---

```

31, 31, 32
32, 32, 33
33, 33, 34
34, 34, 35
35, 35, 36
36, 36, 37
37, 37, 38
38, 38, 39;
39, 39, 40;
40, 40, 41;
41, 41, 42;
42, 42, 43;
43, 43, 44;
44, 44, 45;
45, 45, 46;
46, 46, 47;
47, 47, 48;
48, 48, 49;
49, 49, 50
50, 50, 51];

% Boundary conditions needs to be specified in "solveq"
% Define boundary condition matrix (bc) relate to nodes freedom
bc = [51, 0];

% Get dimensions of problem
nel = 50; %Calculate number of elements
(nel)
ndof = 51; %number of dofs (ndof)

% Define vector with applied loads (load_vector)
load_vector=[p1 p2 p3 p4 p5 p6 p7 p8 p9 p10];

% Define vector with locations of applies loads (load_position)
load_position=[(ndof-49) (ndof-45) (ndof-39) (ndof-35) (ndof-29)
(ndof-25) (ndof-19) (ndof-15) (ndof-9) (ndof-5)];

% Preallocate matrices and vectors
K = zeros(ndof);
for iel=1:nel
    Ke=springle(Ep(iel));
    K(Edof(iel,2:end),
    Edof(iel,2:end))=K(Edof(iel,2:end),Edof(iel,2:end))+Ke; % Assembled
    stiffness matrix
end

% Global load vector
f =zeros(ndof, 1);

% Apply nodal loads
% Tasks: Insert the load_vector in the fl vector in the positions
specified by load_position

```

---

---

```

for i = 1:length(load_position)
    f(load_position(i)) = f(load_position(i)) + load_vector(i);
end
% f(load_position) = f(load_position) + load_vector;    % Assembled
% load vector

% Solving the system
u=solveq(K,f,bc);          % Obtaining the translations for the DOF

% Results
fprintf('\nDisplacements:\n');
fprintf('a%1u = %7.4f mm\n', [(1:ndof)', u*1000]); % Printing the
% displacements in mm (conversion by a*1000)

% Define the range for the x-axis based on the load_vector
x_range = linspace(min(load_vector), max(load_vector), numel(u));

% Plot displacement (a) as a function of force (P)
plot(x_range, u, '-o', 'LineWidth', 1);
xlabel('Force (N)');
ylabel('Displacement (m)');
title('Displacement (u) as a Function of Force (N)');
grid on;
legend('Displacement (u)', 'Location', 'best');

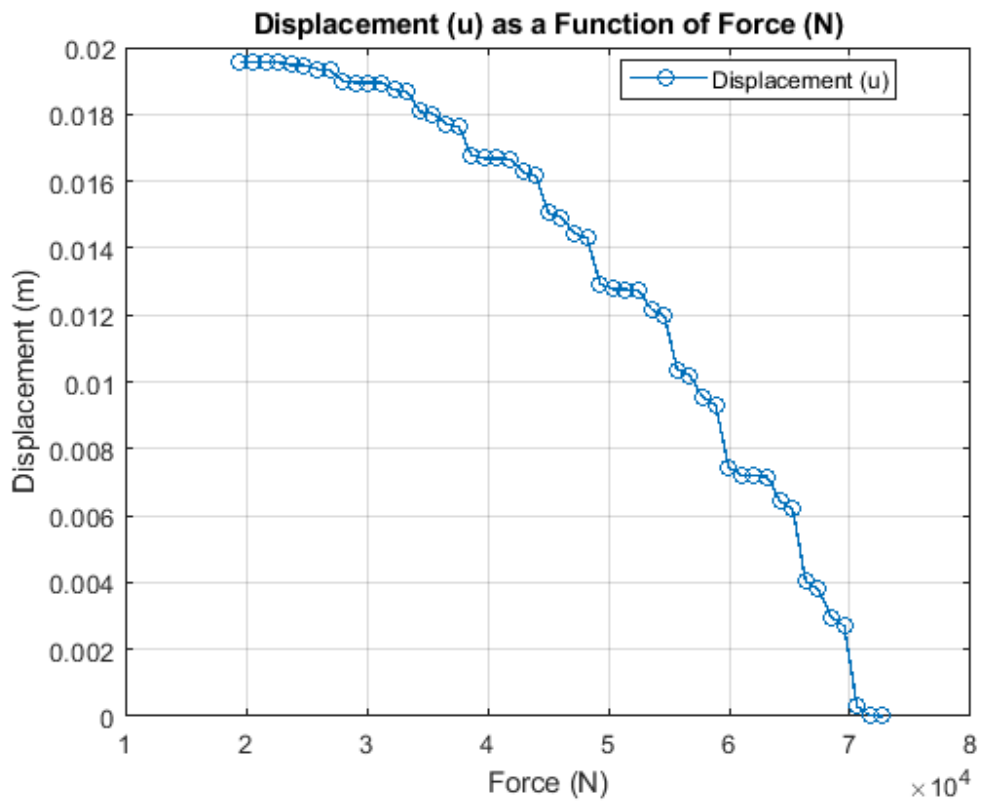
```

```

Displacements:
a1 = 19.5770 mm
a2 = 19.5770 mm
a3 = 19.5530 mm
a4 = 19.5449 mm
a5 = 19.4756 mm
a6 = 19.4676 mm
a7 = 19.3540 mm
a8 = 19.3162 mm
a9 = 18.9883 mm
a10 = 18.9504 mm
a11 = 18.9476 mm
a12 = 18.9419 mm
a13 = 18.7389 mm
a14 = 18.6712 mm
a15 = 18.0847 mm
a16 = 18.0171 mm
a17 = 17.7245 mm
a18 = 17.6270 mm
a19 = 16.7820 mm
a20 = 16.6845 mm
a21 = 16.6772 mm
a22 = 16.6625 mm
a23 = 16.2805 mm
a24 = 16.1532 mm
a25 = 15.0496 mm
a26 = 14.9222 mm
a27 = 14.4507 mm

```

a28 = 14.2936 mm  
a29 = 12.9314 mm  
a30 = 12.7742 mm  
a31 = 12.7624 mm  
a32 = 12.7389 mm  
a33 = 12.1778 mm  
a34 = 11.9908 mm  
a35 = 10.3701 mm  
a36 = 10.1831 mm  
a37 = 9.5326 mm  
a38 = 9.3158 mm  
a39 = 7.4365 mm  
a40 = 7.2196 mm  
a41 = 7.2034 mm  
a42 = 7.1709 mm  
a43 = 6.4308 mm  
a44 = 6.1842 mm  
a45 = 4.0463 mm  
a46 = 3.7997 mm  
a47 = 2.9701 mm  
a48 = 2.6936 mm  
a49 = 0.2972 mm  
a50 = 0.0207 mm  
a51 = 0.0000 mm



### A.1.4 CPC connection

**Table A.7:** Displacement per spring

CPC	Displacement [mm]	Load [kN]
a1	16.0	19.5
a2	16.0	
a3	15.3	
a4	15.3	145
a5	15.3	
a6	15.2	
a7	15.2	
a8	15.2	
a9	13.3	
a10	13.3	145
a11	13.3	
a12	13.2	
a13	13.2	
a14	13.2	
a15	10.1	
a16	10.1	145
a17	10.1	
a18	10.0	
a19	10.0	
a20	10.0	
a21	5.7	
a22	5.6	145
a23	5.6	
a24	5.5	
a25	5.5	
a26	5.5	
a27	0.0	
a28	0.0	

**Table A.8:** Displacement per floor no.

	Displacement [mm]	Load [kN]	No. Floor
colum floor 9&10	16.02	19.5	10
colum floor 7&8	15.26	145	8
colum floor 5&6	13.27	145	6
colum floor 3&4	10.06	145	4
colum floor 1&2	5.64	145	2
	0.00	145	0

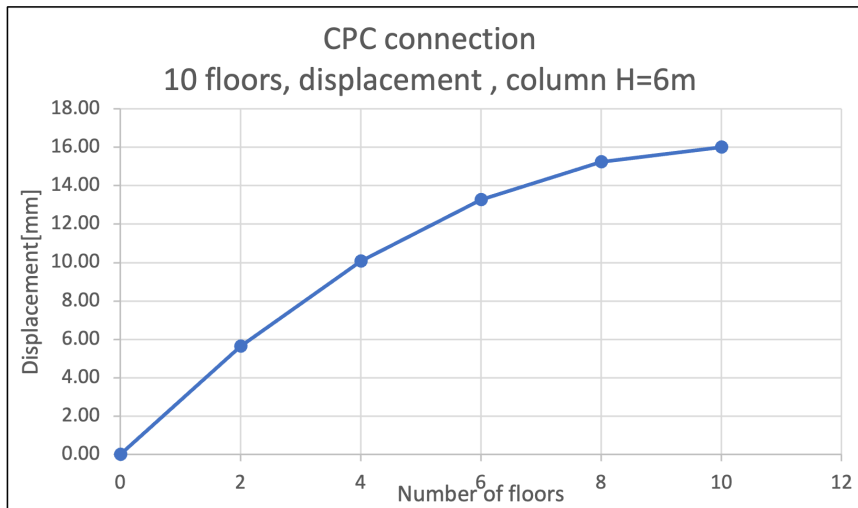


Figure A.4: Displacement per floor no.



---

```

K_Dc    = Ac_Damge*(1/3)*(E_column)/Lc_Damge;    %stiffness damage zone
column [N/m]
K_tp    = A_top_plate*E_top_plate/L_top_plate;  %stiffness top plate
[N/m]
K_bp    = A_bot_plate*E_bot_plate/L_bot_plate;  %stiffness bottom
plate[N/m]
K_C     = A_cylinder*E_cylinder/L_cylinder;    %stiffness cylinder [N/
m]

% loads
p1=19.513*10^+3;                               % [N]
p2=72.719*10^+3;                               % [N]
p3=72.719*10^+3;                               % [N]
p4=72.719*10^+3;                               % [N]
p5=72.719*10^+3;                               % [N]
p6=72.719*10^+3;                               % [N]
p7=72.719*10^+3;                               % [N]
p8=72.719*10^+3;                               % [N]
p9=72.719*10^+3;                               % [N]
p10=72.719*10^+3;                              % [N]

% Problem mesh

% Define element properties column vector (Ep)
Ep = [K_Dc;K_Mc;K_Dc;K_tp;K_C;K_bp;
      K_Dc;K_Mc;K_Dc;K_tp;K_C;K_bp;
      K_Dc;K_Mc;K_Dc;K_tp;K_C;K_bp;
      K_Dc;K_Mc;K_Dc;K_tp;K_C;K_bp;
      K_Dc;K_Mc;K_Dc]; % Element properties

% Define element degrees of freedom matrix (Edof)
Edof = [1, 1, 2;                               % Element degrees of freedom relate to
nodes
        2, 2, 3;
        3, 3, 4;
        4, 4, 5;
        5, 5, 6;
        6, 6, 7;
        7, 7, 8;
        8, 8, 9;
        9, 9, 10;
        10, 10, 11;
        11, 11, 12;
        12, 12, 13;
        13, 13, 14;
        14, 14, 15;
        15, 15, 16;
        16, 16, 17;
        17, 17, 18;
        18, 18, 19;
        19, 19, 20;
        20, 20, 21;

```

---

---

```

        21, 21, 22;
        22, 22, 23;
        23, 23, 24;
        24, 24, 25;
        25, 25, 26;
        26, 26, 27;
        27, 27, 28];

% Boundary conditions
% Define boundary condition matrix (bc) relate to nodes freedom
bc = [28, 0]; % needs to be specified in
"solveq"

% Get dimensions of problem
nel = 27; %Calculate number of elements
(nel)
ndof = 28; %number of dofs (ndof)

% Define vector with applied loads (load_vector)
load_vector=[p1+p2 p3+p4 p5+p6 p7+p8 p9+p10]

% Define vector with locations of applies loads (load_position)
load_position=[(ndof-27) (nel-23) (nel-17) (nel-11) (nel-5)];

% Preallocate matrices and vectors
K = zeros(ndof);
for iel=1:nel
    Ke=springle(Ep(iel));
    K(Edof(iel,2:end),
    Edof(iel,2:end))=K(Edof(iel,2:end),Edof(iel,2:end))+Ke; % Assembled
    stiffness matrix
end

% Global load vector
f =zeros(ndof, 1);

% Apply nodal loads
% Tasks: Insert the load_vector in the fl vector in the positions
specified by load_position
for i = 1:length(load_position)
    f(load_position(i)) = f(load_position(i)) + load_vector(i);
end
% f(load_position) = f(load_position) + load_vector; % Assembled
load vector

% Solving the system
u=solveq(K,f,bc); % Obtaining the translations for the DOF

% Results
fprintf('\nDisplacements:\n');
fprintf('a%1u = %7.4f mm\n', [(1:ndof)', u*1000]'); % Printing the
displacements in mm (conversion by a*1000)

```

---

---

```

% Define the range for the x-axis based on the load_vector
x_range = linspace(min(load_vector), max(load_vector), numel(u));

% Plot displacement (a) as a function of force (P)
plot(x_range, u, '-o', 'LineWidth', 1);
xlabel('Force (N)');
ylabel('Displacement (m)');
title('Displacement (a) as a Function of Force (N)');
grid on;
legend('Displacement (u)', 'Location', 'best');

```

```
load_vector =
```

```

          92232          145438          145438          145438          145438

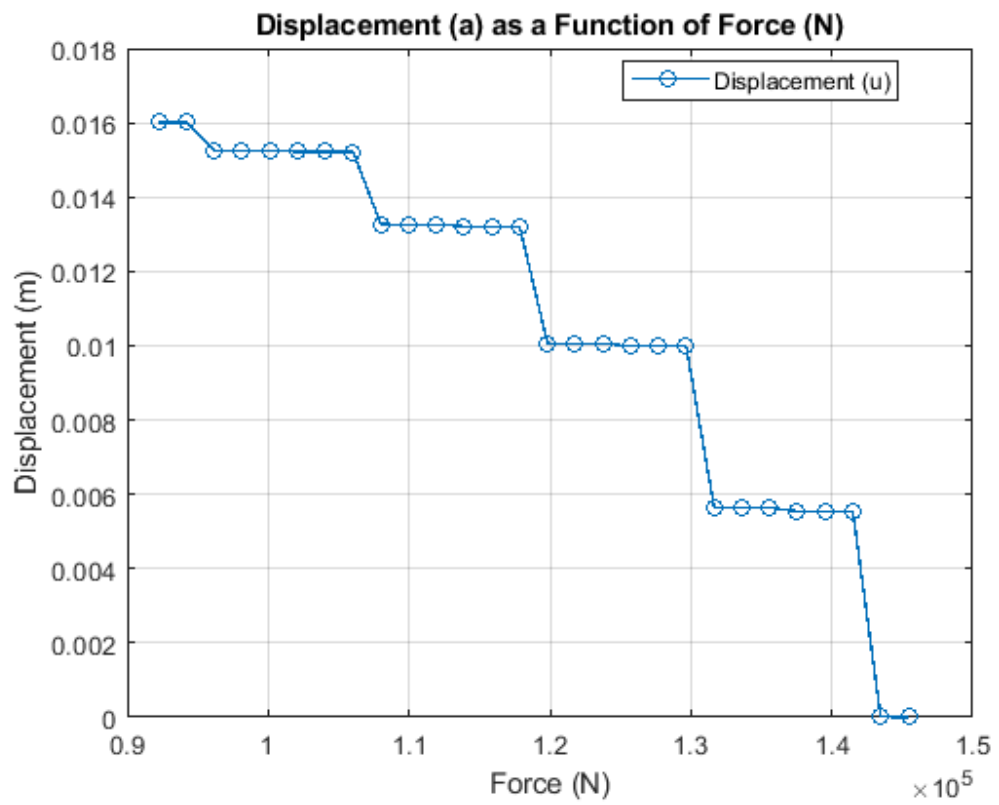
```

```
Displacements:
```

```

a1 = 16.0125 mm
a2 = 16.0106 mm
a3 = 15.2551 mm
a4 = 15.2532 mm
a5 = 15.2531 mm
a6 = 15.2216 mm
a7 = 15.2215 mm
a8 = 15.2167 mm
a9 = 13.2698 mm
a10 = 13.2649 mm
a11 = 13.2648 mm
a12 = 13.2140 mm
a13 = 13.2139 mm
a14 = 13.2060 mm
a15 = 10.0678 mm
a16 = 10.0600 mm
a17 = 10.0598 mm
a18 = 9.9897 mm
a19 = 9.9896 mm
a20 = 9.9787 mm
a21 = 5.6492 mm
a22 = 5.6383 mm
a23 = 5.6381 mm
a24 = 5.5487 mm
a25 = 5.5486 mm
a26 = 5.5347 mm
a27 = 0.0138 mm
a28 = 0.0000 mm

```



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### A.1.5 CPPC connection

**Table A.9:** Displacement per spring

F70L CPPC	Displacement [mm]	Load [kN]
a1	17.4	92
a2	17.4	
a3	16.7	
a4	16.6	145
a5	16.6	
a6	16.6	
a7	14.7	
a8	14.4	145
a9	14.4	
a10	14.4	
a11	11.4	
a12	10.9	145
a13	10.9	
a14	10.9	
a15	6.7	
a16	6.1	145
a17	6.1	
a18	6.1	
a19	0.7	
a20	0.0	

**Table A.10:** Displacement per floor no.

	Displacement [mm]	Load [kN]	No. Floor
colom floor 9&10	17.4	92	10
colom floor 7&8	16.6	145	8
colom floor 5&6	14.4	145	6
colom floor 3&4	10.9	145	4
colom floor 1&2	6.1	145	2
	0.0	145	0

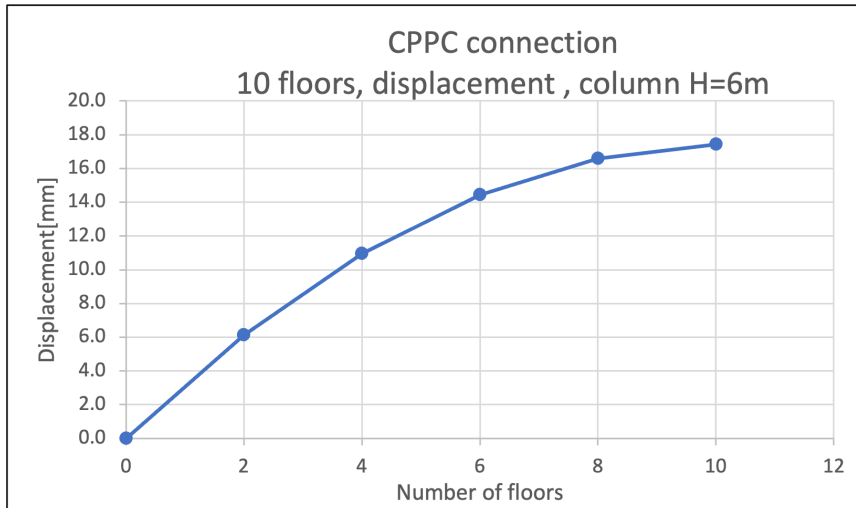


Figure A.5: Displacement per floor no.

