
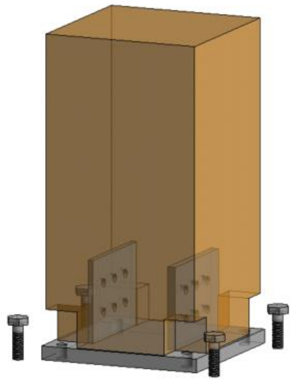
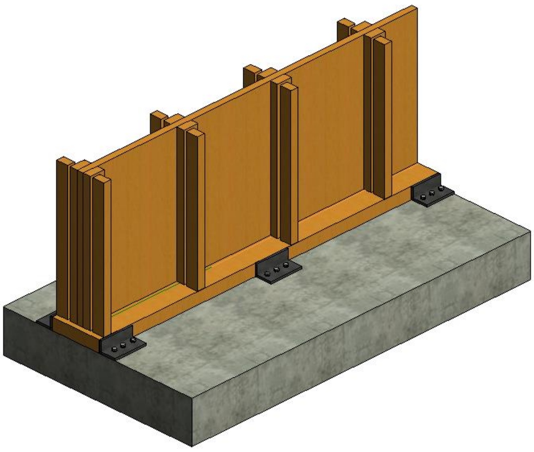

Detachable Connections for Circularity of Timber Buildings

Master’s thesis in the Master´s Programme Structural Engineering and Building Technology

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CHALMERS UNIVERSITY OF TECHNOLOGY
Master’s Thesis ACEX30
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An inspiration of structural timber connections that designed to be disconnected.
Department of Architecture and Civil Engineering

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ABSTRACT

Connections in timber constructions have high importance, as they are responsible for transferring loads between the different structural parts, achieving sufficient stiffness and ductility for the building. Detachable connections present a new concept in terms of building industry, which is cradle to cradle instead of the ordinary one cradle to grave, and that is attended by maximizing the circle of material reuse and cutting down the building-related material waste. This thesis aims to develop a connection that allows the assembly and disassembly of the timber buildings and enhances the reusability of the timber construction elements in other projects. The development of the connections will be applied explicitly to the multy-story building presented by Derome AB. For understanding the assembling and disassembling process, the theory part presents information about different timber connection types and the performance of various fasteners used in practice. Furthermore, the concept of design for disassembling, known as "DFD" illustrates the disassembling process and how it affects various connections. At the same time, the analysis shows a defined criterion that measures the connection suitability for DFD. It was noticed that the criteria factors with the highest impact on the disassembly of connection are wood reuse, accessibility, ease to be assembled, time, and costs. Moreover, the timber connection, which uses certain fasteners types or additional conjunction parts, was better in DFD. In general, reducing the required tasks' number for installing or uninstalling the structural elements, and enhancing the capabilities of mechanical fasteners by adding interfaces between connection parts, increase the connection satisfaction for assembling and disassembling.

Key words: DFD, design for disassembling, detachable connection, timber construction method and timber connection.

Contents

Preface

This master thesis was carried out between January and May 2021 at the Department of Civil and Environmental Engineering, Structural Engineering, at Chalmers University of Technology, Sweden.

We would like to thank our supervisor Anders Carlsson and our examiner Robert Jockwer for their support and guidance during this research.

Göteborg May 2021

Abdulrahman Al Shamaa and Khadeen Saleh

Notations

A	cross section area
$E_{0.05}$	fifth percentile value of modulus of elasticity
$F_{v,rk}$	characteristic capacity per shear plan per fastener
$F_{ax,Rk}$	characteristic withdrawal capacity of the fastener
F_y	yielding capacity of the fastener
I	second moment of area
G_{ks}	characteristic self-weight of the slab
K_{mod}	strength and load duration modification factor
L_k	life loads on slab
$N_{c.0.d}$	capacity in compression parallel to grain
$M_{y.Rk}$	characteristic yielding moment of the fastener
Q_d	the design value of one floor loads
Q_{dl}	the design value of one floor loads per linear meter of the wall
Q_{wd}	the designed value of wind loads
$Q_{wd.w}$	the design value of wind loads
S_w	shear wall self-weight
S_{wd}	design value of shear wall self-weight
v_b	wind speed
Z	building height
β	ratio between embedment strength of two members
λ_{rel}	relative slenderness ratio
λ	slenderness ratio
γ_M	partial coefficient of material
ρ_k	the density of timber
b_w	width of the wall
$c_{e(z)}$	exposure factor
c_{ep}	wind pressure coefficient
d	diameter of the fastener
$f_{h1,k}, f_{h2,k}$	characteristic embedment strength of timber member
$f_{hi,k}$	characteristic embedment strength of timber member
$f_{c,0,d}$	design compression strength parallel to grain
$f_{c,0,k}$	characteristics compression strength parallel to grain
f_u	ultimate strength of metal
h_w	height of supported part of the wall
i	radius of gyration
$k_c.k$	instability factor
l_e	effective buckling length in compression
t_1, t_2	timber broad, timber thickness, or timber penetration depth
q_b	peak of velocity
q_{be}	velocity pressure of the wind
$q_{wd.w}$	the design value of wind loads per panel

1 Introduction

1.1 Background

Wood has been used as a building material for thousands of years, as it has the flexibility to build different structures of different shapes. Despite the complex properties of the wood, man could harness its special characteristics to build unique projects. While in the last two decades, the interest in wood as a building material increased again for its different advantages like, the wood is a natural material that makes it more available and feasible, and the fact that wood ranks among all other building materials by its considerable strength per its low weight (The & Wood, n.d.). Wood also is good thermal insulation, renewable, and environmentally friendly material. In other words, wood, as an intense, light, and sustainable material, makes it a well-adapted one for various structural projects.
Many conventional methods are being used in timber constructions, and one of the most used in wooden buildings is the timber frame construction method (Swedish Wood, 2021). It uses studs and rails, together with boards, to transmit all vertical and horizontal loads to foundations. This method is used in different Derome's projects, like in Nordlyckan and Turnkey Houses in Vejbystrand and multi-floor buildings like Bjorkliden and Charleshill (Derome, 2021).

While the connections in timber constructions have very high importance, as the connections are responsible for transferring loads between the different building parts and achieving sufficient stiffness and ductility for the building, It is common, in timber structure, the governing factor regarding the design is the connections between the structural members. That means the connection's strength reflects on the strength of the structure (Jack Porteous and Abdy Kermani, 1991). Besides, the connections are crucial for deconstruction, which was recently considered a solution for reusing raw material. According to USEPA (The United States Environmental Protection Agency), 25% to 30% of the waste in the United States is generated by the material of buildings demolition and renovation. That makes the concept of DFD (Design for deconstruction) the answer to such a problem by utilizing the obtained knowledge to produce environmentally design (Chono & Schultmann, 2002).

DFD presents a new concept in terms of building industry, which is cradle to cradle instead of the typical one cradle to grave, and that is by maximizing the circle of material reuse and cut down the building-related material waste. That leads to the maximal value of reusing or recycling it, which is associated with the designer's decisions at the beginning of the project before the project executing (ibid).
Derome AB aims, by considering the implementation of easily detachable connection for the deconstruction of the existing structure, is raising the ability to reuse the single elements of an existing building into a new one.

1.2 Aim

This master thesis aims to develop a connection type that assembles and disassembles the timber buildings easier, allowing reusing the timber construction elements in other projects. To attain that, a criterion is needed to highlight the accessibility of detachable connections. The developed connection will be applied explicitly to the multis-story building presented by Derome AB. The results of this research will lead to making the wood more efficient and sustainable as a building material and achieve the circularity use of timber in the building industry.

1.3 Limitation

The assumed limitations for this research are:

- The study is limited to evaluating the behaver of different connection types in a multi-story building (DFS 90), which Derome AB was presented. That implies that certain connections will be presented and analyzed only.
- The applied forces acting on the different connections will be calculated. At the same time, the value of the applied loads (dead and live loads) will be obtained from the Derome AB design introductory.
- FEM analysis will not be conducted due to the limited timeframe of this thesis.
- This study is only about the timber-timber connection and not with other types of materials, and it studies their efficiency in the ease of assembling and disassembling.
- The applied forces on connections are shear forces resulting from vertical and horizontal loads on the building.

1.4 Method

For accomplishing the goal of this master's thesis, these steps are carried:

- Literature reviews are used to study the current way of timber building construction, the loads which act on different structures, and the existing connection types between the timber elements. Literature studies of relevant connections and standards will also be applied. The purpose of that is to understand the current presented theories in this field. With these theories, the analysis can be made based on the information presented by Derome AB to achieve the aim of finding the most suitable connection for this study.
- Derome AB has submitted drawings of a multistorey building (DSF 90). These drawings show a different kind of connection between the members that Derome AB explicitly uses. This project is the primary cause of this study.
- Empirical and numerical analyses are adopted to quantify the requirements on connections and to evaluate their performance. It is necessary to rank the different types of connections which will be the basis to create and improve the studied connection. These analyses will be carried out using Excel.
- The value of applied loads and their influence on the connections will be calculated, as the designed loads of the original connection were not being submitted by the company, while the checking of the connection capacity was calculated according to Euro Code 5.
- Discussion of improvement possibilities will be presented by showing the results of the analyses. By this step, utilizing the theories and analyzing Derome's information will be based on the analytical calculations.

Based on the discussion, this thesis will propose a new connection design that will be quick to assemble and easy to disassemble.

1.5 Targeted stakeholders

- Chalmers University of Technology.
- Derome AB, the company which proposed the research.
- Researchers can use this research as a base for further research.
- Contractors and timber product suppliers.

1.6 Case Study

The DSF 90 building will be studied in terms of the structural timber members' connections, and the examination of the certain connections will be characterized according to the defined assembling and disassembling criterion. The capacity of the defined connections will be designed according to Eurocode 5, while the company provides the drawings and information regarding the building.

1.6.1 Timber building DFS90

The studied building in this research is located in Kungsbacka, Sweden. The building has six stories, and the structural system is mainly composed of engineered timber except the concrete base slab of the ground floor. The building system is called DFS90, a developed system by Derome engineers, allowing up to eight story timber buildings. Moreover, this system is described in detail in the coming chapter. The following figure shows the elevations of the building. See Figure1.1.

Figure (1.1) Front and north elevations (Derome,2021)

The structural system consists of load-bearing walls; the internal and external walls transfer the vertical loads. While the elevator shaft, shearing internal walls, and external walls resist the horizontal loads caused by the wind. The plan drawing of the load-bearing system is presented in figure1.2 bellow

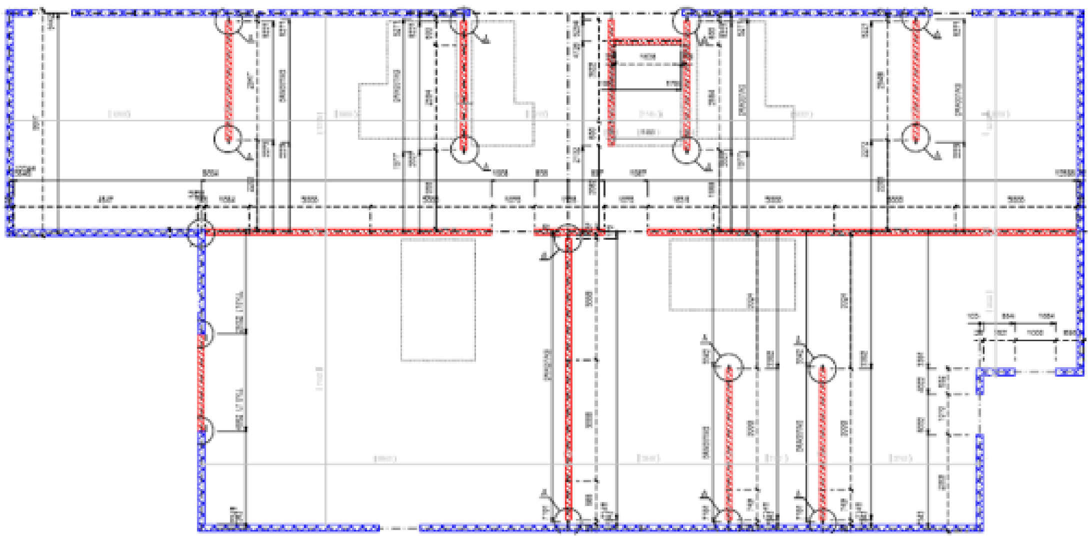


Figure (1.2) 2D plan of the structural walls of multy story building (Derome,2021)

Various types of connections connect these members; for instance, the walls, which are indicated by red colour in the figure (1.2) are connected to the concrete slab by using U shape metal plate along with the structural member, while the blue ones are resting on timber sleeper “limeträsyll,” which connected to the concrete slab also.

1.6.2 Connection system

The connections between structural members are designed to comply with all types of applied forces; most of the connections discussed in this study are located between walls and roof, walls and floors, and walls and the concrete slab.

The connections in this building can be categorized in main groups

- Connections between the walls and concrete slabs, metal plate with bolts and nails are used in these connections
- The connections between walls and floors for inner walls nailed with additional sections of wood, while for outer walls inclined screws are used
- The connections between walls and the roof, inclined screws, or screws with metal angles used to connect bearing walls, and U shape metal plate to connect the dividing walls
- The connections in horizontal level connect the dividing walls, steel angles with screws or only screws used in these connections.

  Figure 1.3. is a section in the building showing the location of the groups.

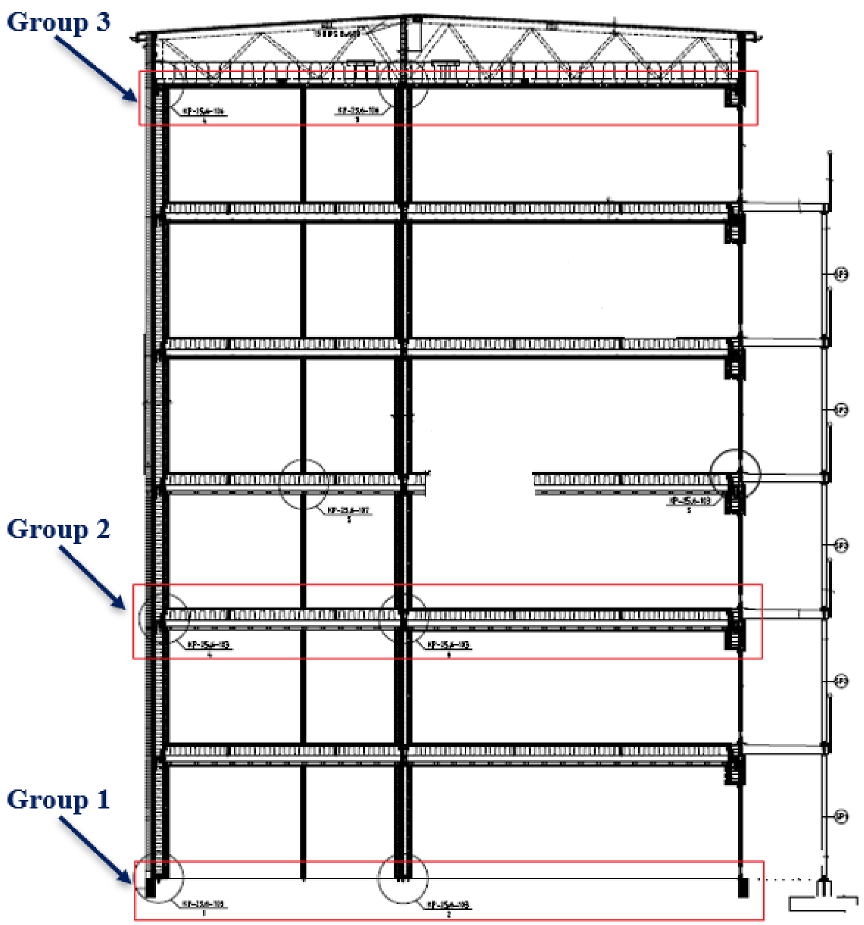
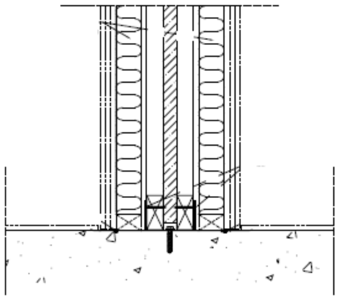
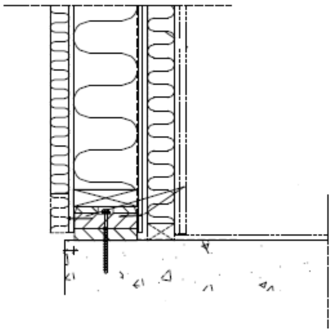
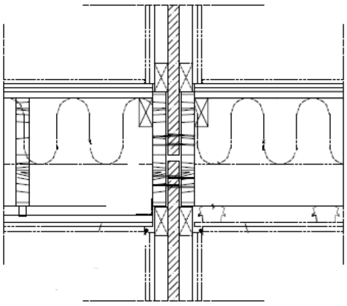
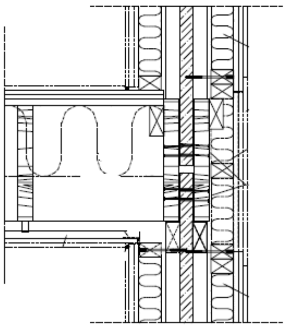
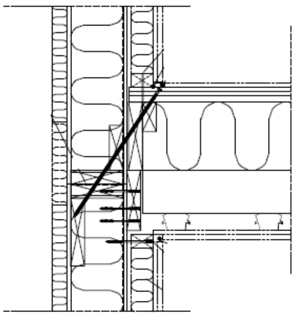
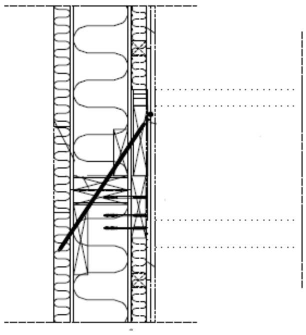
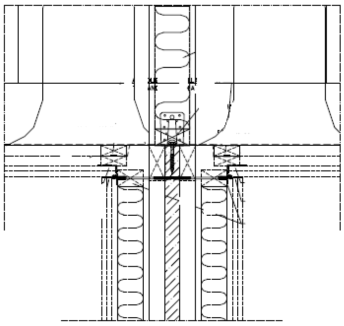
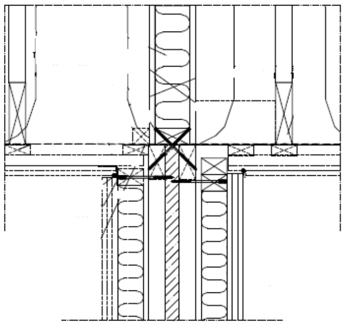
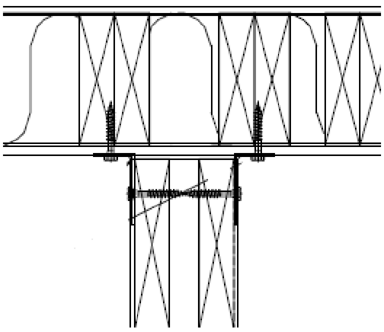
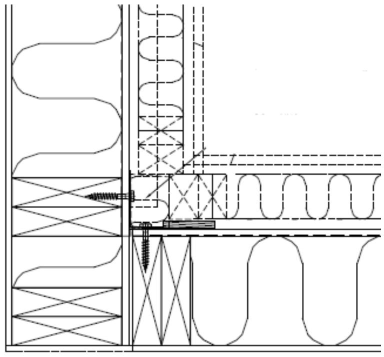


Figure (1.3) 2D plan of the structural walls of multy story building (Derome,2021)

To present some of the connections details Table 1.1 used to illustrate some joints in different locations as the above categorizes.

Table (1.1). Some of applied connections in the studied building

Group 1			Comments The figures show the connections of walls with concrete slab using metal plates and dowel fasteners
Group 2			Comments Nails and additional pieces of timber used to connect inner walls with floors
Group 2			Comments Inclined screws used in connecting the outer walls with floor
Group 3			Comments The connections between bearing walls, and dividing wall with roof using inclined screws and metal angle

			Comments
Group 4			Horizontal connections between the dividing walls, the main used fasteners are metal angle and screws

Moreover, the connection system will be analyzed in detail within coming chapters, where loads, and specifications of connections will be defined, besides, 3D models are made to clarify the actual connections figures.

2 Theory

2.1 Timber in construction

Timber as a construction material is one of the most used forest products worldwide. Even though timber gives limitless prospects for design and construction solutions, due to its unique specification, wood as a building material has a very high strength to weight ratio (Yipintsoi, 1976). It is still governed by the cultural scope and engineering rules (Ramage et al., 2017).
The different kinds of used construction timber are the outcomes of the wood production process at sawmills and then grading them according to their properties and sectional dimensions as it is stated in (EN 336:2013). See Figure 2.1.

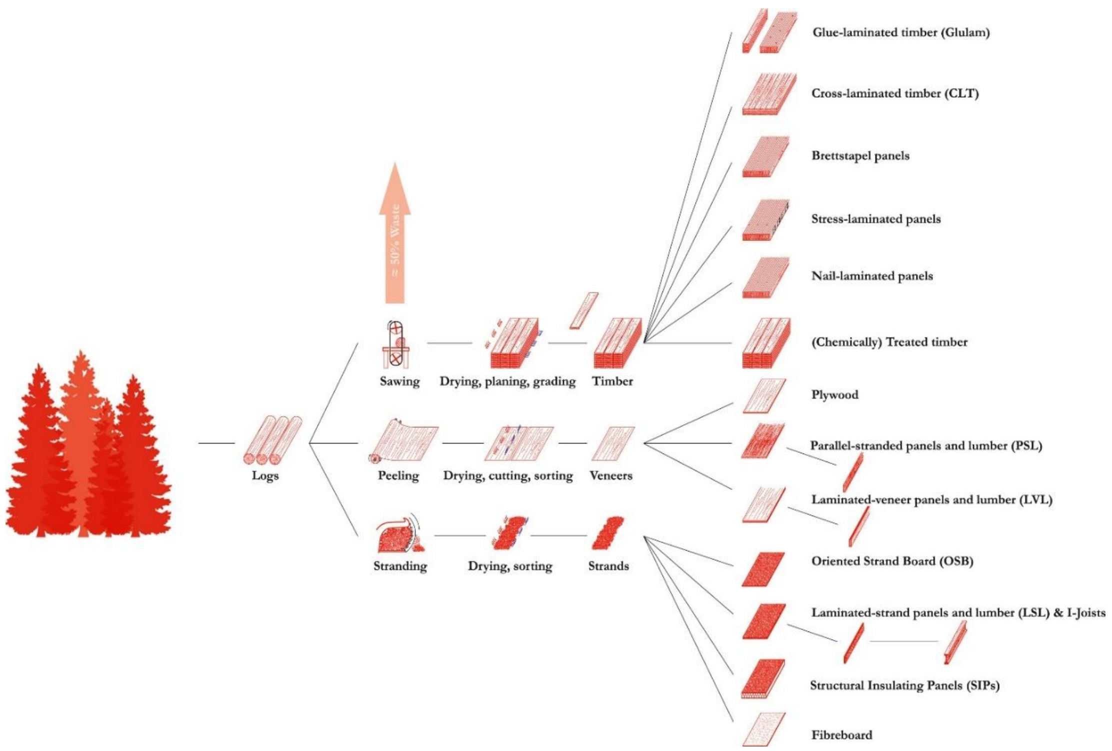


Figure (2.1) The figure shows different types of construction timber according to section dimensions and properties (Ramage, 2017).

2.2 Timber types used in construction

Besides the production processes that timber undergoes at sawmills, it also goes through several procedures to enhance its dimensional stability, increase durability, and improve its mechanical properties. The result of these procedures is an optimized building material known as “engineered timber.” The different types of engineered timber, with their improved specifications, are more appropriate to use as structural members (Ramage et al., 2017). See Figure 2.2.

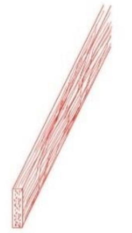
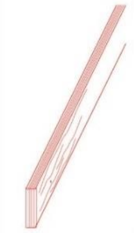
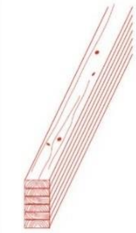
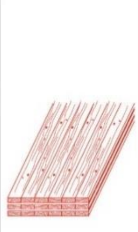
Engineered Timber Product	Parallel Strand Lumber (PSL)	Laminated Veneer Lumber (LVL)	I-Joist	Glulam	Structural Insulating Panel (SIP)	Cross Laminated Timber (CLT)	Brettstappel
Typical Detail							
Application	• Beams • Columns	• Beam • Columns • Cord	• Joist • Beam	• Beam (Long span) • High Loading	• Roof • Wall • Floor	• Roof • Wall • Floor	• Roof • Wall • Floor
Usage	Interior	Interior	Interior	Interior / Exterior	Interior	Interior/ Exterior	Interior/ Exterior

Figure (2.2) The commonly used engineered timber products in Europe (Ramage,2017)

Each kind of engineered timber has its manufacturing specifications, making it more suitable to use in some structural parts more than others. The most used engineered timber in timber construction and in Derome's constructions are discussed in the following sub-chapters

2.2.1 Glued laminated timber (Glulam)

Glulam is a highly creative construction material; it has more considerable strength than the solid lumber of the same size (The Engineered Wood Association, 2021). Glulam is made of several wood laminates glued together, where the grains of laminates are parallel with longitudinal direction. Typically laminates with a thickness of 45 mm are used in the glulam straight parts, while laminates of 33 mm thickness are used in curved ones (Ramage et al., 2017). A combined glulam beam is commonly used with a high-strength timber laminated at the top, and bottom layers of it, where the bending stresses are the highest , and between the top and bottom laminates, less intense laminated layers are used (About glulam, n.d.).

Due to its superior specification, glulam is usually used in columns, beams, arches, trusses, and dome roofs (Ho, 2007) and (APA, 2019).
Glulam is very familiar with industrial service construction as same as the residential buildings; it is a combination of strength and beauty. See Figure 2.3.

Figure (2.3) Combined glulam beam and curved glulam beam (Swedishwood,2021).

2.2.2 Oriented strand board (OSB)

OSB is commonly versatile used structural wood boards. It is made from wood flakes with a rectangular shape, organized in layers in longitudinal orientation, and bonded together with typically moisture resistant adhesive, which is hardened under high temperature. The outer layers are aligned to the main span direction (Ho, 2007).

OSB combines the stiffness and the plywood specifications. The wood flakes and adhesive provide resistant against wrapping, shape distortion, and deflection, besides to its specification as a light-weight material that is easy to handle and install (APA, 2019). OSB is very suitable to use in load-bearing walls, flooring, and wall sheeting because of its mechanical properties and the orientation of the strands (Plywood inspection, 2021). See Figure 2.4.

Figure (2.4) Oriented Strands Board (OSB) (Wikipedia "Oriented Strand Board", 2021).

2.2.3 Cross-laminated timber (CLT)

Cross-laminated timber (CLT) is boards or planks of solid lumber layered alternately at right angles and glued at the broad face of each board (APA, 2019). Usually, the outer layers have the same orientation, and commonly an odd layer number is used for getting symmetrical configuration. The thickness is between 50mm and 500mm and can cover up to 13.5m span length (Ramage et al., 2017). The resizable cross-section of CLT gives structural elements with high load-bearing capacity and stiffness, which makes it suitable for buildings stability; because of that, CLT proves that it is a highly recommended alternative to conventional materials like concrete and steel, especially in residential and commercial buildings (APA, 2019). See Figure 2.5.

Figure (2.5) Cross-laminated Timber (CLT) (Reidmiddleton,2021)

2.2.4 Laminated veneer lumber (LVL)

Laminated veneer lumber (LVL) uses multiple thin wood layers that are approximately 3mm thick, assembled using an adhesive (Ramage et al., 2017). Mostly veneers are oriented with one direction, and some crosswise plies can be added for more dimensional stability, but with higher tensile strength in cross-direction. Usually, it is stronger than solid timber members from the same species, so it can be used as supporting elements like girders, purlins, and headers (Ho, 2007). See Figure 2.6.

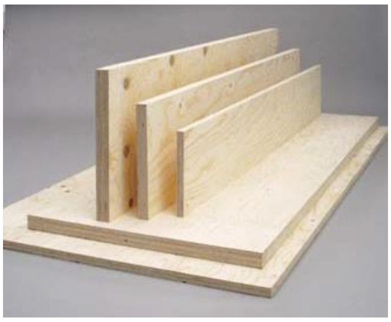


Figure (2.6) Laminated Veneer Lumber (Socomp, 2021).

2.2.5 Other engineered wood based products

Many kinds of engineered timber are used in timber construction; for instance, parallel strands lumber (PSL) is used as structural parts where gluing laminated timber is allowed (Ho, 2007).The strands have a length of 16mm on average and 3,2mm in thickness, bonded together by adhesive. This product is stronger than the sawmill lumber because the strand is glued together in a specific direction, with high applied pressure (ibid).

Another product is nailed laminated timber (NLT), dimensional lumbers placed on edge with individual laminations and gathering mechanically by nails or screws ("Nail laminated timber construction | NLT lumber | Think wood," 2021). NLT does not need a manufacturing process and can be made by the available dimension (ibid).

I-Joist is expensive and sections deeper than solid joists, but it is more stable and stiffer due to its OSB web and small size of solid or LVL flange, so it is less to cup, split, bow, twist, and crown (Ramage et al., 2017). But the disadvantages of it that it can quickly fail due to fire.

Presenting of engineered timber kinds is to give a brief idea about them before discussing the timber connections, as some types of connections may be more suitable for some kinds of engineered timber than others, where PSL, NLT, and I-Joists are rarely used in Derome's timber construction, particularly in A-house building type.

2.3 Structural components of timber construction

Timber construction combines different construction members, these members could have different structural roles according to the used building system, while in a defined system can be a structural member, in another one may be a non-structural member. Even though the principal structural members which use in a different type of timber construction systems are categorized by their location in the building as follows:

2.3.1 The roof

- Ridge beam, the beam that supports rafters and other parts at the ridge; the ridge is the highest point of the rafters' structure roof.
- Rafter is one of the sloped structural parts, runs from the top ridge or the hip to the wall plate, and is designed to support the roof shingles. Purlins support rafters along their length. There are different types of rafters, for instance, common, principle, and jack rafter.
- Purlin provides bending supports to the rafters as it is installed at points along with it and pushes the loads back into the structure.
- A ceiling joist is used in the ceiling to suspend the finishing. It has spacing from the roof structure above it, so it may or may not coincide with the roof.
- The ceiling binder is usually used when the joists' span is long to hold and restrain them. It is installed at half or third of the joist's span (Cradden, 2019). See Figure 2.7.

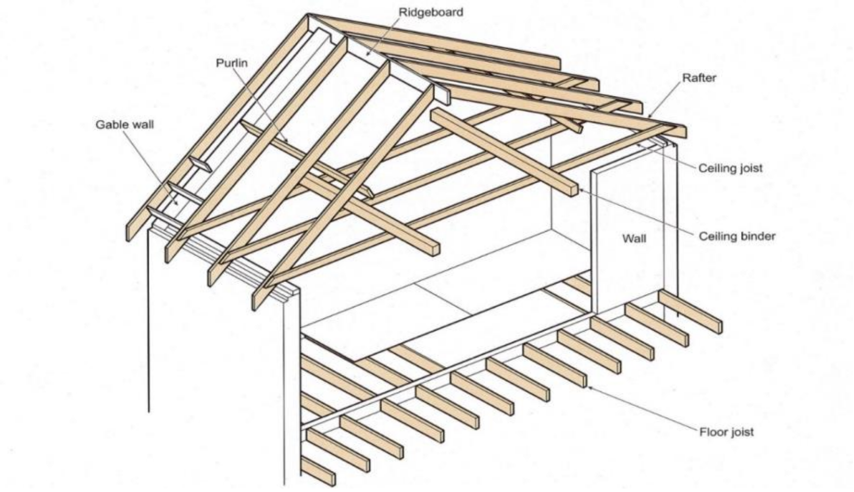


Figure (2.7) Roof Structural Parts Glossary (Kingmoorconsulting.co.uk, 2021).

2.3.2 The truss

Timber truss is a group of timber members forming one of the principal supports; its members' arrangements can cover long spans and transfer heavy loads (Basuki, 2019). Truss supports the different types of timber constructions such as bridges, churches, and building ceilings. Usually, it is used for its functionality, but recently it is used as architectural design more than a structural part. In timber, residential, and commercial building, trusses are used to support the ceiling (ibid).

One type of truss is the King post truss, one of the simplest used trusses as it has the lowest number of timbered members than other truss types (Timber Frame Engineering Council, 2020). Another truss type is the Queen post truss, which is known for having two principal vertical members instead of one as in the king post truss. Usually, it is used when there is an attic or loft under the roof and can cover longer spans than the king post truss (DeStefano et al., 2020). Howe truss is an efficient and economical type of trusses, where the vertical tension members can be made of steel.
The Scissor truss is very popular in architect and timber frame patrons. It can add to the feeling of the open space due to its lowest member rising above the eave line, which leads to an efficiency limitation of its applications (ibid). See Figure 2.10.

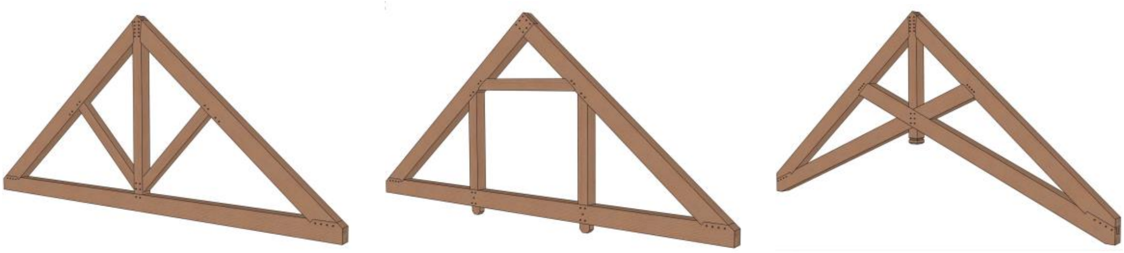


Figure (2.10) King Post, Queen, and Scissor Timber trusses (Heavytimbers,2020)

2.3.3 The Floor

- Bearer is used to rise floor joists above the ground to protect and preserve them, transferring floor loads and adjusting their level
- Floor joist laid on the bearers and it can be one or multiple spans. It holds the floor finishing above it, See Figure 1.8.
- Bridging connects the floor joists. It supports and retrains them (Cochran, 2012). See Figure 2.8.