---

```

clc
clear all
close all

```

## Problem description%%

case 1 10 floors, F70140L column\_ column connection columns are continuous in two floors H=6 m and steel plate in between. Problem geometry

```
:o--\|\|/--o--\|\|/--o--\|\|/--o Analysis model
```

```

%a_1          a_2          a_3          a_4          [Degrees of freedom]
% o--\|\|/--o--\|\|/--o--\|\|/--o--\|\|/--o
%   -(1)->      -(2)->      -(3)->          [Elements]
%       k1=N/m          k2=N/m          k3=N/m
% End of problem description

```

## Problem input

```

% F70140L with holes connector geomerty

L_penterated_plate = 0.5;           %length of the Knife plate[m]
A_penterated_plate = 0.30*0.008;    %cross section area of Knife
    plate[m^2]
L_bot_plat         = 0.005;         % length of the botom plate [m]
A_bot_plat         = 0.3*0.3;       %cross section arae of bottom
    plate[m^2]
L_dowels           = 0.3;           % length of the dowels [m]
d_dowel           = 0.012;         %diameter of the dowels [m]
A_dowel           = pi*0.006^2;     % area of the dowel [m]
n_dowel           = 4;             % number of dowel

% Geomategy column
L_column          = 6;              % length of the column[m]
Lc_Damge          = 0.005;         % length of the damge zone [m]
Lc_middle         = L_column -2*Lc_Damge; %length of the column without
    damge zone [m]
A_column          = 0.3*0.3;        % column area [m^2]
Ac_middle         = 0.3*0.3;        % column area [m^2]
Ac_botDamge      = 0.5*(A_column -A_penterated_plate)-
    2*0.008*(0.3-0.008)/2;
Ac_topDamge      = 0.3*0.3;        % column area [m^2]

% materias properties
E_column = (1.3*10^10)/(1+0.6);     % MOE of the column [ N]
E_penterated_plate = 2*10^11;      % MOE of the knife plate[N]
E_bot_plate = 2*10^11;             % MOE of the bottom plate[N]

```

---

```

% stiffnesses
K_pp      = (E_penterated_plate*A_penterated_plate)/
L_penterated_plate ;
K_bD      =(1/3)*(E_column)*Ac_botDamage /Lc_Damage;

K_Mc      = A_column*E_column/Lc_middle;           %stiffness
midel zone column [N/m]
K_top_Dc  = A_column*(1/3)*(E_column)/Lc_Damage;   %stiffness
damage zone column [N/m]
K_bot_Dc  = 1/(1/K_pp +2/K_bD);
K_p       = E_bot_plate*A_bot_plat/L_bot_plat;

% loads
p1=19.513*10^+3;           % [N]
p2=72.719*10^+3;         % [N]
p3=72.719*10^+3;         % [N]
p4=72.719*10^+3;         % [N]
p5=72.719*10^+3;         % [N]
p6=72.719*10^+3;         % [N]
p7=72.719*10^+3;         % [N]
p8=72.719*10^+3;         % [N]
p9=72.719*10^+3;         % [N]
p10=72.719*10^+3;        % [N]

% Problem mesh

% Define element properties column vector (Ep)
Ep = [K_top_Dc;K_Mc;K_bot_Dc;K_p;
      K_top_Dc;K_Mc;K_bot_Dc;K_p;
      K_top_Dc;K_Mc;K_bot_Dc;K_p;
      K_top_Dc;K_Mc;K_bot_Dc;K_p;
      K_top_Dc;K_Mc;K_bot_Dc]; % Element properties

% Define element degrees of freedom matrix (Edof)
Edof = [1, 1, 2;           % Element degrees of freedom relate to
        nodes
        2, 2, 3;
        3, 3, 4;
        4, 4, 5;
        5, 5, 6;
        6, 6, 7;
        7, 7, 8;
        8, 8, 9;
        9, 9, 10;
        10, 10, 11;
        11, 11, 12;
        12, 12, 13;
        13, 13, 14;
        14, 14, 15;
        15, 15, 16;

```

---

---

```

        16, 16, 17;
        17, 17, 18;
        18, 18, 19;
        19, 19, 20];

% Boundary conditions
% Define boundary condition matrix (bc) relate to nodes freedom
bc = [20, 0]; % needs to be specified in
"solveq"

% Get dimensions of problem
nel = 19; %Calculate number of elements
(nel)
ndof = 20; %number of dofs (ndof)

% Define vector with applied loads (load_vector)
load_vector=[p1+p2 p3+p4 p5+p6 p7+p8 p9+p10]

% Define vector with locations of applies loads (load_position)
load_position=[(ndof-19) (nel-15) (nel-11) (nel-7) (nel-3)];

% Preallocate matrices and vectors
K = zeros(ndof);
for iel=1:nel
    Ke=springle(Ep(iel));
    K(Edof(iel,2:end),
    Edof(iel,2:end))=K(Edof(iel,2:end),Edof(iel,2:end))+Ke; % Assembled
    stiffness matrix
end

% Global load vector
f =zeros(ndof, 1);

% Apply nodal loads
% Tasks: Insert the load_vector in the fl vector in the positions
specified by load_position
for i = 1:length(load_position)
    f(load_position(i)) = f(load_position(i)) + load_vector(i);
end
% f(load_position) = f(load_position) + load_vector; % Assembled
load vector

% Solving the system
a=solveq(K,f,bc); % Obtaining the translations for the DOF

% Results
fprintf('\nDisplacements:\n');
fprintf('a%1u = %7.4f mm\n', [(1:ndof)', a*1000]); % Printing the
displacements in mm (conversion by a*1000)

%figure

```

---

---

```

% Define the range for the x-axis based on the load_vector
x_range = linspace(min(load_vector), max(load_vector), numel(a));

yyaxis left; % Use left y-axis for displacement
plot(x_range, a, '-o', 'LineWidth', 1);
ylabel('Displacement (m)');

% Hide the right y-axis
yyaxis right;
set(gca, 'YColor', 'none');

xlabel('Force (N)');
title('Displacement (a) as a Function of Force (P)');
grid on;
legend('Displacement (a)', 'Location', 'best');

```

```
load_vector =
```

```

          92232      145438      145438      145438      145438

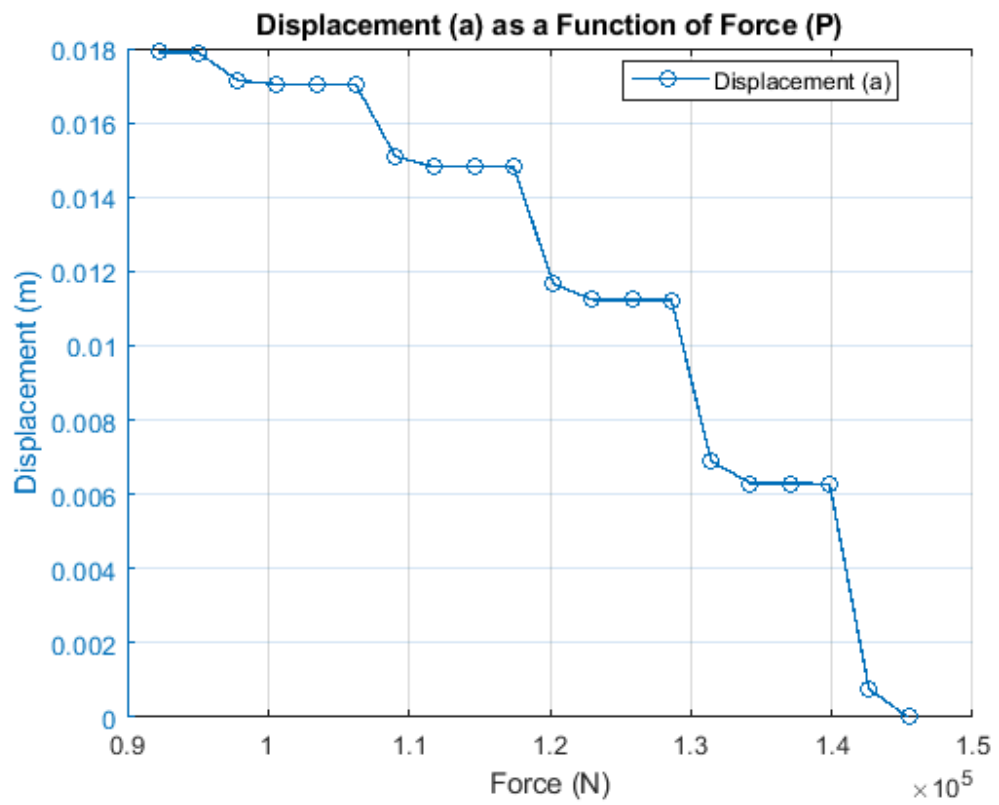
```

```
Displacements:
```

```

a1 = 17.8968 mm
a2 = 17.8949 mm
a3 = 17.1394 mm
a4 = 17.0351 mm
a5 = 17.0350 mm
a6 = 17.0302 mm
a7 = 15.0833 mm
a8 = 14.8146 mm
a9 = 14.8144 mm
a10 = 14.8066 mm
a11 = 11.6684 mm
a12 = 11.2352 mm
a13 = 11.2350 mm
a14 = 11.2242 mm
a15 = 6.8946 mm
a16 = 6.2970 mm
a17 = 6.2968 mm
a18 = 6.2830 mm
a19 = 0.7621 mm
a20 = 0.0000 mm

```



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## A.2 20 floors

### A.2.1 CPC connection

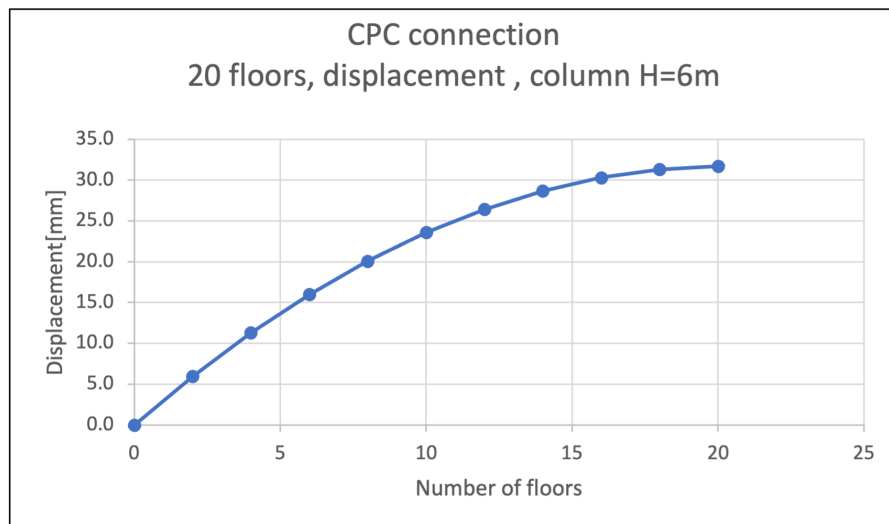
Table A.11: Displacement per spring

CPC-20	Displacement [mm]	Load [kN]
a1	31.7	19.5
a2	31.7	
a3	31.3	
a4	31.3	145
a5	31.3	
a6	31.3	
a7	31.3	
a8	31.3	
a9	30.3	
a10	30.3	145
a11	30.3	
a12	30.3	
a13	30.3	
a14	30.3	
a15	28.7	
a16	28.7	145
a17	28.7	
a18	28.6	
a19	28.6	
a20	28.6	
a21	26.4	
a22	26.4	145
a23	26.4	
a24	26.4	
a25	26.4	
a26	26.3	
a27	23.6	
a28	23.6	145
a29	23.6	

CPC-20	Displacement [mm]	Load [kN]
a30	23.5	
a31	23.5	
a32	23.5	
a33	20.1	
a34	20.1	145
a35	20.1	
a36	20.0	
a37	20.0	
a38	20.0	
a39	16.0	
a40	16.0	145
a41	16.0	
a42	15.8	
a43	15.8	
a44	15.8	
a45	11.3	
a46	11.3	145
a47	11.3	
a48	11.1	
a49	11.1	
a50	11.1	
a51	6.0	
a52	5.9	145
a53	5.9	
a54	5.8	
a55	5.8	
a56	5.7	
a57	0.0	
a58	0.0	

**Table A.12:** Displacement per floor no.

	Displacement [mm]	Load [kN]	No. Floor
colum floor 19&20	31.7	19.5	20
colum floor 17&18	31.3	145	18
colum floor 15&16	30.3	145	16
colum floor 13&14	28.7	145	14
colum floor 11&12	26.4	145	12
colum floor 9&10	23.6	145	10
colum floor 7&8	20.1	145	8
colum floor 5&6	16.0	145	6
colum floor 3&4	11.3	145	4
colum floor 1&2	5.9	145	2
	0.0	145	0



**Figure A.6:** Displacement per floor no.

---

```

clc
clear all
close all

```

## Problem description%%

PIL80S 20 floors, column\_ column connection columns are continuous in two floors H=6 and steel plate in between. Problem geometry

```
:o--/\V/--o--/\V/--o--/\V/--o Analysis model
```

```

%a_1      a_2      a_3      a_4      [Degrees of freedom]
% o--/\V/--o--/\V/--o--/\V/--o--/\V/--o
%      -(1)->      -(2)->      -(3)->      [Elements]
%      k1=N/m      k2=N/m      k3=N/m
% End of problem description

```

## Problem input

```

% PIL80S connector geomerty

L_top_plate = 0.02;           %thickness of the top plate[m]
L_cylinder  = 0.3;           %length of the cylinder[m]
L_bot_plate = 0.02;           %thickness of the bottom plate[m]
A_top_plate = 0.45*0.4;      %Area of the top plate[m^2]
A_cylinder  = pi*0.06^2;     %Area of the cylinder [m^2]
A_bot_plate = 0.45*0.4;      %Area of the bottom plate[m^2]

% Geomategy column
L_column    = 6;             %length of the column [m]
Lc_Damge    = 0.005;        %length of the column damage
zone[m]
Lc_midel    = L_column -2*Lc_Damge; %length of the column middle
zone[m]
A_column    = 0.45*0.4;      %Area of the column [m^2]
Ac_Damge    = 0.45*0.4;      %Area of the column damage zone
[m^2]
Ac_middle   = 0.45*0.4;      %Area of the column middle zone
[m^2]

% material properties
E_column    = (1.3*10^10)/(1+0.6); %MOE of the column [N]
E_top_plate = 2*10^11;       %MOE of the top plate [N]
E_bot_plate = 2*10^11;       %MOE of the bot plate[N]
E_cylinder  = 2*10^11;       %MOE of the cylinder [N]

% stiffnesses
K_Mc        = A_column*E_column/Lc_midel; %stiffness middle zone
column [N/m]
K_Dc        = Ac_Damge*(1/3)*(E_column)/Lc_Damge; %stiffness damage zone
column [N/m]

```

---

```

K_tp = A_top_plate*E_top_plate/L_top_plate; %stiffness top plate
      [N/m]
K_bp = A_bot_plate*E_bot_plate/L_bot_plate; %stiffness bottom
      plate[N/m]
K_C  = A_cylinder*E_cylinder/L_cylinder; %stiffness cylinder [N/
      m]

% loads
p1=19.513*10^+3; % [N]
p2=72.719*10^+3; % [N]
p3=72.719*10^+3; % [N]
p4=72.719*10^+3; % [N]
p5=72.719*10^+3; % [N]
p6=72.719*10^+3; % [N]
p7=72.719*10^+3; % [N]
p8=72.719*10^+3; % [N]
p9=72.719*10^+3; % [N]
p10=72.719*10^+3; % [N]
p11=72.719*10^+3; % [N]
p12=72.719*10^+3; % [N]
p13=72.719*10^+3; % [N]
p14=72.719*10^+3; % [N]
p15=72.719*10^+3; % [N]
p16=72.719*10^+3; % [N]
p17=72.719*10^+3; % [N]
p18=72.719*10^+3; % [N]
p19=72.719*10^+3; % [N]
p20=72.719*10^+3; % [N]

% Problem mesh

% Define element properties column vector (Ep)
Ep = [K_Dc;K_Mc;K_Dc;K_tp;K_C;K_bp;
      K_Dc;K_Mc;K_Dc;K_tp;K_C;K_bp;
      K_Dc;K_Mc;K_Dc;K_tp;K_C;K_bp;
      K_Dc;K_Mc;K_Dc;K_tp;K_C;K_bp;
      K_Dc;K_Mc;K_Dc;K_tp;K_C;K_bp;
      K_Dc;K_Mc;K_Dc;K_tp;K_C;K_bp;
      K_Dc;K_Mc;K_Dc;K_tp;K_C;K_bp;
      K_Dc;K_Mc;K_Dc;K_tp;K_C;K_bp;
      K_Dc;K_Mc;K_Dc;K_tp;K_C;K_bp;
      K_Dc;K_Mc;K_Dc]; % Element properties

% Define element degrees of freedom matrix (Edof)

Edof = [1, 1, 2; % Element degrees of freedom relate to nodes
        2, 2, 3;
        3, 3, 4;
        4, 4, 5;
        5, 5, 6;
        6, 6, 7;
        7, 7, 8;