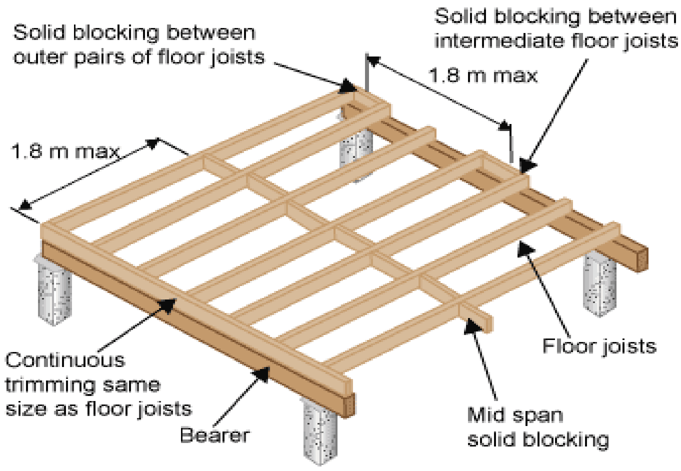


Figure (2.8) Floor Structural Parts Glossary (Dlsweb.rmit.edu.au,2021)

2.3.4 The Wall

- Common stud (King Stud) is the vertical part of the framed wall that allows transferring loads from the roof to the bottom plate. Usually, the spacings between common studs are about 450mm-600mm.
- Jamb stud is the stud located at wall openings as it resists large shear force, so its section should be bigger, or usually, a double-section is being used.
- Jack stud is the stud located above and below the wall openings (windows and door) so, it supports the lintel trimmer and sill trimmer.
- Nogging is the horizontal part, which supports the studs, and increases their resistance to buckling or twisting. It fixes aligned with stud center or flushes with one side to hold the cladding (Timber Frame - Passivehouseplus.Ie, n.d.)
- The bottom plate is the lowest part of the wall frame. It attaches to the floor system while the studs lay on it. Usually, it is installed along the whole wall except for door openings. See Figure 1.9.
- The beam is a horizontal timber part that can be “load-bearing, supporting joists, or non-load-bearing” rested above walls or columns. It is usually used as rafters,

ridge beams, stair stringers, and doors or windows headers. It can be as glulam, parallel strand lumber, and I-joists (Timber Frame Homes," 2019).See Figure 2.9.

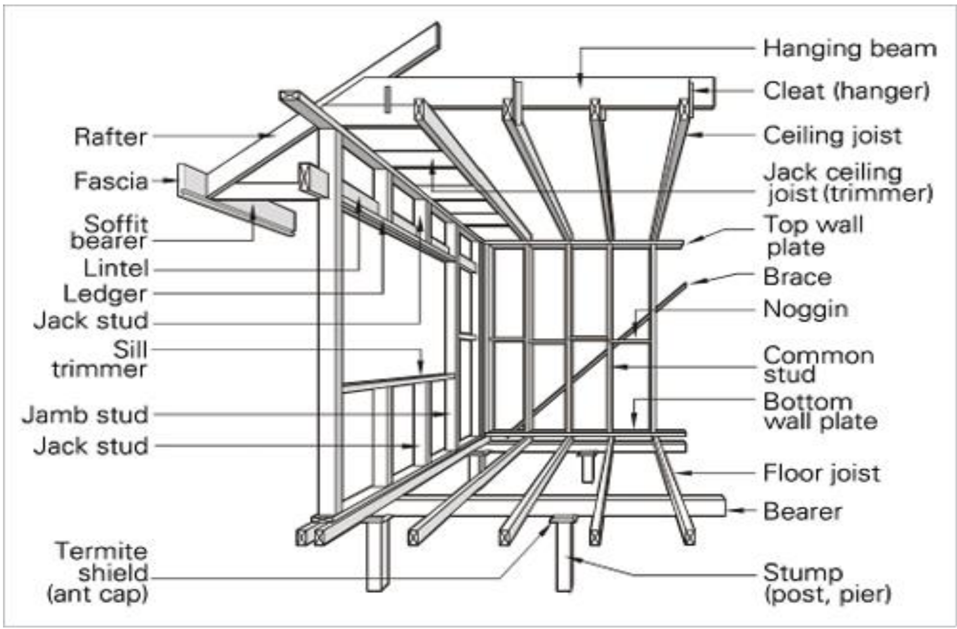


Figure (2.9) Wall Structural Parts Glossary (Yourhome, 2013).

2.4 Timber construction methods

The current wood constructions are defined more and more by a high rate of prefabrication, ease of assembly, shorter construction time, and more control of planning and quality assurance. Due to that, new modern ways for timber construction from manufacturing till completion have been created. So, these various ways of timber building constructions, which were raised following the new design, modeling, and implementation ways, became an industry model more than a traditional construction action (Wood construction systems in the building process, n.d.)

2.4.1 General timber construction methods

Different methods used in timber constructions are presented as follows

- Load-bearing walls system is a common used system in timber constructions, and it is mainly used in the multi-story-building system. The load-bearing walls can be constructed by using light frame elements or CLT sections. The load-bearing lines can both the external and internal walls, where the internal walls are usually the dividing walls, which are located between apartments. Floors and other walls participate in increasing the building rigidity ("Typical structural system,"2019).See Figure 2.11.
- The post and beam system is a standard construction method. In this method, all structural parts such as floors, walls, and roof are built on glulam, or laminated venire lumber post-beam frame (Swedish Wood, 2016). Most posts achieve the rigidity of the building and stiffening joints which are installed diagonally. This method allows high flexibility for choosing the locations of the interior walls during the life cycle of the building. Moreover, the installation of the building is very quick using this method, and the customer can select the thickness of external and internal walls, as most of the structural parts are one-dimension parts ("Typical structural system,"2019). See Figure 2.11.

- In the modular building method, the buildings' structural frame parts are prefabricated as modules, even as box or surface units, including the walls, floors, and ceilings. In the box units, all surfaces and services are pre-installed, and it needs only to connect them at the site. While the building with surface units, walls, and floors units are delivered to the site, almost fully finished, and then assembled at the site. This construction method counts as a quick construction one, but it needs weather protection when the roof tightening cannot be done in one day (Wood construction systems in the building process, n.d.)See Figure 2.11.
- One of the newest methods in timber construction is the CLT solid wood apartment block. This method uses the transversely glued CLT boards as loadbearing walls, where the floors and walls CLT boards act as structural stiffeners in a box units method. By using this method, buildings of 12 stories can be built with a flexible design; moreover, building parts can be delivered to the site with different degrees of readiness ("Typical structural system,"2019).Figure 2.11.

Load-bearing wall	*Post and beam system*	*Modular system*	*Solid Wood Block CLT Technology*
			

Figure (2.11) Various timber construction systems (Woodproducts,2021)

2.4.2 Derome´s way of construction

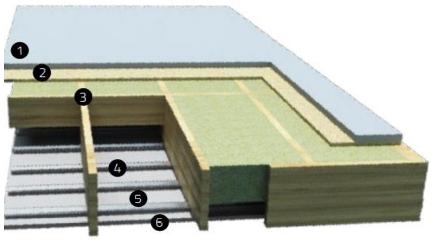
Derome uses DFS 90 "Derome flervåningssystem" for their projects. DFS90 a multi-story building system that allows building up to eight stories using wood as building material. This building system has been adapted and devolved by Derome's engineers. Specification and characteristics of structural components and nonstructural components are defined. The DFS90 provides sound insulation, fire-resisting regarding the customers' demanded. DFS90 contains all the needed information about the construction members such as bearing, outer, divider walls, and floor. The characteristic of this system shows the used type of timber member, its length, and cross section dimension. Figure 2.12 below is 3D-modeling shows the configuration of outer and bearing inner walls (Plusshus, n.d.)

(a) (b)

Figure (2.12) The layout of outer and inner walls. (by author)

The arrangements of the walls are seen in the figure above. The specifications of the model (a) starts from the exterior facade with the masonry layer following by insulation and plywood, where the structural member is composed of LVL with dimension 360mm*45mm. Model (b) is an example of a bearing wall used as a divider between the apartments. The structural members are composed of timber studs C24 with dimension 45*95 cc 600 and OSB board located between the studs.

The configuration of the floor is presented in Figure 2.13. The table below shows the numbers presented in the 3D modeling to illustrate the type and diminution of the used material. The structural floor of this system has a maximum span length limited by 7500 mm and can provide REI60 as a fire class.



1	2x13mm gypsum bord
2	22 mm OSB panel
3	360 LVL beam with insulation
4	acoustic profile
5	13 mm gypsum
6	15 mm gypsum

Figure (2.13) The floor comigration of DFS90. (Derome,2021)

Derome specializes in the construction of multi-story buildings of wood and timber houses. The construction systems adapt the prefabricated elements. According to Derome's engineers' interview, the preparation of these components is in the plant, where the environmental aspects are controlled. Since the characteristic of timber can be sensitive to the climate factor, the processing is made in a dray condition. Using prefabricated elements results in decreasing in the construction time. The fact behind this statement is the efficiency and the speed of processing in the factory. As a result, the assembling time is shortened since the working hours on the construction site are less (ibid).

Using multi-story timber buildings rises in Sweden in the last two decades, for its many advantages, as there is no dry time, it is fast installation process, and less cost. In addition, materials like CLT increase the potential of the height of the timber buildings. Derome, between 2003-2014, worked on developing ways for constructing timber building by studying the factors that affect the construction process of multi-stories buildings. Derome worked on testing, comparing, viewing, and reviewing practical solutions for 11years to develop its unique timber construction way, applied in A type of house building (Johannesson, 2019)

Furthermore, Derome uses surface elements to build up to seven stories buildings, the units prefabricated in the plants, then installed on-site, in addition to developing a new product of four stories. Wooden box units are also used in Lindbäcks Bygg with an internal ceiling height of 2.5m; the outer walls are load-bearing while the ceiling and floors are suspended from the walls. The module in this design can have two small rooms, while the bigger rooms contain two modules. The walls are stud framed, and the openings are compensated with glulam beams (Swedish Wood, 2021).

Derome’s engineers have described the steps of six stories timber construction. The process starts with installing the concrete slab as foundation, which is designed to fulfill the demand such as the applied dead and live loads. The outer walls are anchored with the slabs with “SYLL” using a concrete screw. Metal plates from both sides of the wall are used with nails to connect the wall to the “SYLL.” It is essential to mention that the

dimension of the anchor is relevant to the standard sections of the wood used in the wall. The inner wall is installed using a U-shaped metal plate. The plate is anchored to the concrete slab by using screws; then, the wall is fixed to the U plate by nails.
After installation, the finishing layers of the outer and inner wall, then the ceiling can be applied to the bearing wall, temporary supports are used to help of buildings assembling, while the flooring slabs are resting on the bearing walls.
The second floor is conducted with the same steps explained above, starting with installing the outer and inner walls, then the floor slab, and so on. to connect these members, mechanical connectors are used. The outer wall is connected to the floor using screws while the inclined screw connects several members together, floor with wall and wall extension. In addition, eight rows of nails are applied to connect the floor panels. Finally, the connection between the last storey and the roof has some similarities in terms of components Norberg, O. (2021, March 9). Personal interview.

2.5 Timber connections

It is known that the timber structure is a constructed assembly of joints separated by members (McMullin, 2018) and (Andrew Livingstone, 2016). In timber construction, the connections are critical for design, affecting the structural stiffness, flexibility, and structure members' size (McMullin, 2018). Usually, connections are used when the span is longer than the available material length, so a joint between two pieces or more is used to increase the length and transfer the loads between different structure members. Timber connections resist two types of forces, withdrawal when the applied forces are parallel with the connection direction and shear when the applied forces are perpendicular to connections (ibid). See Figure 2.14.

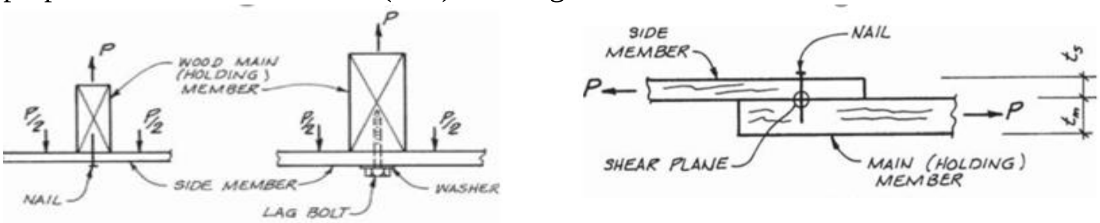


Figure (2.14) Axial and shear forces in Connection (Design of Wood Structure,2007)

There is a wide variety of connectors, and fasteners that are used in timber constructions, so they can be categorized in different ways, for instance. At the same time, the mechanical connections refer to the joints which use fasteners or other hardware types; the joinery joints refer to those that use cutting and removing from wood, even though both types of connections show the same resistance to the same applied forces (Breyer et al., 2007). Also, the connections can be an indirect one when the timber parts are connected by using an extra metal piece and a direct connection when the timber parts are connected directly by fasteners or dowels (Kaufmann & Krötsch, 2021).
Usually, the design and type of connection are governed by many conditions.

- Wood dowel bearing strength
- Wood member thickness
- Angel to the grain
- Fastener (diameter, penetration, yielding capacity)
- Edge/ End distance
- Spacing between fasteners

The commonly used types of timber connections can be presented as follows:

2.5.1 Joinery (traditional) connection

Joinery connection is a classic elegant to produce wood-wood joint; it is used to bring timber frame skeleton or truss and bent system together (Lawrence A. Soltis & Michael Ritter, 1997). It is typically created by cutting notches, tongues, and holes so they can be interlocked together. This type of connections transfer compression / bearing forces in principle, and in case of tension, wood or metal key is needed to prevent the separation (reThink Wood, 2015). Mortise and tenon, and dovetail are the most used timber joinery connections (Timber Framing vs. Post and Beam | Riverbend, 2019).See Figure 2.15.

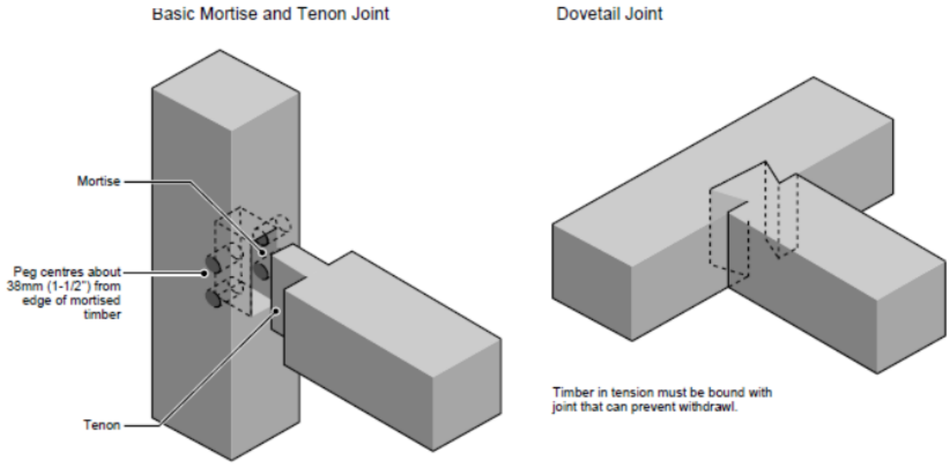


Figure (2.15) Mortise and tenon, dovetail traditional timber connections(cwc,2021)

2.5.2 Mechanical connection

There are three general types of mechanical connections in timber constructions dowel type fasteners, punch-metal plate fasteners, and bearing connectors. While the dowel type fasteners transmit either the lateral or axial loads, the bearing connections transmit the bearing loads only (Lawrence A. Soltis & Michael Ritter, 1997).

1- Dowel type fasteners

- Nails are commonly used dowels fasteners. There are many different types of nails with different diameters, lengths, and head shapes, making it a very adaptable type of connectors for different timber members (McMullin, 2018). The smooth steel wired nails with circular cross-sections are the most used ones. See Figure 2.16.

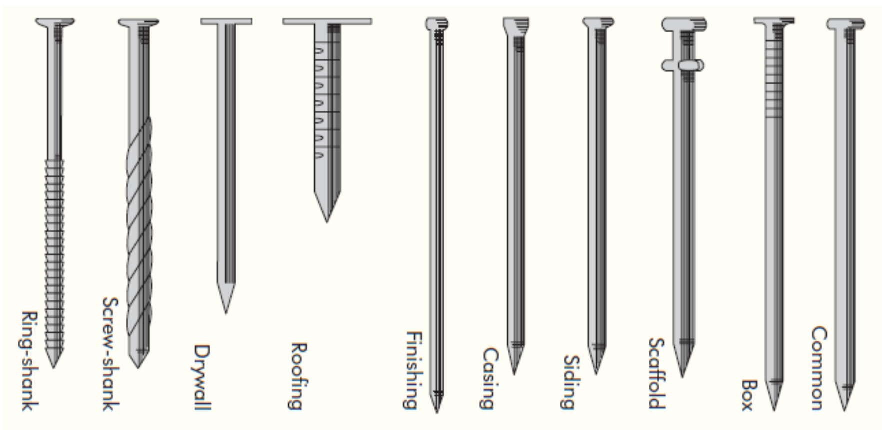


Figure (2.16) Different types of used nails (Engineered wood handbook and grading glossary,2012)

- Screws are a prevalent type of timber fasteners, and in some cases, they are more satisfactory than nails, as they have good resistance for withdrawal forces and in some other special conditions like moisture exposer (ReThink Wood, 2015). See Figure 2.17.

Figure (2.17) Different types of used screws (livingstone.2016)

- Dowels are circular rods of timber, steel, or carbon-reinforcement plastic. They are driven into the wood by making identical, or margin hole sizes and they are used to transfer large forces between different timber building parts. Moreover, dowels are mainly designed to resist the shearing loads (Breyer et al., 2007). See Figure 2.18.

Figure (2.18) Different types of used dowels

- Bolts are dowel-type fasteners with heads and nuts; they are usually placed in the pre-drilled hole with 1-2 mm oversized and used in timber-timber or timber-steel connections. As the washer and nut are tightened, the different parts will close to each other. However, they are convenient to resist heavy loads, so fewer of them need to be used (McMullin, 2018). See Figure.2.19.

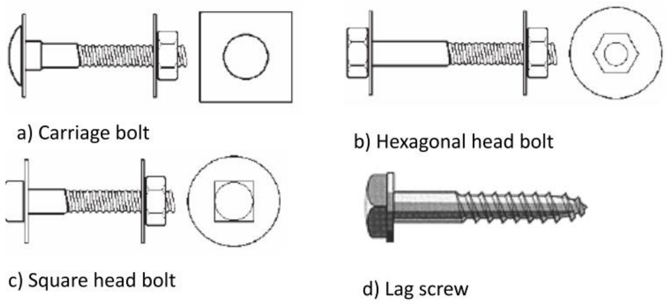


Figure (2.19) Different Types of Bolts (Timber Design, McMullin,2016)

2- Punch- metal plate fasteners (truss plate)

It is another mechanical connection that is frequently used in light-frame prefabricated wood trusses. It is a light gauge metal that connects trusses members. The nails on a metal plate are usually formed by applying pressure on it, and its capacity is measured by the amount of load that the unit of area can resist. In trusses, the size of the used plate is determined by the loads applied to the truss connection. Using metal plates in trusses is specialized by the manufacturer, and it should be under quality observation (Breyer et al., 2007). See Figure 2.20.

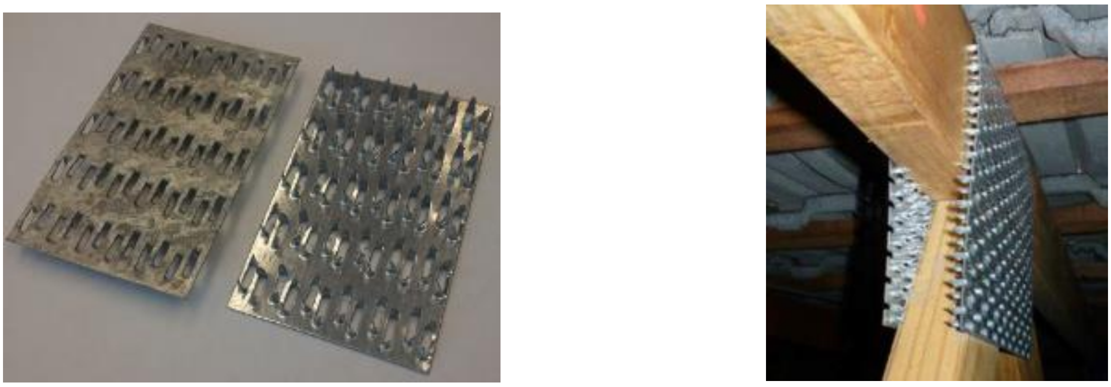
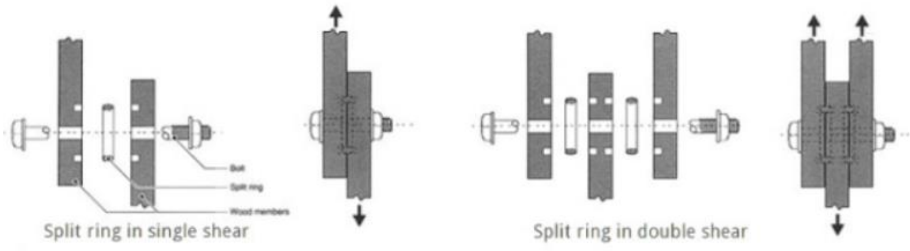


*Figure (2.20) Punch-metal plate (*Seblog.strongtie,*2021)*

3- Bearing connectors

Split rings and shear rings act as large bolts. The split ring is used in timber-timber connections, and the shear ring is used in steel-timber connections. They are used when a fully rigid connection is needed. The shear ring connection has a greater share capacity than bolt connections, which reduces the number of user connections (Gershfeld et al., n.d.).Figure 2.21.



Figure(2.21) Split ring (Builders metalworke.com, 2021)

2.5.3 Adhesive connections

The adhesive connections are usually stiffer than other kinds of connections, needs less timber, and has a better look. Adhesives, resins, or glues are used to connect timber parts in particular conditions, so the result is a strong connection with better resistance to fire and corrosion, even it shows a brittle behavior (Ozelton & Baird, 2008).

2.6 Easy to assemble connections

The timber connection consists of two or more timber members; moreover, it is the part of the structure that transfer the loads between the connected members, due to that the interest in connection stiffness, capacity, and ductility factors, besides the ease of installation, practicality, and the consumed time and cost for installation are recently raised (Lawrence A. Soltis & Michael Ritter, 1997).

2.6.1 Design of timber connection

The connection capacity of withdrawing or bearing is governed by both the wood and fasteners capacities. As a result, the timber connections are influenced by the same factors, which affect the strength properties of the wood (Lawrence A. Soltis & Michael Ritter, 1997). So, the size, number, the direction of the load towards the wood grain, and the fastener type influence the connection design. In other words, timber connection capacity is limited to the wood capacity and its strength specs (reThink Wood, 2015).

The dowel connection design has been changed from translating the lateral strength requirements of empirical fits to experimental data in NDS86 to the European Yield Theory, which calibrated to the experimental data (ibid). NDS91 gives the direct relation between the wood specifications and the strength of the connection, while NDS86 design of withdrawing forces depends on the specifications of connected parts, while for lateral forces, it depends on the fastener group behavior (Lawrence A. Soltis & Michael Ritter, 1997).

- **Other parameters**

➢ Regarding loads angles to timber grains, the lateral capacity of small diameter loaded dowelled fastener is independent of the direction of member grains, but for the large-diameter ones, their capacities are in relation with the timber grain direction due to splitting& slipping (Lawrence A. Soltis & Michael Ritter, 1997).
➢ Besides, the capacity of the fasteners, the wood connection strength also depends on the capability of the timber structural member. According to that, the connected timber members should already have the strength to transmit the applied loads in addition to the connection itself (ibid).
➢ Another parameter is the net area, which is the remaining area of the wood at the connection after subtracting the wood area, which is removed by connection. So, according to load type, size, and location of connections, this subtracts wood area can significantly influence the capacity of the connection.
➢ The final parameter is the eccentricity as a parameter. The eccentric loading at connection occurs when the applied force of a connected member is offset from the connection. Eccentricity in connection creates tension forces perpendicular to the grains, which can affect the resistance of the connection (ibid).

- **Connection design capacity**

Shear capacity, when the applied forces have an angle with the fastener, most often perpendicular to the same, the fastener will create a pressure force on the surrounded wood grains, producing embedding pressure against the dowel (Swedish Wood, 2016). See Figure 2.22.

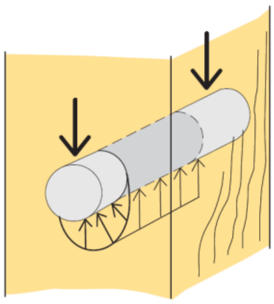


Figure (2.22) Embedding pressure against dowel (Swedishwood,2016)

The capacity of the dowel fastener connection is governed by three factors, timber embedding strength f_h, the tensile resistance, which is presented by anchorage capability F_{ax}, and the dowel ability illustrated by the yielding moment M_y.
The embedding strength shows the dowel pressure force that the timber can afford, usually, it is influenced by the fastener diameter, the timber density, the angle α

between the grains and applied force, the moisture content, and if the hole is pre-drilled or no. the characteristic value of embedding strength can be calculated by the equation

$$f_{h.0.k} = 0.082\rho_k d^{-0.3} \quad \text{without pre-drilling, d<8mm} \quad (2.1)$$

$$f_{h.0.k} = 0.082(1-0.01d)\rho_k \quad \text{with pre-drilling} \quad (2.2)$$

For nails the angle between the force and grain does not influence the capacity of the connection, but for the screws it will and the new embedding strength with angle α

$$f_{h.\alpha.k} = \frac{f_{h.0.k}}{k_{90} sin\alpha^2 + cos\alpha^2} \quad \text{N/mm}^2 \quad (2.3)$$

$$k_{90} = 1.35 + 0.15d$$

The dowels yield capacity refers to as the plastic moment of the dowel steel, and it is influenced by the fastener diameter d and the ultimate steel strength f_u , the characteristic yielding capacity of dowels can be presented by following equations

$$M_{hy,Rk} = \frac{f_u}{600} 180d^{2.6} N.mm \quad \text{for round nails} \quad (2.4)$$

$$M_{hy,Rk} = \frac{f_u}{600} 270d^{2.6} N.mm \quad \text{for square and grooved nails} \quad (2.5)$$

$$M_{hy,Rk} = 0.3 f_u d^{2.6} N.mm \quad \text{for all other fastener types d > 8mm} \quad (2.6)$$

The connection failure mode for shearing force will differ in accordance with the relation between the embedding strength, yielding moment of the fastener, and the thickness of timber member (ibid).
Besides, the failure modes of timber connections take different cases, for instance single shear or double shear, if the shear level is between two timber parts or three, or between the steel plate and timber member, two steel plates and timber member. See Figure 2.23.

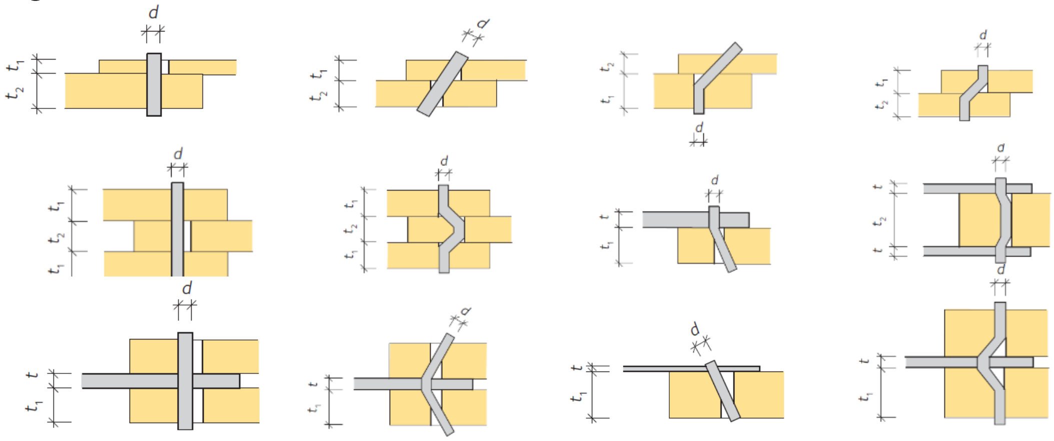


Figure (2.23) Some possible shear failure modes in various cases (Swedishwood,2016)

The used equation for calculation connection capacity is also differ according to each failure case, the equation of single and double shear for timber-timber connection as following

For single shear timber-timber

$$F_{v,Rk} = min\begin{cases} f_{h1,k}t_1d \\ f_{h2,k}t_2d \\ \frac{f_{h1,k}t_1d}{1+\beta}\left[\sqrt{\beta+2\beta^2\left[1+\frac{t_2}{t_1}+\left(\frac{t_2}{t_1}\right)^2\right]+\beta^3\left(\frac{t_2}{t_1}\right)^2}-\beta\left(1+\frac{t_2}{t_1}\right)\right]+\frac{F_{ax,Rk}}{4} \\ 1.05\frac{f_{h1,k}t_1d}{2+\beta}\left[\sqrt{2\beta(1+\beta)+\frac{4\beta(2+\beta)M_{y.Rk}}{f_{h1,k}{t_1}^2d}}-\beta\right]+\frac{F_{ax,Rk}}{4} \\ 1.05\frac{f_{h1,k}t_2d}{1+2\beta}\left[\sqrt{2\beta^2(1+\beta)+\frac{4\beta(2+\beta)M_{y.Rk}}{f_{h1,k}{t_2}^2d}}-\beta\right]+\frac{F_{ax,Rk}}{4} \\ 1.15\sqrt{\frac{2\beta}{1+\beta}}\left[\sqrt{2M_{y.Rk}f_{h1,k}d}\right]+\frac{F_{ax,rk}}{4} \end{cases}$$

For double shear timber-timber

$$F_{v,Rk} = min\begin{cases} f_{h1,k}t_1d \\ 0.5f_{h2,k}t_2d \\ 1.05\frac{f_{h1,k}t_1d}{2+\beta}\left[\sqrt{2\beta(1+\beta)+\frac{4\beta(2+\beta)M_{y.Rk}}{f_{h1,k}{t_1}^2d}}-\beta\right]+\frac{F_{ax,Rk}}{4} \\ 1.15\sqrt{\frac{2\beta}{1+\beta}}\left[\sqrt{2M_{y.Rk}f_{h1,k}d}\right]+\frac{F_{ax,Rk}}{4} \end{cases}$$

For single shear steel-timber

$$F_{v,Rk} = min\begin{cases} 0.5f_{h2,k}t_2d \\ 1.15\sqrt{2M_{y.Rk}f_{h2,k}d}+\frac{F_{ax,Rk}}{4} \end{cases}$$

For double shear timber – steel

$$F_{v,Rk} = min\begin{cases} 0.4f_{h,k}t_1d \\ 1.15\sqrt{2M_{y.Rk}f_{h,k}d}+\frac{F_{ax,Rk}}{4} \end{cases}$$

2.6.2 Criteria of easy assembling connection

The uses of engineered timber continue to grow, even beyond the traditional uses, while the interest in using timber in high buildings increases ascendingly.

Besides, timber flexibility allows the expansion in its uses range from residential, commercial buildings to educational, public, and corporate constructions (reThink Wood, 2015). All of that increased the concentration on timber connections. The ease of use, ability to apply in the factory, ability to assemble at the site, reusability, cost and time-consuming, and strength properties became essential requirements in new timber connections (Pozzi, 2019).

The main evaluation factors of easy to apply connection are as follows

1- The number of connected elements
It refers to the number of connected members by the same connection; the increase in the connected members will influence the connection preparation works, its complexity, the required time of its installation, and may influence its capacity.

2- The complexity
The connection complexity is linked with the number of connected members; a more complex connection design means more preparation works as the connection shape will be more compound, costly, and time-consuming installation process, and a problematic efficiency definition.

3- Prefabrication works
It means the amount of machinery preparation works to make connection application is possible; this factor rises clearly in joinery connections. The rise in prefabrication works can decrease the connection capacity if the removed wood at connection is large, besides the needed time and cost, and the aligning problems at assembling (ibid).

Furthermore, the DEI method, which developed by (Das, Yedlarajiah & Narendra ,2000) allows to include more criteria for easy to assemble connections, for instance

4- The accessibility
It refers to the needed number of sides for connection installation, the connections which need one accessing side is more reliable for installation than which need two or more accessing points.

5- The operator skills
It points to the required skills for installing the connection; both cost and time of connection assembling will increase when experiences are needed for the installation.

6- The visibility
Timber connections can be fully or partially visible or even hidden. This factor can limit the possible options at design, which influences the chosen type of connection and the application way.

7- The connection strength
It refers to the connection material capacity, flexibility, and ductility more than the wood strength properties, which are already discussed in the connection capacity. (Pozzi, 2019).

2.7 Design for Disassembly (DFD)

Structural engineers and architects can create the foundation for the next level of sustainability by implementing the design for deconstruction in a functional and aesthetics manner (Hurley et al., 2002). New methods in terms of construction, improvement of tools and techniques need to be adapted to reach this new level of sustainability. Current materials should be re-used in new projects without compromising their quality (ibid). The method DFD, which stands for "Design for Deconstruction," is used for a design for disassembly. DFD enables disassembly, which makes it preferable for building or product design (Thormark, 2007). The method aims to minimize material use consumption and reduce the waste generated by the building process. By applying this, even the use of energy and resources will be reduced (ibid). Research highlights the different benefits of DFD in different aspects. Environmentally, DFD can achieve sustainability in the building industry and close the material loop (ibid). Further, DFD simplifies the building modifications since buildings are usually renovated instead of replaced (Webster & Costello, 2005).

The benefits of DFD are not limited to the environmental aspects but also comprehend the economic aspects in terms of costs since DFD provides more straightforward methods to construct. Large proportions of any building mass are accounted for in the structural parts of that building, implementing DFD to the buildings industry-valued since DFD allows the re-use of the structural part in existing projects to a new project (Webster & Costello, 2005). The strength of DFD lies under the potential of design in terms of disassembly (Thormark, 2007).

Implementation of DFD by the designer will increase the value of building ingredients and elements. That could be the entrance to sustainable design conferred to the client. By benefiting from existing components and finding the suitable way to use them in other projects, low cost and low consumption of raw material could be obtained (Chan, 2011).

2.8 Potential reuse of different materials

Building materials in civil engineering are the fundamental components of any construction project. No projects are conceivable without a full understanding of their use and characteristic (Zhang, 2011) . Concrete, steel, and timber are essential materials in any structural system. The selection of these materials is governed by several factors such as the environmental and economic aspects (Webster & Costello, 2005).

2.8.1 Concrete

The use of concrete members in the structural system is characterized by casting in-suite and precast concrete. Cast in situ is widely used in most concrete buildings (Morgan & Stevenson, 2005).The dismantling of structural components of the cast in situ construction is challenging, since the members are joined with non-demountable connections; besides, the concretes’ reinforcement decreases the possibility of concrete deconstruction. All these obstacles make this way of design hard to salvage (Webster & Costello, 2005).

For precast concrete, the mechanism, and standards of connecting the members, in terms of size and reinforcement ratio, provide a higher salvage potential comparing to the cast in situ construction (Webster & Costello, 2005).Theoretically, the reuse of precast members is possible for specific components like beams, slabs, and columns, but the main hinder is that most of these elements are topped by the cast-in-place concrete (Morgan & Stevenson, 2005). Statistics in Finland show that precast concrete is the most used component as load bearings members by 35%, even though the participants consider the concrete as the lowest potential material to be reused (Huuhka & Hakanen, 2015).

2.8.2 Steel

After the second world war, the adaption of steel structural was highly demanded in the market. That resulted a high consumption of raw materials (Smith and Frangi, 2014). The reuse concept is not common in the field of steel structure. Instead, there are extensive actions of recycling. The motivations for this fact are the potential of recycling the steel and the sufficient weariness of the process itself (Morgan & Stevenson, 2005). Other designers consider the steel a highly reused material due to its characteristic and member individuality if DFD is applied (Silverstein JUL, Silverstein, and Engineering, 2009).

Prefabricated steel is ranked as high as timber in terms of reuse. The degree of reuse varies between different structural components. Members like beams and columns usually have a higher potential of reuse than other members like trustees and sandwich panels (Huuhka & Hakanen, 2015). The obstacles of reused steel components are characterized by cost, demand, and knowledge. The lack of knowledge about dismantling the structural components results in a long process that will lead to higher costs. The practical method of establishing the DFD is not sufficient. These are the main challenges for this material to be reused (Huuhka & Hakanen, 2015). There are no standards or codes to determine the quality of used structural components, which is another challenge when using DFD (Morgan & Stevenson, 2005).

2.8.3 Timber

Structural timber is not limited to the new era of humankind. Evidence shows the application of timber engineering had been initiated since 300000 up to 1 million years ago. For instance, in China, “Peking man” had used the timber components as struts to build their shelters (Smith & Frangi, 2014). The history of using timber as a structural material is continued in the 20th century (ibid). The demand for timber as structural material highlights the concept of DFD again in terms of reuse and establishing environmental sustainability. A survey has considered timber to be equal to steel in its ability to be reused (Huuhka & Hakanen, 2015). The higher ability of reuse and recycling promote the wood as a proper material to design for deconstruction (Philip, 2001).

In current structures, the potential of reuse depends on the type of members. Columns and beams usually have a higher salvage ability than other components, as with steel (Huuhka & Hakanen, 2015). The methods used to assemble the buildings affect the potential use of the DFD. Usually, timber-framed wood structure is more accessible to be dismantled than the wood-framed with dimension lumber (Webster & Costello, 2005). Establish the foundation of making timber design to be demountable; the essential barrier needs to be solved. Researches refer that the primary optical is the nature of timber as being a biodegradable material. However, using CLT may surpass this issue (Hurley *et al.*, 2002).

2.9 Why DFD?

In 2008, the European Waste Framework Directive stated that re-use of materials should be prioritized over recycling if it is technically and financially feasible. In terms of this statement, DFD as a tool can fulfill this proposal (Huuhka & Hakanen, 2015). Adequate thinking in maintaining the resources and minimizing the waste is the re-use of current components. To aim for the highest potential of the material re-use, DFD should be considered in the early stages of the design process and not at the ending of it. To implement DFD, engineers need to design for DFD (Webster & Costello, 2005). Few countries have realized the importance of DFD application and its benefits and took serious steps to develop new techniques, methods, and guidelines for disassembly. However, the value of DFD is still neglected by other countries (Thormark, 2007).

One of the most outstanding examples in DFD is the projects that have been done in the Netherlands by the Ministry of Housing, Spatial Planning and the Environment known by (VROM). The project is called “Industrial, flexible and demountable (IFD).” This project reflects the highest number of buildings that allow the potential of disassembly. However, the Netherlands is not the only country that has utilized this method. Countries like Canada, Britain, and Australia identify DFD as one of the ultimate assets that need to be adapted, developed, and applied in future environmental building projects. That is because these countries governments demanded to develop and improve the building code regarding the environmental case (Thormark, 2007).

To emphasize the answer to the most intuitive question, “Why the tool Design for Disassembly,” the figure below is presented and further discussed.

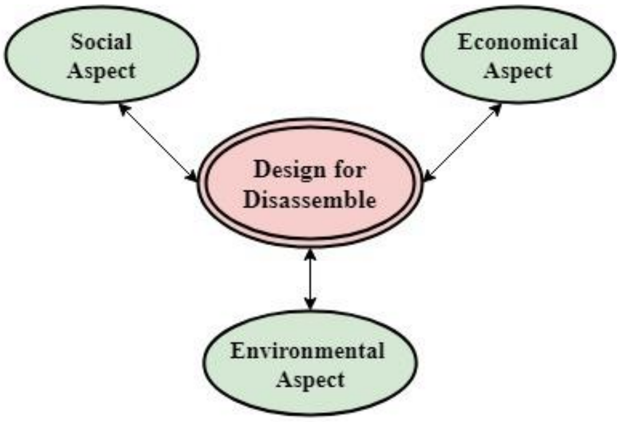


Figure (2.24) Aspects of the needs to DFD. (by authors)

2.9.1 Economical aspects

Most European countries apply economic tools aiming for environmental goals since a high proportion of entire costs is conducted to waste and resources (Thormark, 2007). The adaptation of this tool is increased day by day. Besides this, many countries such as Sweden, Holland, Finland, and the UK have implemented a tax rate on waste. The tax value has been ten doubled in Denmark in 2001 compared with the tax value in 1987. In addition, countries like Sweden and France introduced an extra tax on raw materials. However, these actions indicate that easier demountable will cut down costs and salvage resources (Thormark, 2007). The main obstacle in terms of economic aspects is the required time to accomplish the deconstruction process, which will increase the costs to use DFD. However, since costs cover the amount of waste disposed of in the landfill per ton, which can be high in different municipalities, applying DFD can benefit from this tipping fee and overcome this obstacle (Chan, 2011).

Different companies worldwide pointed out the necessity of environmental rating to keep the market rolling and supply aid to clients. In addition, a survey had been made on the consumers that shows that 32% of the participants are willing to pay extra costs to get environmentally produced product and around 48% were ready to pay for it. There is a wide variety of environmental rating systems. However, the definition of this system is characterized by enhancing the production of environmental products. Buildings designed for disassembly will provide a high potential for recycling and reusing the materials that will positively influence the environmental rating system (Thormark, 2007). The kind of materials that are used in different facilities affects the final value of the facility. Since a high percentage of house owners are willing to pay extra costs for environmental material, DFD can optimize the final value of a facility (Chan, 2011).

Some factors are associated with the value of buildings in markets. One of these factors is the accessibility to building locating, but the demand for residential buildings may change due to certain conditions. The value of buildings with the potential of deconstruction, instead of the buildings that have not, will increase (Thormark, 2007).

Furthermore, if DFD was considered at the beginning of the project, it will be easier to assemble the building, which will increase the final value of the building itself (Chan, 2011).

2.9.2 Environmental aspects

One obstacle that comes to mind and that needs to be treated in environmental buildings is the waste generated by the construction and demolition. It has been a lot of researches, articles even surveys that highlight the amount of waste. For instance, Denmark's waste statistic shows that 33% of all waste comes from the construction and demolition process. Nonetheless, if these buildings were designed for deconstruction, the accessibility to re-use and recycle will increase, and the amount of waste will drop (Thormark, 2007). Tools like DFD or demountable buildings are considered an effective solution to deal with construction waste (Rios, Chong, and Grau, 2015).

In addition, higher consumption of materials from existing resources results in less amount of reservoir. Geological authority in Sweden stated that due to the high demand for natural gravel in different municipalities, the reservoir could be emptied within 20 years (Thormark, 2007). One of the essential strategies for sustainable building design is lowering the percentage of used resources, explaining the fundamental part of DFD to achieve this strategy (Philip, 2001).

2.9.3 Social aspects

Several statistics show a growth in personal households. For instants, the portion of one-person household percentage expands from 30% to 40 % in Sweden. In addition, the population is expected to increase by 30 % in many countries ,these demands an increase in buildings number, resulting in higher energy consumption and raw materials, which is why DFD is highlighted in the building industry (Thormark, 2007).

As a solution for the social mass housing, "Support structures" are presented. Support structures can be demountable, altered, and even replaced (Chan, 2011). As a result of implementing DFD, the demand for the labor force will increase, which will create a lot of job opportunities (Soh, Ong and Nee, 2015).

In terms of the designed lifetime of different facilities, surveys in many counties reveal that 30 % of the demolished residential or commercial buildings have not reached 50 % of their intended lifetime. Particularly in Sweden, the numbers indicate that around 30% of demolished facilities are less than 30 years old (Thormark, 2007).
To conclude, adapting the design for deconstruction to the current projects means developing sustainable buildings that demand a new design strategy approach. The benefits of this method are conducted to environmental, economic, and social aspects.

2.9.4 Summary

Current buildings have several challenges to be deconstructed. These are time, cost, and lack of tools in this field. However, the critical factor is that the facilities are not designed for disassembly in the intuitive phase (Chini & Schultmann, 2002). Connection, joint, and fasteners between the structural system components are the factors that enable the design of deconstruction. A successful demountable requires innovation and improvement of deconstructable connection (Hurley et al., 2002).

There is a high demand for demountable connections in the market since the final decisions that allow any residual or commercial buildings to be dismantled are the type of connection and joints carried by the structural system (Morgan & Stevenson, 2005a) be presented in the next chapter.

2.10 Timber connections in term of DFD

The primary way to use DFD in the timber structural is to introduce a connection system that allows disassembles the components (Pozzi, 2019). The fundamental idea about the potential of using DFD is about; the connection needs to be categories into three different types; which are direct connection, Indirect connection, and infilled connection (Morgan & Stevenson, 2005). The integral connection (direct) is categorized by overlapped and interlocked connection. When the edges of the components form the shape of the connection, then the connection can be considered a direct connection. Commonly overlapped connections apply between vertical elements or between vertical and horizontal members. In contrast, the interlocked connection is an internal connection where the assembly process can be limited to the connectors' edge, which complicates the deconstruction. The disassembly sequences for this type of connection depend mainly on the material used in the connection (Durmisevic, 2006).

Frequently the direct connections do not provide the potentials of dismantling between the components since the members overlap to be assembled (Morgan & Stevenson, 2005). Likewise, the infilled connection, which includes glued or weld connection, cannot be deconstructable (Morgan & Stevenson, 2005). The assembly of this type is time-consuming, and that increases the construction time and revers higher costs. The disassembly percentage is almost zero for this type (Durmisevic, 2006).

That is highlights the indirect connection, which is an applicable connection to be used in DFD since this type provides independence and the possibility of exchange (Morgan & Stevenson, 2005). Indirect connection adapts additional devices that are used to connect the components. Two types form the indirect connection. They are internal and external. Sine additional devices are used to design the connection, the dismantling is easier (Durmisevic, 2006).

Determination of the connection characteristic for deconstruction is highly bonded by the components that form the connection, like the connection material type and its specifications and the number of devices used in it. Creating a demountable building system, allows the reusing of system components instead of eliminating them, two essential benchmarks should apply to the entire system and through all levels. They are the penetration between the component in the structural system need to be avoided, and the components or the elements should constantly be separated; and using the dry joint method instead of the chemical techniques (Durmisevic, 2006). Based on this fact, the connections can be categorized between fixed to flexible. Table 2.1. describes how the connection varies between fixed to flexible.

Table (2.1) Description of connection varies from fixed to fixable (Durmisevic, 2006).

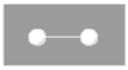
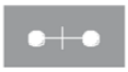
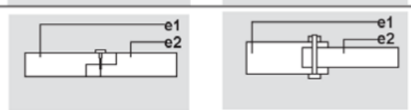
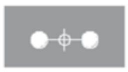
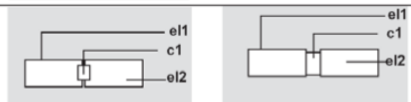
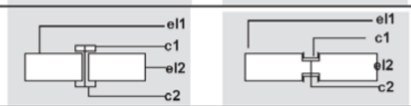
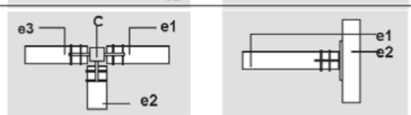
fixed → flexible		type of connection	graphic representation	dependence in assembly
fixed		**I Direct chemical connection** two elements are permanently fixed (no reuse, no recycling)		m1—el2
		**II direct connections between two pre-made components** two elements are dependent in assembly/ disassembly (no component reuse)		el1→el2
		**III indirect connection with third chemical material** two elements are connected permanently with third material (no reuse, no recycling)		m1 el1—el2
		**IV direct connections with additional fixing devices** two elements are connected with accessory which can be replaced. If one element has to be removed than whole connection needs to be dismantled		c1 el1 el2
		**V indirect connection via dependent third component** two elements/components are separated with third element/component, but they have dependence in assembly (reuse is restricted)		el1→c1→el2
		**VI indirect connection via independent third component** there is dependence in assembly/ disassembly but all elements could be reused or recycled		c1 el1 el2 c2
flexible		**VII indirect with additional fixing device** with change of one element another stays untouched all elements could be reused or recycled		e3→C←e1 ↑ e2

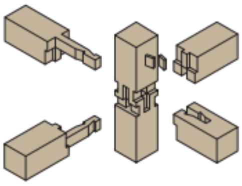
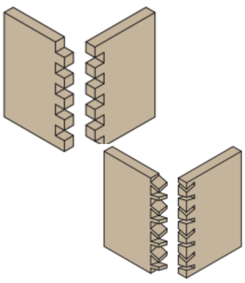
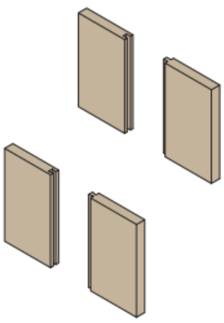
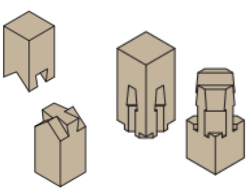
Table 2.1. provides the solution with a description of each type of connection. The direct mechanical connection is the lowest in terms of flexibility and the highest as a fixed connection. Such design delivers no reuse either recycling; if the changes are required in this principle, the material needs to be demolished as the scale move closer to the flexible connection, the configuration of the connection changes. Alternatives 4 is an example of the type of connection that used additional devices as a connector; the potential of deconstruction depends on the type of the accessory. Principle seven, which indicates the indirect connection with additional fixing devices, is a practical choice to implement disassembly in the connection system. This table can consider as a guideline used to determine the potential of deconstruction depends on the degree that ranged from fixed to fixable (Durmisevic, 2006).

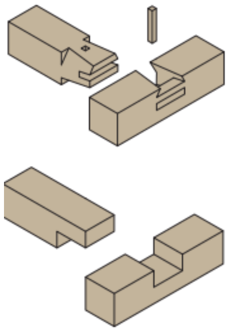
Carpentry connections are usually adapted when aiming to minimize the number of nails or screws, this type of connection can be applied only between wood-wood components. There are several types of this connection usually; they are governed by the aim of use, for intense the mortise and tenon joint most likely can be used between beam-beam and beam-column. The functionality of this joint is back to the mortise, which represents the cut and the tenon that fits into the mortise (Pozzi, 2019). The depth of mortise and the length of tenon influence the resistance against the bending moment, where increasing both will increase the resistance and vice versa. It has been noticed that if the obtained tolerance is closed between the mortise and the tenor, the joint can result in high strength (Kasal & Eckelman, 2005).

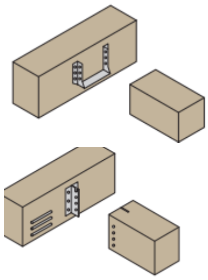
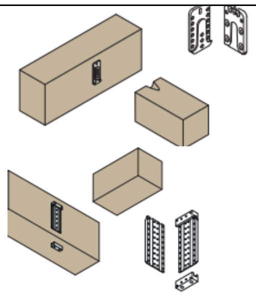
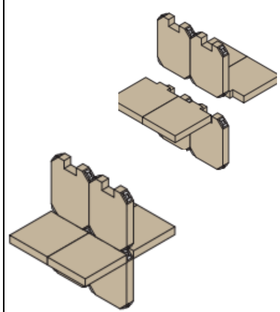
2.10.1 Comparison of various structural connection

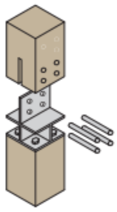
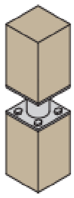
A study has been made to compare different categories of connection systems and evaluate their potential to be disassembled (Pozzi, 2019). Table 2.2 summarize this comparison.

Table (2.2). Evaluation and compression of various category in field of detaching.

Type of connection		Description	Evaluation and comparison
Carpentry connections		Complex mortise and tenon joint usually is used between beam-beam and beam-column. The functionality of this joint is divided between the mortise, which represents the cut, and the tenon which made to fit into the mortise.	The potential of disassembly is considered **relatively low** since the **accessibility** is limited to one side, which could be time-consuming and required intense labor work. Also, the assembled process is challenging due to the **complex configuration** of the geometry. However, the connection needs **no fasteners**, so the reuse is promising if the member is not damaging.
		Box joint used as panels connection where the wood members are interlocking each other. Such design is used to connect the wood corner members. Mostly glue is added to strengthen the connection and prevent any slip in it.	Using the glued effect, the dismantling process and gives **no degree of deconstruction**. Infield connection ranked the lowest in terms of DFD. The assembly process is also **time-consuming** and requires CNC operation to form the connection and complicated woodworking required, which increases both time and cost.
		Complex and simple tongue, groove joint, this type of connection is needed between panel to panel. The way of connecting between the panel is from one side, there is a groove along the edge, and on the other edge, there is a tongue to fit together.	The form of the edges makes the deconstruction **relatively easy**. However, the **accessibility is low** since the deconstruction can only occur along the direction of the groove. The interlocking between the member provides **resisting against the tensile** force, but this capacity is small and depends on the groove's dimension and the tongue. Labor work is not that intense, and the **cost is low**.
		Horizontal and inclined column splice joint aimed to increases the length of wood components. When the direction has locked, the movements of that direction cannot occur. The main use of this connection is between column-column to transfer the vertical loads.	Like the previous joint, the deconstruction is limited **to one direction,** which complicated the process of dismantling. The labor **time** is **relatively high**, which led to an **increase in cost**. Moreover, the assembly is challenging due to the form of the connector. The structural **strength is high** due to the interlocking of the elements. The reusability is high under the condition that none of the edges that formed the connection are damages.

		Self-locking and simple lap connection aims to have the same thickness as the thickest member. This design needs to use nails, dowel, or screws to strengthen the connection. The locked member can be provided in any direction needed. The structural connection depends on the type and dimension of the used fastener.	Both the assembly and disassembly processes depend on the **shape of the connectors**. Likewise, the complex self-locking more **time-consuming, and CNC operation** is needed if the shape is complexed. In the term of reuse, most carpentry connections have a high potential for reuse. However, the number of used fasteners and their characteristics influence the reuse of the material

Type of connection		Description	Evaluation and compression
Mechanical connections		External and internal metallic hanger counted as the most used connectors in timber frame structures. The connection is used to connect beam to beam or column. The main parts of this connection are metallic plates, dowels, screw, and bolts.	The internal connection is an obstacle to be demountable since the **visibility** of the **connectors is low**. in contrast, the external one is preferable to be used. The **wood reuse is high** due to the additional devices that are used to connect the wood member. Both the connectors and the wood member can **be reused**. However, the external and the internal hanger were considered easy **to assemble** and required no intensive labor time. The cost of assembling and deconstruction was evaluated as **low cost** due to the facts mentioned above.
		Hook connector used to connect beam to beam or column. The connector is attached to the timber members with mechanical fasteners. Thin connector forms a strong connection by interlocking with each other. The main aim of this design to shorten the assembly time and lower the costs.	The type of connection **highly suitable** to be DFD sine it counted as **indirect** connection **provides good accessibility, low cost, and no need for such heavy labor time.** The potential of wood reuse is promising, and all parts can be reused without being separating from the connected elements. This connection is considered a practical solution to **speed up** the assembling process and lower the cost since only simple tools are required.
		X-RAD is a system that aims to connect timber panels. The system uses sole corner connection to transfer the tensile and shear forces. This system has been designed to speed up the installation process and provides easiness to be dismantled.	The evaluation of this system showed the **highest score** under the criteria easy to disassembly. The reasons behind that are short labor **time**, **low** work instruction, and the tolls that need to deconstruct such connection in **simple**. The system also showed a **good** score in **installing** the connection due to the same reasons as above. The potential for wood **reuse** is **high** since the

			connection can be used without disturbing or dismantling the other members.
	 	Cross and circular Post connector is a connection method which is used between column and column in a timber structure. This type of system transfers the vertical loads between the components in the structural system. This type of connection is composed of a metal connector, metal dwell, and bolts. The metal connector is attached to the timber elements by screw or bolts, the dwell used to provide more capacity to this connection system.	The circular post connector is weighted as **suitable** to be DFD because the configuration of the connectors demands **no heavy work** instruction to be disassembled, so the **cost** is accounted to be relatively **low**. Besides that, the connectors provide proper **visibility** and good accessibility. The **reuse** of the wood members and the connector is **high** since all parts can be reused several times without separating the components. The cross-post connector provides a reasonable degree of **disassembly** since it has similar advantages as the circular post. However, the **hidden** connectors **lower** the visibility and limit the accessibility of the connection. The reuse is low for this connection since some of the fasteners need to be **removed** to dismantle the connection
Fastener		Fastener connection applies to all lever of the structural system. and it has been well described in the chapter 2.5	The factors that govern wood reuse and the DFD are the **numbers, type** of fasteners, and their **characteristic**. Using a vast number of fasteners reduces the possibility of reuse and increases the labor time of dismantling the connection, increasing the cost. However, this type of connection was evaluated as a fast connection to be installed in the worksite, and the cost counted as low cost.

After examining the different connection categories, the results show that the mechanical connection is preferable over the other categories if the aim is to design for dissembling in the field of time, cost, and labor instruction (Pozzie, 2019). This type is considered a reliable choice to design for disassembly since the primary strategy of detachable connections is to avoid direct interference between the structural components (Morgan and Stevenson, 2005). The benefits of mechanical connection can also be shown in the assembling process, wherein heavy timber structures, adapting this category accelerate the assembling process and reduces some cost in the early stage (Angeli *et al.*, 2010).

2.10.2 Pro and cons of different fasteners

Since the fundamental aspects of using the detachable connection in timber structural are covered by the components of the connection and the way of construction (Morgan & Stevenson, 2005b) and (Gafner & Gerber, 2018), describe the advantages and disadvantages of using a different type of fasteners and their application. The summary of this description is presented in Table 2.3.

Table (2.3). Description of pro& cons of different fasteners

	Type	Applicable	Advantage	Disadvantage
Mechanical	Nails	Light frames connections; shear wall and diaphragms; most connection without withdrawal forces; it is used with most kind of engineered timbers.	Commonly used; no needs for skill labor; small and flush head; can be installed with angle; it needs one side of the connection to be exposed; quick to install.	Low capacity per fastener; small resistance; it could be an external connection; reduce timber area at the connection; no withdrawal forces can be applied; timber can be damage when disassembling; possibility of wood splitting; spacing restrictions; not possible to reuse the connected member part.
	Screws	Light frame connections; shear wall and diaphragms; most connection with shear and tension loads; it is used with most kind of engineered timbers.	Available; it needs some skills; small and flush head, the connection is difficult to See; it can be installed with angle; it needs one side of the connection to be exposed; relatively quick to install; pre-drilling is not always required (self-drilled heads).	Low capacity per fastener; small resistance; it could be an external connection; reduce timber area at the connection; necessary to specify the screw due to wide varies; timber can be damage when disassembling; the possibility of wood splitting; spacing restrictions; relatively short standard length; not possible to reuse the connected member part.
	Dowels	Walls to the floor slab; column to column; primarily for connection with; big shear loads; it is used with glulam, CLT, and mass timber.	Common; transfer heavy loads; easy to disassemble if it was visible; various types and kinds (wood, steel); usually, one exposed side of the connection is enough; relatively quick to install; economic and easy to produce.	Skills and machines are needed; it is difficult to See or, in some cases, invisible; it could be an external connection; reduce timber area at the connection; the accurate design is needed as a big area of wood is removed; not possible to reuse the connected member part, it should be perpendicular to wood grains.

	Bolts	Beam to a column via a plate; truss to a column via a plate; beam to beam (shear); suggested for saddle and bearing connections; mostly for connection with heavy loads (moments); it is used with glulam, CLT, and mass timber with big sections.	Available; transfer heavy loads; easy to assemble and disassemble; it can be used for timber-timber or timber-metal connections; no high skill needed for assembling; can be used to get a rigid connection.	Skills and machines are needed for manufacturing; usually, the metal part is included in, affects the lock; it could be an external connection; the accurate design is needed as a big area of wood is removed; not possible to reuse the connected member part; both sides of the connection should be accessible; needs to re-check when wood moisture changes; bolt, nut, washer all should be perpendicular to the surface or notched.
	Metal plate	Used with glulam and mass timber only; usually used only in a truss and prefabricated light-frame.	Commonly used; transfer heavy loads; relatively easy for installation; it needs one side of the connection to be exposed; reduce splitting; force resistance for all connected parts.	Skills and machines are needed for manufacturing; should be done in the factory with quality observation; very difficult to disassemble; the accurate design is needed as it designed for the unit of area load resistance; not possible to reuse the connected member part; the narrow part should be parallel to the grain.
Adhesive	Glued	It uses with all types of engineered timber; used in manufacturing some engineered timber, usually to extend the length of structural parts (beams).	Really available; not visible; produces stiff connection; different adhesives can be used to get different advantages; resist corrosive atmosphere; less area of removed timber than a mechanical one.	Very sensitive for big fluctuating in timber moisture; it is challenging to disassemble; mostly the connected part of the member will be broken when disconnected; restrictions and special conditions needed when it applied; unstable in case very heavy loads applied perpendicular to glue plan; for some cases (like finger joints) machinery is needed so it will become costly somehow.

3 Analyses

To achieve the goal of this research, the analysis will be conducted within four main steps

- Firstly, a criterion is proposed based on the theory part. In this criterion, the fundamental factors , which govern the decision of determining how the connections system can be designed to be demount-able, are described.
- Secondly, weighted and scale factors are defined. In this step, the factor that governs the decision is weighted numerically. The weighted factor reflects the importance of the problematic aspects to the criteria itself. Simultaneously, the scale factor refers how the examined connection is suitable for the chosen aspects. This step is the foundation of the evaluation phase.
- Thirdly, the evaluation phase. In this step, the evaluation process occurs, where the connection system will be examined by the designed criteria using both the waited and the scale factors. For that, the chosen connection from Derome's presented systems will be categorized into three main groups, according to their location in the DFS 90.
- The final step of the analysis is to suggest a catalog that contains several solutions of the chosen connections, which are retrieved from the evaluation phase of step three. Then the suggested alternatives will be examined according to the same evaluation criteria, and to the discussion with Derome engineers to choose the most suitable choices. The chosen connection should satisfy the used criterion and fulfill the demand. Also, a static calculation is carried to prove the efficiency of the developed connection. The figure below illustrates the general steps of the analysis part. See Figure 3.1.

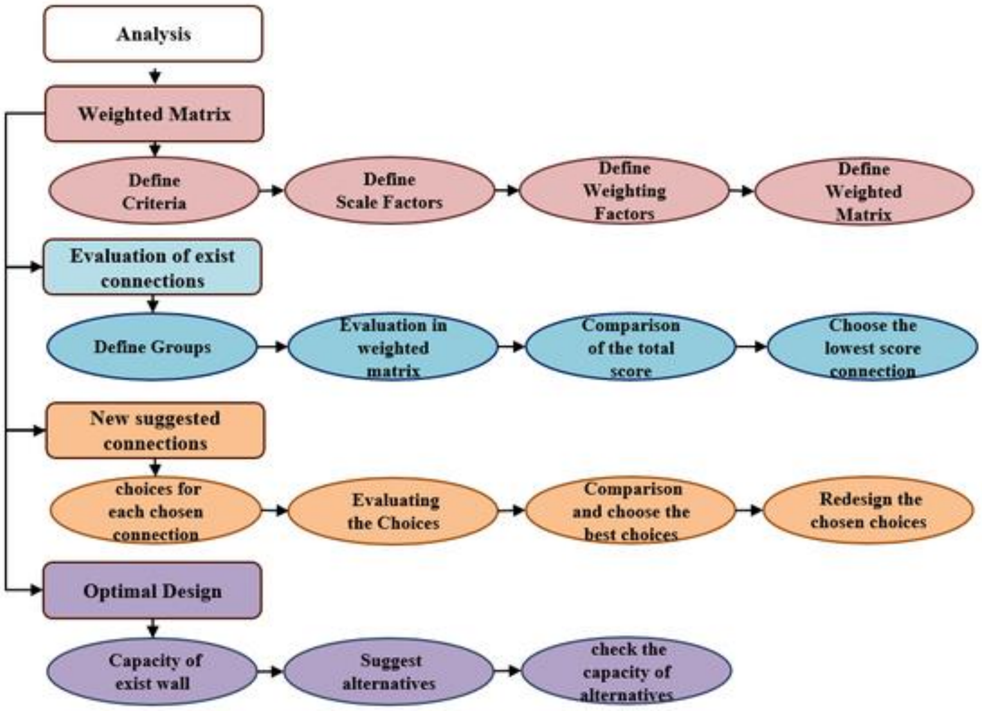


Figure (3.1) The diagram of analyzing steps

3.1 Defining design criteria

Various factors are involved in developing a connection system with the advantages of both the assembling and disassembling process. The design criteria help in customizing this purpose. However, to make this guideline reliable, it should be considered through all project phases, starting with intuitive design until the implementation phase. For criterion application, the aspects like capacity, accessibility, cost, and wood reuse need to be involved. Furthermore, the whole life cycle of the timber construction should be taken into consideration, according to that the essential prioritized criteria factors are

1-Connection capacity

The connection capacity is the crucial purpose of the connection design. The connection cannot be adopted if its capability is not sufficient, which means the connection should have the ability to transfer loads between the connected structural members and provides enough resistance that fulfills the design demands.

2-Connector strength

The strength and stability of timber construction are highly governed by the strength and stiffness of the connection. The strength of the connector depends on its material, but its type also influences it. Both nails and screws are metal and have almost the same shear capacity, but the screws' withdrawal capacity is considerably more significant than the nails.

3-Availability

The available connectors are the easily obtainable ones, the commonly used in connections, besides those which can be applied without any limitations. Usually, the designed connections use the commonly available connection like nails, screws, and dwells. While using a custom-made connection will increase the cost and time and may need more design calculations.

4-Accessibility

The degree to reach the current connection system play a vital role in the disconnecting design criteria. The accessibility of connection refers to the need for one exposed side of the connection or more so, the connecting and disconnecting it will be possible; likewise, the screws and nails require one exposed side to extract them while disassembling other types of connections may need two exposed sides.

5-Time

One of the essential aspects that need to be considered in the criterion is the process consumed time. It has been highlighted in theory parts, the importance of time as a factor governs both the assembly and disassembly process.

6-Assemble and disassemble skills

Different types of connections need different labor skills; when the used connection needs fewer skills to install, it becomes a practical, commonly used one. For instance, using screws or nails is simple and requires no such experience, so they are more practical than combined types of connections, which need more skills to apply.

7-Wood reusability

It refers to the possibility of reusing the connected parts of timber members; in general, installing timber connections will cause removing or distorting some wood of the connected member part; the degree of distorting differs from one connection type to another. Nails distort timber relatively less than bolts and nuts while using connections like tongue and fork or dovetail remove much wood.

8- Complexity

The chosen shape of connection highly affects the connection assemble and disassemble needed time. As the connection shape or the installation method becomes complex, it becomes costly, more time-consuming, and more difficult to disassemble.

9- Machinery works

The machinery works can be needed for both assembling and disassembling the connections. Some used timber connections do not need any preparation works; others need prefabrication works before they can be applied. Prefabrication works (CNC, preinstalled connections….) means more time and cost besides the aligning problems, which can arise when gathering parts at the site. The same for disassembling while some types of combined connections need machines to disconnect, the simple ones need some tools for disconnecting.

10- Visibility

For many cases, the visibility of chosen connection affects both the architectural decision and the disassembling possibility. While the invisible connections are hard to be detected, so they are hard to disconnect, some of the used dowels and bolts are being hidden in the timber, so disconnecting them is more complicated, even so in some cases, the hidden connection is recommended for fire-resisting.

11- Cost

The lowest cost capable connection is always desired; the lowest cost connections include the material of connection, the number of needed connectors, its complexity, the needed labor, or machine works to fabricate, installing and disassemble the connection. The cost should consider in design criteria as it will affect the chosen type of connections.

12- Number of connected elements

This criterion is somehow related to the complexity of the connection; the same connection connects more timber members means fewer connections are needed, but it also means more complex, higher capacity, and costly ones.

13- Special condition to apply

For some types of wood connections, special conditions should be applied while installing them, like the glued connection should be applied in particular conditions of moisture and temperature, and the metal plate can only be installed in factories; in this case, using these types of connections will be costly, and undesirable for projects, which depend on gathering the structural at the site. This factor has a more considerable influence on assembling connections rather than disassembling them.

14- The ability to reuse the connector

This factor discusses reusing the used fastener when disassembles; most of the used timber connectors can be reused, but reusing some fasteners is difficult after disassembling, while in other cases, the disconnecting process that retains them for reuse will be costly.

15- Easy to assemble

This criterion measures the ease of connection system application. It includes the needed time to connect different parts, the complexity of connection, which refers to the simplicity and practicality of the connection shape, the number of the connected parts; by reducing this number, the assembly time and the cost of the connection will be reduced, and the needed prefabrication works, which leads to more time for preparing the connection besides, to the aligning problem which may arise at the site Chapter (2.6.2).

3.1.1 Weighted Factor

One of the main steps to evaluate the connection is measuring the importance of criteria. The factors importance scaling is an essential step for a more real connections appraisal.