```

---

---

```
8, 8, 9;  
9, 9, 10;  
10, 10, 11;  
11, 11, 12;  
12, 12, 13;  
13, 13, 14;  
14, 14, 15;  
15, 15, 16;  
16, 16, 17;  
17, 17, 18;  
18, 18, 19;  
19, 19, 20;  
20, 20, 21;  
21, 21, 22;  
22, 22, 23;  
23, 23, 24;  
24, 24, 25;  
25, 25, 26;  
26, 26, 27;  
27, 27, 28;  
28, 28, 29;  
29, 29, 30;  
30, 30, 31;  
31, 31, 32;  
32, 32, 33;  
33, 33, 34;  
34, 34, 35;  
35, 35, 36;  
36, 36, 37;  
37, 37, 38;  
38, 38, 39;  
39, 39, 40;  
40, 40, 41;  
41, 41, 42;  
42, 42, 43;  
43, 43, 44;  
44, 44, 45;  
45, 45, 46;  
46, 46, 47;  
47, 47, 48;  
48, 48, 49;  
49, 49, 50;  
50, 50, 51;  
51, 51, 52;  
52, 52, 53;  
53, 53, 54;  
54, 54, 55;  
55, 55, 56;  
56, 56, 57;  
57, 57, 58];
```

```
% Boundary conditions  
% Define boundary condition matrix (bc) relate to nodes freedom
```

---

```

bc = [57, 0]; % needs to be specified in
"solveq"

% Get dimensions of problem
nel = 57; %Calculate number of elements
(nel)
ndof = 58; %number of dofs (ndof)

% Define vector with applied loads (load_vector)
load_vector=[p1+p2 p3+p4 p5+p6 p7+p8 p9+p10 p11+p12 p13+p14 p15+p16
p17+p18 p19+p20]

% Define vector with locations of applies loads (load_position)
load_position=[(ndof-57) (nel-53) (nel-47) (nel-41) (nel-35) (nel-29)
(nel-23) (nel-17) (nel-11) (nel-5)];

% Preallocate matrices and vectors
K = zeros(ndof);
for iel=1:nel
    Ke=springle(Ep(iel));
    K(Edof(iel,2:end),
    Edof(iel,2:end))=K(Edof(iel,2:end),Edof(iel,2:end))+Ke; % Assembled
    stiffness matrix
end

% Global load vector
f =zeros(ndof, 1);

% Apply nodal loads
% Tasks: Insert the load_vector in the fl vector in the positions
specified by load_position
for i = 1:length(load_position)
    f(load_position(i)) = f(load_position(i)) + load_vector(i);
end
% f(load_position) = f(load_position) + load_vector; % Assembled
load vector

% Solving the system
u=solveq(K,f,bc); % Obtaining the translations for the DOF

% Results
fprintf('\nDisplacements:\n');
fprintf('a%1u = %7.4f mm\n', [(1:ndof)', u*1000]); % Printing the
displacements in mm (conversion by a*1000)

% Define the range for the x-axis based on the load_vector
x_range = linspace(min(load_vector), max(load_vector), numel(u));

% Plot displacement (a) as a function of force (P)
plot(x_range, u, '-o', 'LineWidth', 1);
xlabel('Force (N)');
ylabel('Displacement (m)');

```

---

---

```
title('Displacement (a) as a Function of Force (N)');
grid on;
legend('Displacement (u)', 'Location', 'best');
```

```
load_vector =
```

```
Columns 1 through 6
```

```
          92232          145438          145438          145438          145438
145438
```

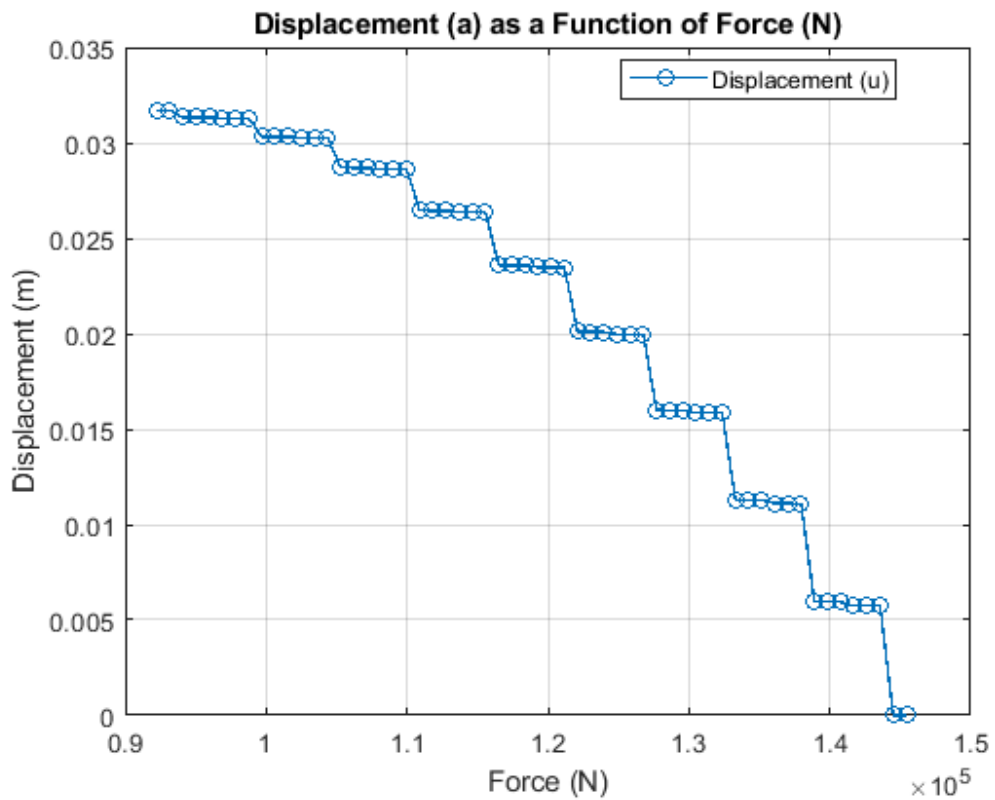
```
Columns 7 through 10
```

```
          145438          145438          145438          145438
```

```
Displacements:
```

```
a1 = 31.7080 mm
a2 = 31.7071 mm
a3 = 31.3293 mm
a4 = 31.3284 mm
a5 = 31.3282 mm
a6 = 31.2967 mm
a7 = 31.2966 mm
a8 = 31.2941 mm
a9 = 30.3207 mm
a10 = 30.3183 mm
a11 = 30.3181 mm
a12 = 30.2673 mm
a13 = 30.2670 mm
a14 = 30.2631 mm
a15 = 28.6940 mm
a16 = 28.6901 mm
a17 = 28.6898 mm
a18 = 28.6197 mm
a19 = 28.6194 mm
a20 = 28.6140 mm
a21 = 26.4492 mm
a22 = 26.4438 mm
a23 = 26.4434 mm
a24 = 26.3540 mm
a25 = 26.3536 mm
a26 = 26.3467 mm
a27 = 23.5863 mm
a28 = 23.5793 mm
a29 = 23.5789 mm
a30 = 23.4702 mm
a31 = 23.4698 mm
a32 = 23.4614 mm
a33 = 20.1052 mm
a34 = 20.0968 mm
a35 = 20.0963 mm
a36 = 19.9683 mm
```

a37 = 19.9678 mm  
 a38 = 19.9579 mm  
 a39 = 16.0061 mm  
 a40 = 15.9962 mm  
 a41 = 15.9956 mm  
 a42 = 15.8483 mm  
 a43 = 15.8477 mm  
 a44 = 15.8363 mm  
 a45 = 11.2888 mm  
 a46 = 11.2774 mm  
 a47 = 11.2767 mm  
 a48 = 11.1102 mm  
 a49 = 11.1095 mm  
 a50 = 11.0966 mm  
 a51 = 5.9535 mm  
 a52 = 5.9406 mm  
 a53 = 5.9398 mm  
 a54 = 5.7540 mm  
 a55 = 5.7532 mm  
 a56 = 5.7388 mm  
 a57 = 0.0000 mm  
 a58 = 0.0000 mm



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# B

## Appendix 2

## B.1 Stress in plate

Table B.1: Stress in the plate (450×400) diagonally, in varying thicknesses

plate	450*400	cylinder	60
diagonal	thickness [mm]		
	20	15	10
[mm]	stress [MPa]		
0.0	0.138	0.061	0.026
12.0	0.079	0.031	0.009
24.1	0.036	0.010	-0.001
36.1	0.026	0.007	-0.002
48.2	0.012	0.001	-0.004
60.2	0.003	-0.001	-0.004
72.2	-0.005	-0.002	-0.003
84.3	-0.012	-0.002	-0.002
96.3	-0.020	-0.001	0.000
108.4	-0.030	-0.002	0.003
120.4	-0.043	-0.004	0.006
132.5	-0.064	-0.012	0.010
144.5	-0.092	-0.027	0.013
156.5	-0.132	-0.054	0.012
168.6	-0.195	-0.111	-0.010
180.6	-0.274	-0.190	-0.050
192.7	-0.355	-0.287	-0.155
204.7	-0.506	-0.522	-0.443
216.7	-0.839	-0.774	-0.542
228.8	-2.642	-2.664	-2.465
240.8	-7.194	-8.203	-9.030
252.9	-3.742	-3.488	-3.221
264.9	0.121	-0.235	-1.414
277.0	-0.555	-1.354	-2.222
289.0	-0.838	-1.513	-2.100
301.0	-0.922	-1.561	-2.213
313.1	-0.831	-1.530	-2.153
325.1	-0.500	-1.281	-2.152
337.2	0.261	-0.096	-1.306
349.2	-3.826	-3.573	-3.295
361.2	-7.316	-8.285	-9.058
373.3	-2.631	-2.697	-2.576
385.3	-0.830	-0.777	-0.560
397.4	-0.502	-0.511	-0.429
409.4	-0.354	-0.284	-0.151
421.5	-0.274	-0.191	-0.050
433.5	-0.195	-0.111	-0.010
445.5	-0.132	-0.054	0.012
457.6	-0.092	-0.027	0.013
469.6	-0.063	-0.012	0.010
481.7	-0.043	-0.004	0.006
493.7	-0.030	-0.002	0.003
505.7	-0.020	-0.001	0.000
517.8	-0.012	-0.002	-0.002
529.8	-0.005	-0.002	-0.003
541.9	0.003	-0.001	-0.004
553.9	0.012	0.001	-0.004
566.0	0.026	0.007	-0.002
578.0	0.036	0.010	-0.001
590.0	0.079	0.031	0.009
602.1	0.138	0.061	0.026

**Table B.2:** Stress in the plate (350×300) diagonally, in varying thicknesses

plate	350*300		cylinder	60
diagonal		thickness [mm]		
in column	in plate	20	15	10
[mm]	[mm]	stress [MPa]		
70.7	0.0	1.278	0.817	0.305
79.9	9.2	0.442	0.216	0.047
89.1	18.4	0.078	0.020	-0.015
98.4	27.7	0.013	0.001	-0.008
107.6	36.9	0.016	0.013	-0.002
116.8	46.1	-0.021	-0.012	-0.010
126.0	55.3	-0.044	-0.013	0.001
135.2	64.5	-0.075	-0.027	0.005
144.5	73.8	-0.102	-0.040	0.007
153.7	83.0	-0.138	-0.062	0.008
162.9	92.2	-0.180	-0.093	0.001
172.1	101.4	-0.233	-0.138	-0.013
181.3	110.6	-0.304	-0.207	-0.059
190.6	119.9	-0.384	-0.288	-0.071
199.8	129.1	-0.450	-0.415	-0.321
209.0	138.3	-0.606	-0.658	-0.473
218.2	147.5	-0.974	-1.145	-1.199
227.4	156.7	-1.059	-0.790	-0.633
236.7	166.0	-3.348	-3.003	-2.605
245.9	175.2	-5.897	-5.813	-4.957
255.1	184.4	-1.907	-0.689	0.484
264.3	193.6	-0.149	-0.391	-1.458
273.5	202.8	-0.398	-1.201	-1.817
282.8	212.1	-0.691	-1.417	-2.142
292.0	221.3	-0.892	-1.545	-2.039
301.2	230.5	-0.948	-1.539	-2.039
310.4	239.7	-0.896	-1.548	-2.062
319.6	248.9	-0.683	-1.396	-2.075
328.9	258.1	-0.449	-1.326	-2.087
338.1	267.4	-0.077	-0.313	-1.406
347.3	276.6	-1.952	-0.961	-0.319
356.5	285.8	-5.794	-5.734	-5.020
365.7	295.0	-3.428	-3.208	-3.059
375.0	304.2	-1.106	-0.891	-0.790
384.2	313.5	-0.948	-1.107	-1.154
393.4	322.7	-0.626	-0.689	-0.508
402.6	331.9	-0.456	-0.423	-0.316
411.8	341.1	-0.386	-0.295	-0.091
421.1	350.3	-0.304	-0.207	-0.056
430.3	359.6	-0.233	-0.138	-0.011
439.5	368.8	-0.181	-0.094	0.000
448.7	378.0	-0.138	-0.062	0.007
457.9	387.2	-0.102	-0.040	0.007
467.2	396.4	-0.075	-0.027	0.005
476.4	405.7	-0.044	-0.013	0.002
485.6	414.9	-0.021	-0.012	-0.010
494.8	424.1	0.016	0.013	-0.002
504.0	433.3	0.013	0.001	-0.008
513.2	442.5	0.078	0.020	-0.015
522.5	451.8	0.442	0.217	0.047
531.7	461.0	1.279	0.817	0.305

**Table B.3:** Stress in the plate (250×200) diagonally, in varying thicknesses

plate	250*200		cylinder	60
diagonal		thickness [mm]		
in column	in plate	20	15	10
[mm]	[mm]	stress [MPa]		
141.4	0.0	1.787	2.472	1.615
147.8	6.4	0.780	1.019	0.557
154.2	12.8	0.091	0.144	0.026
160.6	19.2	-0.325	-0.291	-0.151
167.0	25.6	-0.306	-0.230	-0.106
173.4	32.0	-0.264	-0.147	-0.040
179.8	38.4	-0.296	-0.190	-0.088
186.2	44.8	-0.362	-0.261	-0.131
192.6	51.2	-0.422	-0.341	-0.215
199.0	57.6	-0.481	-0.410	-0.290
205.5	64.0	-0.581	-0.546	-0.343
211.9	70.4	-0.740	-0.847	-0.589
218.3	76.8	-0.862	-1.139	-1.219
224.7	83.2	-1.078	-0.850	-0.633
231.1	89.6	-2.981	-2.700	-2.182
237.5	96.0	-7.558	-8.739	-9.736
243.9	102.5	-7.992	-8.942	-9.653
250.3	108.9	-4.327	-3.713	-2.934
256.7	115.3	-0.876	0.062	0.317
263.1	121.7	-0.259	-0.520	-1.728
269.5	128.1	-0.415	-1.146	-2.123
275.9	134.5	-0.582	-1.295	-1.934
282.3	140.9	-0.765	-1.454	-2.140
288.7	147.3	-0.918	-1.556	-2.091
295.1	153.7	-0.979	-1.598	-2.089
301.5	160.1	-0.967	-1.587	-2.125
307.9	166.5	-0.984	-1.619	-2.147
314.3	172.9	-0.960	-1.638	-2.220
320.7	179.3	-0.802	-1.512	-2.222
327.1	185.7	-0.595	-1.307	-1.937
333.5	192.1	-0.394	-1.114	-2.057
339.9	198.5	-0.263	-0.577	-1.795
346.3	204.9	-0.855	0.000	0.143
352.7	211.3	-4.174	-3.554	-2.805
359.1	217.7	-7.868	-8.806	-9.510
365.5	224.1	-7.555	-8.785	-9.835
371.9	230.5	-2.944	-2.662	-2.155
378.3	236.9	-1.065	-0.833	-0.613
384.7	243.3	-0.881	-1.161	-1.225
391.1	249.7	-0.753	-0.861	-0.587
397.5	256.1	-0.586	-0.553	-0.345
403.9	262.5	-0.482	-0.412	-0.290
410.4	268.9	-0.424	-0.343	-0.217
416.8	275.3	-0.365	-0.264	-0.131
423.2	281.7	-0.298	-0.192	-0.088
429.6	288.1	-0.265	-0.149	-0.042
436.0	294.5	-0.306	-0.229	-0.105
442.4	300.9	-0.325	-0.290	-0.151
448.8	307.4	0.090	0.143	0.026
455.2	313.8	0.777	1.018	0.558
461.6	320.2	1.781	2.470	1.616

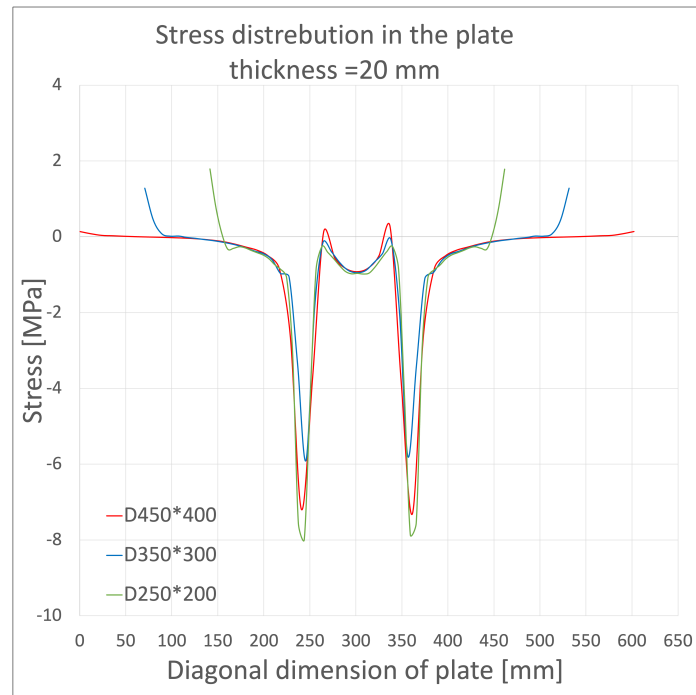


Figure B.1: Stress in the plate, thickness 20, with different dimensions

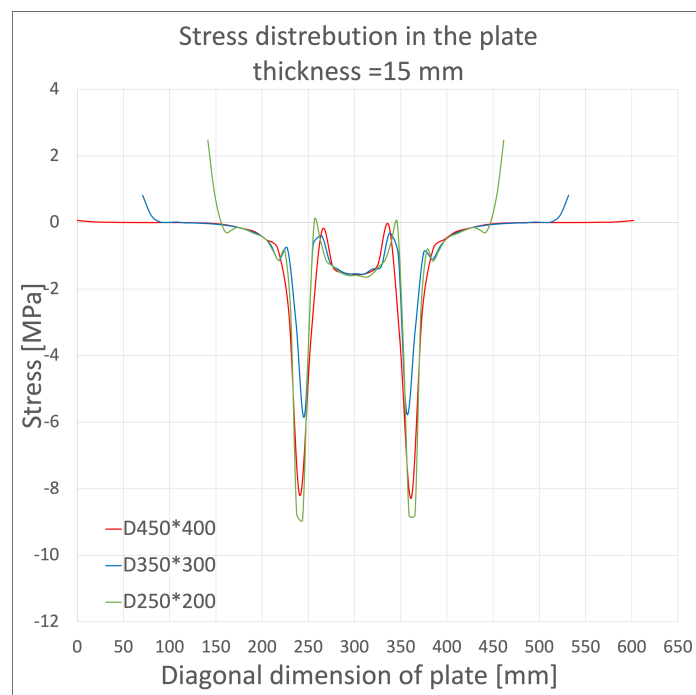
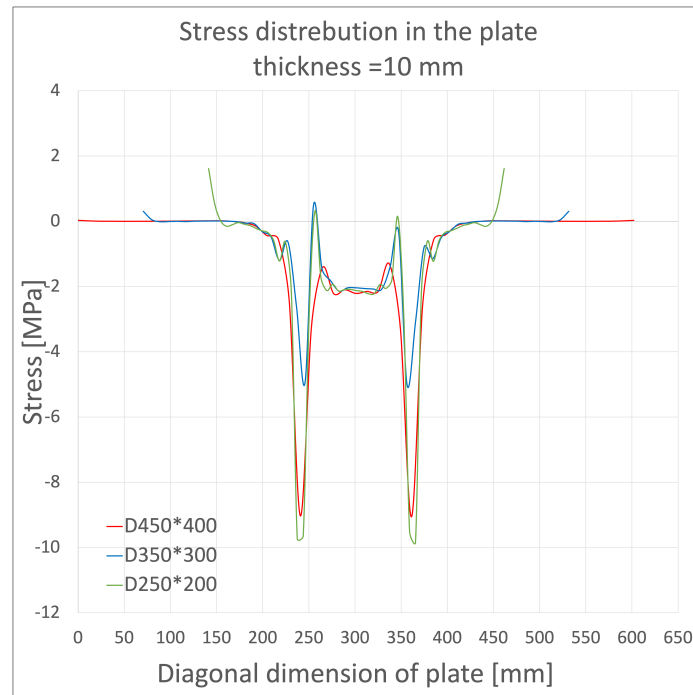
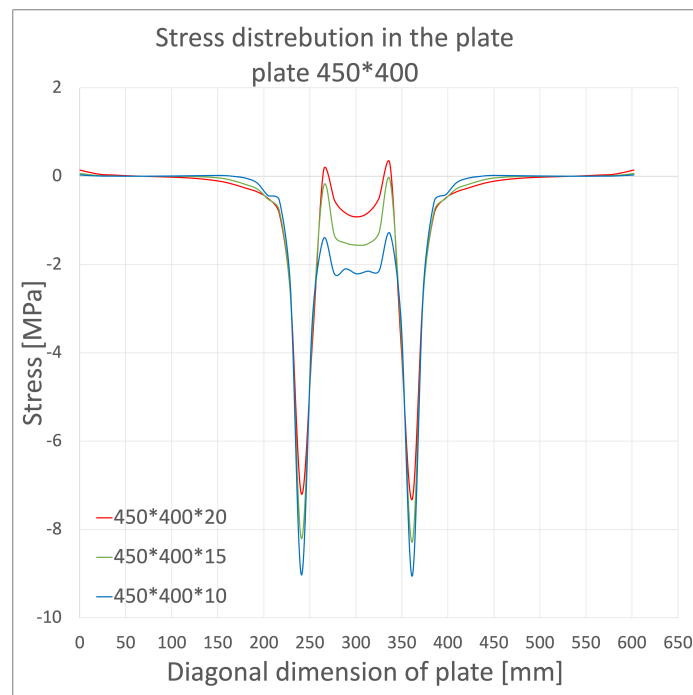


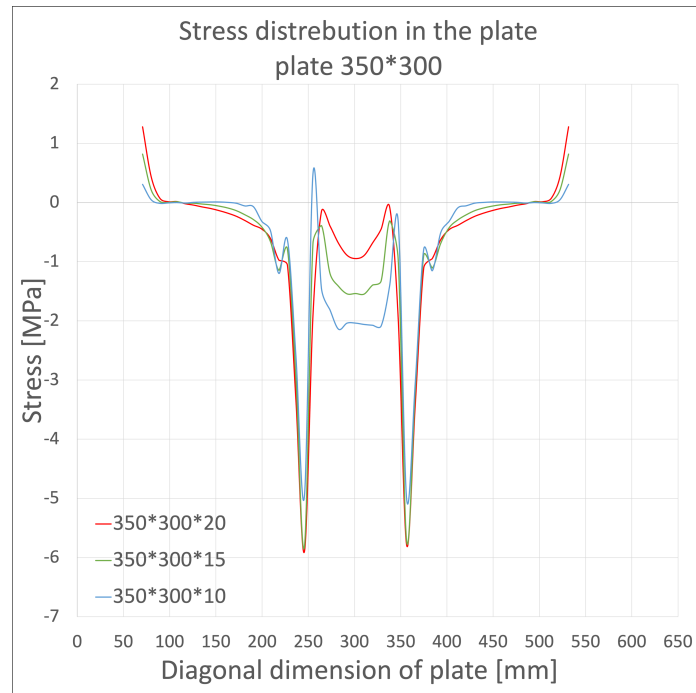
Figure B.2: Stress in the plate, thickness 15, with different dimensions



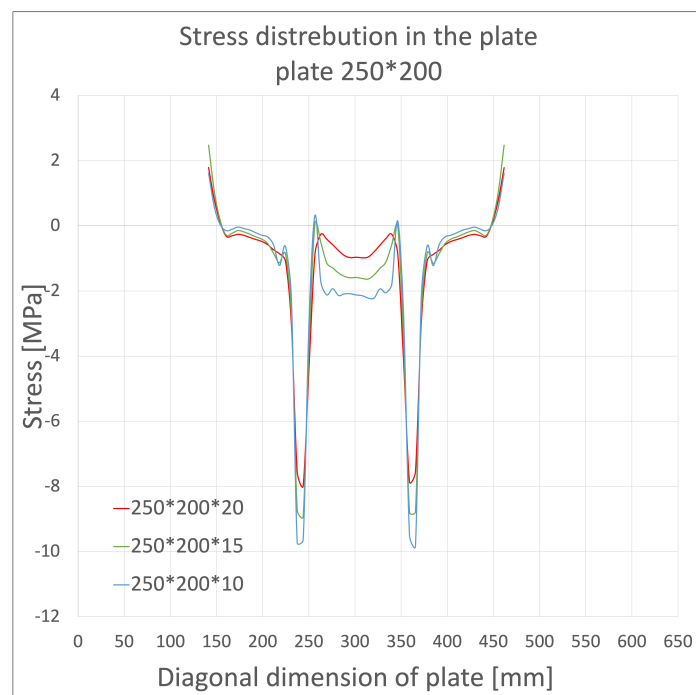
**Figure B.3:** Stress in the plate, thickness 10, with different dimensions



**Figure B.4:** Stress in the plate, dimensions 450×400, with varying thicknesses



**Figure B.5:** Stress in the plate, dimensions  $350 \times 300$ , with varying thicknesses

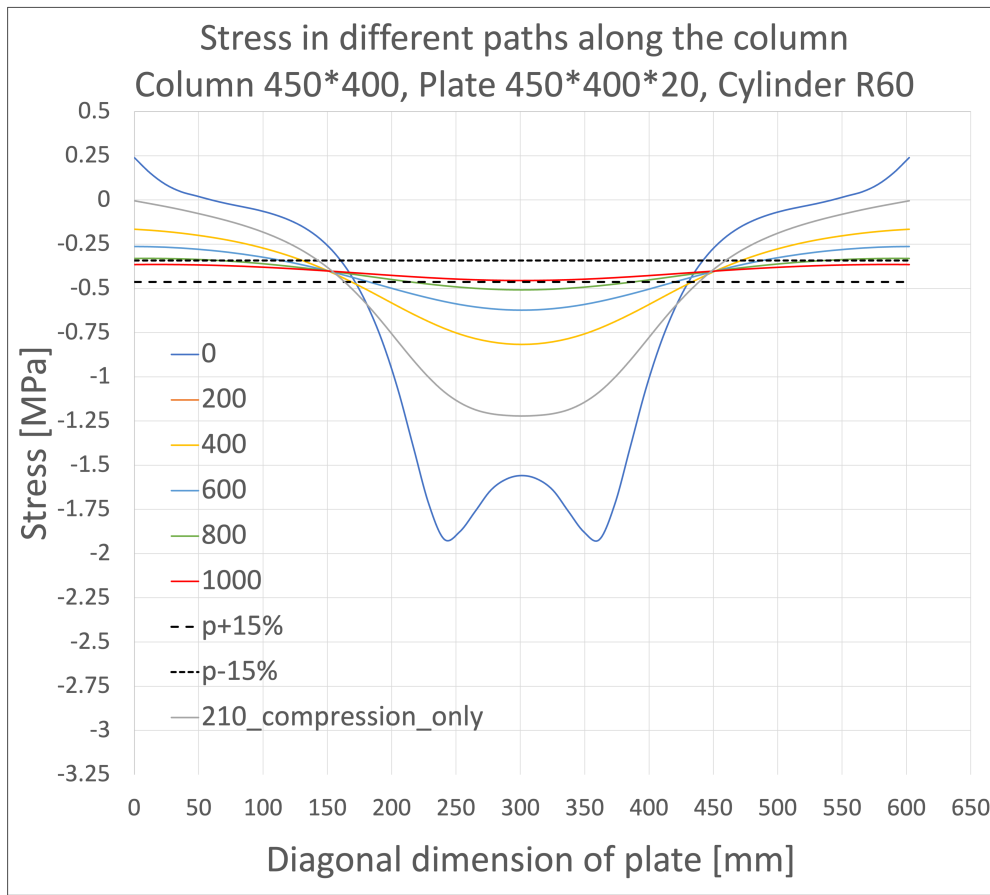


**Figure B.6:** Stress in the plate, dimensions  $250 \times 200$ , with varying thicknesses

## B.2 Stress in column

**Table B.4:** Stress in the column in different paths along the column diagonally with plate 450×400×20

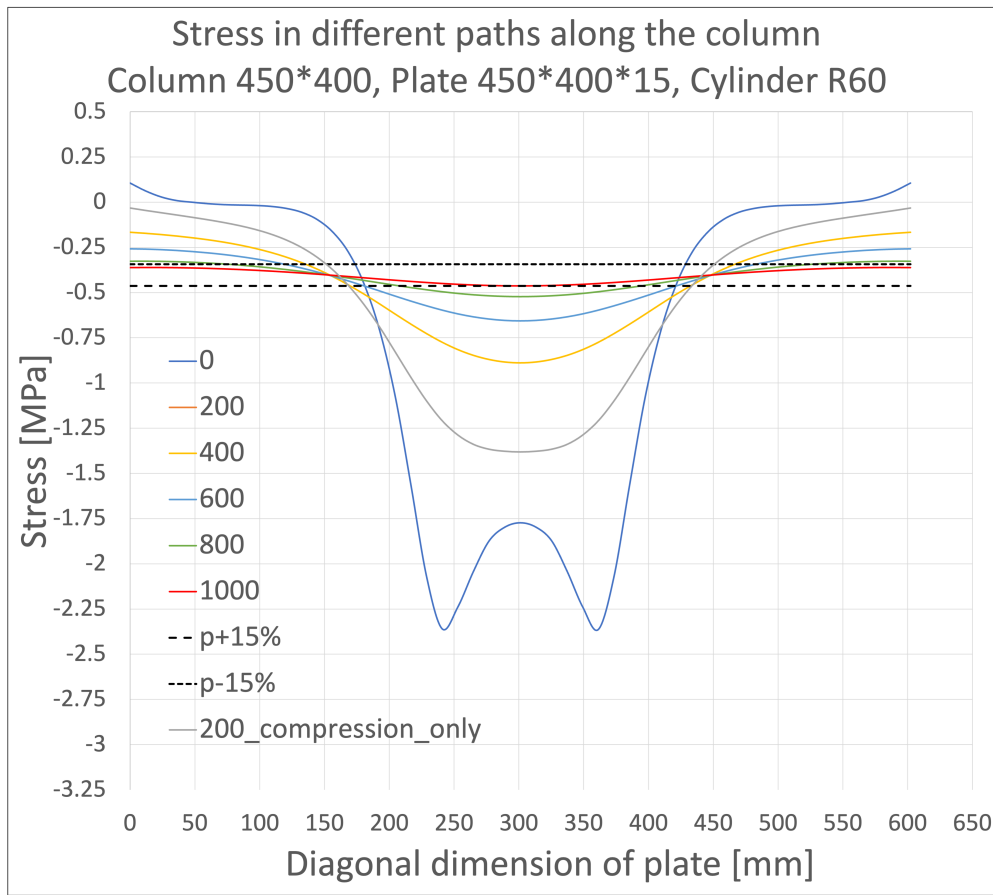
path-D	plate	450*400*20		cylinder	60	pressure(p)	0.403
diagonal [mm]	Stress [MPa] in the column in different path [mm]						
	0	200	210_ compression_ only	400	600	800	1000
0.0	0.239	-0.005	-0.005	-0.166	-0.263	-0.331	-0.365
12.0	0.153	-0.021	-0.021	-0.172	-0.265	-0.331	-0.365
24.1	0.088	-0.037	-0.037	-0.179	-0.267	-0.332	-0.365
36.1	0.046	-0.055	-0.055	-0.188	-0.272	-0.334	-0.366
48.2	0.022	-0.074	-0.074	-0.199	-0.278	-0.337	-0.367
60.2	-0.001	-0.095	-0.095	-0.212	-0.286	-0.340	-0.369
72.2	-0.022	-0.118	-0.118	-0.227	-0.295	-0.345	-0.372
84.3	-0.039	-0.143	-0.143	-0.245	-0.307	-0.352	-0.375
96.3	-0.058	-0.172	-0.172	-0.266	-0.320	-0.359	-0.379
108.4	-0.082	-0.206	-0.206	-0.290	-0.335	-0.367	-0.383
120.4	-0.114	-0.246	-0.246	-0.317	-0.352	-0.376	-0.388
132.5	-0.159	-0.294	-0.294	-0.348	-0.370	-0.385	-0.393
144.5	-0.222	-0.352	-0.352	-0.383	-0.391	-0.396	-0.399
156.5	-0.309	-0.420	-0.420	-0.421	-0.413	-0.407	-0.405
168.6	-0.429	-0.499	-0.499	-0.463	-0.436	-0.419	-0.411
180.6	-0.591	-0.590	-0.590	-0.508	-0.461	-0.431	-0.417
192.7	-0.801	-0.692	-0.692	-0.554	-0.485	-0.443	-0.423
204.7	-1.071	-0.800	-0.800	-0.601	-0.510	-0.454	-0.429
216.7	-1.397	-0.906	-0.906	-0.647	-0.533	-0.465	-0.435
228.8	-1.721	-1.004	-1.004	-0.689	-0.555	-0.476	-0.440
240.8	-1.920	-1.085	-1.085	-0.727	-0.575	-0.485	-0.444
252.9	-1.877	-1.146	-1.146	-0.759	-0.592	-0.493	-0.448
264.9	-1.761	-1.186	-1.186	-0.784	-0.605	-0.499	-0.452
277.0	-1.642	-1.208	-1.208	-0.802	-0.615	-0.504	-0.454
289.0	-1.580	-1.218	-1.218	-0.814	-0.621	-0.507	-0.455
301.0	-1.559	-1.222	-1.222	-0.817	-0.624	-0.508	-0.456
313.1	-1.579	-1.218	-1.218	-0.814	-0.621	-0.507	-0.455
325.1	-1.641	-1.208	-1.208	-0.802	-0.615	-0.504	-0.454
337.2	-1.761	-1.186	-1.186	-0.784	-0.605	-0.499	-0.452
349.2	-1.877	-1.146	-1.146	-0.759	-0.592	-0.493	-0.448
361.2	-1.922	-1.085	-1.085	-0.727	-0.575	-0.485	-0.444
373.3	-1.722	-1.004	-1.004	-0.689	-0.555	-0.476	-0.440
385.3	-1.398	-0.906	-0.906	-0.647	-0.533	-0.465	-0.435
397.4	-1.071	-0.800	-0.800	-0.601	-0.510	-0.454	-0.429
409.4	-0.801	-0.692	-0.692	-0.554	-0.485	-0.443	-0.423
421.5	-0.591	-0.590	-0.590	-0.508	-0.461	-0.431	-0.417
433.5	-0.429	-0.499	-0.499	-0.463	-0.436	-0.419	-0.411
445.5	-0.309	-0.420	-0.420	-0.421	-0.413	-0.407	-0.405
457.6	-0.222	-0.352	-0.352	-0.383	-0.391	-0.396	-0.399
469.6	-0.159	-0.294	-0.294	-0.348	-0.370	-0.385	-0.393
481.7	-0.114	-0.246	-0.246	-0.317	-0.352	-0.376	-0.388
493.7	-0.082	-0.206	-0.206	-0.290	-0.335	-0.367	-0.383
505.7	-0.058	-0.172	-0.172	-0.266	-0.320	-0.359	-0.379
517.8	-0.039	-0.143	-0.143	-0.245	-0.307	-0.352	-0.375
529.8	-0.022	-0.118	-0.118	-0.227	-0.295	-0.345	-0.372
541.9	-0.001	-0.095	-0.095	-0.212	-0.286	-0.340	-0.369
553.9	0.022	-0.074	-0.074	-0.199	-0.278	-0.337	-0.367
566.0	0.046	-0.055	-0.055	-0.188	-0.272	-0.334	-0.366
578.0	0.088	-0.037	-0.037	-0.179	-0.267	-0.332	-0.365
590.0	0.153	-0.021	-0.021	-0.172	-0.265	-0.331	-0.365
602.1	0.239	-0.005	-0.005	-0.166	-0.263	-0.331	-0.365