For weighting, a scale of (1-0) measures the relations between different criteria factors is assumed to be used, as number 1 refers to a strong relation and effect between the factors, number 0 refers to a weak or no relation between them; as a result, each factor will be evaluated with the other 12 factors. For the process simplification and regulating, reevaluation of each factor's scaling results will be measured according to another scale as follow

Total scale results are between (0-4), the scaling factor will be assumed as 1, and if the result is between (5-8), the scaling factor will be evaluated as 2, and from (9-12), the weighting factor will be (3). See Annex (A).

The result is a fundamental weighting factor, which will be used in the weighted matrix to represent the role of the factors in the studied case of connections assembling and disassembling. See Table 3.1.

Table (3.1) The model of criteria weighted factors

	Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity	Machinery	Visibility	Time	No. Connected Members	Reuse Connector	Easy to Assemble	Total Score	Weighted Factors
Capacity															
Accessibility															
Availability															

3.1.2 Scale Factor

The scale factor reflects the aptness and satisfaction of each connection with the criteria factors. The scale factor is usually influenced by the research goal, applying field, and comparison way, and helps the decision-making by estimating how each connection fulfills the criterion.

A convenient scale has been chosen for scale factors evaluation; this system measures the connection compatibility from the scale (5-1). The numbers meaning according to the evaluation process are as following

Number 5: the connection is very compatible with the criteria factor

Number 4: the connection is not fully compatible with the defined criteria

Number 3: the connection is partially suitable with criterion

Number 2: there is limited compatibility between the criteria and connection

Number 1: the connection does not fulfill the criteria factor.

This method in scaling allows a more reliable presenting of the connection suitability with the criteria, and more realistic results will be obtained. See Annex (A)

The scale and weighted factors will multiply to get the weighted score of each criterion; the weighted score illustrates the achieved value of each defined connection according to the defined criteria. Table.3.2

Table (3.2) The model of criteria weighted score

Criteria / Connection	Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity	Machinery	Visibility	Time	No. Connected Members	Reuse Connector	Easy to Assemble
Connection 1													
Connection 2													

3.1.3 Weighted Matrix

For evaluation of the chosen connections, a weighting matrix will put in application.By doing that the suitable and less suitable used connections will be defined. For this research, Saat & Vargas simplified weighting matrix is applied where the weighted factor is presented by three scaling degrees, and the scale factor is presented by five degrees.

The total weighted score is the sum of each criterion's weighted score, which is the result of multiplying the weighted scale by the scale factor. The total score illustrates the connection convenience degree for disassembling process.

Since the chosen criteria factors state the practical suitability of the connections disassembling, a second factor will be adopted for connection evaluation from a different perspective. This un-weighted factor will show the importance of the connection; it measures the frequent use of this connection in the whole construction and its crucial role in loads transformation (connection failure results).

This factor will represent in the weighting matrix as following

1- Very important (V) if the connection is used frequently or to transfer heavy loads.
2- Important (M) if it is using less frequent or transfers smaller loads.
3- Not important (N) if it is rarely used or the transferred loads are small.

Since there are many types of connections at different building levels and locations, the chosen connections are categorized into three main groups to make the comparison between connections more reliable

Group 1: includes some of the connections between walls and the last roof.

Group 2: includes the frequent connections between the wall extensions and floors in different stories.

Group 3: includes some chosen connection between wall and concrete floor, wall to wall, and beam to wall.

3.2 Evaluation and comparison of the connection system

The evaluation of the existing connection system is carried in this chapter using the design criteria mentioned above. At the same time, the examination results will be presented in Annex (B). Annex (B) shows the evaluation process, where the examination and calculation of the final total score of each connection are presented.

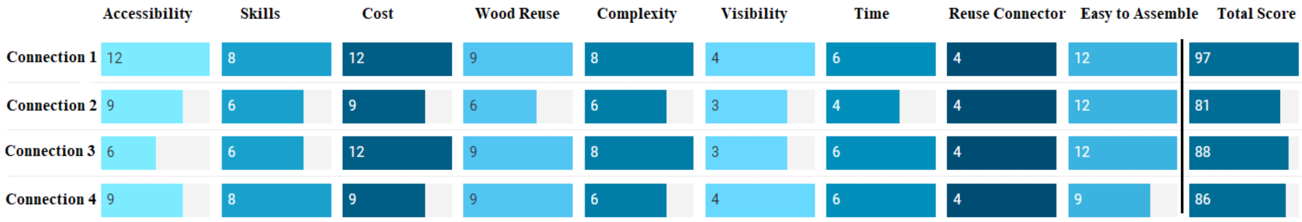
The results reveal the capable and the less capable connection from the disconnecting perspective and help decide the connection that needs to be replaced or improved.

While the selection of the connection will be upon the total weighted score of each, with considering the importance of un-weighted factor, the analysis results will be presented by using the bar chart; the bar chart states the numerical result of criteria aspects, which have a more considerable influence on the total results. As the connection system was categorized into three groups, the comparison of the result will focus on the connections of each group.

- **Group 1**

The connections of this group are located between the bearing, dividing walls, and the roof. Group 1 is indicated by the code KP – 25.6 -106 and contains four connections 1,2,3 and 4. Annex (B) shows more details, location, and specifications about each one.

The four connections examined by the weighted matrix, the total scores were different for the connections, connection 1 got the highest score (97), connection 2 got the lowest score (81), and connection 3 and 4 got (88, 86) respectively. While some of the criteria aspects scores were equal ,(for instance the availability, and the connector reusability) they did not include in the comparison study. These variations can be explained by the differences in connection type and components. The bar chart 3.1 below states the main various criteria factors of the four connections.



Bar chart (3.1) The scores of Group 1 connections according to the defined criteria

It can be noticed that the four connections achieved a high score for assembling, excluding connection four, as they all use the screws as connectors, and screws count as a simply used fastener, besides, the easy accessibility to the connected parts when assembling. Connection 1 has a higher weighted score for ease of assembling as it contains a steel angle that makes screws fastening easier, while connection 4 gets the lowest due to the need for U shape metal plate installing first.

For wood reuse, the four connections got almost the same results; for connection one, a larger number of fasteners are used, which will limit the possibility of reusing the wood, the same for connections three and four, moreover using two additional inclined screws in connection two influences the score of reuse the connected parts after disconnecting.

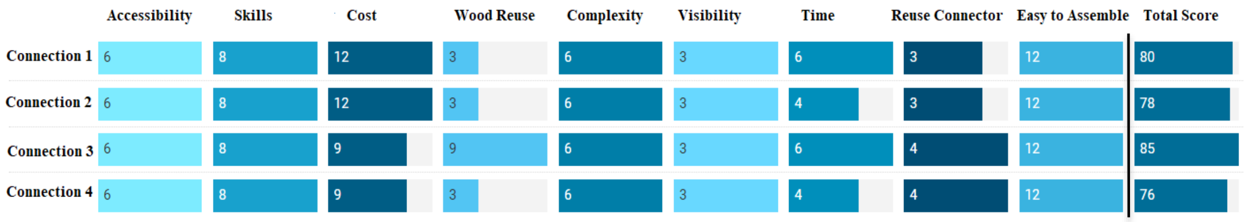
The disassembling consuming time got low scores in general, even though the four types of connections have many fasteners. Since connections 2 contain inclined screws, and the need to disconnect the screws of the roof side, it achieved the lowest result, while connections 1,3, and 4 get the highest points as there are no inclined screws.
There are some variations in accessibility weighted score results; for disconnecting connections, 2,4 accessibility is needed from two sides besides the roof. In contrast, in connection three, which is for the outer wall, the accessibility is needed from one side and the roof only, so it achieved the lowest score, while for connection one, the accessibility to deconstruct it is needed from the roof only.
From the cost perspective, connections2,3 and four disassembling will cost less as only a drill is needed for a limited number of fasteners; for connection one, the number of fasteners is less, due to the metal angle, that will improve the cost of disassembling.

The visibility score of all connections’ fasteners was low that because screws had a small head, which will be very difficult to distinguish on the wood surface with time, but for the connections with a metal angle, the screws head will stay clear, the same results were for fasteners reuse as the reusing of screws again may not be possible.

- **Group 2**

These group connections connect the floors with wall extensions, and the code KP-25.6-104 indicates it in the company's detailed drawings. It also contains four types of connections, specifications, and details illustrated in Annex (B).

The weighted scores for the four connections were almost the same, while connection 3 got the highest total result of 85, the lowest one 76 was for connection 4, connections 1and 2 got 80 and 78 points, respectively. These slight variations in weighting scores of four connections back to minor differences in their components and applied location, as in general, they almost use the same connecting way. The following bar chart 3.2 presents the weighted score for the leading criteria factors.



Bar chart (3.2) The scores of Group2 connections according to the defined criteria

The four connections scored high results for the assembling criteria factor because both nails and screws as fasteners are easy and commonly used connectors. The slight difference between connections 1,2 and 3,4 is the number and the angle between the wood surface and the connections' fasteners.

The reuse wood score was low for all connections because of the considerable number of used fasteners and the connecting method. Using eight nails in connection one makes the possibility of wood damage massive when disconnecting; the same can be noticed in connection four, where inclined screws are used in connecting the structural timber that will affect the possibility of reusing the connected parts of timber. In general, using nails in connections leads to a high probability of wood distorts at disconnecting.

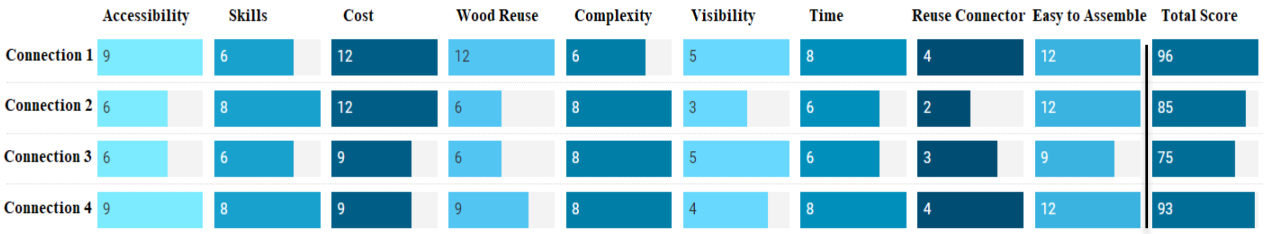
For disconnecting time, the weighted score also was low, usually removing nails somehow needs less time than removing screws. However, even that nails still consider time-consuming fasteners at disconnecting, the same is for screws, especially at using many of them in the connections; besides, applying inclined screws could also increase disassembling time as connection four.

On the other hand, the locations, and the method of connecting timber make the accessibility for different connections the same; it is clear the accessing the connections needs removing covering layers of walls and floors, and it should be from the four connection sides until it is the disconnecting will be not possible. That reflected on the accessibility scores, which each connection has achieved.

For all connections that use nails and screws as fasteners, the disassembling cost is considerably low; simple tools may be needed to remove nails, and drills will be used for screws, which appears in the high score cost factor in disassembling process.
The ability to reuse fasteners is very low for all connections, while it is lower for the nails than screws as the nails mostly will be useless after the disconnecting. The needed skill to disassemble all connections is the same as simple connections, using the same type of fasteners.

- **Group 3**

The connections of this group connect the walls horizontally, the wall and concrete slab, and the wall and a beam. They are indicated by KP -25.6 – (H, 05, 04) in detailed company drawings. The specifications, locations, and more details of the four chosen connections are shown in Annex (B). As the four connections present various connection types connecting different structural members, a wide variation in total weighted scores is obtained. The connections 1 and 2 that connect the walls horizontally got 96 and 85 total scores, respectively, while connection three between the concrete slab and wall achieved 75, connection four between the wall and beam has 93 points. The following bar chart 3.3 displays the weighted scores of the four connections for the essential criterion factors.



Bar chart (3.3). The scores of Group3 connections according to the defined criteria

The assembling score of the three connections was high, as the accessibility for applying connection was clear, and using screws, nails, and steel angles make connection installation more practical and quicker, while for connection 2, the assembling is more complex, as fixing the U metal shape in concrete slab should be done first. In contrast, the scores of disconnecting times were relatively low compared to connecting time and that because of the number and type of fasteners used in each one. For connection three large number of nails were used to connect the U shape metal plate to the wall, also the same for connection two, where the nails were used for connecting walls together, while for connections 1, and 4 a limited number of screws were used, that leads to relatively more minor time for the disassembling.

The variations were almost non between connections for the wood reuse, which can be back to the type of fasteners. For connections 2 and 3, while nails were used in both, but the wood damage caused by nails in connection 2 is larger, even with the metal plate that protects the wood from distorting during nails removal, but enormous numbers of nails were used from both sides. For connections 1,4, limited numbers of screws were used, and that allows considering the timber reuse.

The same is for accessing to connections factor; scores vary back basically to the connection’s locations while reaching the connection one needs removing specific parts of wall covering layers from inside, connections two needs remove all wall covering layers to reach it, and the accessibility it will be only from the inner side of the wall. For beam-wall connections, removing the suspended ceiling is needed to access the connection, but for wall-concrete slabs, the lower wall layers at least should be removed to reach the nails.

The disconnection costs were almost the same for four connection types, as only simple tools and drills are needed to remove nails or screws.
For this group, the visibility of used connectors is good as they are easy to be distinguished on metal parts of connections, while no skills are needed for disassembling them, so all of group three connections got high scores in skill factor.

To conclude, the connections that scored the lowest amount in the examination system will be redesigned and presented in a catalog See Annex (C). In this catalog, several alternatives for each connection are proposed. In which the concept of DFD is already considered in the primary step of the design.

3.3 Updated Design

Three ways of thinking developed the practical suggested solution.

- Firstly, no major changes in the dimension and structural components of the connection system are made.
- Secondly, the dimensions, the structural and non-structural parts are updated in the new design.
- Thirdly, a new structural system that can carry several alternatives is adopted.

The choices in this catalog are examined in the same criteria to choose the suitable solution for DFS90 improvement. The assessment of this sub-chapter starts by defining the applied loads on the building. The influence of these loads on the studied connections will be discussed, and 3D drawings of the loads are presented to illustrate their types and directions.

3.3.1 Loads

To improve the reliability of the suggested solutions, the load system needs to be described. In addition, transferring these loads to the chosen connections will be presented in the sketch to illustrate how these forces affect the connection.

The loads that affect the building can be categorized as the following:

1- Vertical Loads:

- Dead load (DL) is the load due to the self-weight of the structural members. These loads transfer through the structural members such: slabs, beams or bearing walls, columns, and finally, foundations.
- Life load (LL) is defined according to the time of applied loads. These loads are also transferred in the building in the same way as dead load.
- The snow load (SL) is defined in Euro Code according to the building location, and the shape of the roof, the transfer path of snow load, is from the roof slab to the trusses and then to the bearing wall to the concrete slab and foundation.
- The wind Load (WL) is defined in Euro Code according to the building location, height, and roof shape. When wind load affects the roof, it creates two forces: uplifting forces, which affect a part of the roof, and push forces affect the other part of the roof. Which creates a moment, and usually, these forces resist the shearing walls.

2- Horizontal Loads: these loads include

- Wind Load (WL) effects on the building elevations, it creates a horizontal force. The direction and value of it are defined by the location of the building and its dimensions. This force usually resists by shearing walls and by the floor slabs. Which transfer these forces to the beams or bearing walls. The following figures illustrate the wind loads and shear wall distribution in ‘A’ house building type. Figure 3.2. shows the possible effects of the wind load on the building, and the shearing wall locations. For more details about applied loads, see Annex (E).

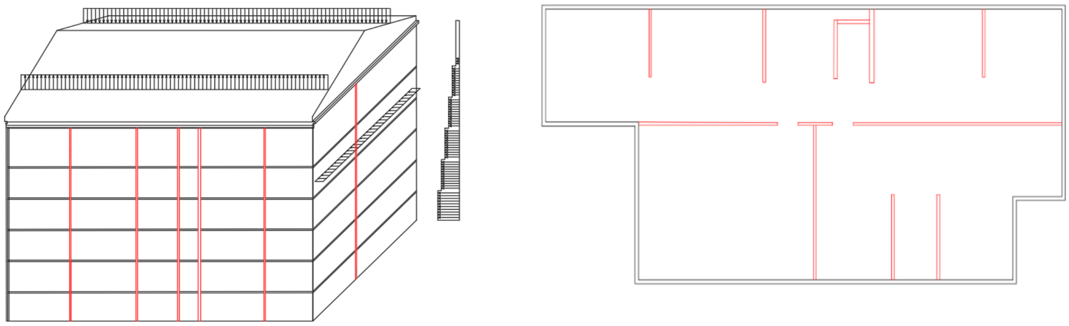


Figure (3.2) Illustrates the shearing wall distribution in A-house, and the wind loads acting on

The forces that transfer by the connections are related to their locations in the structural system. So, for defining the force types that affect each connection, the connections' position in the building should be defined. The following Figure3.3 shows the chosen connections' locations in section c-c.

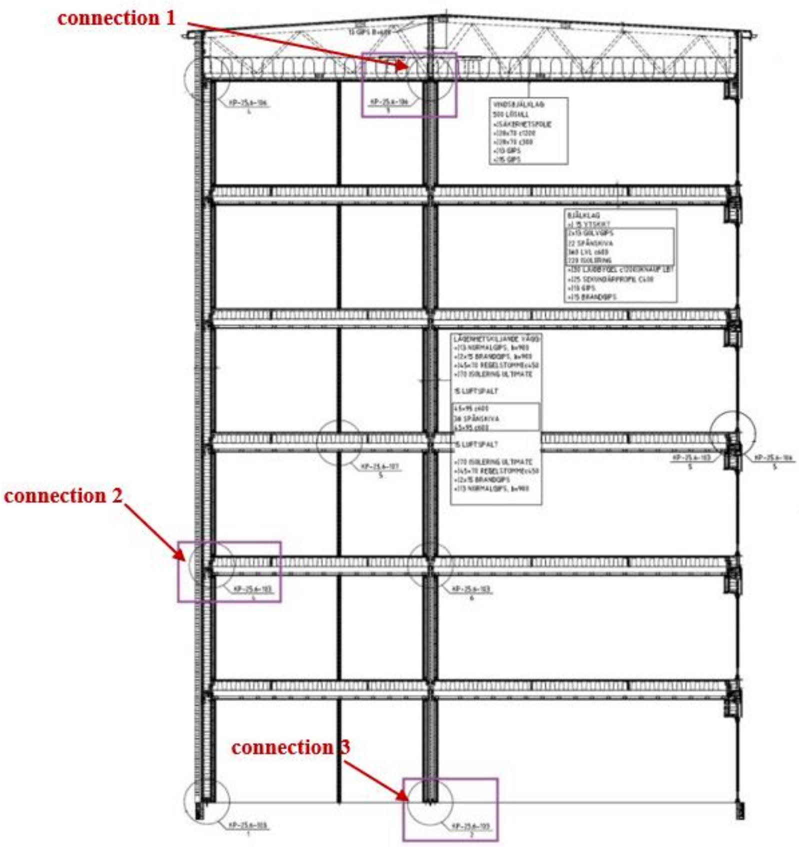


Figure (3.3) Shows the connections locations in C-C section

Connection 1:
This connection connects the bearing wall with a small dividing wall above the roof, it contains two inclined screws which connect a timber purlin 95mm*45mm, above the roof with two timber sections of the same size in the bearing wall. As the dividing wall resting directly on the bearing wall, so its self-weight will transfer directly to the bearing wall, and the screws will only transfer horizontal shearing forces between two walls as the Figure 3.4. shows bellow

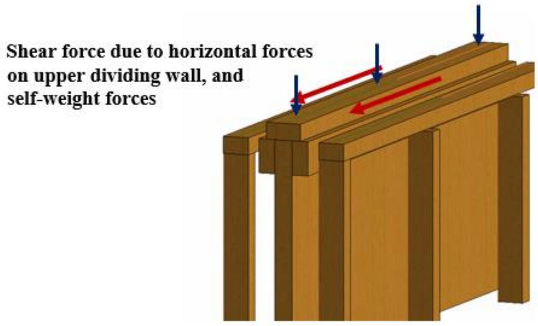


Figure (3.4) Shows the applied shear loads on the connection 1

- Connection 2:

This connection connects the floor with the external wall, at the level of external wall extension, an inclined screw has been used in this connection to fasten the floor with the external wall. This fastener is responsible for transferring the vertical shearing force due to the slab weight, and the horizontal shearing force due to the wind loads. See Figure 3.5.

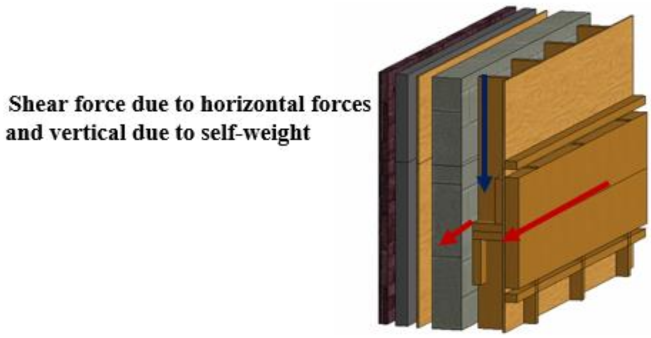


Figure (3.5) Shows the applied shear and self-weight loads on the connection 2

- Connection 3:

This connection connects the concrete slab with the bearing wall at ground level. This connection contains U shape metal plate connecting the wall with the concrete slab. The bolts connect the metal plate to the concrete floor, and the nails connect the wall to the plate. The bearing wall will transfer the vertical loads directly to the concrete slabs, while the nails should transfer the shearing force, which results from the horizontal applied forces, and the bending moments applied on the wall due to the wind load. The bolts that fasten the plate to the concrete slab transfer horizontal shear forces besides the uplifting one. See Figure 3.6.

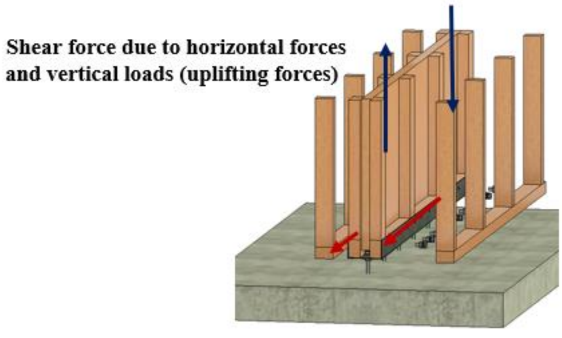


Figure (3.6) Shows the applied shear and uplifting loads on the connection 3

3.3.2 Examination of the updated design

To propose reliable solutions, all the new designs in Annex (C) need to be evaluated. Annex (C) shows the suggested alternative for the chosen connections. To clarify the improvements comparing with the original design. Annex (D) illustrates the evaluation process in similar steps as Annex (B). Following tables illustrate the comparison between the updated design and the original connection obtained from Annex (D).
Table color reference

0 Enhancing in criteria factor 0 same result in criteria factor 0 worse result in criteria factor

Connection 1

Table (3.3) Final comparison between the new design and the original of connection 1

	Accessibility	Availability	Skills	Cost	Wood Re-use	Complexity	Machinery	Visibility	Time	No.Connected Numbers	Re-use connector	Easy to assemble	Weighted Score
Max score	15	5	10	15	15	10	5	5	10	10	5	15	115
Original	9	5	6	9	6	6	4	3	4	8	4	12	81
Choice 1	12	5	8	15	12	8	5	4	8	8	4	12	106
Choice 2	9	5	8	12	9	8	4	4	6	8	4	12	94
Choice 3	9	5	8	12	9	8	4	3	6	8	4	12	93
Choice 4	6	4	8	12	9	8	4	3	8	8	4	12	91
Choice 5	9	5	8	12	12	8	4	4	6	8	4	12	97
Choice 6	9	5	8	12	12	8	3	4	8	8	3	9	94
Choice 7	9	3	6	9	9	8	3	4	8	8	4	12	88
Choice 8	12	5	8	12	12	8	4	4	8	8	4	12	102
Choice 9	9	4	6	12	12	8	3	2	8	8	4	12	93
Choice 10	9	5	8	12	6	8	4	2	4	8	3	12	86
Choice 11	12	5	8	9	9	8	3	4	6	8	4	12	93

The goal of the new suggested connections is to present better alternatives for the existing one. While alternatives 1, 8, and 5 were the best alternatives according to the criterion, the worst were 7, 3, and 4. Even though all choices scored better than the existing one, it can be noticed that most of the newly designed connections got a better score in cost, wood reuse, time, complexity, and skills. While reusing the connector and easy to assemble, have no significant changes.

Choice 1 and 8 got a high accessibility score (12). Changing the used fasteners in the connections makes the access from one side enough for disconnecting, but for choice 5, the accessibility did not change due to the need to access both sides of the connection to disassemble. For wood reuse, all the best choices achieved a better score than the original. Choice 1 got a high score (15) as using the bolt will limit the distorts in the wood, but the alternative 5 scored (12) as using more screws will cause more wood distorting. In choice 8, the used connector type damages the timber parts more than choice 1.

The same was for the cost, choice 1 achieved (15) as the disassembling needs simple tools, but for designed alternatives 5, and 8 more tools will be used for dismantling like drills and maybe other machines. From a visibility perspective, three choices got a good score. Using bolts in connections 1 and 8 and a metal plate with screws in connection 5 will enhance the connection's visibility and make the distinguishing of it more manageable. Both new connections 1 and 8 use almost the same fasteners, bolts, or dowel with nut, making disconnecting time concise and easy, but in connection 5, using screws leads to a remarkable time-consuming for disassembling. On the other hand, the three connections achieved good easy to assemble results (12) as the original one, using almost the same type of fasteners, did not make many differences in the assembling criteria factors that lead to the same result for the most of connections.

Connection 2

Table(3.4) Final comparison between the new design and the original of connection 2

	Accessibility	Availability	Skills	Cost	Wood Re-use	Complexity	Machinery	Visibility	Time	No.Connected Numbers	Re-use connector	Easy to assemble	Weighted Score
Max Score	15	5	10	15	15	10	5	5	10	10	5	15	115
Original	6	5	8	9	3	6	3	3	4	8	4	12	71
Choice 1	9	5	8	12	12	8	4	4	6	8	4	12	92
Choice 2	12	4	8	12	12	6	4	4	8	8	4	12	94
Choice 3	9	5	8	12	12	8	4	3	8	8	4	12	92
Choice 4	9	5	6	12	12	8	4	3	8	8	4	12	91
Choice 5	9	5	8	12	12	8	4	3	8	8	4	12	94
Choice 6	9	5	6	12	12	8	3	2	8	8	4	12	94
Choice 7	12	5	8	12	12	6	4	4	8	8	3	12	94
Choice 8	6	4	8	12	12	8	4	3	8	8	4	12	89
Choice 9	15	5	6	12	12	8	2	4	8	8	5	12	97
Choice 10	9	5	8	12	6	8	4	2	4	8	3	12	81

All newly designed choices scored better than the existing one and almost scored the same points according to the designed criteria “choices 9.10 will be excluded from comparison because they related to a completely different building system”. The best four choices were 2, 3, 5, and 7, while the worst was choice 10, the rest scored between (89-92) points. All alternatives got higher scores than the original in cost and wood

reuse, and almost all of them in the accessibility, machinery, and time. However, for easy to assemble, reuse connectors, availability, and skills, no considerable improvement was achieved.
Choices 2 and 7 achieved high points for accessibility (12), as they have almost the same way of connecting all members by using metal plate and screws, which makes accessing one side of the connection enough to dismantle. While for alternatives 3, and 5 using bolts to connect slabs with external walls and screws to fix the two walls leads to limited accessibility to the connections. On the other side, all alternatives achieved (12) points for cost because of the simple connection shape, and the fastener types, allowing easy dismantling. The same result is achieved for wood reuse; the high score (12) can be explained by using metal plates, which remarkably decrease the wood damages at disconnecting while using the bolts and steel dowels decrease the number of needed connectors. All connections consider as a non-time consumer for disconnecting and score 8. The type of fasteners, and the way of applying them, give the alternatives the advantages of quick and easy disconnecting.
The same can be mentioned for visibility. Using bolts or screws with metal plates causes better visibility for connectors than using only screws. Connecting wall parts in choices 3 and 5 by screws only will create visibility limitation.

Connection 3

Table(3.5) Final comparison between the new design and the original connection3

	Accessibility	Availability	Skills	Cost	Wood Re-use	Complexity	Machinery	Visibility	Time	No. Connected Numbers	Re-use connector	Easy to assemble	Weighted Score
Max score	15	5	10	15	15	10	5	5	10	10	5	15	115
Original	6	5	6	9	6	8	4	4	6	4	3	9	74
Choice 1-3	9	5	8	12	9	8	4	5	8	8	4	12	92
Choice 4-5	12	5	10	15	12	8	4	5	8	10	5	15	109
Choice 6	12	5	10	9	12	8	4	5	8	10	5	15	106
Choice 7	12	3	8	12	12	8	3	4	8	10	5	15	100

All the suggested choices show good results according to the criterion comparing to the original connection. Choice 1 and 5 consist of the exact wall members as the original one. So, there are no changes in the dimensions or the capacity of the vertical and horizontal studs. The wall's bottom and top horizontal studs, in choice 6, are illuminated and substituted by a sufficient larger cross-section stud. The horizontal stud acts as an additional connecting member.
Choice 7 presents a new structural system where a column and massive wall timber substitutes the existing wall. The idea is to examine this new system according to the same criteria to determine its potential in DFD. The access in updated choices is designed to be easy from both sides. The structural members in choice 3 are designed to be one block, which will reduce the wood members of the wall, even during the structure installation, or in case of deconstructing and shifting it, more description in Annex(C). The accessibility in the rest choices better than the original, and alternatives

1 and 3. Choices 4, 5, and 6 consider the wall as one block. In choices 3 and 4, the structural and nonstructural members are attached to the metal plate, so there is no disturbing to these components if the block needs to be connected or disconnected with the concrete slab for more details; See Annex (C & D). Choice 6 suggested changing the wall configuration by adding a horizontal stud at the bottom of the wall. The advantage of it is to limit the connection between the concrete slab and the stud itself for more details regarding the shape of the connection. See Annex (C).

In general, the wood reusability of all alternatives has improved compared with the original design since the updated connections' shapes consider the wall as one block. For instance, in choice 6, the additional stud in the bottom of the wall is more reusable than the used ones in the original design since the applied connection between the stud and concrete slab used a lower number of fasteners. See the catalog of the suggested choices in Annex (C) and capacity check Annex (E). Remarkably, alternatives 1 and 3 scored lower than the other solution because the wall has no additional member to restrict the connection see Annex (C).However, the cost of this solution is less as the solution adopted a new type of fasteners only. See Annex (C). The rest of the choices show similar results in terms of wood reuse.

At the same time, they vary in terms of cost. Choice 7 uses a new structural system as described in Annex (C), where the section dimensions of the new horizontal stud are larger than the existing one see Annex (C). While choices 4 and 5 were the best in cost, there are no new wall layout adjustments. In addition, it provides a higher degree of wood reuse under the condition of treating the wall as one member attached to the concrete slab see Annex (C). Under the factor easy to assemble, the suggested solution expresses an excellent score than the original connection. Options 4 and 7 are scored the best because the connectors are customized and connecting it to the wood member is in the factory, so no skills are required to install its components. However, choices 1 and 3 achieved a lower score than the others because the nonstructural frame needs to be installed at the worksite, which needs more time and skills. See Annex (A).

3.4 Analytical calculation

This sub-chapter is going to address the different calculation of each selected choice. The purpose of this calculation is to determine the reliability of suggested alternatives. Moreover, a comparison of the advantages of new suggested alternatives and the original one is discussed. See Annex (E) for calculations of connections detail.

- **Connection 1**

It connects the bearing wall with a dividing wall above the roof by two screws of 6.5mm diameter and length 160mm with space center to center 600mm. If the distance between the trusses is 1200 mm, so six number of screws are used to connect each wall to the bearing wall. The applied force on the screws is shear force due to the horizontal movement of the wall. The capacity of one screw is 1.22kN, so for six screws the capacity is 7.3kN, and it is the total designed force that should be resist by the suggested choices.

- Choice 1

In choice one the connector is a bolt of 10mm diameter, with metal plate of t=2mm thickness. The capacity of this connection for shear force is 3.7kN for each bolt, so the total needed connections are only 2 with capacity of 7.4kN. See Figure 3.7.

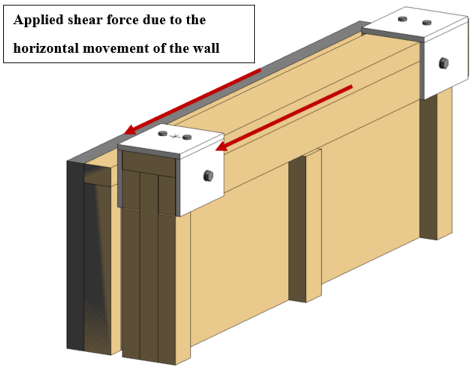


Figure (3.7) The applied forces on choice 1, connection 1

- Choice 5

As figure 3.8 shows, a metal plate is used with two screws of 6mm diameter and 50mm length from each side. The capacity of single screw is 0.74kN so the total capacity of six plates with 12 screws is 12kN or two plates with 6 numbers of screws can be used instead of six.

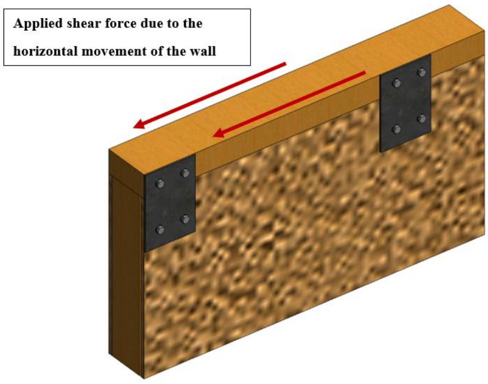


Figure (3.8) The applied forces on choice 5 connection 1

- Choice 7

As shown in Figure 3.9, a screw with wood and metric thread and a nut is used to connect the bearing wall with the lower stud of dividing wall the three connectors of 10mm diameter have the capacity of 7.7kN.