**Figure B.7:** Stress in the column in different paths along the column diagonally with plate 450×400×20

**Table B.5:** Stress in the column in different paths along the column diagonally with plate 450×400×15

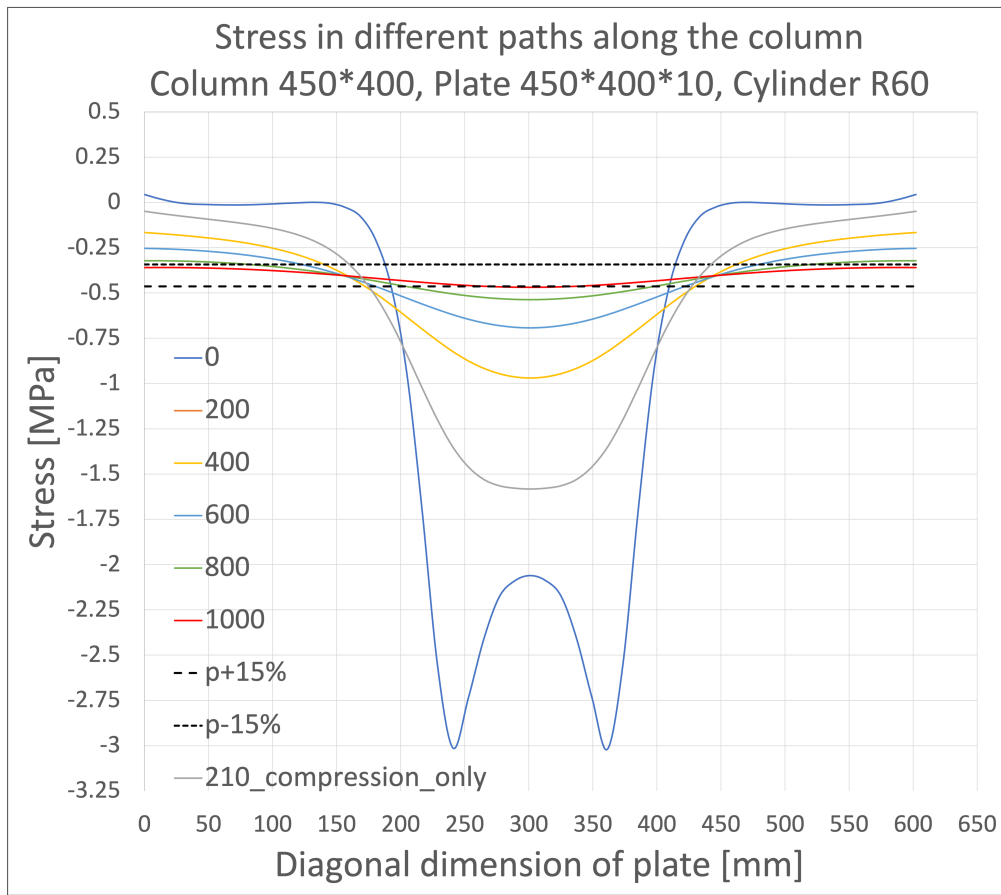
path-D	plate	450*400*15		cylinder	60	pressure(p)	0.403
diagonal [mm]	Stress [MPa] in the column in different path [mm]						
	0	200	200_ compression_ only	400	600	800	1000
0.0	0.105	-0.033	-0.033	-0.166	-0.258	-0.327	-0.362
12.0	0.061	-0.046	-0.046	-0.172	-0.260	-0.327	-0.362
24.1	0.028	-0.059	-0.059	-0.179	-0.263	-0.327	-0.362
36.1	0.008	-0.071	-0.071	-0.187	-0.267	-0.329	-0.363
48.2	-0.001	-0.084	-0.084	-0.197	-0.273	-0.332	-0.364
60.2	-0.009	-0.098	-0.098	-0.208	-0.281	-0.336	-0.367
72.2	-0.014	-0.113	-0.113	-0.221	-0.290	-0.342	-0.369
84.3	-0.016	-0.130	-0.130	-0.237	-0.301	-0.348	-0.373
96.3	-0.018	-0.151	-0.151	-0.255	-0.314	-0.355	-0.377
108.4	-0.024	-0.177	-0.177	-0.277	-0.328	-0.363	-0.381
120.4	-0.035	-0.209	-0.209	-0.304	-0.345	-0.373	-0.387
132.5	-0.056	-0.252	-0.252	-0.334	-0.365	-0.383	-0.392
144.5	-0.097	-0.306	-0.306	-0.370	-0.387	-0.395	-0.398
156.5	-0.167	-0.376	-0.376	-0.412	-0.411	-0.407	-0.405
168.6	-0.279	-0.463	-0.463	-0.458	-0.436	-0.420	-0.411
180.6	-0.455	-0.568	-0.568	-0.509	-0.464	-0.433	-0.418
192.7	-0.713	-0.692	-0.692	-0.563	-0.492	-0.446	-0.425
204.7	-1.080	-0.830	-0.830	-0.619	-0.520	-0.460	-0.432
216.7	-1.567	-0.970	-0.970	-0.675	-0.548	-0.472	-0.438
228.8	-2.072	-1.100	-1.100	-0.727	-0.574	-0.484	-0.444
240.8	-2.360	-1.209	-1.209	-0.774	-0.598	-0.495	-0.449
252.9	-2.239	-1.288	-1.288	-0.815	-0.618	-0.505	-0.454
264.9	-2.042	-1.340	-1.340	-0.847	-0.635	-0.512	-0.458
277.0	-1.874	-1.367	-1.367	-0.870	-0.647	-0.518	-0.460
289.0	-1.798	-1.378	-1.378	-0.884	-0.654	-0.521	-0.462
301.0	-1.773	-1.382	-1.382	-0.888	-0.657	-0.522	-0.463
313.1	-1.797	-1.378	-1.378	-0.884	-0.654	-0.521	-0.462
325.1	-1.872	-1.367	-1.367	-0.870	-0.647	-0.518	-0.460
337.2	-2.041	-1.340	-1.340	-0.847	-0.635	-0.512	-0.458
349.2	-2.239	-1.288	-1.288	-0.815	-0.618	-0.505	-0.454
361.2	-2.363	-1.209	-1.209	-0.774	-0.598	-0.495	-0.449
373.3	-2.073	-1.100	-1.100	-0.727	-0.574	-0.484	-0.444
385.3	-1.567	-0.970	-0.970	-0.675	-0.548	-0.472	-0.438
397.4	-1.080	-0.831	-0.831	-0.619	-0.520	-0.460	-0.432
409.4	-0.713	-0.692	-0.692	-0.563	-0.492	-0.446	-0.425
421.5	-0.455	-0.568	-0.568	-0.509	-0.464	-0.433	-0.418
433.5	-0.279	-0.463	-0.463	-0.458	-0.436	-0.420	-0.411
445.5	-0.167	-0.376	-0.376	-0.412	-0.411	-0.407	-0.405
457.6	-0.097	-0.306	-0.306	-0.370	-0.387	-0.395	-0.398
469.6	-0.056	-0.252	-0.252	-0.334	-0.365	-0.383	-0.392
481.7	-0.035	-0.209	-0.209	-0.304	-0.345	-0.373	-0.387
493.7	-0.024	-0.177	-0.177	-0.277	-0.328	-0.363	-0.381
505.7	-0.018	-0.151	-0.151	-0.255	-0.314	-0.355	-0.377
517.8	-0.016	-0.130	-0.130	-0.237	-0.301	-0.348	-0.373
529.8	-0.014	-0.113	-0.113	-0.221	-0.290	-0.342	-0.369
541.9	-0.009	-0.098	-0.098	-0.208	-0.281	-0.336	-0.367
553.9	-0.001	-0.084	-0.084	-0.197	-0.273	-0.332	-0.364
566.0	0.008	-0.071	-0.071	-0.187	-0.267	-0.329	-0.363
578.0	0.028	-0.059	-0.059	-0.179	-0.263	-0.327	-0.362
590.0	0.061	-0.046	-0.046	-0.172	-0.260	-0.327	-0.362
602.1	0.105	-0.033	-0.033	-0.166	-0.258	-0.327	-0.362



**Figure B.8:** Stress in the column in different paths along the column diagonally with plate  $450 \times 400 \times 15$

**Table B.6:** Stress in the column in different paths along the column diagonally with plate 450×400×10

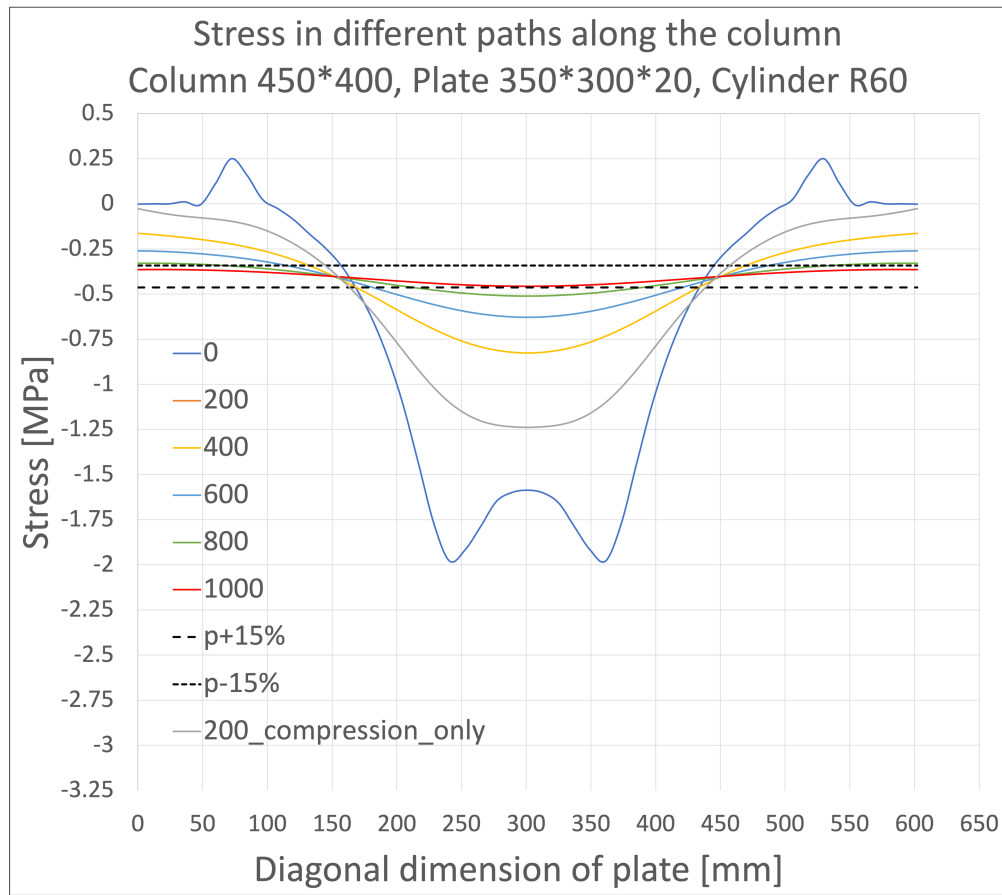
path-D	plate	450*400*10		cylinder	60	pressure(p)	0.403
diagonal [mm]	Stress [MPa] in the column in different path [mm]						
	0	200	210_ compression_ only	400	600	800	1000
0.0	0.043	-0.049	-0.049	-0.166	-0.254	-0.323	-0.360
12.0	0.019	-0.061	-0.061	-0.172	-0.256	-0.323	-0.359
24.1	0.000	-0.071	-0.071	-0.179	-0.259	-0.324	-0.359
36.1	-0.009	-0.081	-0.081	-0.186	-0.264	-0.326	-0.360
48.2	-0.012	-0.091	-0.091	-0.195	-0.269	-0.329	-0.362
60.2	-0.014	-0.101	-0.101	-0.205	-0.277	-0.333	-0.364
72.2	-0.015	-0.112	-0.112	-0.216	-0.285	-0.338	-0.367
84.3	-0.013	-0.124	-0.124	-0.230	-0.296	-0.344	-0.371
96.3	-0.010	-0.138	-0.138	-0.247	-0.308	-0.352	-0.375
108.4	-0.006	-0.156	-0.156	-0.267	-0.323	-0.360	-0.380
120.4	-0.003	-0.180	-0.180	-0.291	-0.340	-0.370	-0.385
132.5	0.000	-0.213	-0.213	-0.321	-0.359	-0.381	-0.391
144.5	-0.005	-0.258	-0.258	-0.356	-0.382	-0.393	-0.398
156.5	-0.028	-0.321	-0.321	-0.399	-0.407	-0.406	-0.405
168.6	-0.078	-0.407	-0.407	-0.448	-0.435	-0.420	-0.412
180.6	-0.210	-0.520	-0.520	-0.504	-0.465	-0.435	-0.419
192.7	-0.469	-0.666	-0.666	-0.566	-0.497	-0.450	-0.427
204.7	-0.941	-0.840	-0.840	-0.633	-0.530	-0.465	-0.434
216.7	-1.704	-1.024	-1.024	-0.700	-0.562	-0.479	-0.442
228.8	-2.560	-1.202	-1.202	-0.765	-0.592	-0.493	-0.448
240.8	-3.013	-1.353	-1.353	-0.825	-0.621	-0.505	-0.454
252.9	-2.734	-1.461	-1.461	-0.876	-0.646	-0.516	-0.459
264.9	-2.409	-1.530	-1.530	-0.917	-0.666	-0.525	-0.464
277.0	-2.178	-1.565	-1.565	-0.946	-0.681	-0.531	-0.467
289.0	-2.089	-1.578	-1.578	-0.964	-0.690	-0.536	-0.469
301.0	-2.060	-1.583	-1.583	-0.970	-0.693	-0.537	-0.469
313.1	-2.088	-1.578	-1.578	-0.964	-0.690	-0.536	-0.469
325.1	-2.174	-1.565	-1.565	-0.946	-0.681	-0.531	-0.467
337.2	-2.406	-1.530	-1.530	-0.917	-0.666	-0.525	-0.464
349.2	-2.733	-1.461	-1.461	-0.876	-0.646	-0.516	-0.459
361.2	-3.019	-1.353	-1.353	-0.825	-0.621	-0.505	-0.454
373.3	-2.557	-1.201	-1.201	-0.765	-0.592	-0.493	-0.448
385.3	-1.701	-1.024	-1.024	-0.700	-0.562	-0.479	-0.442
397.4	-0.940	-0.839	-0.839	-0.633	-0.529	-0.465	-0.434
409.4	-0.469	-0.666	-0.666	-0.566	-0.497	-0.450	-0.427
421.5	-0.210	-0.520	-0.520	-0.504	-0.465	-0.435	-0.419
433.5	-0.078	-0.407	-0.407	-0.448	-0.435	-0.420	-0.412
445.5	-0.027	-0.321	-0.321	-0.399	-0.407	-0.406	-0.405
457.6	-0.005	-0.258	-0.258	-0.356	-0.382	-0.393	-0.398
469.6	0.000	-0.213	-0.213	-0.321	-0.359	-0.381	-0.391
481.7	-0.003	-0.180	-0.180	-0.291	-0.340	-0.370	-0.385
493.7	-0.006	-0.156	-0.156	-0.267	-0.323	-0.360	-0.380
505.7	-0.010	-0.138	-0.138	-0.247	-0.308	-0.352	-0.375
517.8	-0.013	-0.124	-0.124	-0.230	-0.296	-0.344	-0.371
529.8	-0.015	-0.112	-0.112	-0.216	-0.285	-0.338	-0.367
541.9	-0.014	-0.101	-0.101	-0.205	-0.277	-0.333	-0.364
553.9	-0.012	-0.091	-0.091	-0.195	-0.269	-0.329	-0.362
566.0	-0.009	-0.082	-0.082	-0.186	-0.264	-0.326	-0.360
578.0	0.000	-0.071	-0.071	-0.179	-0.259	-0.324	-0.359
590.0	0.019	-0.061	-0.061	-0.172	-0.256	-0.323	-0.359
602.1	0.043	-0.049	-0.049	-0.166	-0.254	-0.323	-0.360



**Figure B.9:** Stress in the column in different paths along the column diagonally with plate  $450 \times 400 \times 10$