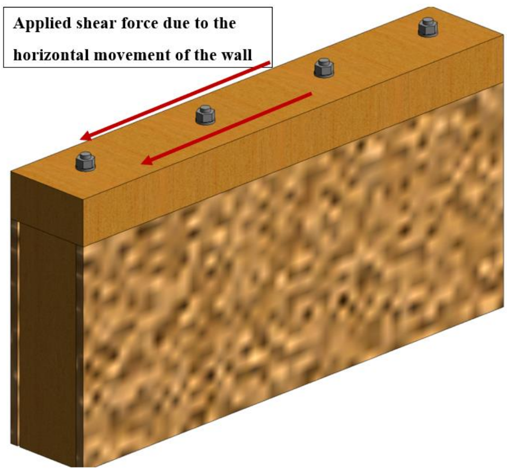


Figure (3.9) The applied forces on choice 7 connection 1

- **Connection 2:**

This connection connects the floor slab with the outer wall at the connecting two frames of the outer wall. The use fasteners in this connection are screws with 9mm diameter and length of 500mm with spacing 300 mm. The applied forces on this connection vertical shear force due to the weight of the slab, and horizontal shear force due to the horizontal movements of the two parts of the outer wall.
The capacity of the screw at the most possible failure mode (the most possible failure level is that where the slab timber section connects the wall timber section as both vertical and horizontal forces may be applied together) is 1.53kN, so if the wall length is 3000mm the total capacities of all fasteners is 15.3kN.

- Choice 2

In this alternative, a steel plate of 2mm thickness is used with screws to connect all timber parts. For this connection, there are two shear levels; a steel plate-timber shear level, and a timber-timber. The capacity of it is the smaller capacity between the two levels, which is equal to 1.25kN. By using 2 screws with diameter of 7mm and length of 90mm, so the total number of needed connections is six. See Figure 3.10.

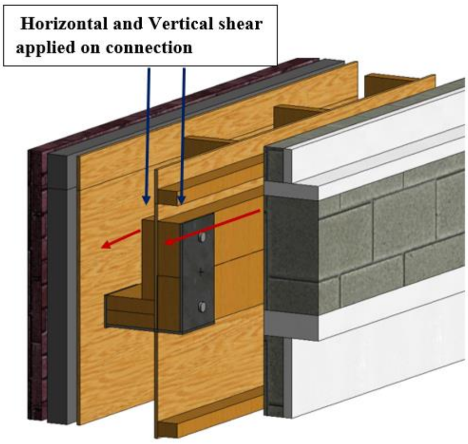


Figure (3.10) The applied forces on choice2 connection 2

- Choice 3

U-shape plate of 2mm thickness is used with bolts and nuts. By using a bolt of 8mm diameter, the total number of needed bolts for 3000mm wall length is 7 bolts. For the two parts of the wall 10mm diameter screw or nail with 90mm length with spacing 500mm is needed. See Figure 3.11.

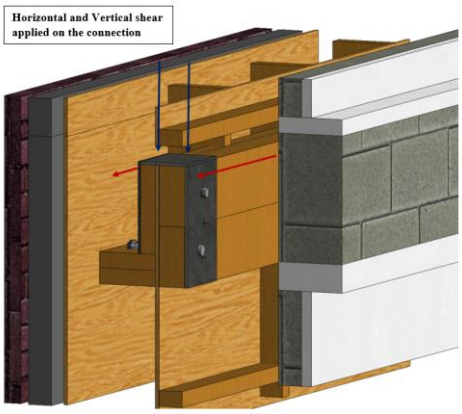


Figure (3.11) The applied forces on choice3 connection 2

- Choice 5

In this choice, a bolt with size of 9mm*120mm, joins the upper wall with the timber joist of the floor. To achieve capacity, only six bolts are needed for a length of 3000mm. In the case of bolts as couples, only three connections are needed. For connecting two parts of the wall using screws or nails size 10mm*90mm with spacing of 500mm will be sufficient. See Figure 3.12.

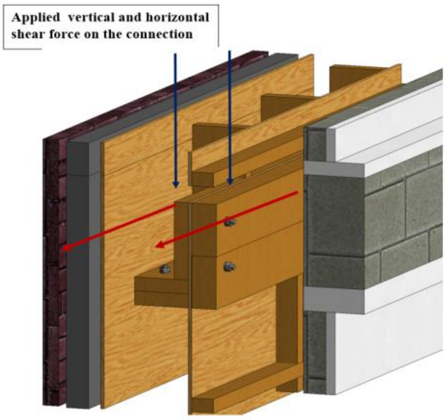


Figure (3.12) The applied forces on choice 5 connection 2

- Choice 7

As figure 3.13 shows, a steel plate is used with screws or nails and as the general design as choice 2. Screw of size 8mm*50mm is used whose, capacity is equal to1.2 kN and 13 screws is needed. By using two or three screws in each plate the number of connections can be reduced.

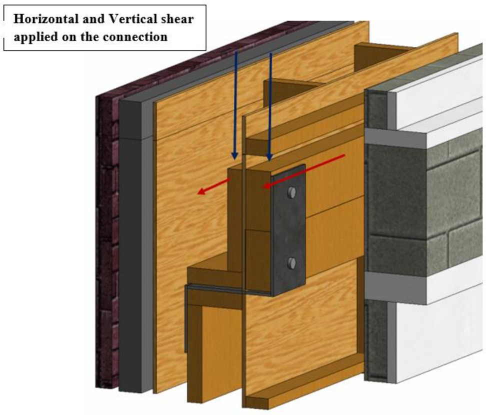


Figure (3.13) The applied forces on choice 7 connection 2

- Connection 3

It connects the wall by a U-shape steel plate; the applied forces on the used screws, in this case, are the sear force because of horizontal movement of the wall and shear force because of the vertical forces (uplifting forces due to wind loads). The used fasteners in the original connection are two screws of size 4mm*40mm, with distance 50mm, so all fasteners capacity of the wall with 3lm length is 0.7kN, and the total capacity is 83.6kN. Most of the choices use bolts and nuts instead of screws, so calculation for its capacity, in general, will be the same; by using bolts of 10mm, the total needed fasteners are 40 with the capacity of 87.3kN. See Figure 3.14.

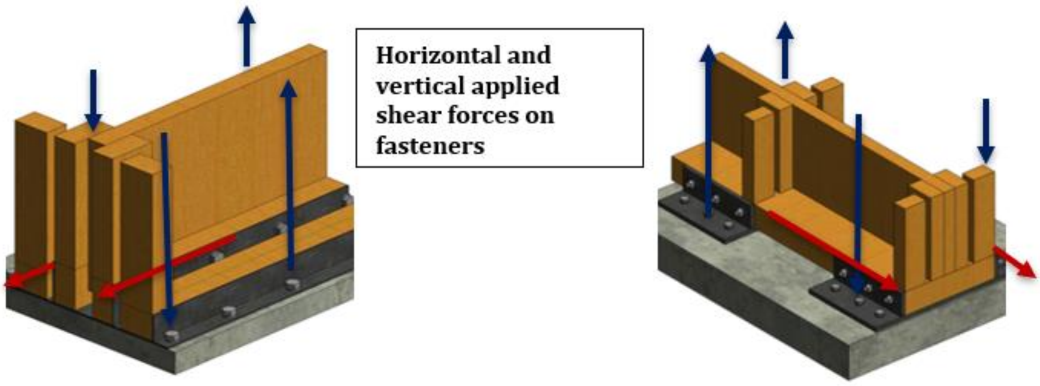


Figure (3.14) The applied forces on choices (5.6b) of connection 3.

3.5 Optimal design

This sub-chapter is going to propose an optimized design. In this suggestion, the structural member of the wall is re-designed to minimize the number of components that have direct contact with the connection compared to the original wall. The number of vertical studs was reduced by using others with bigger cross-sections. For instance, the original design composed of 20 numbers of 45mm*95mm vertical studs were distributed within 6000mm. This number is reduced to 6 studs in this design, within the same distance. The horizontal members are also updated to bigger dimensions to fulfill the demand in the proposed design. In addition, the number of OSB panels is changed from 5 to 4 to fit the updated model. Figure 3.15 is a 3D model of the original wall, and the new one shows the differences.

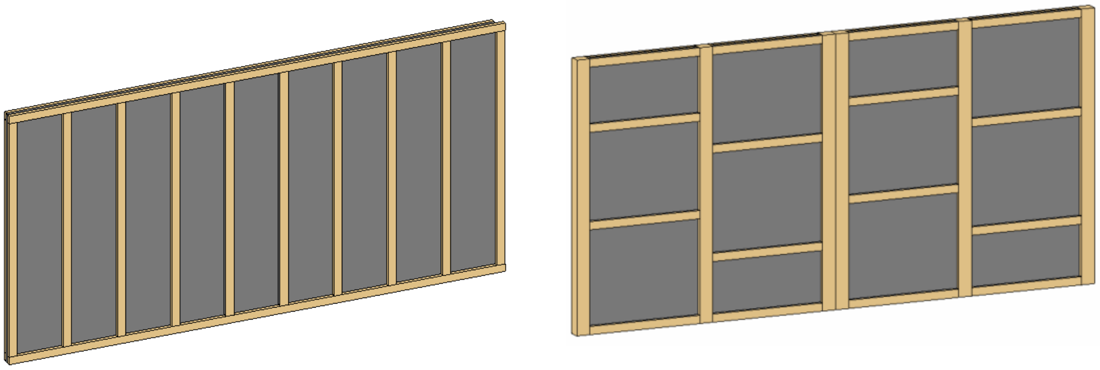
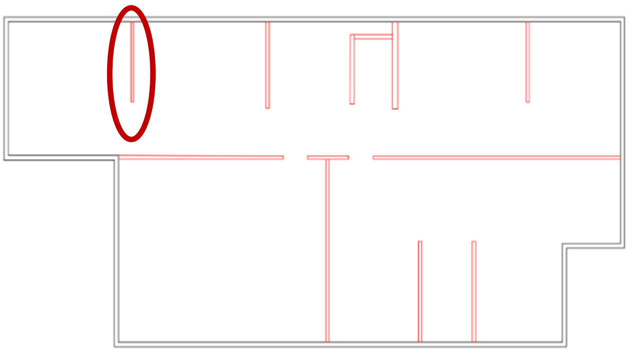


Figure (3.15) Original and suggested design for shear wall.

The studied wall is marked on the building plan, the length of the wall is 3000mm, and its thickness is 130 mm. See Figure 3.16



Figure(3.16) The studied wall on shear force.

To check the reliability of the suggested wall design, several controls should be conducted. Annex (E) illustrates the needed controls with specific calculations and dimensions of the structural members. Firstly, the vertical studs should be able to carry the vertical loads. Therefore, an analysis for the studs' capacity under parallel forces to the grains is checked. Secondly, the racking shear action and shear buckling on the OSB panels are examined, in addition, to define the required number of fasteners for resisting the shear force. Finally, a connection is designed to satisfy the uplifting force due to the wind load.

3.5.1 Capacity of the wall for vertical load

To check the capability of new suggested wall design, the vertical applied forces should be calculated:

1- Dead load: it includes the self-weight of the wall (3kN/m), and the self-weight of the slab with finishing layers (1kN/m^2, according to the company design summary).

2- Life loads: the life loads (2kN/m^2, according to company design summary) will be included in checking the capacity of the wall for vertical loads, but it will be excluded in calculating the wall capacity for uplifting forces.

3- Wind & Snow load: the vertical wind and snow loads on the roof is assumed to be transferred by the roof trusses, and as the transfer way of the forces from trusses to the walls are not clear so that these forces will be excluded. For that the capacity of existing wall will be used to compare the suggested alternatives capacities.
The contributed load area that affects the wall is 5000mm*4000mm. See Figure 3.17, the vertical forces on the wall.

Table (3.6) The active vertical loads on the selected wall.

Wall self-weight	Slab self-weight	Life Load	Total designed loads at ground floor
3 kN/m	6.7 kN/m for floor	13.3 kN/m for floor	165.3kN/m

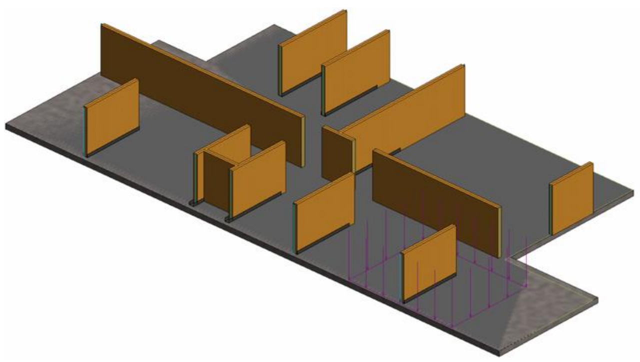


Figure (3.17) The contributed vertical load area on the designed wall.

For the first suggested wall design, the main three studs 130mm*110mm have enough capacity to resist the vertical loads, which the wall must resist.
While for the second suggesting design the three studs 90mm*150mm, also have enough capacity to transfer the vertical loads. See Annex (E).

3.5.2 Capacity of the wall for horizontal loads

The design applied wind force on the elevation of the building is equal to 1.72 kN/m^2, so the design applied wind load on the wall is 137.6 kN. See Figure 3.18.

The maximum moment capacity at the bottom of the wall of 16m height is 1101kN.m.
For more details see Annex (E)

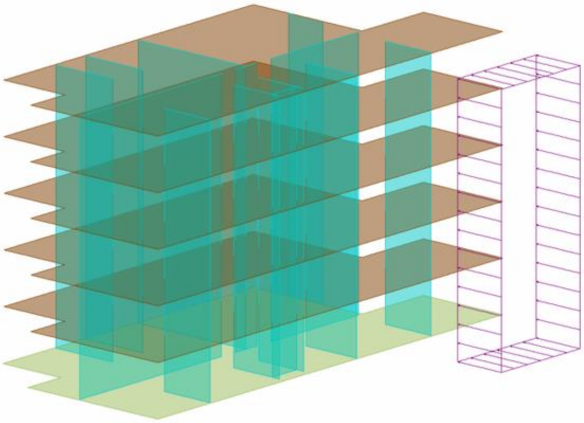


Figure (3.18) The contributed wind load area on the designed wall.

Both wall designs have the enough capacities for horizontal loads, for details check Annex (E).

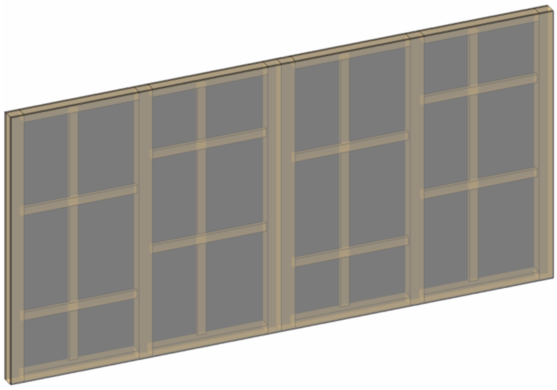


Figure (3.19) The design of suggested shearing timber wall (second alternative).

4 Discussion

This thesis aims to develop a connection type that makes the assemble and disassemble of timber building easier. For attaining that, a developed criterion will measure the connection suitability for detaching, and new alternatives are suggested to improve this aspect in Derome’s building DFS 90.

It is essential to highlight that the examination criterion is designed to consider the whole life cycle of the construction timber from design to the deconstruction stages. That is to ensure the possibility of practical construction dismantling, and at the same time reusing the structural elements, for those fifteen different criteria factors are used to examine each chosen connection. The results show,” wood reuse, accessibility, easy to assemble, time, and cost” are five essential factors that govern the disassembling degree of the connection. But, on another side, as the design for disassembling (DFD) means more cost and time-consuming in the design stage, the added value will increase by the ease of deconstruction and elements reusability. So, considering time and cost as vital factors was with good reason, besides the other three crucial factors.
Moreover, even this criterion is designed to examine the timber connections, but it is still applicable for other material connections, with few adjustments to fit the new material, as some factors cannot be used for various materials.

The analysis applied on DSF 90s’ different connections type for developing the more satisfactory ones, which can be used in the same building. The new suggested connections achieved high scores according to the defined criteria in comparison with the original one. Enhancing the accessibility, wood reuse, ease to assemble, task time, and cost were the critical factors that boost the disconnecting gauge. Using these connections will raise the added value of the timber constructions by increasing the structural parts, which can be prepared in the factory, decreasing the cost and the consumed time in assembling and disassembling, and ameliorate the reusability and the conveyance of the constructions. For this case, applying these alternatives will increase the usability of DSF 90. It will make its construction and deconstruction easier and quicker and grant the possibility of reconstruction by the same used timber members to reduce both factors cost and time in the building construction and deconstruction.

The analysis results show that, as the connection type is transferred from direct to indirect, it becomes more suitable for disassembling, also reducing the connecting and disconnecting tasks has a positive influence on the connection. The existing connections were chosen to be easy to connect, so they got a high score for assembling, but their preliminary design did not consider the disconnecting, so their scores were low. In contrast, the new connections detaching process is improved by appraising disconnecting factors, besides the first purpose of being easy assembling ones. Using the new connections will upgrade the building’s sustainability by allowing dismantling and reusing timber parts again in different timber construction. This improvement in detachable features resulted from the change in the design of existing connections by using different fasteners with a better specification which reduced the number of disconnecting tasks or by redesigning them to be more indirect connections by adding interfaces between the fastener and timber.

Finally, considering wood reusability in future timber construction will become an essential factor, and that will be realized by using better connections, which allow wood reusability in addition to their easy attaching and detaching.

5 Conclusion

This chapter is divided into two sub-chapters, the summary, and further research suggestions. The summary wraps the main ideas of this research, while the suggestions give the main steps to improve the timber deconstruction.

5.1 Summary

Sustainability and material reuse has essential values today. Companies desire to build for societies at present and in the future, making them an attractive workplace, and pioneer companies in their working field. Growing this trend affects the construction industry and requires a complete understanding of building materials using and specifications, as they are the essential components for project construction. That is applied to engineering timber, which using as building material increases due to its high reusability and recycling, for that timber becomes a chosen candidate for studying in terms of DFD.

The constructing, according to DFD, is an effective tool for companies to achieve sustainable buildings, increase the value of their projects, and decrease material cost and waste, which leads to expanding the studies within the assembling and disassembling field. For timber constructions, the connections which are used today need developing to be more convenient with the disassembling process, and this study reveals the potentiality of developing connections to be sufficient for DFD. As this study concentrates on Derome's DFS 90 building type, it is limited by the available data and design summary, and the suggested solutions may be more relevant to this building type, but using more data, and expanding the scope, can give more accurate results, which are applicable in various building kinds.

The first step to developing a detachable connection was evaluating the existing building and examining its used connections to abstract the general view and define the allowable change boundary. The next step was by suggesting new replacements for the exits connections and evaluating their functionality.
When the connection system of a timber building is designed to be detachable at an early stage, then the possibility of construction transfer or reuse in other projects will be very high. By doing so, sustainability can be achieved, and the material life cycle can be closed.

5.2 Suggestions for further research

This master thesis reflects an opportunity to push the limits of design for disassembly forward, to narrow the gap of building materials waste and squander as the DFD is an integrated concept that needs cooperating between all active people in this field, " researchers, engineers, designers, etc." to raise it to a level that makes it adopted in all future construction designs.

As a manifold concept, DFD needs to collect all possible data about the existing projects, the possibility of their recycling and reusability, and defining the catalysts and the obstructive; as a preliminary step, this step can be following by analyzing the gathering data to define a specific pattern which can be developed to be an introductory statement of standards for design disassembly construction. These standards, with more researches and applying the gained experiences through different projects, can be developed to be a guideline that evaluates the degree of disassembly possibility for each type of construction and its structural elements, which can be used to help designers,

engineers, and civil planners to develop their views and applications towards the DFD. Finally, this guideline can be added to BIM software, which can give the ability to specify the suitability degree for any design as a reusable one.
In the end, we hope this research will be a valuable part of many researches about DFD and helping to aware of the importance of this concept in the future life.

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7 Annex (A)

Weighted Factors

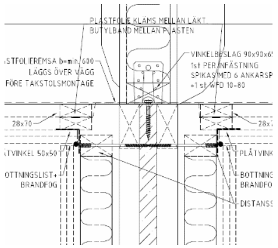
	Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity	Machinery	Visibility	Time	No. Connected Members	Reuse Connector	Easy to Assemble	Total Score	Weighted Factors
Capacity		0	0	0	0	0	0	0	0	0	0	0	0	0	1
Accessibility	1		0	1	1	1	1	1	1	1	1	0	1	10	3
Availability	1	0		0	1	0	0	0	0	0	0	0	0	2	1
Skills	1	1	0		1	1	1	0	1	1	0	0	0	7	2
Cost	1	1	0	1		1	1	1	1	1	1	1	1	10	3
Wood Reuse	1	1	1	1	1		1	1	1	0	1	0	1	10	3
Complexity	1	1	0	1	0	0		1	1	1	1	0	0	7	2
Machinery	1	0	1	1	1	1	0		0	1	0	0	0	6	2
Visibility	1	1	0	1	1	1	0	0		1	1	0	0	7	2
Time	1	1	0	1	1	0	1	1	1		1	0	0	8	2
No. Connected Members	1	1	0	1	1	0	1	1	0	1		0	0	7	2
Reuse Connector	1	1	0	0	1	0	0	0	0	1	0		0	4	1
Easy to Assemble	1	1	1	1	1	1	1	1	0	1	1	0		10	3

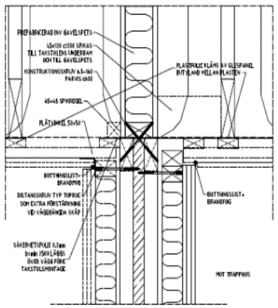
Scale Factors

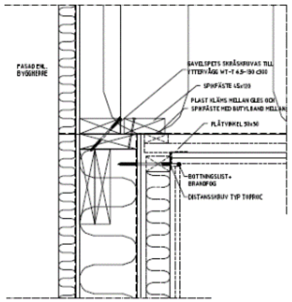
Accessibility	5	Easy to access from all sides without damaging finishing layers
	4	Easy to access with little damage for the wall layers
	3	To access the connection some parts should be demolished
	2	Two sides of the connectors are needed to demolish to access the connection
	1	Three sides should be damage to access the connection
Availability	5	The connector is common and very available
	4	The connector is available
	3	The connector is not common
	2	The connector is difficult to find / rarely used
	1	The connector is custom made
Skills	5	Deconstruction the connection does not need skills
	4	Trained labor is needed to disassemble
	3	Some skills is needed to disconnect
	2	A very high level of skills is required
	1	Experts are required for disconnecting

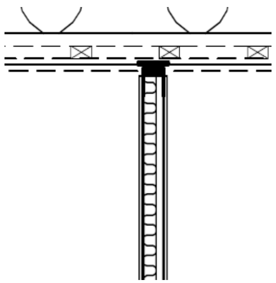
Cost	5	No need to use any machines
	4	Simple electrical tools are needed to dismantle (drills)
	3	More tools needed to be used
	2	Some big tools should be used
	1	heavy equipment to disconnect
Wood Reuse	5	The connected part can be used again with full potential
	4	The connected part little distorts that could affect its reuse
	3	The member can be used with restrictions (cut some parts and check the capability)
	2	Some damages occurred and may not be suitable to use
	1	The connected part is totally damaged and cannot be reused
Complexity	5	The shape of the connection is very simple
	4	The connection is less simple a few numbers of fasteners are used
	3	The connection is relatively complex, some fasteners make an angel with surface
	2	The shape is complex, and more fasteners are used
	1	The shape of the connection is very complex, and great number of fasteners are used
Machinery	5	Only very simple tools are needed to disconnect
	4	A simple equipment is used for disassembling (drills)
	3	More machines should be used to disconnect
	2	Bigger machines use to dismantle
	1	Heavy equipment is needed to disconnect
Visibility	5	The connector is very easy to be distinguished
	4	The connector is easy to be Seen
	3	The connector has relativity limited visibility
	2	The connector is partly hidden
	1	The connector is hidden by connected parts
Time	5	Dismantling time is very sufficient
	4	Deconstruction connection time sufficient
	3	Disconnecting is relatively consuming
	2	To disconnect more time is consumed
	1	A long time is needed to disconnect
No. of connected members	5	The connection is connected to one element, so its disconnecting is very easy
	4	Two members are within the same connections, so dismantling it will be not easy
	3	The connection is used to connect three or four elements
	2	Combined connection, with more connected members
	1	Many members are connected with combined connection, which means difficulties at disassembling
Easy to assemble	5	Very easy to assemble (in term of time, cost, work capacity)
	4	Easy to assemble (according to type and number of fasteners)
	3	Relatively difficult according to the type of used connection
	2	Difficult to install connection
	1	Very difficult to implement

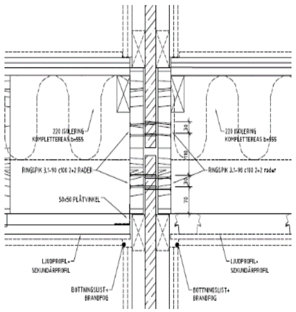
8 Annex (B)

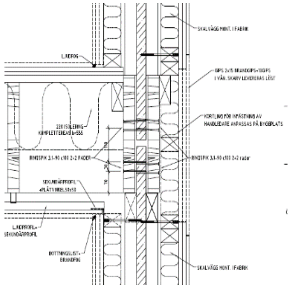
Group1 / Connection 1		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
Importance: V	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	4	5	4	4	3	4
		For all connections, the capacity assumed to be fulfilled	**The Accessibility is limited, from the roof side**	**The used fasteners are commonly used**	**Some skills are needed to disassemble due to steel angle**	**Disconnecting is a little costly as a drill is needed**	**Screws distort wood when applied and may damage it when removed**	**It is a little complex as there are metal plate, and screw**
	Weighted Score	5	12	5	8	12	9	8
KP - 25.6 -106 Mechanical connection Fasteners are screws with metal angle Horizontal level Connect an internal bearing wall and roof Very important as it is with bearing wall and repeated frequently		**Machinery**	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	4	4	3	4	4	4	
		Only drill will be needed to disconnect it	**The metal angle allows distinguishing the screw's head**	**Consumed time for disconnecting to distinguish side screws**	**Connects two Structural members**	**Screws may be damaged when removing**	**Relatively easy to assemble due metal angle using**	**Total score**
	Weighted Score	4	4	6	8	4	12	**97**

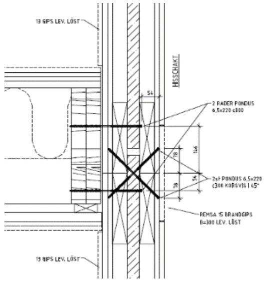
Group 1 / Connection 2		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
Importance: V	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	3	5	3	3	2	3
		It connects between the bearing wall and roof so it should have enough capacity	**Accessibility is limited Accessing to inclined screws is more challenging**	**Screws are common fasteners, and available**	**Releasing the inclined screws needs some skills**	**Disconnecting is a little costly Due to inclined screws more tools may be used**	**Inclined Screws distorts wood more when applied and may damage it when removed**	**It is more complex as inclined screws are used**
	Weighted Score	5	9	5	6	9	6	6
▪ KP – 25.6 - 106 ▪ Mechanical connection ▪ Fasteners are straight and inclined screws ▪ Horizontal level ▪ Connect an internal bearing wall and roof ▪ Very important as it connects the bearing wall and repeated frequently		**Machinery**	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Scale factors	4	3	2	4	4	4	
		The only drill will be needed to disconnect it	**It is a little difficult to distinguish the head of screws**	**Exist inclined screws will increase consumed time, besides, the limited accessibility**	**Connects two structural members**	**There is a chance for screws to be damaged**	**It is direct connections but with two inclined screws**	**Total score**
	Weighted Score	4	3	4	8	4	12	**81**

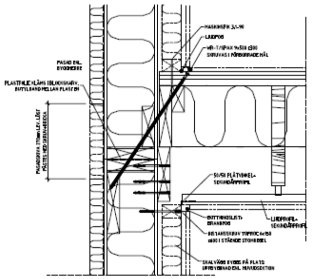
Group 1 / Connection 3		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
Importance: V	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	2	5	3	4	3	4
		It connects between the bearing wall and roof so it should have enough capacity	**The accessing to connector is from in inner side only, and roof layers should be damaged**	**Screws are available fasteners**	**Some skills needed for inclined screws**	**Drill is needed to disconnect it**	**The member can be used after checking**	**The connection is relatively simple**
	Weighted Score	5	6	5	6	12	9	8
▪ KP – 25.6 -106 ▪ Mechanical connection ▪ Fasteners are straight and inclined screws ▪ Horizontal level ▪ Connect an external bearing wall and roof ▪ Very important as it connects the bearing wall and repeated frequently		**Machinery**	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Scale factors	4	3	3	4	4	4	
		The only drill will be needed to disconnect it	**It is little difficult to distinguish the head of screws**	**Disconnecting is a time consuming**	**Only two main members are connected**	**Screws can be damaged when it removed**	**Installing the connection with inclined screws is relatively challenging**	**Total score**
	Weighted Score	4	3	6	8	4	12	**88**

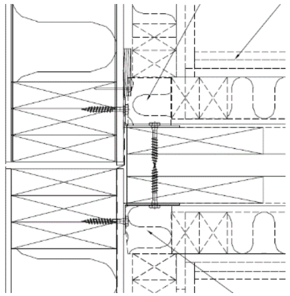
Group 1 / Connection 4		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
Importance: M	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	3	5	4	3	3	3
		It connects between the dividing wall and roof so it should have enough capacity	**Finishing layers should be removed from both sides**	**Screws are commonly used fasteners**	**Some skills are needed**	**Disconnecting is a little costly**	**Using u shape metal allows limiting the wood damage**	**Using U shape metal, and screws increase the complexity**
	Weighted Score	5	9	5	8	9	9	6
▪ KP – 25.6 -106 ▪ Mechanical connection ▪ Fasteners are screws and U shape metal plate ▪ Horizontal level ▪ Connect an internal dividing wall and roof ▪ Medium important as it connects dividing wall and repeated frequently		**Machinery**	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Scale factors	4	4	3	4	4	3	
		The only drill will be needed to disconnect it	**The screws can be Seen on the metal plate**	**Time is needed to disassemble the screws then detaching the metal plate**	**Only two members connected**	**Some of the fasteners cannot be used again**	**The connection shape and the used fasteners are relatively easy to apply**	**Total score**
	Weighted Score	4	4	6	8	4	9	**86**

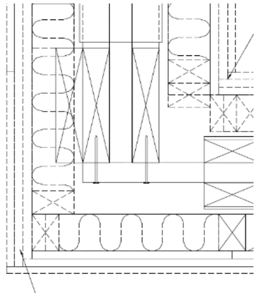
Group 2 / Connection 1		**Capacity**	**Accessibility**	**Availability**	**Skills**	**Cost**	**Wood Reuse**	**Complexity**
Importance: V 	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	2	5	4	4	1	3
		It connects between dividing wall and floor it should have enough capacity	**It is difficult to access through floors, and from both sides**	**Nails are available fasteners**	**Some skills are needed**	**Disconnecting is a little costly as some tools are needed**	**While removing nails there is a big possibility to damage the wood**	**Using extra timbers in connection makes it more complex**
	Weighted Score	5	6	5	8	12	3	6
▪ KP – 25.6 -104 ▪ Mechanical connection ▪ Fasteners are nails ▪ Horizontal level ▪ Connect walls extension with floor ▪ High important as it connects the wall with the floor and repeated frequently		**Machinery**	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Scale factors	3	3	3	4	3	4	
		Tools are needed to disconnect	**The visibility of nails head will decrease over time**	**Dismantling consumes time due to the assembling way and using extra timber**	**Only two members connected**	**Big chance for nails to be damaged and cannot be used again**	**There is no complexity in the shape, and the used fasteners are simple**	**Total score**
	Weighted Score	3	3	6	8	3	12	**80**

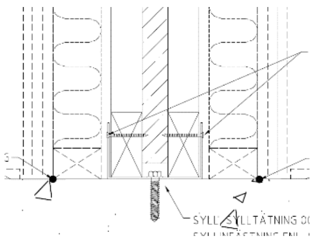
Group 2 / Connection 2		**Capacity**	**Accessibility**	**Availability**	**Skills**	**Cost**	**Wood Reuse**	**Complexity**
Importance: V 	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	2	5	4	4	1	3
		It connects between the elevator wall and floor so it should have enough capacity	**Accessing the connection is difficult at least from one side**	**Screws and nails are commonly used fasteners**	**Some skills are needed**	**Disconnecting is a little costly as tools are needed**	**High possibility for wood to be damaged**	**Using the extra parts of timber increases its complexity**
	Weighted Score	5	6	5	8	12	3	6
▪ KP – 25.6 -104 ▪ Mechanical connection ▪ Fasteners are nails and screws ▪ Horizontal level ▪ Connect walls with the floor at the elevator ▪ High important as it connects the wall with the floor and repeated frequently		**Machinery**	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Scale factor	3	3	2	4	3	4	
		Tools and drills will be needed to disconnect it	**The visibility of nails and screws head will be limited**	**Disconnection needs a long time for nails, and screws from one side**	**Only two members connected**	**Nails mostly will not be used again**	**The current connection is easy to apply**	**Total score**
	Weighted Score	3	3	4	8	3	12	**78**

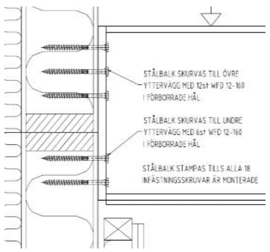
Group 2 / Connection 3		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
Importance: V	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	2	5	4	3	3	3
		It connects between the dividing wall and roof so it should have enough capacity	**Accessing the connection is difficult at least from one side**	**Various kinds of screws are available**	**Some skills are needed For inclined screws**	**Disconnecting is a little costly as a more than drill may be needed**	**The way of fastening by inclined screws can limit the reusing wood**	**Two inclined screws are used**
	Weighted Score	5	6	5	8	9	9	6
▪ KP – 25.6 -104 ▪ Mechanical connection ▪ Fasteners are straight and inclined screws ▪ Horizontal level ▪ Connect walls with the floor at the staircase ▪ High important as it connects the77 wall with floor and repeated frequently		**Machinery**	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Scale factors	4	3	3	4	4	4	
		Only drill will be needed to disconnect it	**Head of screws visibility will be limited by time**	**Disconnection consuming time with inclined screws existing**	**Only two members connected**	**The screws may not be used**	**Screws apply is very simple**	**Total score**
	Weighted Score	4	3	6	8	4	12	**85**

Group 2 / Connection 4		**Capacity**	**Accessibility**	**Availability**	**Skills**	**Cost**	**Wood Reuse**	**Complexity**
Importance: V	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	2	5	4	3	1	3
		It connects between the external wall and floor so it should have enough capacity	**Accessing the connection is difficult at least from one side as it is outer wall**	**Screws are commonly used fasteners**	**Some skills are needed**	**Disconnecting is a little costly as tools and a drill is needed**	**Due to many used screws reusing the wood may not be acceptable**	**Inclined, and many screws are used**
	Weighted Score	5	6	5	8	9	3	6
▪ KP – 25.6 -104 ▪ Mechanical connection ▪ Fasteners are straight and inclined screws ▪ Horizontal level ▪ Connect external walls with floor ▪ High important as it connects the wall with the floor and repeated frequently		**Machinery**	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Scale factors	3	3	2	4	4	4	
		Only a drill will be needed to disconnect it	**Head of screws visibility will be limited by time**	**Disconnection consumes time due to the large number of screws**	**Only two members connected**	**The screws may not be used**	**Screws apply is very simple**	**Total score**
	Weighted Score	3	3	4	8	4	12	**76**

Group 3 / Connection 1		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
Importance: M	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	3	5	3	4	4	3
		It connects between the dividing wall and roof so it should have enough capacity	**Some of wall layers should be removed**	**The fasteners are commonly used**	**Good experience needed to deconstruct the current connection**	**Disconnecting is a little costly as a drill is needed**	**Reuse the wood is very high as angle shape metal plate is used**	**The connection is relatively complex to disconnect**
	Weighted Score	5	9	5	6	12	12	6
▪ KP – 40.6 - H ▪ Mechanical connection ▪ Fasteners are screws ▪ Vertical level ▪ Connect dividing walls ▪ Medium important as it attaches dividing wall together and repeated frequently		**Machinery**	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Scale factors	4	5	4	4	4	4	
		The only drill will be needed to disconnect it	**The screws are easily be Seen on the metal angle**	**No long time is needed to dismantle**	**Only two members connected**	**The screws may not be used**	**Applying the connection is almost simple**	**Total score**
	Weighted Score	4	5	8	8	4	12	**96**

Group 3 / Connection 2		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
Importance: M 	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	2	5	4	4	2	4
		It connects between the dividing wall and roof so it should have enough capacity	**Accessing to connection is difficult as it is from the outer side**	**Nails are very used fasteners**	**No skills are needed**	**Disconnecting is a little costly as tools are needed**	**Big possibility to damage the wood when removing nails**	**It is not complex**
	Weighted Score	5	6	5	8	12	6	8
▪ KP – 40.6 - H ▪ Mechanical connection ▪ Fasteners are screws ▪ Horizontal level ▪ Connect external walls ▪ Medium important as it attaches to an external wall and repeated frequently		**Machinery**	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Scale factors	4	3	3	4	2	4	
		Simple tools are needed to disconnect	**Distinguishin g nails heads will be difficult over time**	**Deconstruct consumes time as the accessibility from one side**	**Only two members connected**	**Mostly nails cannot be used again**	**Screws apply is very simple**	**Total score**
	Weighted Score	4	3	6	8	2	12	**85**

Group 3 / Connection 3		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
Importance: V	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	2	5	3	3	2	4
		It connects between the dividing wall and concrete slab so it should have enough capacity	**Accessibility is limited to accessing the connection several layers are needed to be dismantle**	**Metal plate, screws and nail are very available fasteners**	**No skills are needed**	**Disconnecting is costly as tools and a drill are needed**	**Reuse wood is limited due to the number of transversal used fasteners**	**It is not complex, but the metal U shape plat should be dismantled**
	Weighted Score	5	6	5	6	9	6	8
▪ KP – 40.6 - 05 ▪ Mechanical connection ▪ Fasteners are screws with U shape plate ▪ Vertical level ▪ Connect dividing walls to the concrete slab ▪ Very important as it attaches the wall with concrete slab and repeated frequently		**Machinery**	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Scale factors	4	4	3	2	3	3	
		The only drill will be needed to disconnect it	**On the metal plate, the heads of fasteners are clear**	**Time-consuming to remove the wall and then the metal plate**	**Several members are connected that makes dismantling challengeable**	**Some restriction in term of reuse the fasteners**	**Considering the numbers of connected elements, time, and cost**	**Total score**
	Weighted Score	4	4	6	4	3	9	**74**

Group 3 / Connection 4		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
Importance: V	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	3	5	4	3	3	4
		It connects between the dividing wall and roof so it should have enough capacity	**Accessing is limited as the beam could be cover by the suspended ceiling**	**Screws are common fasteners**	**Some skills required for disconnectin g**	**More tools are needed to disassemble the connection**	**Large number of fasteners are used**	**It is simple**
	Weighted Score	5	9	5	8	9	9	8
▪ KP – 40.6 - 04 ▪ Mechanical connection ▪ Fasteners are screws ▪ Horizontal level ▪ Connect wall with a beam ▪ Very important as it attaches to the wall and beam and repeated frequently		**Machinery**	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Scale factors	4	4	4	4	4	4	
		The only drill will be needed to disconnect it	**The head of screws are visible on the steel plate**	**Some time is needed to disconnect the beam**	**Only two members connected**	**The screws may not be used**	**Screws applying is very simple**	**Total score**
	Weighted Score	4	4	8	8	4	12	**93**

Annex (C)

In association with
Derome AB

A variety of different timber connections that allows DFD

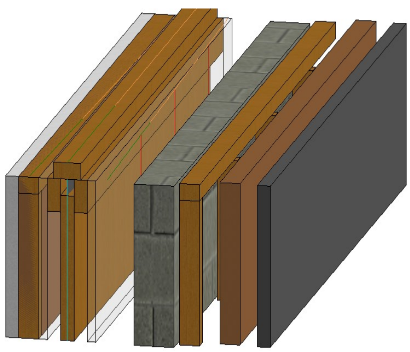
(Derome, 2021)

Written by Abdulrahman Al Shamaa and Khadeen Saleeh

Supervised by Robert Jockwer and Ander Karlsson

Wall components properties

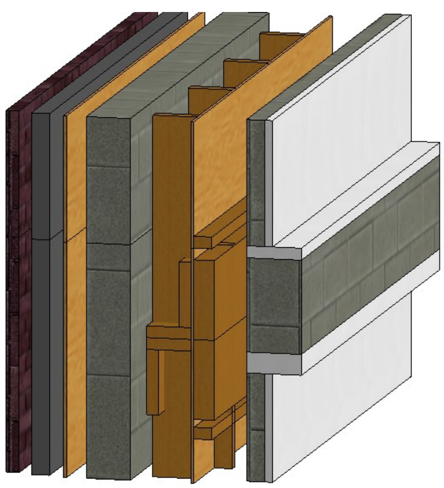
The 3D-modeling and the tables below illustrate the original wall design, functionality, dimensions, and material properties.



Layers

EXTERIOR SIDE

	Function	Material	Thickness	
1	Finish 1 [4]	Gypsum Wall Board	45.0	☑
2	Thermal/Air Layer [3]	Polyurethane Foam	70.0	☑
3	Thermal/Air Layer [3]	Air	30.0	☑
4	**Core Boundary**	**Layers Above Wrap**	**0.0**	
5	Structure [1]	Timber-C24	138.0	☐
6	**Core Boundary**	**Layers Below Wrap**	**0.0**	
7	Thermal/Air Layer [3]	Air	30.0	☑
8	Thermal/Air Layer [3]	Polyurethane Foam	70.0	☑
9	Finish 1 [4]	Gypsum Wall Board	45.0	☑



Layers

EXTERIOR SIDE

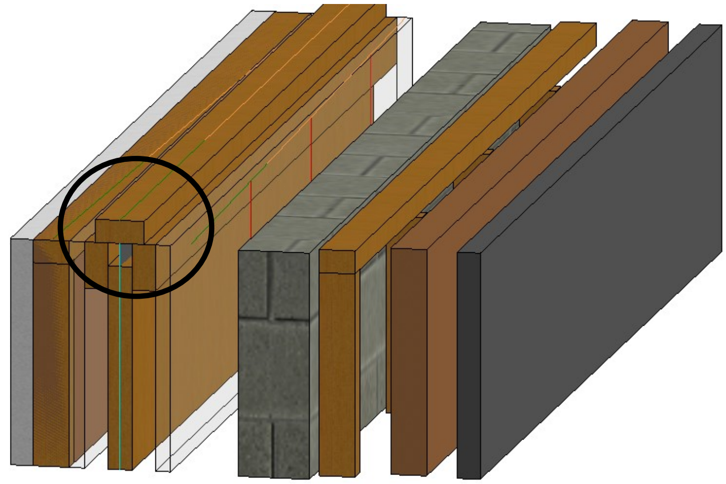
	Function	Material	Thickness	V
1	Finish 1 [4]	Brick, Common	50.0	☑
2	Thermal/Air Layer [3]	Rigid insulation	70.0	☑
3	Substrate [2]	Plywood, Sheathing	11.0	☑
4	**Core Boundary**	**Layers Above Wrap**	**0.0**	
5	Structure [1]	CMU, Lightweight	170.0	☐
6	**Core Boundary**	**Layers Below Wrap**	**0.0**	
7	Substrate [2]	Plywood, Sheathing	11.0	☑
8	Thermal/Air Layer [3]	CMU, Lightweight	70.0	☑
9	Finish 1 [4]	Gypsum Wall Board	30.0	☑

Layers

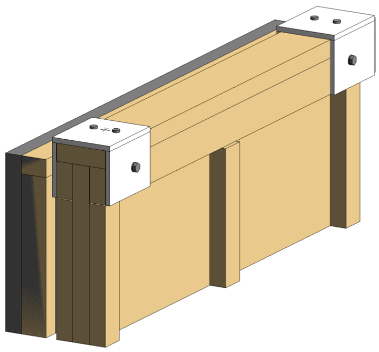
EXTERIOR SIDE

	Function	Material	Thickness	
1	Finish 1 [4]	Gypsum Wall Board	45.0	☑
2	Thermal/Air Layer [3]	Polyurethane Foam	70.0	☑
3	Thermal/Air Layer [3]	Air	30.0	☑
4	**Core Boundary**	**Layers Above Wrap**	**0.0**	
5	Structure [1]	Timber-C24	138.0	☐
6	**Core Boundary**	**Layers Below Wrap**	**0.0**	
7	Thermal/Air Layer [3]	Air	30.0	☑
8	Thermal/Air Layer [3]	Polyurethane Foam	70.0	☑
9	Finish 1 [4]	Gypsum Wall Board	45.0	☑

Connection 1

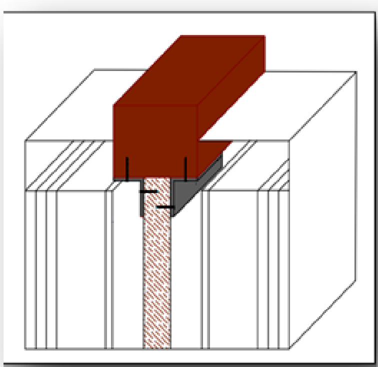


Choice 1



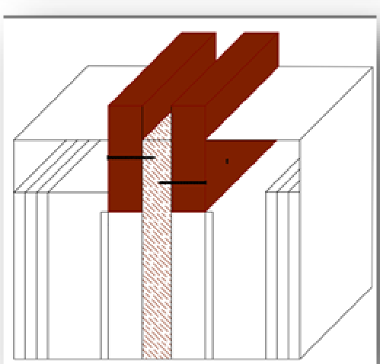
Description	Improvement
The timber section above the roof was replaced by a bigger one, and bolts with a single shear connector were added with U shape metal plate instead of inclined screws.	The new connection is quicker and easier to disconnect as only the release of the bolt is needed. By using the bolt instead of screws, fewer connectors are used as the shear capacity of bolts is larger. But, by using the bolt, a bigger predrilled hole is needed that may allow for slight horizontal movement for the parts.

Choice 2



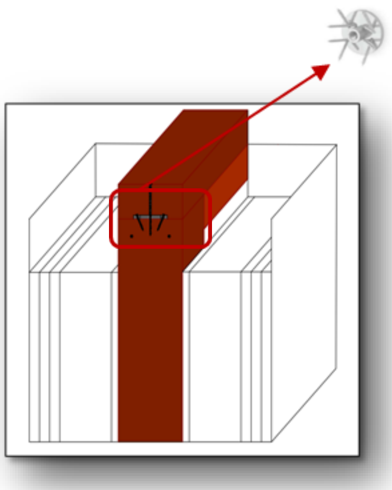
Description	Improvement
All timber sections were replaced by a bigger one that will extend to the roof, and it is connected to OSB by steel angle and screws. If using the screws is not practical with OSB, a bolt with a nut can be used instead	The disconnecting time will be shorter by using metal, and distinguishing the screw head will be easier. Using steel angles will allow the use of fewer screws with a smaller diameter. However, connecting the angle to OSB can be nonpractical. Besides. Using one large timber section may require some changes in the wall section.

Choice 3



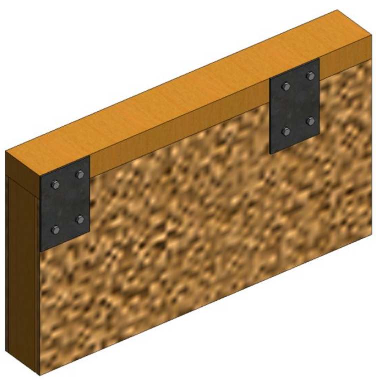
Description	Improvement
In this connection, the timber section above the roof is canceled, and two more significant timber sections at the end of the wall are used instead, which allow connecting the parts of the upper wall directly to them with no need for extra section, the used fastener, in this case, can be nails or screws, without any need to use the inclined screws.	By Using this connection, no significant changes in the wall's section are needed, but on another side, the same fastener types were used, while the inclined ones are canceled. By removing the inclined screws, the connection will be better in terms of disconnecting, but it will not better connect timber sections to OSB, and parts of the upper wall will be by screws.

Choice 4



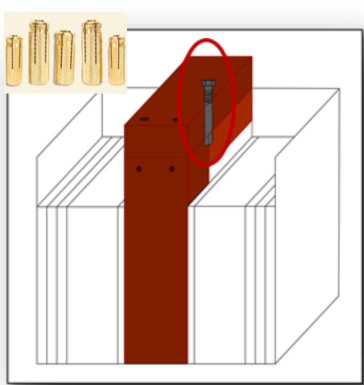
Description	Improvement
In this connection choice, some changes for wall sections will take place, a more significant section should be added above the roof, and another section opposite to it at the top of the wall, so the new disk connector can be added, but on another side, the disconnecting will be very simple, as only releasing the upper screw is needed.	This type of connectors making assembling and disassembling very easy and quick as the connection disk can be prefixed, and only a screw is needed at the site to join the two members, with no need for any different kinds of fasteners. However, fixing the disk need more fasteners that could cause some distorts for the timber section. Besides, the screw from the roof side should be reached for disconnecting as it is a hidden connection on another side as a hidden connection will have some advantages for fire resistance, and by using bolts instead of screws, the used number of the connector can be reduced.

Choice 5



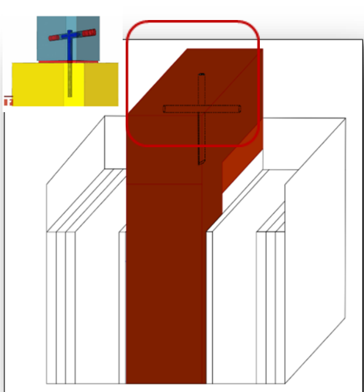
Description	Improvement
For this choice, the wall structure should be changed, two OSB boards will be the outer parts of the wall, and a wider timber section will be at the start and the end of the wall the same for the timber section roof. A metal plate and screws will be used in this connection to connect the upper section to the wall. Using a metal plate with a screw will reduce the needed number of connections	Using metal plate with screws will increase the ability for screws to be seen easily; also, even using the metal plate has a negative effect like more damage for the wood at its location, but using more screws in metal plate will reduce the number of user connections, that will lead to quick and easy parts detaching.

Choice 6

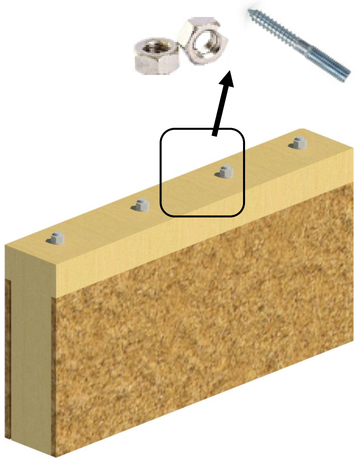


Description	Improvement
For this choice, the wall structure should be changed; bigger timber sections will be used at the top and side of the wall and above the roof. An anchor brass with a bolt is used to connect parts together.	By using bolt and anchor brass, connecting and disconnecting will be easier. By releasing the bolt, the two timber sections will be separated easily. Using bolt will reduce the number of fasteners, which means less wood distorts, but the bolt in the roof should be reached to disconnect the connection.

Choice 7

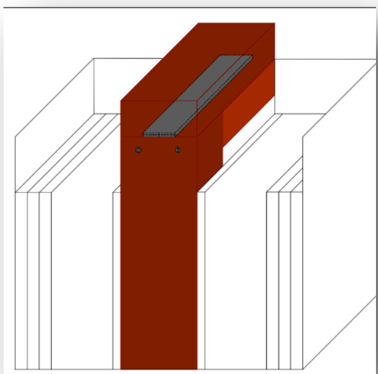


Description	Improvement
For this choice, the wall structure should be changed. Bigger timber sections will be used at the top and side of the wall and above the roof. A new type of hidden connection is used, consisting of a bolt with brass, and it can tighten or release from sides.	Using this type of connection will reduce the needed number of connectors. However, also larger timber sections should be used to apply it. Reaching it from the sides only, and both sides should be released to disconnect it. As it is a hidden connection, more wood should be removed, affecting reusing the wood



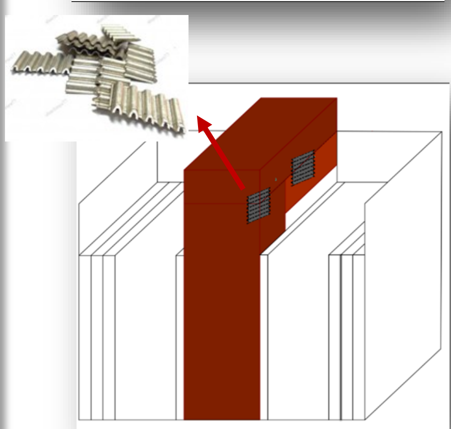
Choice 8

Description	Improvement
As the previous choices, wider timber sections should be used, steel dowel and bolt will join the timber parts.	In this connection, using a bigger diameter will decrease the used connector, and for disassembling it, releasing the nut is only needed, but as it is hidden, the only way to disconnect it is to release the nut from the roof side.



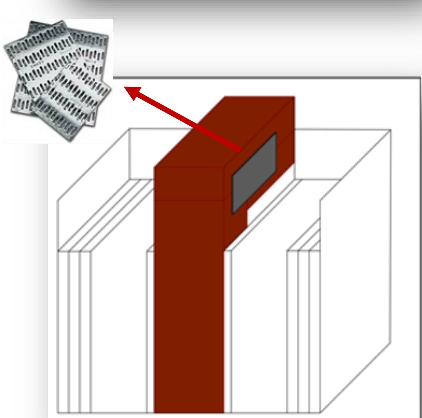
Choice 9

Description	Improvement
This choice as the previous choices wider timber sections should be used, steel channel is used to connect the parts together.	The metal channel will lead to fewer used fasteners, as fixing the metal channel needs fewer screws to fix, and the upper part also the same. This connection will be hidden to detached the joined parts. The screws from the roof should be released first.



Choice 10

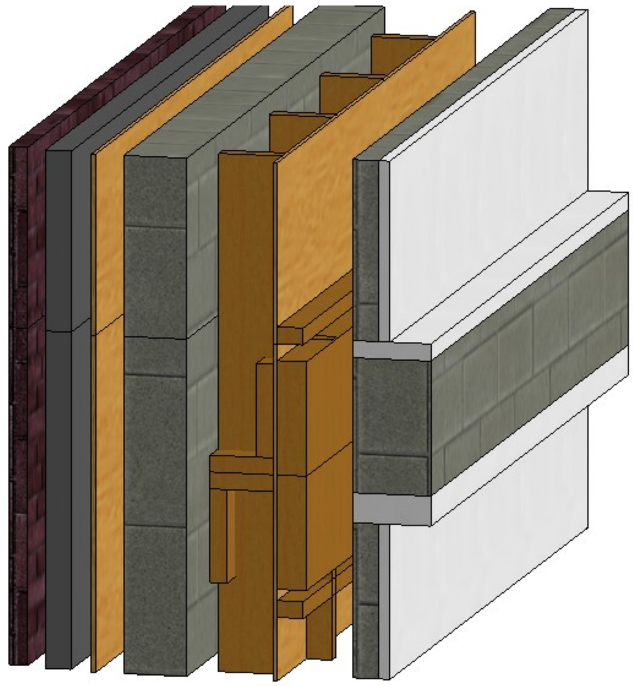
Description	Improvement
Corrugated steel connection is used in this choice to connect parts. In this option, the timber section in the roof should be changed to a wider one, while other used parts may stay the same	This connection will be tough to be distinguished, and it is not easy to dismantle, so for disconnecting wood broken at connection apply has a high possibility.

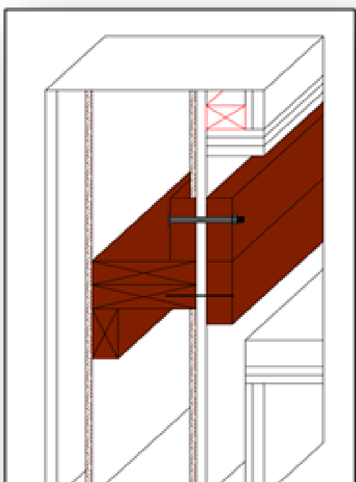


Choice 11

Description	Improvement
Applying nailed steel plate is suggested in this choice, for this suggestion wider timber sections were used, it is easy to assemble and few numbers of this connection type is needed.	This connection will be very hard to dismantle, and the possibility of reuse the wood at fixing location is low, but on the other side, the needed number is very few as its capacity is large.

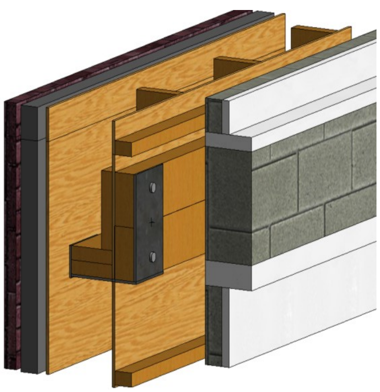
Connection 2





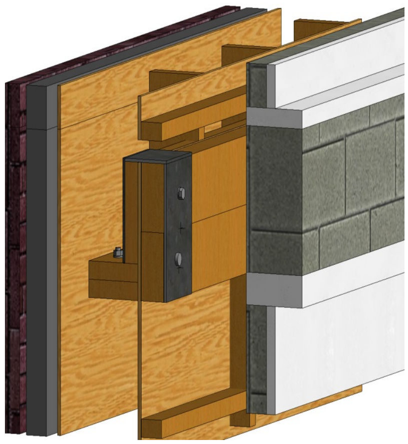
Choice 1

Description	Improvement
The same timber sections were used instead of using the inclined screw, the timber sections were connected together by bolts for the top wall and screw for the lower wall.	Using the bolt instead of the inclined screw will decrease the disconnecting time and will reduce the number of fasteners while using a screw with a larger diameter for the lower part of the wall will lead to fewer needed screws.



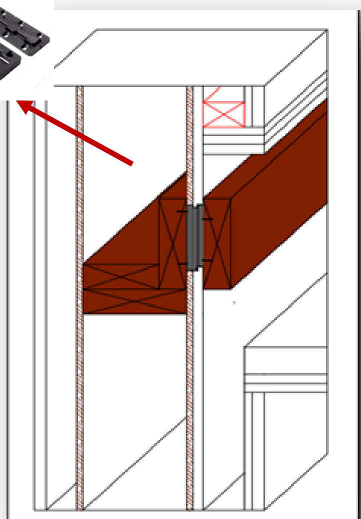
Choice 2

Description	Improvement
In this choice the almost the same timber sections were used, and they joined by a metal plate and screws, the upper screw can be replaced by a bolt.	Using a metal plate will make disconnecting easier, as the screws will be visible. Accessing the connection from one side is enough to release the connected parts. Besides, the needed number of connections will be less as the capacity of this connection is bigger.



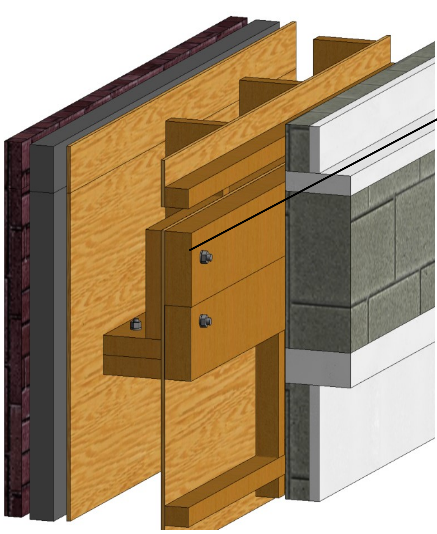
Choice 3

Description	Improvement
In this choice, almost the same timber sections were used. U shape a metal plate is used to connect timber sections with bolts and screws as a fastener.	Assembling and disassembling of this connection is easy and quick. Releasing the bolt will disconnect the timber section, and the accessing is needed from one side only.



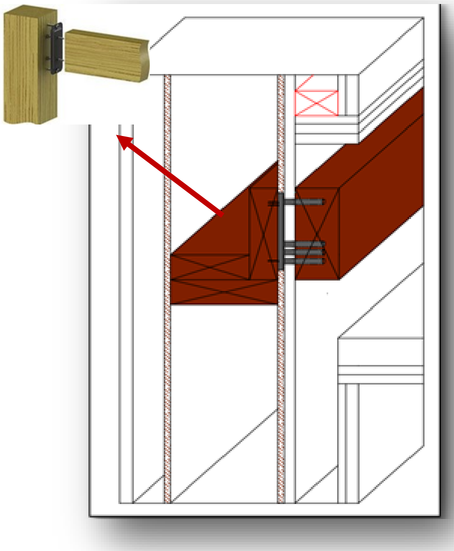
Choice 4

Description	Improvement
For this choice, bigger sections of timber were used, and a connector of two pieces was used to connect the timber section. The connector was fixed by screws.	Fixing the parts of the connector can be at the site or in the factory makes assembling very active; for disassembling, it only needs to shift one timber section upper to release the connection.



Choice 5

Description	Improvement
For this choice, bigger sections of timber were used, and the connector is a metal dowel with a nut for joining the timber sections.	Using metal dowel with nut makes the mental and dismantle the connection easy and can be done at the site. Releasing the nut is enough to disconnect the parts, and accessing from one side is enough.

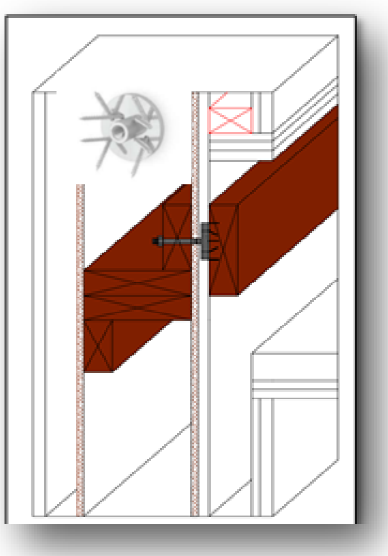


Choice 6

Description	Improvement
For this choice bigger sections of timber was used, and the connector is a metal plate with dowels.	Using this kind of connector is practical as connecting and disconnecting is very easy but it needs to remove more wood from the section.

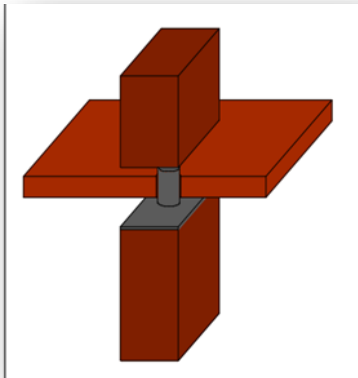
Choice 7

Description	Improvement
In this connection, the timber section of floor slab was changed only, and the connection is connecting only the lower wall by the slab. 2mm metal plate and screws were used for connection timber members.	This connection allows disconnecting the upper wall separately from the slab. That gives an advantage when deconstructing the whole building. Removing the screws in the slab timber section is enough to detach all parts, but in this case, only access from the slab is available for dismantling.



Choice 8

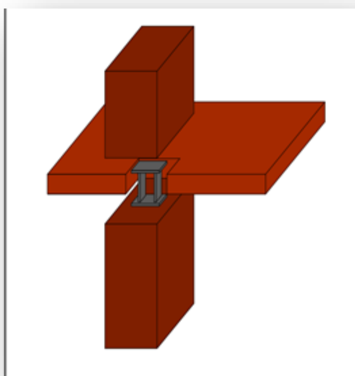
Description	Improvement
In this connection, the timber section of the floor slab was changed only, and a disk connection is used for connecting the slab with the external wall. In this case, bolts are used to connect a disk with the outer wall timber part as it is easier to release. A screw can be used instead of a bolt.	This choice is effortless to assemble and disassemble. The disk can be prefixed, and at the side, adding the bolt is needed only, but as a hidden connection, the access will be available from one side only, and using more screws to fix the disk can cause wood distorting at its fixing location.



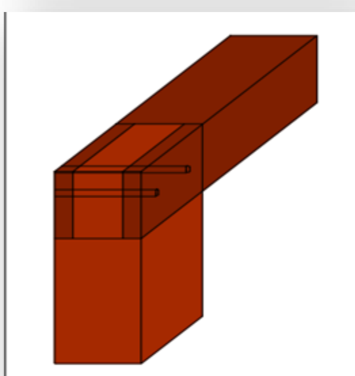
Choice 9a

Description	Improvement
This connection applies to slab and column construction types. Big column section and CLT slab will be used, cy-lindrical metal connection to connect the columns, and slab will lay on the column.	This connection is very suitable for this construction system, it can be prefixed, and it needs only the joining at the site while fixing the slap on the column is simple this system is suitable for de-construction

Choice 9b



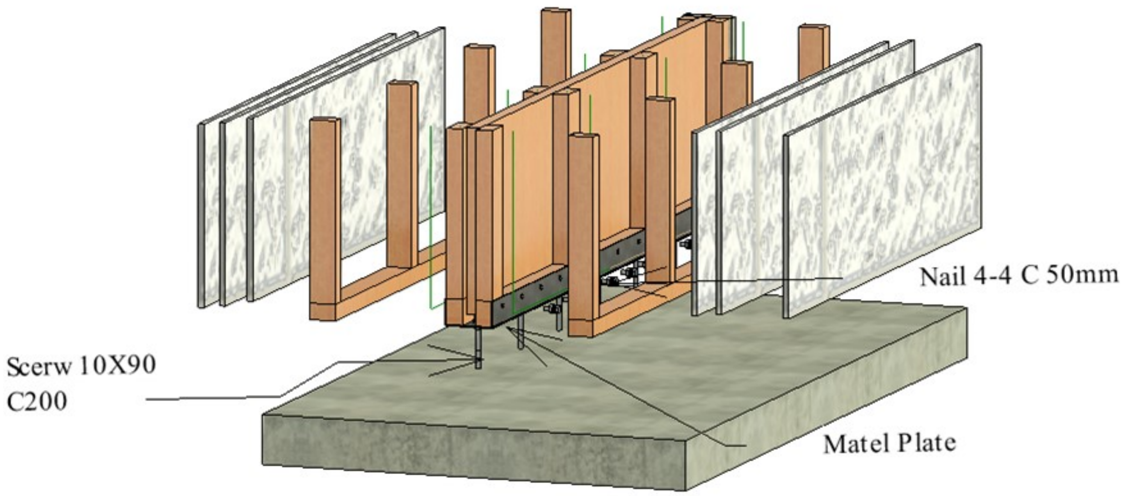
Description	Improvement
As the previous choice, this connection applies to slab and column construction types. Big column section and CLT slab will be used as a structural mem-ber, and metal H shape uses to connect the columns while the slab will lay on it.	Also, this type of connection is very suitable for this construction system, the connection can be fixed at the site or prefixed at the factory and then needs only joining at the site, slab fix-ing will be with the column, and it is simple and easy. For disconnecting, the connection is exposed from all sides, and by removing the bolts, the column will be detached. In this system, there is no need at all to remove any wood from timber sections. in general, this system is proper for assembling and disassembling



Choice 10

Description	Improvement
This choice uses in beam and column construction, joinery connection is applied by using wooden dowels, and glue to fasten the beam with column.	This connection is not easy to apply machinery works are needed to prepare the wood, besides large part of timber sections at the connection loca-tion should be removed. Furthermore, using the glue will delete any possibil-ity for disconnecting the connecting with keeping timber sections in good condition to be reused.

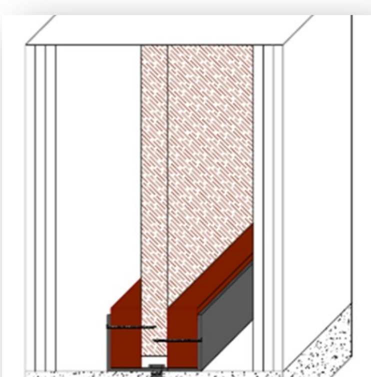
Connection 3



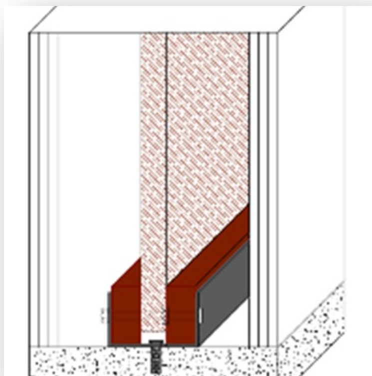
This 3D model has been made to distinguish the processes of accessing the examined connection. Firstly, the finishing layers need to be removed. Secondly, the nonstructural framing and the insulation between them will also be removed. This is required it be made from both sides of the wall. A huge number of nails, as the figure indicates, are used on both sides. The process of dismantling such a connection is highly time-consuming and costly. In addition, the potential of wood re-use is relatively limited. This model will be referred to as the original design.

Choice 1

Description	Improvement
As the figure indicates, the connection is composed of the same configuration as the 3D model presented under the title of this chapter. In terms of characteristic and dimension, the same metal plate is used and the same arrangements to the structural and nonstructural members. The difference in this choice is the use of a different type of fasters that provide a higher shear capacity to minimize the number of connectors.	There is a slight improvement in this choice. For instance, choosing a higher dimensioned fastener will indicate a higher shear capacity to resist the shear force. This will minimize the number of connectors in the connection. Another improvement is using dowels or even other mechanical connectors. The slight change increases the potential reuse, which is the structural member located between the U shape. Using a smaller number of fasteners reduces the labor time and cost, but the effect of the minor improvement is small since there are no significant changes in the configuration in general. However, the accessibility is still limited with this design since reaching the connecter is the same as the 3D model.