**Table B.7:** Stress in the column in different paths along the column diagonally with plate 350×300×20

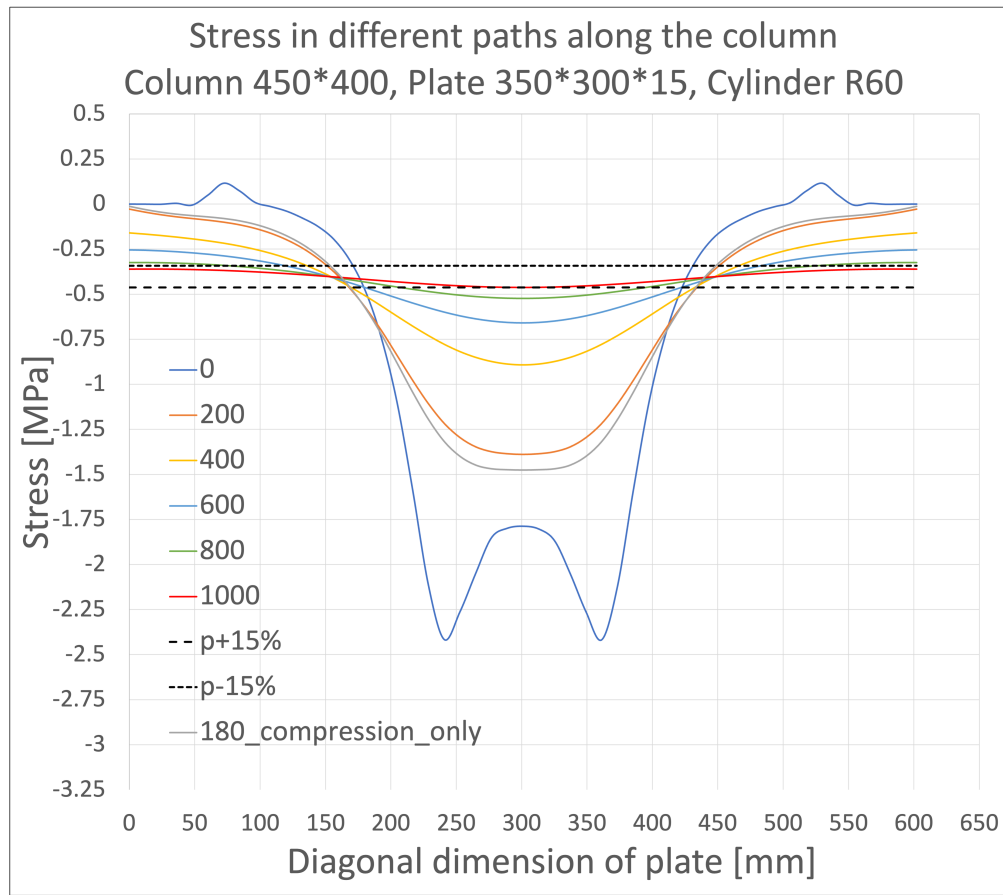
path-D	plate	350*300*20		cylinder	60	pressure(p)	0.403
diagonal [mm]	Stress [MPa] in the column in different path [mm]						
	0	200	200_ compression_ only	400	600	800	1000
0.0	-0.002	-0.027	-0.027	-0.164	-0.260	-0.329	-0.364
12.0	0.000	-0.044	-0.044	-0.171	-0.262	-0.329	-0.364
24.1	0.000	-0.058	-0.058	-0.178	-0.265	-0.330	-0.364
36.1	0.011	-0.069	-0.069	-0.187	-0.270	-0.332	-0.365
48.2	-0.005	-0.077	-0.077	-0.197	-0.276	-0.335	-0.366
60.2	0.114	-0.085	-0.085	-0.209	-0.284	-0.339	-0.368
72.2	0.250	-0.097	-0.097	-0.223	-0.293	-0.344	-0.371
84.3	0.159	-0.114	-0.114	-0.240	-0.304	-0.350	-0.374
96.3	0.025	-0.140	-0.140	-0.259	-0.317	-0.357	-0.378
108.4	-0.028	-0.176	-0.176	-0.283	-0.332	-0.366	-0.383
120.4	-0.088	-0.221	-0.221	-0.311	-0.350	-0.375	-0.388
132.5	-0.166	-0.275	-0.275	-0.343	-0.369	-0.385	-0.393
144.5	-0.242	-0.340	-0.340	-0.379	-0.390	-0.396	-0.399
156.5	-0.337	-0.415	-0.415	-0.419	-0.412	-0.407	-0.405
168.6	-0.468	-0.500	-0.500	-0.463	-0.436	-0.419	-0.411
180.6	-0.632	-0.596	-0.596	-0.509	-0.461	-0.431	-0.417
192.7	-0.843	-0.701	-0.701	-0.557	-0.487	-0.443	-0.424
204.7	-1.108	-0.812	-0.812	-0.605	-0.512	-0.455	-0.430
216.7	-1.437	-0.921	-0.921	-0.652	-0.536	-0.467	-0.435
228.8	-1.773	-1.019	-1.019	-0.695	-0.558	-0.477	-0.441
240.8	-1.979	-1.102	-1.102	-0.734	-0.579	-0.487	-0.446
252.9	-1.916	-1.162	-1.162	-0.767	-0.596	-0.495	-0.450
264.9	-1.787	-1.203	-1.203	-0.793	-0.610	-0.502	-0.453
277.0	-1.649	-1.226	-1.226	-0.811	-0.620	-0.507	-0.455
289.0	-1.599	-1.236	-1.236	-0.823	-0.627	-0.510	-0.457
301.0	-1.586	-1.239	-1.239	-0.827	-0.629	-0.511	-0.457
313.1	-1.601	-1.236	-1.236	-0.823	-0.627	-0.510	-0.457
325.1	-1.658	-1.226	-1.226	-0.811	-0.620	-0.507	-0.455
337.2	-1.788	-1.203	-1.203	-0.793	-0.610	-0.502	-0.453
349.2	-1.916	-1.162	-1.162	-0.767	-0.596	-0.495	-0.450
361.2	-1.980	-1.102	-1.102	-0.734	-0.579	-0.487	-0.446
373.3	-1.775	-1.019	-1.019	-0.695	-0.558	-0.477	-0.441
385.3	-1.438	-0.921	-0.921	-0.652	-0.536	-0.467	-0.435
397.4	-1.109	-0.812	-0.812	-0.605	-0.512	-0.455	-0.430
409.4	-0.843	-0.702	-0.702	-0.557	-0.487	-0.443	-0.424
421.5	-0.632	-0.596	-0.596	-0.509	-0.461	-0.431	-0.417
433.5	-0.468	-0.500	-0.500	-0.463	-0.436	-0.419	-0.411
445.5	-0.337	-0.415	-0.415	-0.419	-0.412	-0.407	-0.405
457.6	-0.242	-0.340	-0.340	-0.379	-0.390	-0.396	-0.399
469.6	-0.166	-0.275	-0.275	-0.343	-0.369	-0.385	-0.393
481.7	-0.088	-0.221	-0.221	-0.311	-0.350	-0.375	-0.388
493.7	-0.028	-0.176	-0.176	-0.283	-0.332	-0.366	-0.383
505.7	0.024	-0.140	-0.140	-0.259	-0.317	-0.357	-0.378
517.8	0.159	-0.114	-0.114	-0.240	-0.304	-0.350	-0.374
529.8	0.250	-0.097	-0.097	-0.223	-0.293	-0.344	-0.371
541.9	0.114	-0.085	-0.085	-0.209	-0.284	-0.339	-0.368
553.9	-0.005	-0.077	-0.077	-0.197	-0.276	-0.335	-0.366
566.0	0.011	-0.069	-0.069	-0.187	-0.270	-0.332	-0.365
578.0	0.000	-0.058	-0.058	-0.178	-0.265	-0.330	-0.364
590.0	0.000	-0.044	-0.044	-0.171	-0.262	-0.329	-0.364
602.1	-0.002	-0.027	-0.027	-0.164	-0.260	-0.329	-0.364



**Figure B.10:** Stress in the column in different paths along the column diagonally with plate 350×300×20

**Table B.8:** Stress in the column in different paths along the column diagonally with plate 350×300×15

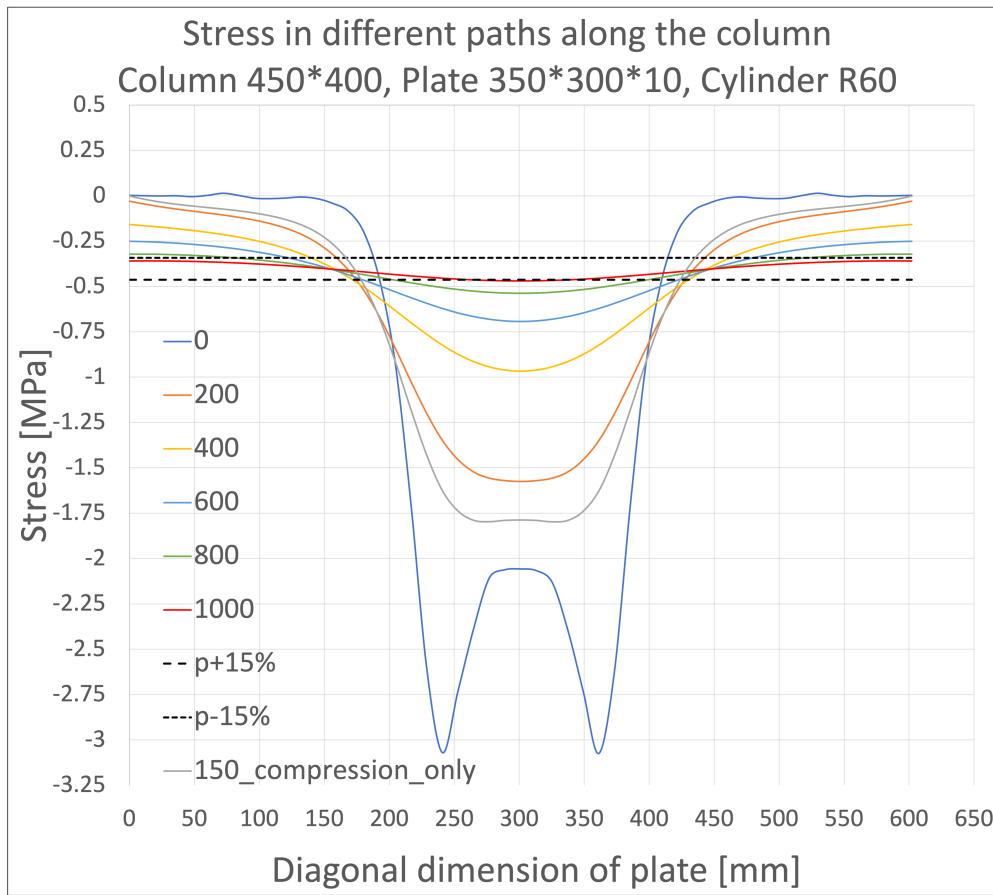
path-D	plate	350*300*15	cylinder	60	pressure(p)	0.403	
diagonal [mm]	Stress [MPa] in the column in different path [mm]						
	0	180_compression_only	200	400	600	800	1000
0.0	0.000	-0.013	-0.028	-0.160	-0.255	-0.325	-0.361
12.0	0.000	-0.030	-0.045	-0.167	-0.256	-0.325	-0.361
24.1	-0.001	-0.045	-0.059	-0.174	-0.260	-0.326	-0.361
36.1	0.004	-0.056	-0.071	-0.183	-0.265	-0.328	-0.362
48.2	-0.005	-0.064	-0.080	-0.193	-0.271	-0.331	-0.364
60.2	0.050	-0.071	-0.090	-0.204	-0.279	-0.335	-0.366
72.2	0.116	-0.080	-0.101	-0.217	-0.288	-0.340	-0.369
84.3	0.073	-0.093	-0.115	-0.233	-0.299	-0.347	-0.372
96.3	0.009	-0.113	-0.135	-0.252	-0.312	-0.354	-0.376
108.4	-0.014	-0.140	-0.163	-0.274	-0.327	-0.363	-0.381
120.4	-0.040	-0.177	-0.198	-0.301	-0.344	-0.372	-0.386
132.5	-0.078	-0.224	-0.245	-0.332	-0.364	-0.383	-0.392
144.5	-0.125	-0.285	-0.303	-0.369	-0.386	-0.395	-0.398
156.5	-0.196	-0.363	-0.377	-0.411	-0.411	-0.407	-0.405
168.6	-0.311	-0.460	-0.467	-0.458	-0.437	-0.420	-0.412
180.6	-0.484	-0.579	-0.574	-0.510	-0.464	-0.433	-0.419
192.7	-0.741	-0.722	-0.700	-0.565	-0.493	-0.447	-0.425
204.7	-1.099	-0.882	-0.839	-0.622	-0.522	-0.460	-0.432
216.7	-1.589	-1.045	-0.979	-0.678	-0.550	-0.473	-0.439
228.8	-2.117	-1.195	-1.108	-0.730	-0.576	-0.485	-0.445
240.8	-2.416	-1.318	-1.217	-0.778	-0.600	-0.496	-0.450
252.9	-2.262	-1.400	-1.295	-0.819	-0.621	-0.506	-0.455
264.9	-2.049	-1.449	-1.347	-0.851	-0.637	-0.513	-0.458
277.0	-1.852	-1.469	-1.374	-0.874	-0.649	-0.519	-0.461
289.0	-1.799	-1.474	-1.385	-0.888	-0.657	-0.522	-0.463
301.0	-1.788	-1.476	-1.389	-0.892	-0.660	-0.524	-0.463
313.1	-1.803	-1.474	-1.385	-0.888	-0.657	-0.522	-0.463
325.1	-1.868	-1.469	-1.374	-0.874	-0.649	-0.519	-0.461
337.2	-2.051	-1.449	-1.347	-0.851	-0.637	-0.513	-0.458
349.2	-2.262	-1.400	-1.296	-0.819	-0.621	-0.506	-0.455
361.2	-2.418	-1.318	-1.217	-0.778	-0.600	-0.496	-0.450
373.3	-2.122	-1.196	-1.109	-0.730	-0.576	-0.485	-0.445
385.3	-1.592	-1.045	-0.979	-0.678	-0.550	-0.473	-0.439
397.4	-1.100	-0.882	-0.839	-0.622	-0.522	-0.460	-0.432
409.4	-0.741	-0.722	-0.701	-0.565	-0.493	-0.447	-0.425
421.5	-0.484	-0.579	-0.575	-0.510	-0.464	-0.433	-0.419
433.5	-0.311	-0.460	-0.467	-0.458	-0.437	-0.420	-0.412
445.5	-0.196	-0.363	-0.377	-0.411	-0.411	-0.407	-0.405
457.6	-0.125	-0.285	-0.303	-0.369	-0.386	-0.395	-0.398
469.6	-0.078	-0.224	-0.245	-0.332	-0.364	-0.383	-0.392
481.7	-0.039	-0.177	-0.198	-0.301	-0.344	-0.372	-0.386
493.7	-0.014	-0.140	-0.163	-0.274	-0.327	-0.363	-0.381
505.7	0.009	-0.113	-0.135	-0.252	-0.312	-0.354	-0.376
517.8	0.073	-0.093	-0.115	-0.233	-0.299	-0.347	-0.372
529.8	0.116	-0.080	-0.101	-0.217	-0.288	-0.340	-0.369
541.9	0.050	-0.071	-0.090	-0.204	-0.279	-0.335	-0.366
553.9	-0.005	-0.064	-0.080	-0.193	-0.271	-0.331	-0.364
566.0	0.004	-0.056	-0.071	-0.183	-0.265	-0.328	-0.362
578.0	-0.001	-0.045	-0.059	-0.174	-0.260	-0.326	-0.361
590.0	0.000	-0.030	-0.045	-0.167	-0.256	-0.325	-0.361
602.1	0.000	-0.013	-0.028	-0.160	-0.255	-0.325	-0.361