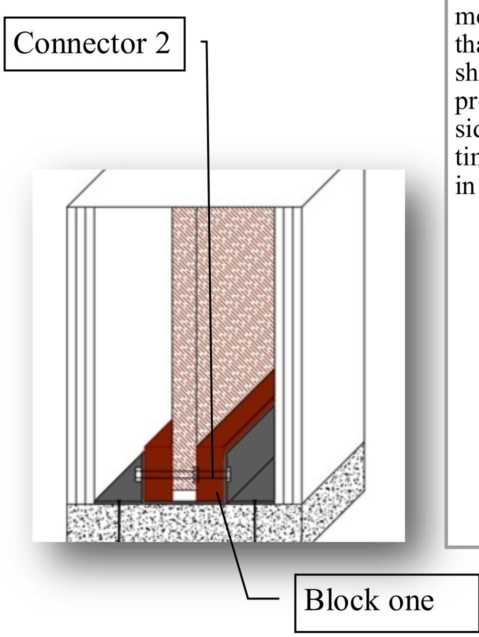


Choice 2

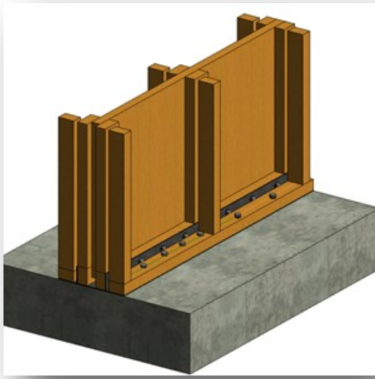


Description	Improvement
All timber sections remain the same. There are no changes in the dimensions of the structural member. The connection consists of a U-plate connecting the structural member to the concrete slabs using bolts instead of screws, as in the 3D model. The timber member is attached with the OSB with bolts as well. In addition, a double-sided toothed connector between the timber-Regel and the OSB is installed.	The main difference of this choice is applying bolts and using the double-sided toothed connector. Using bolts minimizes the number of fasteners and provides the same capacity as the original 3D design. DFD guideline highlights that reducing the number of fasteners is preferable with the condition that the stability is not compromised. Both the potential of reusing the structural members and the connectors are good. This small change will influence the assembling process by reducing the labor time at the worksite. As the updated design affects only the structural member of the wall, the accessibility to reach the connectors is still limited. From an engineering point of view, using the single or double-sided toothed connector will improve the performance of bolts in general and overcome the tolerance.

Choice 3

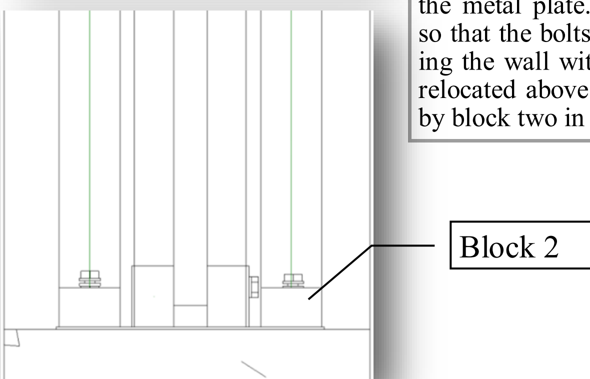


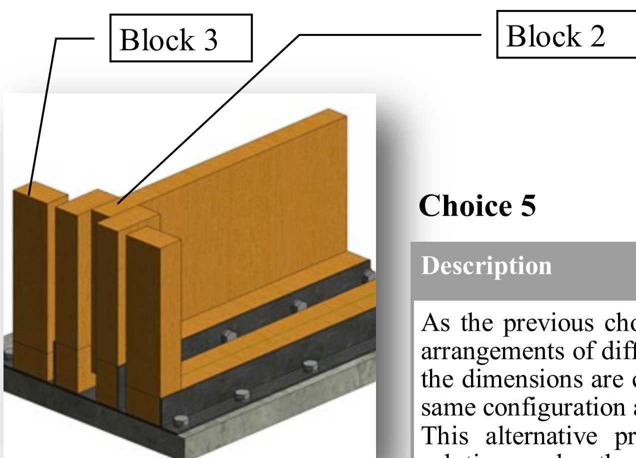
Description	Improvement
There are no changes in the dimension of the structural and nonstructural members. The dimensions are the same as the original design. According to the figure, the new changes are the use of bolts to connect block one with the metal plate. The plate is designed so that the bolts are shifted outside the U-shape, which makes it easier to approach the connecters. The double-sided toothed connector between the timber-Regel and the OSB is adapted in this design	This design gives more degree of freedom to the frame-OSB, considering block one. Since the screws that are connecting the wall to the concrete slabs are relocated outside the U-shape, the possibilities of assembling and deconstructing the wall member as one block are higher. If there is a desire to use the structural member, block one, in another project, there is no need to remove the bolts, referred to as “connector two” in the figure. Compared to the original design, this design provides a practical solution that matches the DFD guideline since it is categorized as an indirect connection. Such connection aims to shorten both the construction and deconstruction process under the condition that the members can be assembled in the factory and attached with the plate and then transferred directly to the site. The potential of reuse and accessibility to reach this connector is higher than the original design.



Choice 4

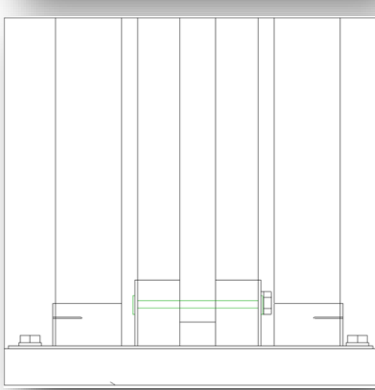
Description	Improvement
This design of the connection is composed of the same dimension as the original one regarding the timber members. Bolts and a double-sided toothed connector are used to connect the timber frame with the OSB and then with the metal plate. The plate is designed so that the bolts responsible for attaching the wall with the concrete slab are relocated above the member, indicated by block two in the 3D modeling.	The proposed choice shares the same benefits as the previse one in terms of DFD, considering the structural member as one block. Both alternatives provide a higher degree of reuse of the structural member. The main difference between this choice and choice number three is reducing the number of bolts where the bolts are used to install the nonstructural member, see block two, and the metal plate to the concrete

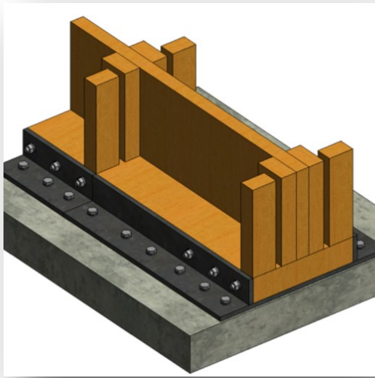




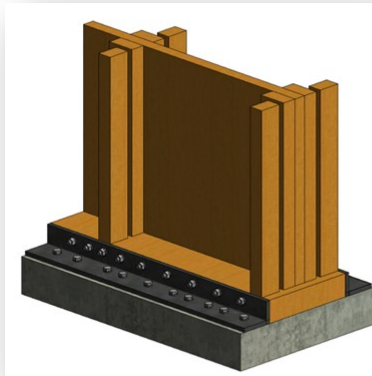
Choice 5

Description	Improvement
As the previous choices, the structural arrangements of different members and the dimensions are carried out with the same configuration as the original wall. This alternative provides a practical solution under the condition that all members, structural and nonstructural, are one block. Block number two is connected to the plate using different fasteners with a toothed connector. Then the outer framing is attached to the plate using a mechanical fastener as block three. The final step is connecting the entire wall to the concrete using the outer bolts.	Such a connection can be customized and installed in the factory. Then, the wall with the plate is transferred to the worksite to being installed directly. The suggested alternative accelerates the process of assembling since most of the work is done in the factory. If the elements need to be dismantled as one block, then the outer bolts are the only connector that is needed to be dealt with. Such design has a higher degree of accessibility and visibility. The amount of work that is needed to deconstruct the element is lower than the previous alternatives if the number of fasteners is the leading comparison.

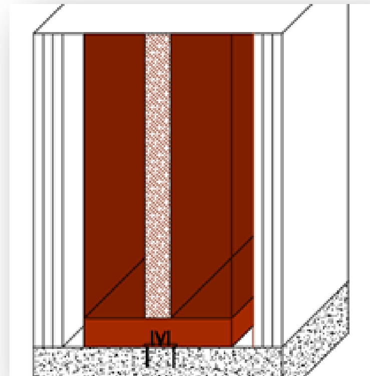




a



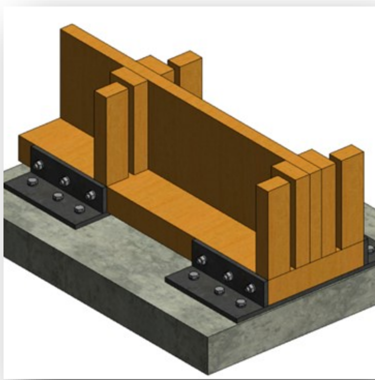
d



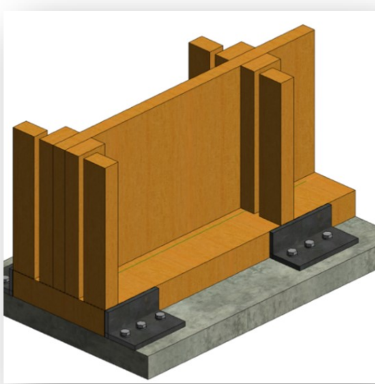
e

Choice 6

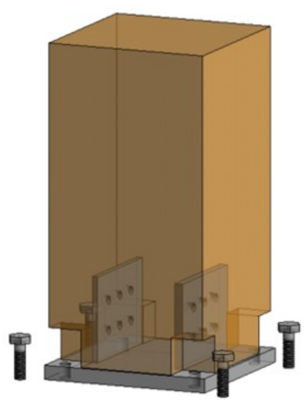
Description	Improvement
The idea of this alternative is to add a third member, which is responsible for connecting the structural and nonstructural members to the concrete. The third member in this design is the beam, located at the bottom of the wall, as the 3D modeling indicates. The process of doing so starts with connecting the framing to the bottom using a mechanical fastener. As a result, the wall can become one block. The connection will only take place between the bottom beam with the concrete slab. There are several alternatives to installing such a connection. However, this paper has presented one of the suitable connections to this case.	The thought behind this design is to add a connecter that allows the change in the connection without disturbing the other wall members. Installing or de-installing the wall will only be associated with the beam that is located on the bottom, as the 3D modeling shows. The benefits of this design can be seen in a good degree of accessibility and time in terms of assembling and dismantling. To reach this connection, only the finishing layers need to be dealt with. Then the whole connection can be dissembled and relocated to another worksite. This design could increase the speed of deconstruction and require no work experience. The new design gives many possibilities to connect the wall with the concrete slab as the 3D figures vary between a-d, the shape of metal plats changes to suit the demand for the company. In addition, the alternative 6e shows different solutions by using channel connections located on the bottom of the beam, which can act like the tongue placed in the groove on the top of the concrete slab or vice versa. All this alternative is designed according to the criteria that are proposed to evaluate the current connection. Another suggestion is to attach the bottom beam only to the structural member, leading to a cheaper solution instead of using a larger piece of wood. Practically, this suggestion can carry out the same connectors as the designs presented in this choice.



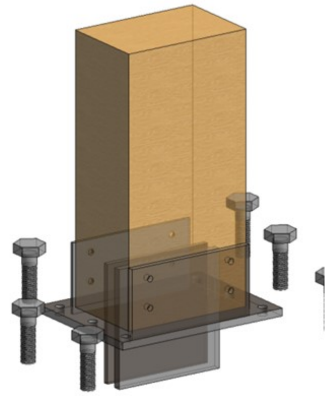
b



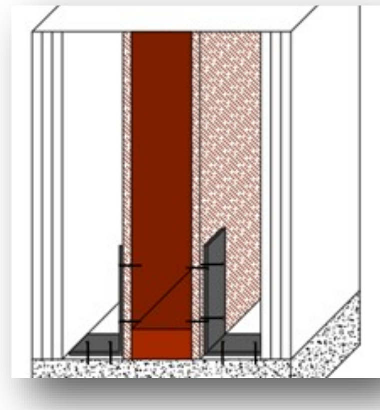
c



a



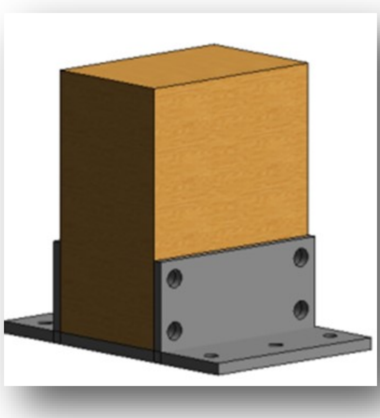
d



e

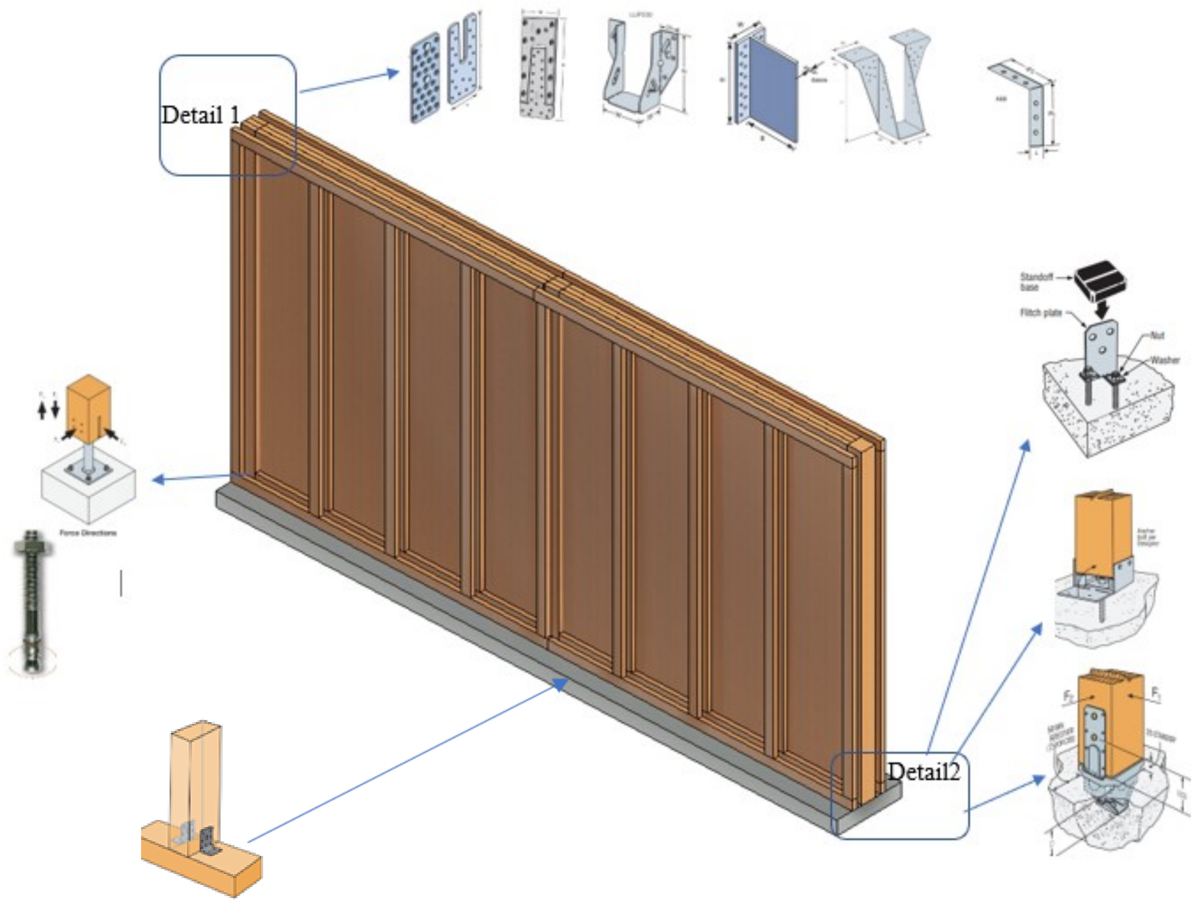
Choice 7

b



c

Description	Improvement
The presented connection can be applied to a column-beam system or wall instead of framing. The Wall system could be a cross-laminated timber wall or laminated dowel timber, where the structural member is considered one section. Column-beam system is suitable to be designed for disassembly since the connector can be counted as an indirect connector with additional devices. The alternatives in this choice vary between a-e to explain how the structural element can be connected with indirect connectors.	In general, using a column system can reduce the number of members that need to be connected. DFD guideline highlights that using a structural system that is contained of a lower number of members is preferable to other systems. Besides that, the potential of using an indirect connecter is higher than the panel wall since the dimension of the column provides a wide variety of different connectors. For instance, alternative a is an excellent example of an indirect connecter that is used to connect the column with the slab. The wide variety of connection configurations can be customized according to the demand. Such connection has a high degree of accessibility. Even the nonstructural member can be salvaged. However, using such a system can be more costly than the wall panel, even though the construction time can be shortened using this type of system. Alternative (e) is practical and a common connection if the wall system is adapted. The metal plate shaped like an L can be installed in the factory or the worksite. However, this system is more expensive than the wall panel. All the previous alternatives can provide the potential of adapting indirect connectors, which by itself gives more potential of reusing the structural member in different projects sine the accessibility, visibility, and labor demand could be better than the current wall configuration.

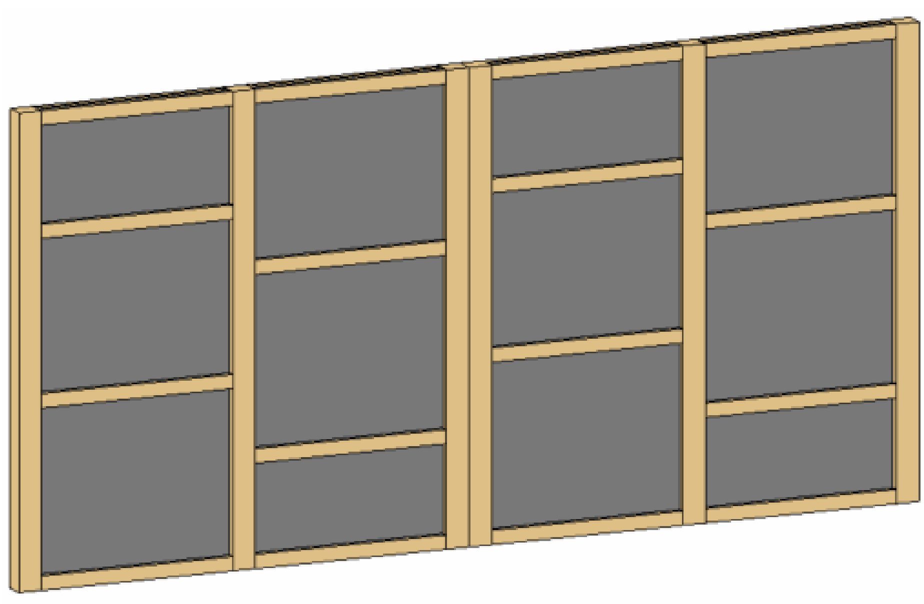


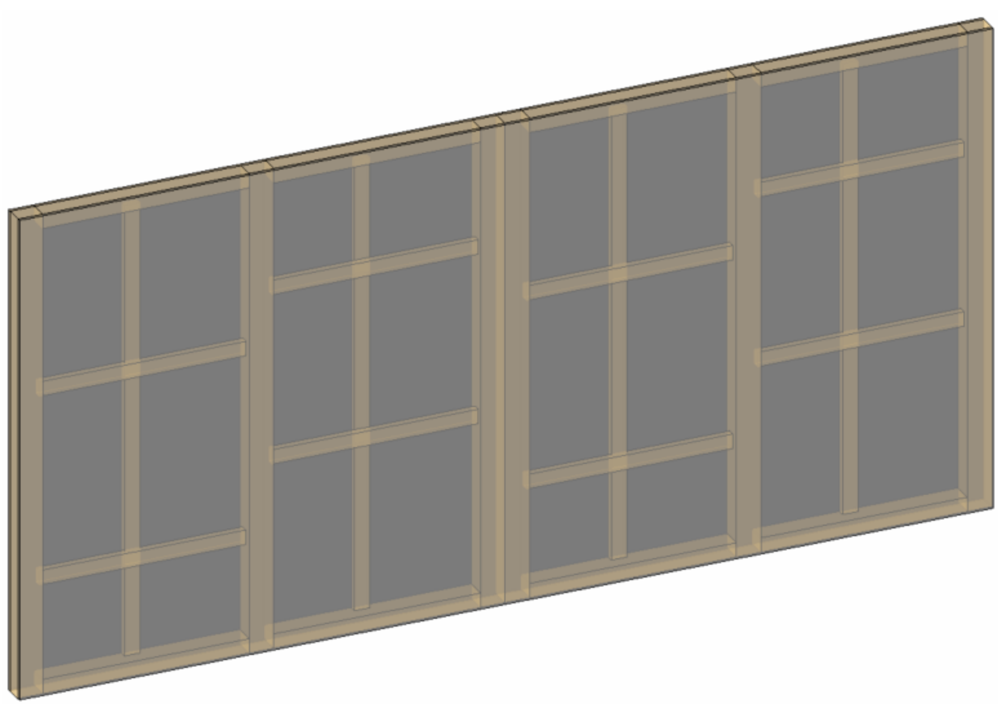
(Simpson strong-tie 2017)

Optimal Choice

Description	improvement
The idea behind this design is to contain the same configuration as the original design with improvement by adapting studs that provide higher capacity in the wall. The studs are used and located strategically in a way that fulfills the stability of the wall. Using this new design gives several alternatives to connect the wall to the concrete slab using the benefits of the existing studs. Moreover, the frame can also be attached to the columns using indirect connectors.On the next page, there are two alternatives to wall design. The difference between them is the thickness and the location of the OSB boards. However, these alternatives are discussed with details in sub-chapter 3.5.	The new design can provide a more possibility to use indirect connectors, as the figure indicates. Detail 1 suggests various mechanical connectors where the horizontal studs can be attached to the vertical studs using them instead of using fasteners to minimize the need for works to achieve the connection. Detail 2 proposes how the vertical studs can be joined to the concrete floor.

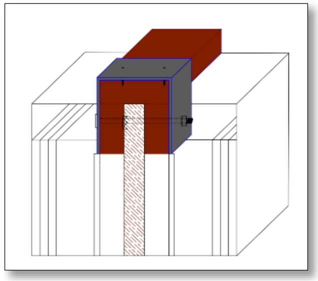
Optimal Choice a-b

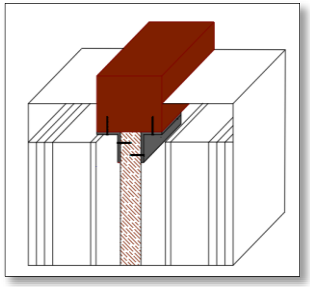


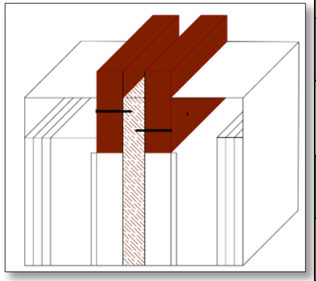


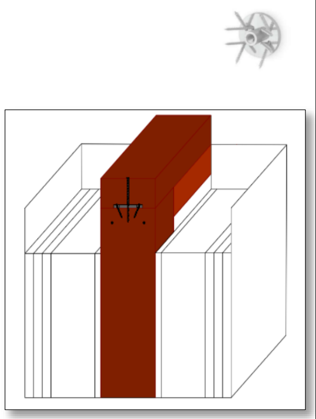
9 Annex (D)

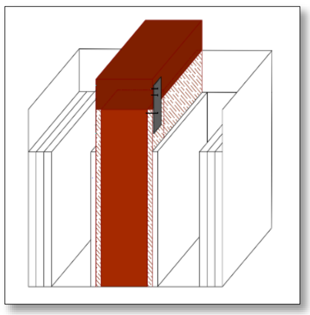
Connection 1

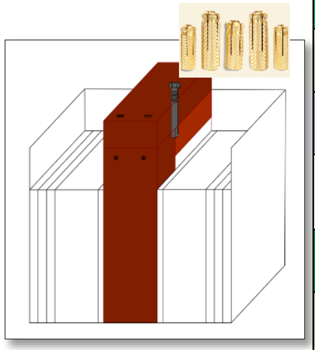
Choice 1		**Capacity**	**Accessibility**	**Availability**	**Skills**	**Cost**	**Wood Reuse**	**Complexity**
	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	4	5	4	5	4	4
	Weighted Score	5	12	5	8	15	12	8
		Machinery	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	5	4	4	4	4	4	
	Weighted Score	5	4	8	8	4	12	**106**

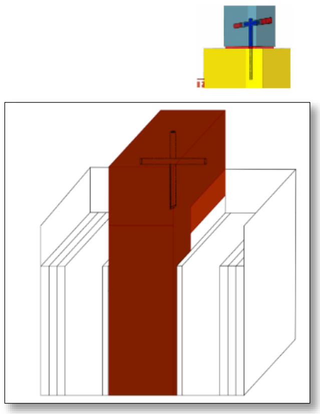
Choice 2		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	3	5	4	4	3	4
	Weighted Score	5	9	5	8	12	9	8
		Machinery	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	4	4	3	4	4	4	
	Weighted Score	4	4	6	8	4	12	**94**

Choice 3		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	3	5	4	4	3	4
	Weighted Score	5	9	5	8	12	9	8
		Machinery	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	4	3	3	4	4	4	
	Weighted Score	4	3	6	8	4	12	**93**

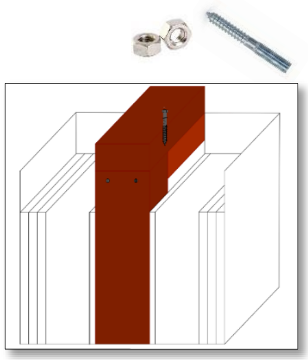
Choice 4		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	2	4	4	4	3	4
	Weighted Score	5	6	4	8	12	9	8
		Machinery	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	4	3	4	4	4	4	
	Weighted Score	4	3	8	8	4	12	**91**

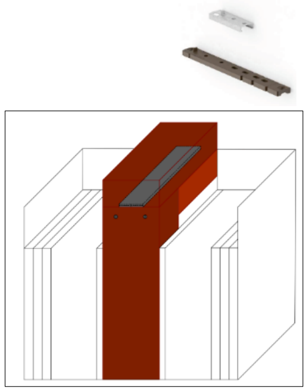
Choice 5		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	3	5	4	4	4	4
	Weighted Score	5	9	5	8	12	12	8
		Machinery	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	4	4	3	4	4	4	
	Weighted Score	4	4	6	8	4	12	**97**

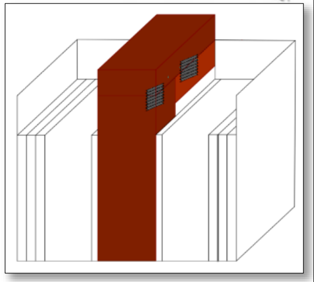
Choice 6		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	3	5	4	4	4	4
	Weighted Score	5	9	5	8	12	12	8
		Machinery	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	3	4	4	4	3	3	
	Weighted Score	3	4	8	8	3	9	**94**

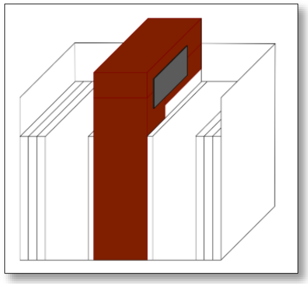
Choice 7		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	3	3	3	3	3	4
	Weighted Score	5	9	3	6	9	9	8
		Machinery	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	3	4	4	4	4	4	
	Weighted Score	3	4	8	8	4	12	**88**

(Timber framehq,2021)

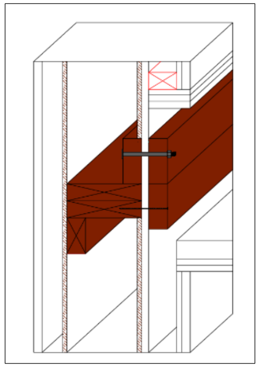
Choice 8		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	4	5	4	4	4	4
	Weighted Score	5	12	5	8	12	12	8
		Machinery	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	4	4	4	4	4	4	
	Weighted Score	4	4	8	8	4	12	**102**

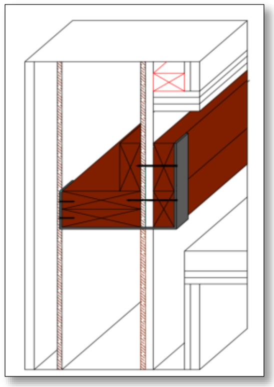
Choice 9		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	3	4	3	4	4	4
	Weighted Score	5	9	4	6	12	12	8
		Machinery	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	3	2	4	4	4	4	
	Weighted Score	3	2	8	8	4	12	**93**

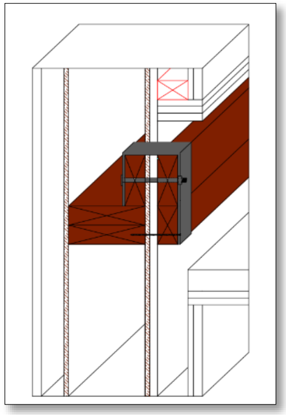
Choice 10		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
 	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	3	5	4	4	2	4
	Weighted Score	5	9	5	8	12	6	8
		Machinery	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	4	2	2	4	3	4	
	Weighted Score	4	2	4	8	3	12	**86**

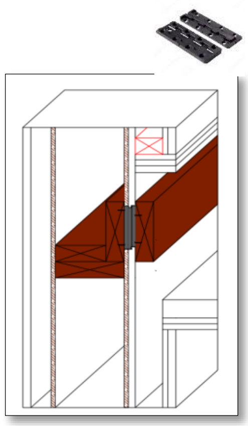
Choice 11		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
 	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	4	5	4	3	3	4
	Weighted Score	5	12	5	8	9	9	8
		Machinery	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	3	4	3	4	4	4	
	Weighted Score	3	4	6	8	4	12	**93**

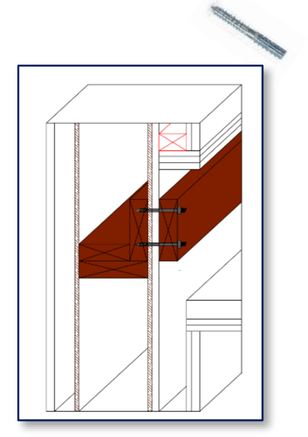
Connection 2

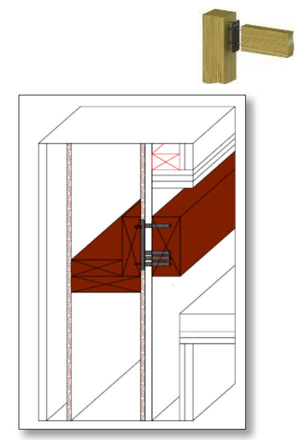
Choice 1		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	3	5	4	4	4	4
	Weighted Score	5	9	5	8	12	12	8
		Machinery	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	4	4	3	4	4	4	
	Weighted Score	4	4	6	8	4	12	**97**

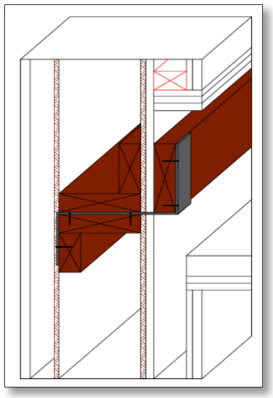
Choice 2		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	4	4	4	4	4	3
	Weighted Score	5	12	4	8	12	12	6
		Machinery	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	4	4	4	4	4	4	
	Weighted Score	4	4	8	8	4	12	**99**

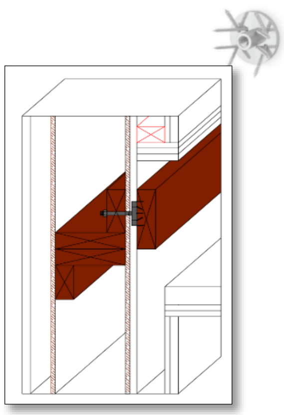
Choice 3		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	3	5	4	4	4	4
	Weighted Score	5	9	5	8	12	12	8
		Machinery	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	4	3	4	4	4	4	
	Weighted Score	4	3	8	8	4	12	**98**

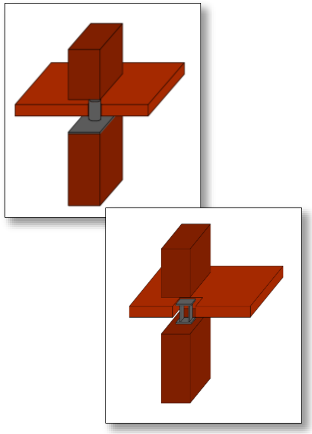
Choice 4		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	3	5	3	4	4	4
	Weighted Score	5	9	5	6	12	12	8
		Machinery	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	4	3	4	4	4	4	
	Weighted Score	4	3	8	8	4	12	**96**

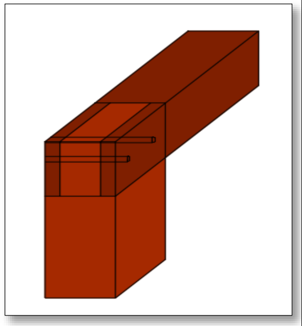
Choice 5		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	3	5	4	4	4	4
	Weighted Score	5	9	5	8	12	12	8
		Machinery	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	4	3	4	4	4	4	
	Weighted Score	4	3	8	8	4	12	**98**

Choice 6		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	3	5	3	4	4	4
	Weighted Score	5	9	5	6	12	12	8
		Machinery	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	3	3	2	4	4	4	
	Weighted Score	3	2	8	8	4	12	**94**

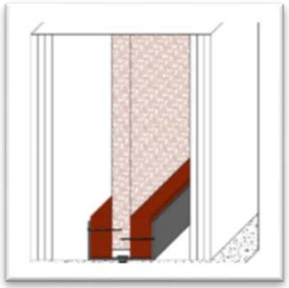
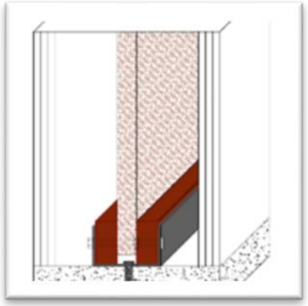
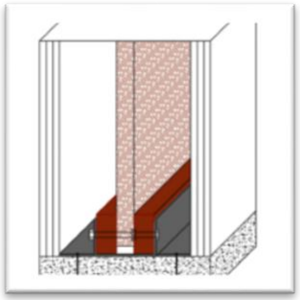
Choice 7		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	4	5	4	4	4	3
	Weighted Score	5	12	5	8	12	12	6
		Machinery	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	4	4	4	4	4	4	
	Weighted Score	4	4	8	8	3	12	**99**

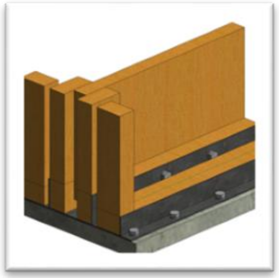
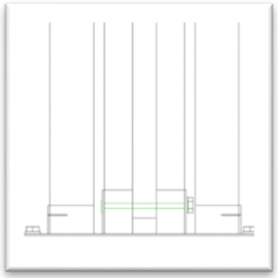
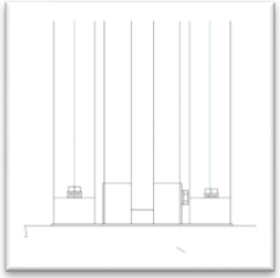
Choice 8		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	2	5	4	4	4	4
	Weighted Score	5	6	4	8	12	12	8
		Machinery	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	4	3	8	4	4	4	
	Weighted Score	4	3	8	8	4	12	**94**

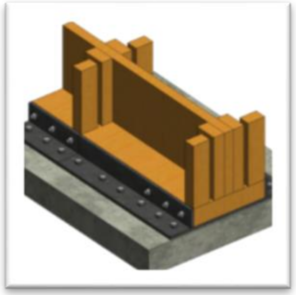
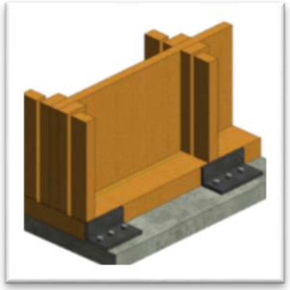
Choice 9 (a.b)		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	5	5	3	4	4	4
	Weighted Score	5	15	5	6	12	12	8
		Machinery	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	2	4	4	4	5	4	
	Weighted Score	2	4	8	8	5	12	**105**

Choice 10		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	2	5	4	3	1	3
	Weighted Score	5	9	5	8	12	6	8
		Machinery	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	3	3	2	4	4	4	
	Weighted Score	4	2	4	8	3	12	**86**

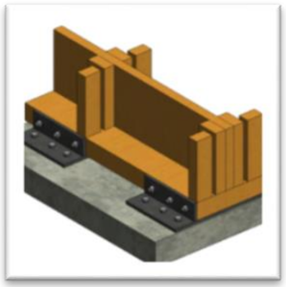
Connection 3

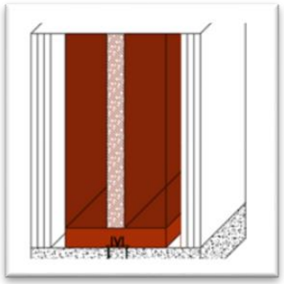
Choice 1-2-3		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	3	5	4	4	3	4
	Weighted Score	5	9	5	8	12	9	8
		**Machinery**	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	4	5	4	4	4	4	
	Weighted Score	4	5	8	8	4	12	**97**
	Note The previous evaluations are done for choice 3, the reason behind that all the connections composed of the same wall configuration as the original design with minor changes. However, choice three scores the highest among the other choices due to the higher degree of accessibility that design 3 provides. Wood reuse also better than the other choices since the structural members are considered as one block.							