**Figure B.11:** Stress in the column in different paths along the column diagonally with plate 350×300×15

**Table B.9:** Stress in the column in different paths along the column diagonally with plate 350×300×10

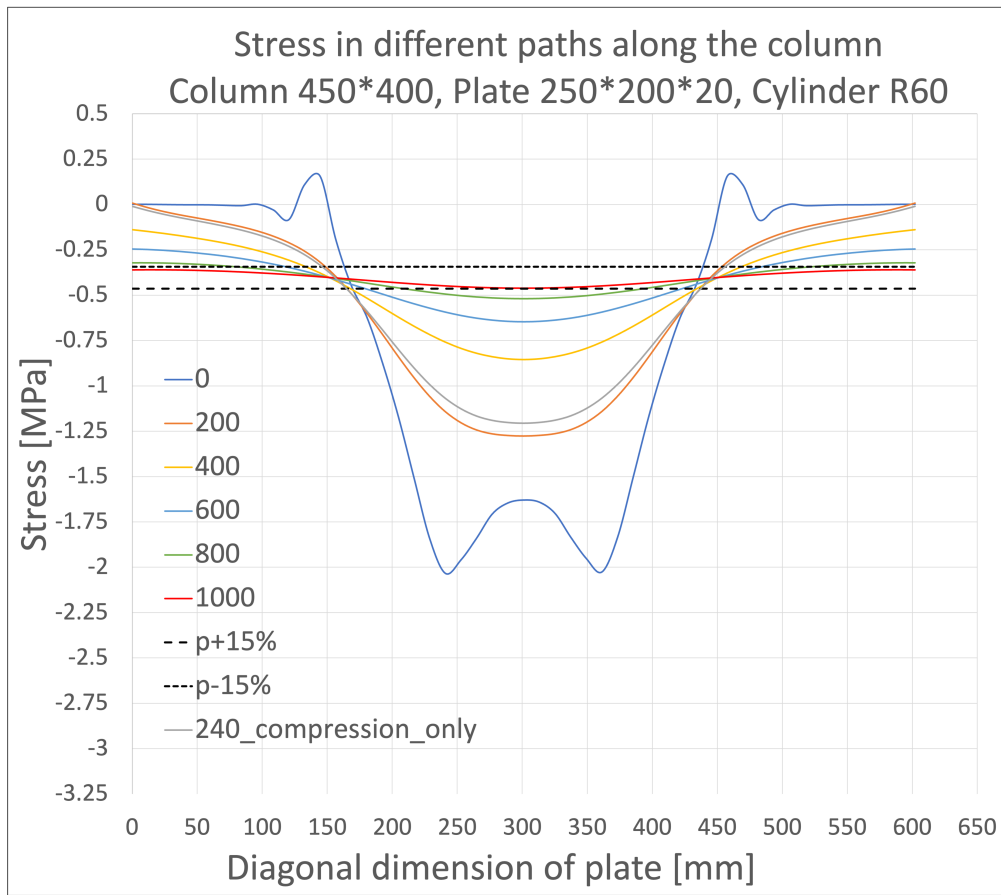
path-D	plate	350*300*10	cylinder	60	pressure(p)	0.403	
diagonal [mm]	Stress [MPa] in the column in different path [mm]						
	0	150_ compression_ only	200	400	600	800	1000
0.0	0.002	-0.001	-0.030	-0.158	-0.251	-0.322	-0.359
12.0	0.000	-0.020	-0.047	-0.165	-0.253	-0.321	-0.359
24.1	-0.002	-0.035	-0.061	-0.173	-0.256	-0.322	-0.359
36.1	-0.001	-0.047	-0.074	-0.181	-0.261	-0.325	-0.360
48.2	-0.005	-0.056	-0.085	-0.191	-0.267	-0.328	-0.362
60.2	0.002	-0.065	-0.095	-0.201	-0.275	-0.332	-0.364
72.2	0.013	-0.074	-0.107	-0.214	-0.284	-0.337	-0.367
84.3	0.001	-0.083	-0.119	-0.228	-0.294	-0.344	-0.370
96.3	-0.014	-0.095	-0.135	-0.245	-0.307	-0.351	-0.375
108.4	-0.016	-0.111	-0.154	-0.266	-0.322	-0.360	-0.380
120.4	-0.013	-0.132	-0.180	-0.291	-0.339	-0.370	-0.385
132.5	-0.007	-0.161	-0.214	-0.321	-0.359	-0.381	-0.391
144.5	-0.017	-0.204	-0.260	-0.357	-0.382	-0.393	-0.398
156.5	-0.043	-0.267	-0.324	-0.399	-0.407	-0.406	-0.405
168.6	-0.087	-0.360	-0.411	-0.449	-0.435	-0.420	-0.412
180.6	-0.205	-0.494	-0.525	-0.505	-0.465	-0.435	-0.420
192.7	-0.469	-0.680	-0.670	-0.567	-0.497	-0.450	-0.427
204.7	-0.932	-0.918	-0.843	-0.634	-0.530	-0.465	-0.435
216.7	-1.708	-1.181	-1.026	-0.700	-0.562	-0.479	-0.442
228.8	-2.606	-1.431	-1.200	-0.764	-0.592	-0.493	-0.448
240.8	-3.069	-1.626	-1.349	-0.824	-0.621	-0.505	-0.454
252.9	-2.729	-1.739	-1.454	-0.875	-0.646	-0.516	-0.460
264.9	-2.385	-1.790	-1.522	-0.915	-0.666	-0.525	-0.464
277.0	-2.106	-1.797	-1.556	-0.944	-0.680	-0.532	-0.467
289.0	-2.061	-1.790	-1.570	-0.962	-0.690	-0.536	-0.469
301.0	-2.057	-1.788	-1.575	-0.968	-0.693	-0.537	-0.469
313.1	-2.066	-1.790	-1.570	-0.962	-0.690	-0.536	-0.469
325.1	-2.129	-1.798	-1.557	-0.944	-0.680	-0.532	-0.467
337.2	-2.389	-1.791	-1.523	-0.915	-0.666	-0.525	-0.464
349.2	-2.731	-1.740	-1.455	-0.875	-0.646	-0.516	-0.460
361.2	-3.074	-1.628	-1.349	-0.824	-0.621	-0.505	-0.454
373.3	-2.620	-1.432	-1.201	-0.764	-0.593	-0.493	-0.448
385.3	-1.716	-1.183	-1.026	-0.700	-0.562	-0.479	-0.442
397.4	-0.934	-0.919	-0.843	-0.634	-0.530	-0.465	-0.435
409.4	-0.469	-0.681	-0.671	-0.567	-0.497	-0.450	-0.427
421.5	-0.205	-0.494	-0.525	-0.505	-0.466	-0.435	-0.420
433.5	-0.086	-0.360	-0.411	-0.449	-0.435	-0.420	-0.412
445.5	-0.042	-0.267	-0.325	-0.399	-0.407	-0.406	-0.405
457.6	-0.016	-0.204	-0.261	-0.357	-0.382	-0.393	-0.398
469.6	-0.007	-0.161	-0.214	-0.321	-0.359	-0.381	-0.391
481.7	-0.013	-0.132	-0.180	-0.291	-0.339	-0.370	-0.385
493.7	-0.016	-0.111	-0.154	-0.266	-0.322	-0.360	-0.380
505.7	-0.014	-0.095	-0.135	-0.245	-0.307	-0.351	-0.375
517.8	0.001	-0.083	-0.119	-0.228	-0.294	-0.344	-0.370
529.8	0.013	-0.074	-0.107	-0.214	-0.284	-0.337	-0.367
541.9	0.002	-0.065	-0.095	-0.201	-0.275	-0.332	-0.364
553.9	-0.005	-0.056	-0.085	-0.191	-0.267	-0.328	-0.362
566.0	0.000	-0.047	-0.074	-0.181	-0.261	-0.325	-0.360
578.0	-0.002	-0.035	-0.061	-0.173	-0.256	-0.322	-0.359
590.0	0.000	-0.020	-0.047	-0.165	-0.253	-0.321	-0.359
602.1	0.002	-0.001	-0.030	-0.158	-0.251	-0.322	-0.359



**Figure B.12:** Stress in the column in different paths along the column diagonally with plate 350×300×10

**Table B.10:** Stress in the column in different paths along the column diagonally with plate 250×200×20

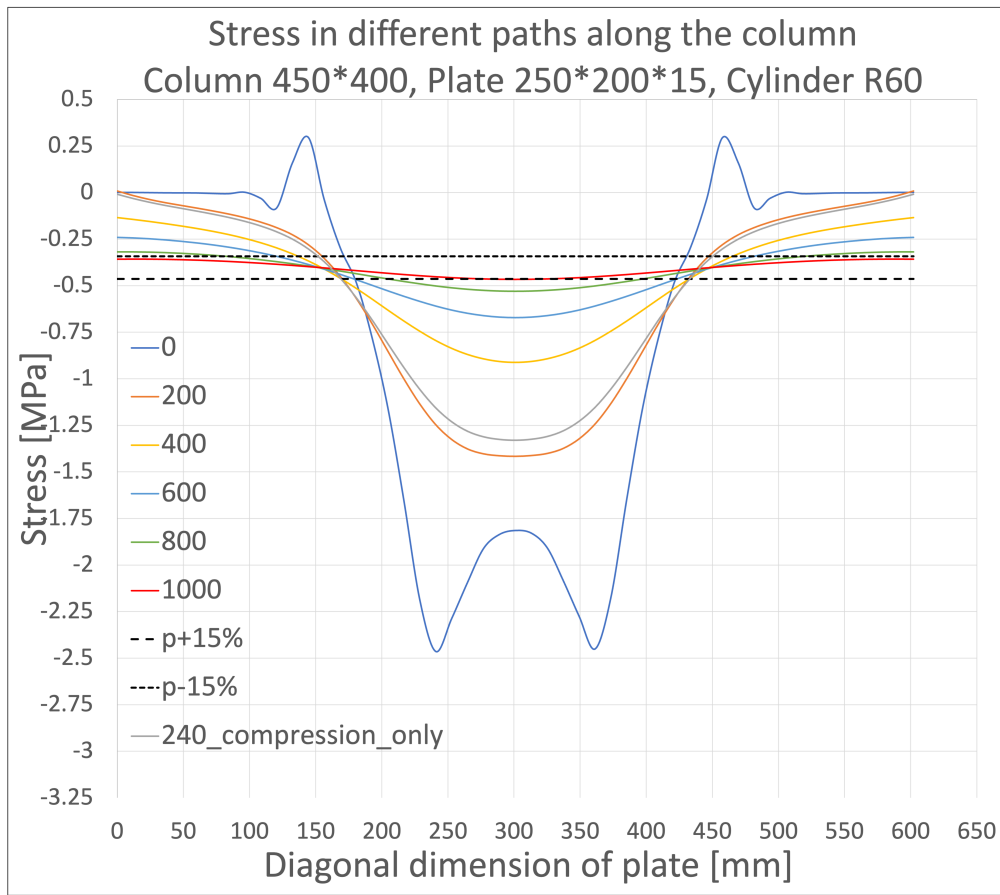
path-D	plate	250*200*20		cylinder	60	pressure(p)	0.403
diagonal [mm]	Stress [MPa] in the column in different path [mm]						
	0	200	240_ compression_ only	400	600	800	1000
0.0	0.001	0.008	-0.010	-0.139	-0.245	-0.322	-0.360
12.0	0.001	-0.017	-0.033	-0.149	-0.248	-0.322	-0.360
24.1	0.000	-0.039	-0.054	-0.160	-0.252	-0.323	-0.360
36.1	-0.001	-0.057	-0.071	-0.172	-0.258	-0.325	-0.361
48.2	-0.002	-0.072	-0.088	-0.185	-0.266	-0.329	-0.363
60.2	-0.002	-0.088	-0.104	-0.199	-0.275	-0.334	-0.365
72.2	-0.005	-0.105	-0.122	-0.215	-0.286	-0.339	-0.368
84.3	-0.006	-0.123	-0.142	-0.233	-0.298	-0.346	-0.372
96.3	0.001	-0.146	-0.165	-0.254	-0.312	-0.354	-0.376
108.4	-0.030	-0.174	-0.194	-0.279	-0.329	-0.363	-0.381
120.4	-0.084	-0.211	-0.230	-0.307	-0.347	-0.373	-0.387
132.5	0.109	-0.257	-0.276	-0.340	-0.367	-0.384	-0.392
144.5	0.155	-0.318	-0.334	-0.378	-0.390	-0.396	-0.399
156.5	-0.193	-0.397	-0.406	-0.421	-0.414	-0.408	-0.405
168.6	-0.449	-0.492	-0.492	-0.467	-0.440	-0.421	-0.412
180.6	-0.625	-0.601	-0.589	-0.517	-0.467	-0.434	-0.419
192.7	-0.878	-0.718	-0.693	-0.569	-0.494	-0.447	-0.425
204.7	-1.171	-0.840	-0.799	-0.621	-0.521	-0.460	-0.432
216.7	-1.509	-0.956	-0.901	-0.671	-0.547	-0.472	-0.438
228.8	-1.843	-1.059	-0.993	-0.718	-0.571	-0.484	-0.444
240.8	-2.034	-1.143	-1.069	-0.759	-0.593	-0.494	-0.449
252.9	-1.960	-1.204	-1.126	-0.793	-0.611	-0.503	-0.454
264.9	-1.839	-1.244	-1.166	-0.820	-0.626	-0.510	-0.457
277.0	-1.706	-1.265	-1.190	-0.839	-0.637	-0.515	-0.460
289.0	-1.646	-1.274	-1.202	-0.851	-0.644	-0.518	-0.461
301.0	-1.630	-1.277	-1.206	-0.855	-0.646	-0.519	-0.462
313.1	-1.641	-1.273	-1.201	-0.851	-0.644	-0.518	-0.461
325.1	-1.703	-1.264	-1.189	-0.839	-0.637	-0.515	-0.460
337.2	-1.834	-1.242	-1.165	-0.820	-0.626	-0.510	-0.457
349.2	-1.952	-1.202	-1.125	-0.793	-0.611	-0.503	-0.454
361.2	-2.026	-1.141	-1.067	-0.758	-0.593	-0.494	-0.449
373.3	-1.835	-1.057	-0.991	-0.717	-0.571	-0.484	-0.444
385.3	-1.503	-0.954	-0.900	-0.671	-0.547	-0.472	-0.438
397.4	-1.166	-0.838	-0.798	-0.621	-0.521	-0.460	-0.432
409.4	-0.875	-0.717	-0.692	-0.569	-0.494	-0.447	-0.425
421.5	-0.623	-0.600	-0.588	-0.517	-0.467	-0.434	-0.419
433.5	-0.448	-0.492	-0.492	-0.467	-0.440	-0.421	-0.412
445.5	-0.193	-0.396	-0.406	-0.420	-0.414	-0.408	-0.405
457.6	0.155	-0.318	-0.334	-0.378	-0.390	-0.396	-0.399
469.6	0.109	-0.257	-0.276	-0.340	-0.367	-0.384	-0.392
481.7	-0.084	-0.210	-0.230	-0.307	-0.347	-0.373	-0.387
493.7	-0.030	-0.174	-0.194	-0.279	-0.329	-0.363	-0.381
505.7	0.001	-0.146	-0.165	-0.254	-0.312	-0.354	-0.376
517.8	-0.006	-0.123	-0.141	-0.233	-0.298	-0.346	-0.372
529.8	-0.005	-0.105	-0.122	-0.215	-0.286	-0.339	-0.368
541.9	-0.002	-0.088	-0.104	-0.199	-0.275	-0.334	-0.365
553.9	-0.002	-0.072	-0.088	-0.185	-0.266	-0.329	-0.363
566.0	-0.001	-0.057	-0.071	-0.171	-0.258	-0.325	-0.361
578.0	0.000	-0.039	-0.053	-0.160	-0.252	-0.323	-0.360
590.0	0.001	-0.017	-0.033	-0.149	-0.248	-0.322	-0.360
602.1	0.001	0.008	-0.010	-0.139	-0.245	-0.322	-0.360



**Figure B.13:** Stress in the column in different paths along the column diagonally with plate 250×200×20

**Table B.11:** Stress in the column in different paths along the column diagonally with plate 250×200×15

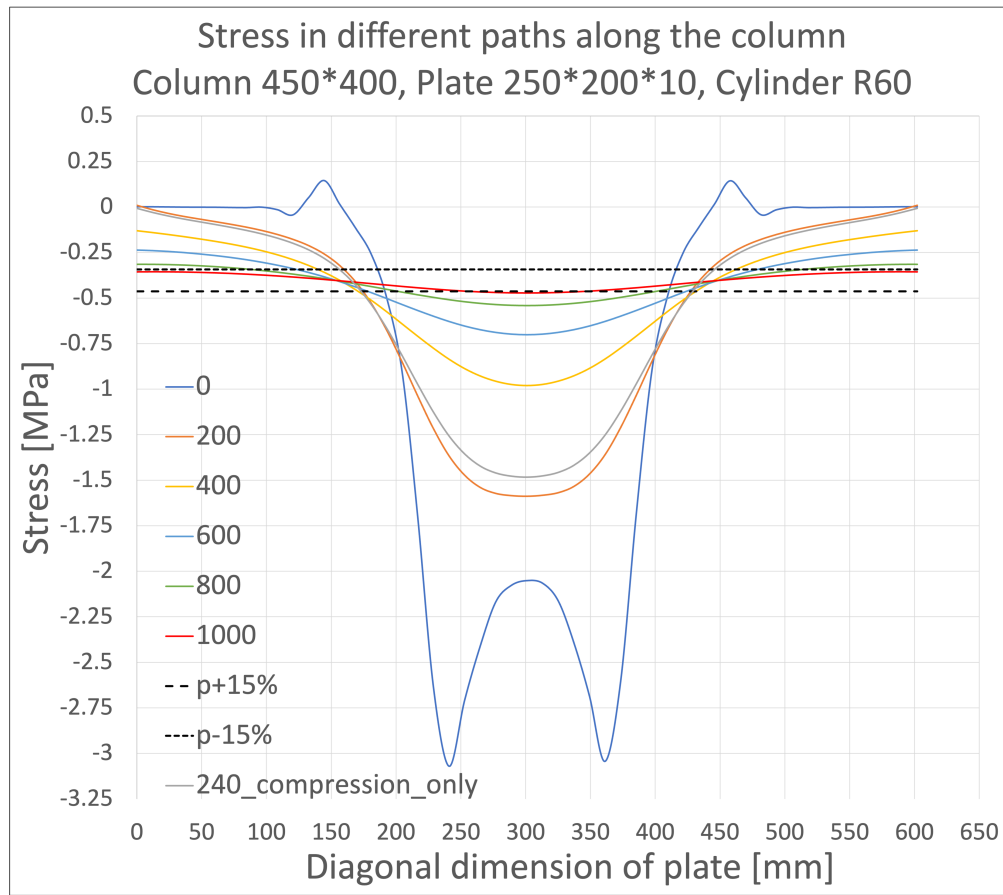
path-D	plate	250*200*15		cylinder	60	pressure(p)	0.403
diagonal	Stress [MPa] in the column in different path [mm]						
	0	200	240_ compression_ only	400	600	800	1000
0.0	0.001	0.008	-0.009	-0.134	-0.240	-0.318	-0.358
12.0	0.001	-0.016	-0.032	-0.144	-0.243	-0.318	-0.358
24.1	0.000	-0.037	-0.051	-0.155	-0.248	-0.320	-0.358
36.1	-0.001	-0.054	-0.068	-0.167	-0.254	-0.322	-0.359
48.2	-0.002	-0.069	-0.084	-0.179	-0.261	-0.326	-0.361
60.2	-0.002	-0.084	-0.099	-0.193	-0.270	-0.330	-0.363
72.2	-0.005	-0.099	-0.116	-0.208	-0.281	-0.336	-0.366
84.3	-0.006	-0.115	-0.133	-0.226	-0.293	-0.343	-0.370
96.3	0.002	-0.135	-0.154	-0.246	-0.307	-0.351	-0.375
108.4	-0.030	-0.159	-0.179	-0.269	-0.323	-0.361	-0.380
120.4	-0.083	-0.188	-0.210	-0.297	-0.342	-0.371	-0.385
132.5	0.160	-0.227	-0.250	-0.329	-0.363	-0.382	-0.392
144.5	0.296	-0.280	-0.303	-0.367	-0.386	-0.394	-0.398
156.5	-0.039	-0.354	-0.372	-0.411	-0.412	-0.407	-0.405
168.6	-0.296	-0.450	-0.459	-0.460	-0.439	-0.421	-0.412
180.6	-0.481	-0.567	-0.564	-0.514	-0.468	-0.435	-0.420
192.7	-0.779	-0.704	-0.684	-0.572	-0.498	-0.450	-0.427
204.7	-1.160	-0.853	-0.813	-0.632	-0.528	-0.464	-0.434
216.7	-1.655	-1.001	-0.940	-0.690	-0.557	-0.477	-0.441
228.8	-2.189	-1.136	-1.057	-0.745	-0.585	-0.490	-0.447
240.8	-2.465	-1.247	-1.157	-0.795	-0.610	-0.501	-0.453
252.9	-2.288	-1.326	-1.231	-0.837	-0.631	-0.511	-0.458
264.9	-2.093	-1.377	-1.282	-0.870	-0.649	-0.519	-0.461
277.0	-1.912	-1.403	-1.312	-0.893	-0.661	-0.525	-0.464
289.0	-1.836	-1.413	-1.326	-0.908	-0.669	-0.529	-0.466
301.0	-1.815	-1.416	-1.330	-0.912	-0.672	-0.530	-0.467
313.1	-1.829	-1.412	-1.325	-0.907	-0.669	-0.529	-0.466
325.1	-1.908	-1.401	-1.310	-0.893	-0.661	-0.525	-0.464
337.2	-2.083	-1.374	-1.280	-0.869	-0.648	-0.519	-0.461
349.2	-2.275	-1.323	-1.228	-0.836	-0.631	-0.511	-0.458
361.2	-2.451	-1.243	-1.154	-0.794	-0.610	-0.501	-0.453
373.3	-2.174	-1.132	-1.055	-0.745	-0.584	-0.490	-0.447
385.3	-1.643	-0.998	-0.938	-0.690	-0.557	-0.477	-0.441
397.4	-1.153	-0.851	-0.811	-0.631	-0.528	-0.464	-0.434
409.4	-0.774	-0.703	-0.682	-0.572	-0.498	-0.450	-0.427
421.5	-0.478	-0.566	-0.563	-0.514	-0.468	-0.435	-0.420
433.5	-0.295	-0.449	-0.459	-0.460	-0.439	-0.421	-0.412
445.5	-0.039	-0.353	-0.371	-0.411	-0.411	-0.407	-0.405
457.6	0.295	-0.280	-0.302	-0.367	-0.386	-0.394	-0.398
469.6	0.159	-0.227	-0.250	-0.329	-0.363	-0.382	-0.392
481.7	-0.083	-0.188	-0.210	-0.297	-0.342	-0.371	-0.385
493.7	-0.030	-0.159	-0.179	-0.269	-0.323	-0.360	-0.380
505.7	0.002	-0.135	-0.154	-0.246	-0.307	-0.351	-0.375
517.8	-0.006	-0.115	-0.133	-0.226	-0.293	-0.343	-0.370
529.8	-0.005	-0.099	-0.115	-0.208	-0.281	-0.336	-0.366
541.9	-0.002	-0.083	-0.099	-0.193	-0.270	-0.330	-0.363
553.9	-0.002	-0.069	-0.084	-0.179	-0.261	-0.326	-0.361
566.0	-0.001	-0.054	-0.068	-0.167	-0.254	-0.322	-0.359
578.0	0.000	-0.037	-0.051	-0.155	-0.248	-0.320	-0.358
590.0	0.001	-0.016	-0.031	-0.144	-0.243	-0.318	-0.358
602.1	0.001	0.008	-0.009	-0.134	-0.240	-0.318	-0.358



**Figure B.14:** Stress in the column in different paths along the column diagonally with plate 250×200×15

**Table B.12:** Stress in the column in different paths along the column diagonally with plate 250×200×10

path-D	plate	250*200*10		cylinder	60	pressure(p)	0.403
diagonal [mm]	Stress [MPa] in the column in different path [mm]						
	0	200	240_ compression_ only	400	600	800	1000
0.0	0.001	0.009	-0.007	-0.130	-0.236	-0.315	-0.356
12.0	0.001	-0.015	-0.030	-0.140	-0.239	-0.315	-0.355
24.1	0.000	-0.035	-0.049	-0.151	-0.243	-0.316	-0.356
36.1	-0.001	-0.052	-0.066	-0.162	-0.249	-0.319	-0.357
48.2	-0.001	-0.066	-0.081	-0.175	-0.257	-0.323	-0.359
60.2	-0.002	-0.080	-0.096	-0.188	-0.266	-0.327	-0.361
72.2	-0.003	-0.095	-0.111	-0.203	-0.276	-0.333	-0.365
84.3	-0.004	-0.111	-0.128	-0.220	-0.288	-0.340	-0.369
96.3	-0.001	-0.129	-0.148	-0.240	-0.303	-0.349	-0.373
108.4	-0.015	-0.151	-0.171	-0.262	-0.319	-0.358	-0.378
120.4	-0.044	-0.178	-0.199	-0.289	-0.338	-0.369	-0.384
132.5	0.051	-0.212	-0.235	-0.321	-0.359	-0.380	-0.391
144.5	0.145	-0.258	-0.282	-0.358	-0.383	-0.393	-0.398
156.5	0.014	-0.322	-0.344	-0.402	-0.409	-0.407	-0.405
168.6	-0.114	-0.410	-0.427	-0.453	-0.438	-0.422	-0.413
180.6	-0.256	-0.526	-0.533	-0.511	-0.469	-0.437	-0.420
192.7	-0.497	-0.675	-0.665	-0.574	-0.502	-0.452	-0.428
204.7	-0.909	-0.852	-0.816	-0.642	-0.535	-0.468	-0.436
216.7	-1.706	-1.039	-0.974	-0.710	-0.568	-0.483	-0.443
228.8	-2.635	-1.216	-1.126	-0.775	-0.599	-0.497	-0.450
240.8	-3.070	-1.366	-1.257	-0.835	-0.628	-0.509	-0.457
252.9	-2.708	-1.472	-1.355	-0.887	-0.653	-0.521	-0.462
264.9	-2.410	-1.539	-1.422	-0.927	-0.674	-0.529	-0.466
277.0	-2.167	-1.572	-1.460	-0.956	-0.689	-0.536	-0.469
289.0	-2.077	-1.584	-1.477	-0.974	-0.698	-0.540	-0.471
301.0	-2.051	-1.588	-1.483	-0.980	-0.701	-0.542	-0.472
313.1	-2.066	-1.582	-1.476	-0.974	-0.698	-0.540	-0.471
325.1	-2.163	-1.568	-1.457	-0.956	-0.688	-0.536	-0.469
337.2	-2.392	-1.534	-1.418	-0.926	-0.673	-0.529	-0.466
349.2	-2.685	-1.466	-1.350	-0.886	-0.653	-0.520	-0.462
361.2	-3.043	-1.360	-1.252	-0.834	-0.628	-0.509	-0.456
373.3	-2.602	-1.210	-1.121	-0.774	-0.599	-0.496	-0.450
385.3	-1.684	-1.034	-0.970	-0.709	-0.568	-0.483	-0.443
397.4	-0.898	-0.848	-0.813	-0.641	-0.535	-0.468	-0.436
409.4	-0.490	-0.673	-0.662	-0.574	-0.502	-0.452	-0.428
421.5	-0.252	-0.524	-0.532	-0.510	-0.469	-0.437	-0.420
433.5	-0.112	-0.409	-0.426	-0.453	-0.438	-0.422	-0.413
445.5	0.014	-0.321	-0.344	-0.402	-0.409	-0.407	-0.405
457.6	0.143	-0.258	-0.282	-0.358	-0.383	-0.393	-0.398
469.6	0.050	-0.212	-0.235	-0.320	-0.359	-0.380	-0.391
481.7	-0.043	-0.178	-0.199	-0.289	-0.337	-0.369	-0.384
493.7	-0.015	-0.151	-0.171	-0.262	-0.319	-0.358	-0.378
505.7	-0.001	-0.129	-0.147	-0.239	-0.303	-0.349	-0.373
517.8	-0.004	-0.111	-0.128	-0.220	-0.288	-0.340	-0.369
529.8	-0.003	-0.095	-0.111	-0.203	-0.276	-0.333	-0.365
541.9	-0.002	-0.080	-0.096	-0.188	-0.266	-0.327	-0.361
553.9	-0.001	-0.066	-0.081	-0.175	-0.257	-0.323	-0.359
566.0	-0.001	-0.052	-0.066	-0.162	-0.249	-0.319	-0.357
578.0	0.000	-0.035	-0.049	-0.151	-0.243	-0.316	-0.356
590.0	0.001	-0.015	-0.030	-0.140	-0.239	-0.315	-0.355
602.1	0.001	0.009	-0.007	-0.130	-0.236	-0.315	-0.356



**Figure B.15:** Stress in the column in different paths along the column diagonally with plate 250×200×10



# C

## Appendix 3

## C.1 Material properties

Table C.1: Material data and weight of each member

Track 1	vertical deformation	g	9.81	Tributary area [m <sup>2</sup> ]	24.638		
material data							
column	GL30C	width [mm]	high [mm]	length [mm]	Density [kg/m <sup>3</sup> ]	self_wigth [kN/m <sup>2</sup> ]	[kN]
	10	300	300	3000	390	11.48	1.033
	20	400	450	3000	390	11.48	2.066
	30	500	500	3000	390	11.48	2.869
beam	GL30C	width [mm]	high [mm]	length [mm]	Density [kg/m <sup>3</sup> ]	self_wigth [KN/m <sup>2</sup> ]	[kN]
		300	550	7300	390	27.93	2.304
		span length [mm]	Thicknes s	Mass [kg/m <sup>2</sup> ]	Self weight [kN]	Self weight [kN/m <sup>2</sup> ]	[kN]
Slab	CLT	7000	265	126	1.23606	1.24	0.299
Roof	concrete	7000	265	400	3.924	3.92	0.948

Table C.2: Loads in the building

Load type	Applied loads	[kN/m <sup>2</sup> ]	[kN/m]	[kN]
v	office	2.5	16.875	55.797
v	partitionwalls	0.5	3.375	12.319
p	installations	0.3	2.025	7.391
v	snow	1.2	8.1	29.565
v	wind	-	-	-
	self-wieght	[kN/m <sup>2</sup> ]	[N/m]	[kN]
p	column_10	11.48		1.0330
p	column_20	11.48		2.0660
p	column_30	11.48		2.8694
p	beam	27.93		2.3041
p	slab	8.34		0.299
p	roof	26.487		0.948

Table C.3: Loads factors

	ULS	SLS	
pratial factor (p)	1.35	1	
partial factor (v)	1.5	1	
	$\Psi_0$	$\Psi_1$	$\Psi_2$
Constructions	0.7	0.5	0.3
office areas	0.7	0.5	0.3
partition walls	0.7	0.5	0.3
snow	0.6	0.3	0.1

## C.2 Loads combination on floors

### C.2.1 10 floors

**Table C.4:** Loads on each floor when the number of floor 10

floor	Permanent [kN]	Variable [kN]	ULS [kN]	SLS (short)[kN]	SLS (long)[kN]
10	10.644	17.739	40.978	28.383	13.60030504
9	26.598	73.536	146.212	100.134	48.659
8	42.553	129.333	251.446	171.886	81.353
7	58.508	185.130	356.680	243.637	114.047
6	74.462	240.927	461.914	315.389	146.740
5	90.417	296.723	567.148	387.140	179.434
4	106.372	352.520	672.382	458.892	212.128
3	122.326	408.317	777.616	530.643	244.821
2	138.281	464.114	882.850	602.395	277.515
1	154.236	519.911	988.084	674.146	310.209

### C.2.2 20 floors

**Table C.5:** Loads on each floor when the number of floor 20

floor	Permanent [kN]	Variable [kN]	ULS [kN]	SLS[kN]	SLS_long [kN]
20	10.644	17.739	40.978	28.383	13.600
19	27.631	73.536	147.606	101.167	49.692
18	44.619	129.333	254.235	173.952	83.419
17	61.607	185.130	360.863	246.736	117.146
16	78.594	240.927	467.492	319.521	150.872
15	95.582	296.723	574.121	392.305	184.599
14	112.570	352.520	680.749	465.090	218.326
13	129.557	408.317	787.378	537.874	252.052
12	146.545	464.114	894.007	610.659	285.779
11	163.532	519.911	1000.635	683.443	319.506
10	180.520	575.708	1107.264	756.228	353.232
9	197.508	631.505	1213.892	829.012	386.959
8	214.495	687.302	1320.521	901.797	420.686
7	231.483	743.098	1427.150	974.581	454.413
6	248.471	798.895	1533.778	1047.366	488.139
5	265.458	854.692	1640.407	1120.150	521.866
4	282.446	910.489	1747.035	1192.935	555.593
3	299.434	966.286	1853.664	1265.719	589.319
2	316.421	1022.083	1960.293	1338.504	623.046
1	333.409	1077.880	2066.921	1411.288	656.773

### C.2.3 30 floors

**Table C.6:** Loads on each floor when the number of floor 30

floor	Permanent [KN]	Variable [KN]	ULS [KN]	SLS(short)[KN]	SLS_long[KN]
30	10.644	17.739	40.978	28.383	13.600
29	28.435	73.536	148.691	101.971	50.496
28	44.390	129.333	253.925	173.722	83.189
27	60.344	185.130	359.159	245.474	115.883
26	76.299	240.927	464.393	317.225	148.577
25	92.253	296.723	569.627	388.977	181.270
24	108.208	352.520	674.861	460.728	213.964
23	124.163	408.317	780.095	532.480	246.658
22	140.117	464.114	885.329	604.231	279.352
21	156.072	519.911	990.564	675.983	312.045
20	172.027	575.708	1095.798	747.734	344.739
19	187.981	631.505	1201.032	819.486	377.433
18	203.936	687.302	1306.266	891.237	410.126
17	219.891	743.098	1411.500	962.989	442.820
16	235.845	798.895	1516.734	1034.740	475.514
15	251.800	854.692	1621.968	1106.492	508.207
14	267.754	910.489	1727.202	1178.243	540.901
13	283.709	966.286	1832.436	1249.995	573.595
12	299.664	1022.083	1937.670	1321.746	606.289
11	315.618	1077.880	2042.904	1393.498	638.982
10	331.573	1133.677	2148.138	1465.250	671.676
9	347.528	1189.473	2253.372	1537.001	704.370
8	363.482	1245.270	2358.606	1608.753	737.063
7	379.437	1301.067	2463.841	1680.504	769.757
6	395.392	1356.864	2569.075	1752.256	802.451
5	411.346	1412.661	2674.309	1824.007	835.144
4	427.301	1468.458	2779.543	1895.759	867.838
3	443.256	1524.255	2884.777	1967.510	900.532
2	459.210	1580.052	2990.011	2039.262	933.226
1	475.165	1635.848	3095.245	2111.013	965.919

### C.3 Verification of beam

Table C.7: Beams dimensions

Dimensions	Length[m]	width[m]	height[m]
beams	7.3	0.3	0.55

Table C.8: Material properties of the beams

Material properites		units
Type	GL30c	
Density	390	Kg/m <sup>3</sup>
kmod	0.7	[-]
service class	1	[-]
gamma-m	1.25	[-]
Elastic modulus E0.05	10800	MPa
fc,o,k	24.5	MPa

Table C.9: Beam parameter

calculation of the beam for both Bending and shaering			
fm,k	30	MPa	
fv,k	3.5	MPa	
fm,d	16.8	MPa	
section constants:			
A	0.165	m <sup>2</sup>	
w	1.51E-02	m <sup>3</sup>	
I	4.16E-03	m <sup>4</sup>	

Table C.10: Loads on the beam

ULS			
load effect:			
self weight from the floor	8.652	KN/m	
self weight from the beam	2.304	KN/m	
reduction factor			
	0.525		
partitionwalls			
	3.65	KN/m	
imposed weight:			
	9.581	KN/m	
load combination			
	34.638	KN/m	
qd			
	34.638	KN/m	

**Table C.11:** Bending check for the beam

Bending			
Md.max	230.734	KNm	
sigma, myd	15.2551	MPa	
check resistance without lateral buckling	0.91		ok < 1

**Table C.12:** Lateral torsional buckling check for the beam

Lateral torsional buckling			
Lef	6.57	m	
sigma,m,crit	209.813	MPa	
Slenderness[lambda]	0.378	[-]	
Kcrit	1		
check leteral torsional buckling	0.91		ok < 1

**Table C.13:** Shear check for the beam

Shear			
Shear force design	126.430	KN	
fv,d	1.96	MPa	
Design value (Vrd)	144.452	KN	
check shear resistance	0.88		ok < 1
Design value (Vrd) should be bigger than shear force design			

## C.4 Verification of column

### C.4.1 10 floors

Table C.14: Column dimension for 10 floors

Dimensions	Length[m]	width[m]	height[m]
column	3	0.3	0.3

Table C.15: Column parameter-1

calculation of column on compression and buckling			
fm,k	30	Mpa	table 3.4/v2
fv,k	3.5	Mpa	
fm,d	16.8	Mpa	table 3.4/v2
section constants:			
A	0.09	m <sup>2</sup>	
Wy	0.0045	m <sup>3</sup>	bending around the strong axis
Wz	0.0045	m <sup>3</sup>	bending around the weak axis
Iy	0.000675	m <sup>4</sup>	
Iz	0.000675	M <sup>4</sup>	
Khy	1.072		
Khz	1.072		

Table C.16: Column parameter-2

ULS			
Lcy	3	m	
Lcz	3	m	
Determination of the buckling coefficient k <sub>cy</sub>			
Iy	0.0866		
Iz	0.0866		
Lambda-y	34.6410		
Lambda-z	34.6410		
Lambda_rel,y	0.5252		
Lambda_rel,Z	0.5252		
beta-c	0.1		glulam column
k-y	0.6492		
k-z	0.6492		
k-c-y	0.9702		if lambda-rel,y>0.3
k-c-z	0.9702		if lambda-rel,z>0.4
f-c.o.d	13.72		
N-c-o,RD,y	1.1980		
N-c-o,RD,z	1.1980		

**Table C.17:** Loads on the column

vertical load (qd)	988.084	KN	
sigma c.o.d	10.979	MPa	
horizontal load	11.844	KN/m	
Myd	13.325	KN.m	
sigma, m.y.d	2.961	MPa	

**Table C.18:** Lateral torsional buckling check for column

Lateral torsional buckling			
I-ef-y	2.7		Uniformly distributed load
I-ef-z	2.7		
sigma.m.crit	936.000	MPa	
Lmbda-rel,m	0.1790		
Kcrit	1		for lambda<=0.75
Verification			
		0.85	ok < 1

**Table C.19:** Compression and bending without lateral buckling check for column

Verification of combined compression and bending without lateral buckling			
		0.99	ok < 1

**Table C.20:** Comparission around weak axis check for the column

Comparission around weak axis			
sigma c.o.d	10.979		
i_z	0.087		
I_cz	3.1		
lambda_z	35.796		
lambad.rel.z	0.543		
beta-c	0.1		
k-z	0.659		
k-c-z	0.967		
verification		0.83	ok < 1

In the same verification method, columns of 450x400 dimensions are used for buildings with 20 floors, while columns of 500x500 dimensions are used for buildings with 30 floors.



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