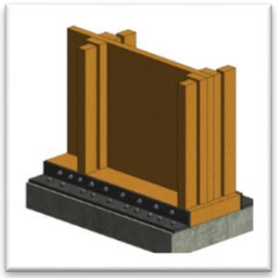
Choice 4-5		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	4	5	5	5	4	4
	Weighted Score	5	12	5	10	15	12	8
		Machinery	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	4	5	4	5	5	5	
	Weighted Score	4	5	8	10	5	15	**114**
	Note The total score, as the table indicates, is for choice 5. The idea that choice five considers the structural and nonstructural members as one block attaches to the metal plate. While choice four is counting the structural member-only as one block. Since the connector is the indirect connection, the accessibility and the wood reuse are suitable for this design and the cost where no such time is required to assemble and deconstruct the element.  							

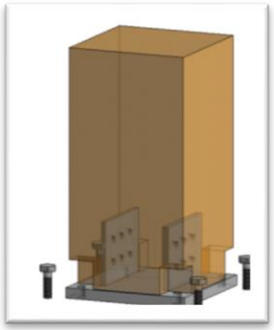
Choice 6		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	4	5	5	3	4	4
	Weighted Score	5	12	5	10	9	12	8
		**Machinery**	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	4	5	4	5	5	5	
	Weighted Score	4	5	8	10	5	15	**111**

Note
The examine choices carry the idea of attaching the structural and the non-structural member to the beam located on the bottom of the wall. By doing so, the connection is governed between the bottom beam and the concrete slab. The total score is matching all the alternatives regarding this choice.



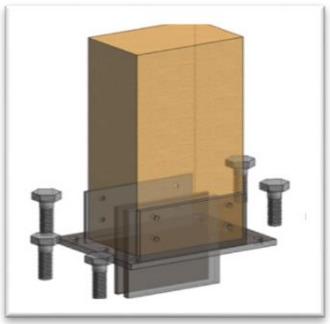
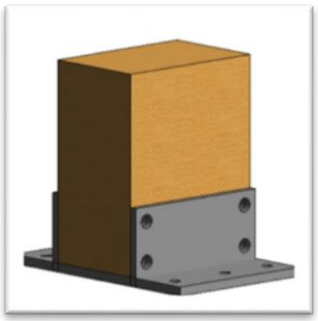
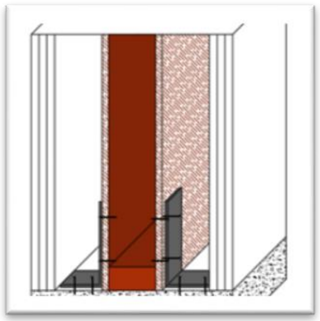


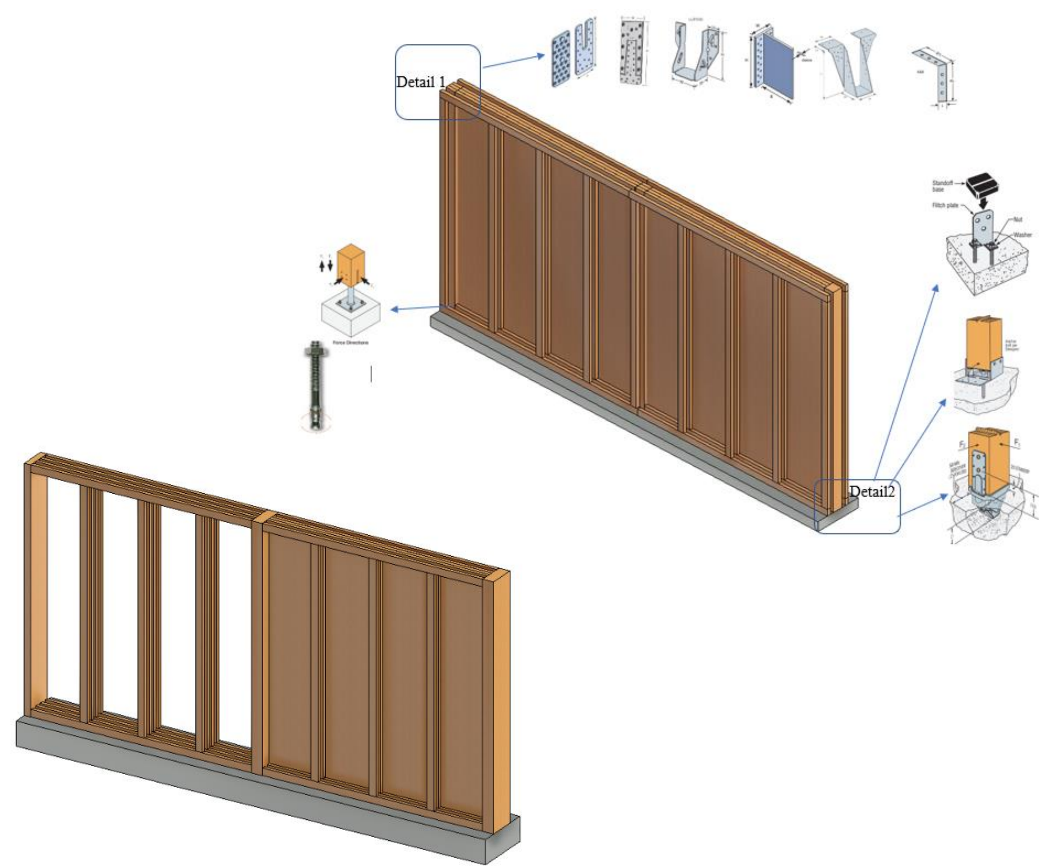


Choice 7		Capacity	Accessibility	Availability	Skills	Cost	Wood Reuse	Complexity
 	Weighted factor	**1**	**3**	**1**	**2**	**3**	**3**	**2**
	Scale factors	5	4	3	4	4	4	4
	Weighted Score	5	12	3	8	12	12	8
		Machinery	**Visibility**	**Time**	**Connected Members**	**Reuse Connector**	**Easy to Assemble**	**Total Score**
	Weighted factor	**1**	**1**	**2**	**2**	**1**	**3**	
	Weighting scale	3	4	4	5	5	5	
	Weighted Score	3	4	8	10	5	15	**105**

Note

The alternatives are applied to the column-beam system. Using a column system can reduce the number of members that need to be connected, which influences the time and cost of the dismantling process. However, this choice is not of interest to the company since the aim is to develop DFS90.



	Weighted factor	Scale factors	Weighted Score
Capacity	1	5	5
Accessibility	3	5	15
Availability	1	4	4
Skills	2	4	8
Cost	3	4	12
Wood Reuse	3	4	12
Complexity	2	5	10
Machinery	1	5	5
Visibility	1	5	5
Time	2	4	8
Connected Members	2	4	8
Reuse Connector	1	5	5
Easy to Assemble	3	5	15
Total Score			112

10 Annex (E)

The following data represent the specification and properties of used connection material, which are used in capacities calculation

- The yielding force of the fasteners and plates will be assumed f_y=235 MPa and ultimate strength is f_u=365 MPa
- The used timber sections are C24, so ρ_k=350 kg/m^3
  - For timber section C24 so the partial coefficient of the section is γ_M=1.3
  - Strength modification factor will be assumed for medium length load is K_{mod} =0.8
- The capacities of original connections and alternative will be calculated according to EC5 equations as follows, while the part $\frac{F_{v,rk}}{4}$ will be ignored in all checking

$$F_{v,Rk} = min \left\{ \begin{array}{c} f_{h1,k}t_1 d \\ f_{h2,k}t_2 d \\ \frac{f_{h1,k}t_1 d}{1+\beta}\left[\sqrt{\beta + 2\beta^2\left[1+\frac{t_2}{t_1}+\left(\frac{t_2}{t_1}\right)^2\right] + \beta^3\left(\frac{t_2}{t_1}\right)^2} - \beta\left(1+\frac{t_2}{t_1}\right)\right] + \frac{F_{ax,Rk}}{4} \\ 1.05\frac{f_{h1,k}t_1 d}{2+\beta}\left[\sqrt{2\beta(1+\beta)+\frac{4\beta(2+\beta)M_{y.Rk}}{f_{h1,k}{t_1}^2 d}} - \beta\right] + \frac{F_{ax,Rk}}{4} \\ 1.05\frac{f_{h1,k}t_2 d}{1+2\beta}\left[\sqrt{2\beta^2(1+\beta)+\frac{4\beta(2+\beta)M_{y.Rk}}{f_{h1,k}{t_2}^2 d}} - \beta\right] + \frac{F_{ax,rk}}{4} \\ 1.15\sqrt{\frac{2\beta}{1+\beta}}\left[\sqrt{2M_{y.Rk}f_{h1,k}d}\right] + \frac{F_{ax,Rk}}{4} \end{array} \right\}$$

While for double shear timber – timber the equations are

$$F_{v,Rk} = min \left\{ \begin{array}{c} f_{h1,k}t_1 d \\ 0.5f_{h2,k}t_2 d \\ 1.05\frac{f_{h1,k}t_1 d}{2+\beta}\left[\sqrt{2\beta(1+\beta)+\frac{4\beta(2+\beta)M_{y.Rk}}{f_{h1,k}{t_1}^2 d}} - \beta\right] + \frac{F_{ax,Rk}}{4} \\ 1.15\sqrt{\frac{2\beta}{1+\beta}}\left[\sqrt{2M_{y.Rk}f_{h1,k}d}\right] + \frac{F_{ax,Rk}}{4} \end{array} \right\}$$

Where:

$f_{h1,k}, f_{h2,k}$	characteristic embedment strength of timber member
t_1, t_2	timber broad, timber thickness, or timber penetration depth
β	ratio between embedment strength of two members
$M_{y.Rk}$	characteristic yielding moment of the fastener
d	diameter of the fastener
$F_{v,rk}$	characteristic capacity per shear plan per fastener
$F_{ax,Rk}$	characteristic withdrawal capacity for fastener

For single shear timber – steel (for $t_{plate} < 0.5d$)

$$F_{v,Rk} = min\begin{Bmatrix} 0.4 f_{h,k} t_1 d \\ 1.15\sqrt{2M_{y.Rk} f_{h,k} d} + \frac{F_{ax,Rk}}{4} \end{Bmatrix}$$

For double shear timber - steel (for $t_{plate} < 0.5d$)

$$F_{v,Rk} = min\begin{Bmatrix} 0.5 f_{h2,k} t_2 d \\ 1.15\sqrt{2M_{y.Rk} f_{h2,k} d} + \frac{F_{ax,Rk}}{4} \end{Bmatrix}$$

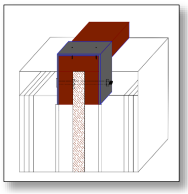
$f_{hi,k}$	characteristic embedment strength of timber member
t_1	the smaller thickness of timber side member, or penetration depth
t_2	thickness of middle timber member

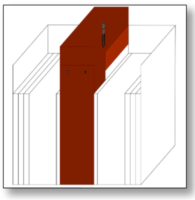
- ➢ Connection 1 and its alternatives capacity

The capacity of the exist connection and its alternative will be calculated according to the EC5 equations as following.

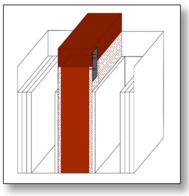
Tables below show the designed capacity of the original connection 1, and the capacities of the alternatives

Connection 1				
Fastener	Double shear timber-timber			
l (mm)	d (mm)	fu (MPa)	fy (MPa)	D cc (mm)
16	6.5	365	235	600
Timber				
lt (mm)	t1 (mm)	t2 (mm)	ρk	No
95	45	45	350	6
Myrk	21334	N.mm	γM	Kmod
f hk	16.4	MPa	1.3	0.8
β	1			
Shear Capacity	Fv1rk	4788		
	Fv2rk	4788		
	Fv3rk	1983		
	Fv4rk	2141		
	Fv5rk	2141		
	Fv6rk	2450		
		Fvrk	1983	N
		Fvrd	1220	N
		Fvrd,tot	7322	N

Choice 1				
Fastener	Double shear timber-timber			
l (mm)	d (mm)	fu(MPa)	fy (MPa)	D cc (mm)
135	10	400	350	1200
Timber				
lt (mm)	t1 (mm)	t2 (mm)	ρk	No
	45	38	440	2
Myrk	47773	N.mm	γM	Kmod
f h1k	32.5	MPa	1.3	0.8
f h2k	32.5			
β	1.0			
Shear Capacity	Fv1rk	14612		
	Fv2rk	6170		
	Fv3rk	6174		
	Fv4rk	6406		
		Fvrk	6170	N
		Fvrd	3797	N
		Fvrd,tot	7593	N

Choice 8				
Fastener	Single shear timber-timber			
l (mm)	d (mm)	fu(MPa)	fy (MPa)	D cc (mm)
	10	400	350	
Timber				
lt (mm)	t1 (mm)	t2 (mm)	ρk	No
	45	30	350	3
Myrk	47773	Nmm	γM	Kmod
f h1k	25.8	MPa	1.3	0.8
f h2k	25.8			
β	1			
Shear Capacity	Fv1rk	11624		
	Fv2rk	7749		
	Fv3rk	22408		
	Fv4rk	5116		
	Fv5rk	4184		
	Fv6rk	5713		
		Fvrk	4184	N
		Fvrd	2575	N
		Fvrd,tot	7725	N

Choice 1				
Fastener	Single shear steel-timber			
l (mm)	d (mm)	fu (MPa)	fy (MPa)	D cc (mm)
	10	400	350	1200
Timber				
lt (mm)	t1 (mm)	t2 (mm)	ρk	No
	45	38	550	12
Myrk	47773	Nmm	γM	Kmod
f hk	32.5	MPa	1.3	0.8
Shear Capacity	Fv1rk	7306		
	Fv2rk	6406		
		Fvrk	6406	N
		Fvrd	3942	N

Choice 5				
Fastener	Single shear steel-timber			
l (mm)	d (mm)	fu (MPa)	fy (MPa)	D cc (mm)
	6	365	235	1200
Timber				
lt (mm)	t1 (mm)	t2 (mm)	ρk	No
	20		550	12
Myrk	17326	Nmm	γM	Kmod
f hk	25.0	MPa	1.3	0.8
				
Shear Capacity	Fv1rk	1201		
	Fv2rk	2623		
		Fvrk	1201	N
		Fvrd	739	N
		Fvrd,tot	8869	N

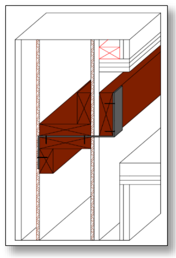
Choice 5				
Fastener	Single shear timber-timber			
l (mm)	d (mm)	fu (MPa)	fy (MPa)	D cc (mm)
	6	365	235	1200
Timber				
lt (mm)	t1 (mm)	t2 (mm)	ρk	No
95	20	30	440	12
Myrk	17326	Nmm	γM	Kmod
f h1k	25.0	MPa	1.3	0.8
f h2k	21.1			
β	0.842385			
Shear Capacity	Fv1rk	3003		
	Fv2rk	3794		
	Fv3rk	5369		
	Fv4rk	1752		
	Fv5rk	1938		
	Fv6rk	2508		
		Fvrk	1752	N
		Fvrd	1078	N
		Fvrd,tot	12940	N

- Connection 2 and its alternatives capacity

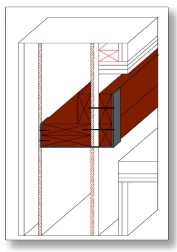
For connection 2 the capacity of the exist one is calculated, besides the new designed choices as the following tables

Connection 2				
Fastener	Single Share timber-timber			
l (mm)	d (mm)	fu (MPa)	fy (MPa)	D cc (mm)
50	9	360	235	300
Timber				
lt (mm)	t1 (mm)	t2 (mm)	ρk	No
	45	45	350	10
Myrk	49039	Nmm	γM	Kmod
f hk	14.8	MPa	1.3	0.8
β	1			
Shear Capacity	Fv1rk	6013		
	Fv2rk	6013		
	Fv3rk	2491		
	Fv4rk	3125		
	Fv5rk	3125		
	Fv6rk	4163		
		Fvrk	2491	N
		Fvrd	1533	N
		Fvrd,tot	15326	N

Choice 7				
Fastener	Single shear steel-timber			
l (mm)	d (mm)	fu (MPa)	fy (MPa)	D cc (mm)
	8	365	235	
Timber				
lt (mm)	t1 (mm)	t2 (mm)	ρk	No
	40			
Myrk	36605	Nmm	γM	Kmod
f hk	15.4	MPa	1.3	0.8
Shear Capacity	Fv1rk	1969		
	Fv2rk	3451		
		Fvrk	1969	N
		Fvrd	1211	N

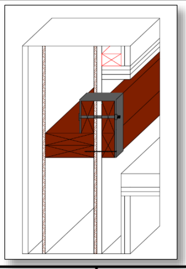


Choice 2				
Fastener	Single shear steel-timber			
l (mm)	d (mm)	fu (MPa)	fy (MPa)	D cc (mm)
	7	365	235	
Timber				
lt (mm)	t1 (mm)	t2 (mm)	ρk	No
	45			
Myrk	25868	Nmm	γM	Kmod
f hk	16.0	MPa	1.3	0.8
Shear Capacity	Fv1rk	2017		
	Fv2rk	2769		
		Fvrk	2017	N
		Fvrd	1241	N



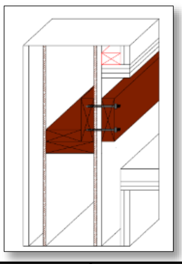
Choice 2				
Fastener	Single Share timber-timber			
l (mm)	d (mm)	fu (MPa)	fy (MPa)	D cc (mm)
90	7	365	235	
Timber				
lt (mm)	t1 (mm)	t2 (mm)	ρk	No
	45	35	350	12
Myrk	25868	N.mm	γM	Kmod
f h1k	16.0	MPa	1.3	0.8
f h2k	16.0	MPa		
β	1			
Shear Capacity	Fv1rk	5043		
	Fv2rk	5043		
	Fv3rk	9643		
	Fv4rk	2938		
	Fv5rk	9912		
	Fv6rk	3799		
		Fvrk	2938	N
		Fvrd	1808	N
		Fvrd,tot	14895	N

Choice 3				
Fastener	Single Share timber-timber			
l (mm)	d (mm)	fu (MPa)	fy (MPa)	D cc (mm)
120	8	400	350	
Timber				
lt (mm)	t1 (mm)	t2 (mm)	ρk	No
	45	45	350	7
Myrk	26743	N.mm	γM	Kmod
f hk	26.4	MPa	1.3	0.8
β	1.0			
Shear Capacity	Fv1rk	9505		
	Fv2rk	9505		
	Fv3rk	3937		
	Fv4rk	3924		
	Fv5rk	3924		
	Fv6rk	3865		
		Fvrk	3865	N
		Fvrd	2379	N
		Fvrd,tot	16651	N



Choice 3				
Fastener	Double shear steel-timber			
l (mm)	d (mm)	fu (MPa)	fy (MPa)	D cc (mm)
	8	400	350	
Timber				
lt (mm)	t1 (mm)	t2 (mm)	ρk	No
	45			
Myrk	26743	Nmm	γM	Kmod
f hk	26.4	MPa	1.3	0.8
Shear Capacity	Fv1rk	4753		
	Fv2rk	3865		
		Fvrk	3865	N
		Fvrd	2379	N

Choice 5				
Fastener	Single Shear timber-timber			
l (mm)	d (mm)	fu (MPa)	fy (MPa)	D cc (mm)
120	9	400	350	
Timber				
lt (mm)	t1 (mm)	t2 (mm)	ρk	No
	45	45	350	6
Myrk	36326	Nmm	γM	Kmod
f hk	26.1	MPa	1.3	0.8
β	1			
Shear Capacity	Fv1rk	10577		
	Fv2rk	10577		
	Fv3rk	4381		
	Fv4rk	4506		
	Fv5rk	4506		
	Fv6rk	4752		
		Fvrk	4381	N
		Fvrd	2696	N
		Fvrd,tot	16177	N



- Connection 3 and its alternatives capacity

The same for connection 3 and their alternatives, the following tables show the capacities of connections

Connection 3				
Fastener	Double Share timber-timber			
l (mm)	d (mm)	fu(MPa)	fy (MPa)	D cc (mm)
80	4	365	235	50
Timber				
lt (mm)	t1 (mm)	t2 (mm)	ρk (avg)	No
	45	30	440	120
Myrk	6038	Nmm	γM	Kmod
f h1k	23.8	MPa	1.3	0.8
f h2k	34.6			
β	1.45			
Shear Capacity	Fv1rk	4285		
	Fv2rk	2077		
	Fv3rk	3630		
	Fv4rk	1131		
		Fvrk	1131	N
		Fvrd	696	N
		Fvrd,tot	83551	N

Connection 3				
Fastener	Single shear steel-timber			
l (mm)	d (mm)	fu (MPa)	fy (MPa)	D cc (mm)
	4	365	235	
Timber				
lt (mm)	t1 (mm)	t2 (mm)	ρk	No
	45			
Myrk	6038	Nmm	γM	Kmod
f hk	23.8	MPa	1.3	0.8
Shear Capacity	Fv1rk	1714		
	Fv2rk	1233		
		Fvrk	1233	N
		Fvrd	759	N

Choice				
Fastener	Double shear steel-timber			
l (mm)	d (mm)	fu (MPa)	fy (MPa)	D cc (mm)
	10	400	365	
Timber				
lt (mm)	t1 (mm)	t2 (mm)	ρk	No
	45			
Myrk	47773	Nmm	γM	Kmod
f hk	18.1	MPa	1.3	0.8
Shear Capacity	Fv1rk	4069		
	Fv2rk	4780		
		Fvrk	4069	N
		Fvrd	2504	N

Choice				
Fastener	Double Share timber-timber			
l (mm)	d (mm)	fu(MPa)	fy (MPa)	D cc (mm)
145	10	400	365	
Timber				
lt (mm)	t1 (mm)	t2 (mm)	ρk (avg)	No
	45	38	440	40
Myrk	47773	N.mm	γM	Kmod
f h1k	18.1	MPa	1.3	0.8
f h2k	18.7			
β	1.03			
Shear Capacity	Fv1rk	8137		
	Fv2rk	3545		
	Fv3rk	6802		
	Fv4rk	3944		
		Fvrk	3545	N
		Fvrd	2182	N
		Fvrd,tot	87267	N

- **Design Of optimal wall**

- Capacity of the wall for vertical load

To check the capability of new suggested design of the wall, the applied forces should be calculated

1- Dead load: self-weight of the wall (3kN/m), and the self-weight of the slab with finishing layers (1kN/m^2), according to company design summery.

2- Life loads: the life loads (2kN/m^2), according to company design summery "The life load value will be included in checking the wall capacity to pressure vertical loads, but it will be excluded for checking against wind uplifting loads".

3- Wind & Snow loads: the pressure wind load and snow load will be ignored in vertical design capacity as there is no complete image of how the loads transfer through the trusses to walls.

The contributed load area that affects the wall is (5.0*4.0) m
Q_d = 1.35 G_k+1.5 L_k

Self-weight of slab G_{ks}= 5.0*4.0*(1)= 20kN
Life load on the slab L_k=2*5.0*4.0= 40kN
One floor design loads Q_d=1.35*20+41*1.5= 87kN
Five floor design loads Q_{dt}=87*5= 435 kN
Self – weight of the wall S_w=5*3*1.35 =20.3 kN/m
Total loads on the wall per linear meter S_{wd}=20.3+(435/3)=165.3 kN/m
Total design loads on each stud in original design $Q_{s,d}$=165.3*3/10=49.6 kN

According to EC5 the capacity of timber for applied forces parallels to grain defined by equations

$$N_{c.0.d} = f_{c,0,d} * A * k_c$$
$$k_c = \frac{1}{k + \sqrt{k^2 - \lambda_{rel}^2}} for \lambda_{rel} > 0.3, k = 0.5(1 + \beta_c(\lambda_{rel} - 0.3) + \lambda_{rel}^2)$$
$$\lambda_{rel} = \frac{\lambda}{\pi}\sqrt{\frac{f_{c,0,k}}{E_{0.05}}}, \lambda = \frac{l_e}{i}, i = \sqrt{\frac{I}{A}}, \beta_c = 0.2 for structural timber$$

$N_{c.0.d}$ capacity in compression parallel to grain
$f_{c,0,d}$ design compression strength parallel to grain
$f_{c,0,k}$ characteristics compression strength parallel to grain
$k_c. k$ instability factor
A cross section area
λ_{rel} relative slenderness ratio
λ slenderness ratio
l_e effective buckling length in compression
i radius of gyration
I second moment of area
$E_{0.05}$ fifth percentile value of modulus of elasticity

The table below illustrates the capacity of existing wall , assuming the transverse studs are distributed at each 1000 mm of the vertical studs so the buckling length will be 1000 mm

b(mm)	h (mm)	A (mm2)	le (mm)	k mod	γm
45	95	4275	1000	0.8	1.3
E0.05 (Mpa)	fc0k (Mpa)	fc0d (Mpa)	β	N	
7400	21	12.9	0.2	10	
I max	3215156.25		i max	27.4	
I min	721406.25		i min	13.0	
λ max	36.46		λrel max	0.62	
λ min	76.98		λrel min	1.31	
k max	0.72		kc max	0.91	
k min	1.45		kc min	0.48	
Nc0,rd. max	50323	N,Capacity of one stud in strong direction			
Nc0,rd, min	26418	N,Capacity of one stud in weak direction			
Nc0,rd, tot. max	503231	N,Capacity of all studs in strong direction			
Nc0,rd,tot min	264183	N,Capacity of all studs in weak direction			

It can be noticed that the capacity of the original wall is enough

- For the first alternative of the wall (OSB board in the center of wall section) the chosen timber section of the main studs will be 130*110 mm, so the capacity of the main three studs is equal

b(mm)	h (mm)	A (mm2)	le (mm)	k mod	γm
130	110	14300	1000	0.8	1.3
E0.05 (Mpa)	fc0k (Mpa)	fc0d (Mpa)	β	N	
7400	21	12.9	0.2	3	
I max	14419166.67		i max	31.8	
I min	20139166.67		i min	37.5	
λ max	31.49		λrel max	0.53	
λ min	26.65		λrel min	0.45	
k max	0.67		kc max	0.94	
k min	0.62		kc min	0.96	
Nc0,rd. max	173679	N,Capacity of one stud in strong direction			
Nc0,rd, min	178056	N,Capacity of one stud in weak direction			
Nc0,rd, tot. max	521037	N,Capacity of all studs in strong direction			
Nc0,rd,tot min	534169	N,Capacity of all studs in weak direction			

Also, it can be noticed the wall has enough capacity for the first suggested alternative

- For the second alternative of the wall (OSB board in outer side of the wall) the chosen timber section of the main studs will be 90*150 mm, so the capacity of the main three studs is equal

b(mm)	h (mm)	A (mm2)	le (mm)	k mod	γm
90	150	13500	1000	0.8	1.3
E0.05 (Mpa)	fc0k (Mpa)	fc0d (Mpa)	β	N	
7400	21	12.9	0.2	3	
I max	25312500.00		i max	43.3	
I min	9112500.00		i min	26.0	
λ max	23.09		λrel max	0.39	
λ min	38.49		λrel min	0.65	
k max	0.59		kc max	0.98	
k min	0.75		kc min	0.90	
Nc0,rd. max	170772	N,Capacity of one stud in strong direction			
Nc0,rd, min	156558	N,Capacity of one stud in weak direction			
Nc0,rd, tot. max	512315	N,Capacity of all studs in strong direction			
Nc0,rd,tot min	469673	N,Capacity of all studs in weak direction			

And it is enough to resist the vertical loads

- Capacity of the wall for horizontal loads

The horizontal loads which are applied on the studied wall are a result of wind load, which affects the large elevation of the building.
The building assumed to be in Gothenburg city, so the wind speed is v_b=25 m/sec
The mean velocity pressure of the wind is $q_b = v_b^2/1600$= 0.39 kN/m^2
By assuming that the building is in terrain category lll, and the total height of the building is z=22 m
The exposure factor $c_{e(z)}$ =2.2
The peak velocity of the wind $q_{be}=q_b$ x $c_{e(z)}$=0.86 kN/m^2
As the ratio h/d =1.6 so the pressure coefficient c_{ep}=1.33
The total designed wind loads is $Q_{wd}= \gamma_m$ x q_{be} x c_{ep} = 1.5*0.86*1.33=1.72 kN/m^2
The design applied wind load on the wall is 16*5.0 *1.72=137.6 kN See Figure 3.17.

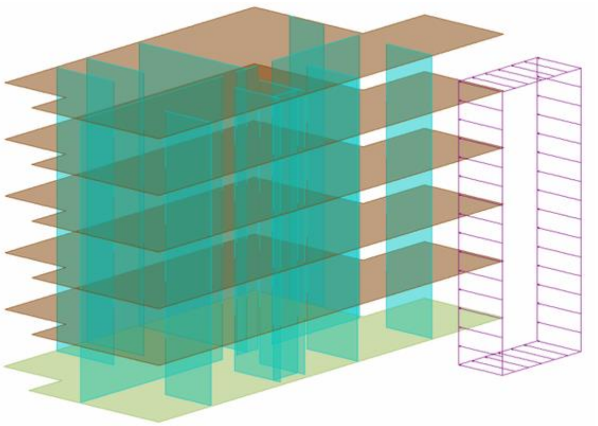


Figure (3.17) The contributed wind load area on the designed wall

The maximum moment at the bottom of the wall of 8.0 m height is 137.6*8= 1101kN.m
The characteristic self-weight of the wall and slab at the bottom of the wall is

(20*5/3)+3*5=48.3 kN/m
The maximum moment of the self-weight of the wall and slab 48.3*3*1.5=217.5 kN.m
The net applied moment 1052-217.5=834.5 kN.m
The uplifting force is 834.5/3=278.2 kN
As a result, the uplifting force distributed on three main studs is 278.2/3=92.7 kN for each one using Hilti anchor bolt KB1 (12.5 mm diameter) and assuming the failure mode is due to concrete failure. Four anchors are enough at each connection as the capacity of the anchor is 25.7 kN with 40MPa concrete strength. See Annex (E)

- The capacity of the wall for shearing force

The applied design wind load is Qwd= gm x qbe x cep
= 1.5*0.86*1.33=1.72 kN/m2
The newly designed wall has four panels of OSB size (0.72*3.0 m). See Figure 3.17.
The applied wind load on the wall is Qwd.w = Qwd x b x h x l= 1.72*3*3*5= 77.4 kN
Where h, b is the height and depth of the wall and l is the contributed width of the elevation
The applied force on each panel is qwd.w=77.4/4= 19.4 kN
For the first suggested alternative, a steel angle, and screws for connecting the OSB to the main studs will be used. The screw size is 5*30 mm, and the angle size is 30*30*10 mm
The design capacity of the screw on the shear force, in this case, will be 1.0 kN
The total needed connections are 20/1=20 Nos
So, a screw of 5mm and angle will be used with a step of 25 cm, See the table below
To check the shear buckling, the ratio 35 no risk for shear buckling
The second suggestion of the wall design is by shifting the OSB boards to the outer side of the wall, the thickness of the OSB board is assumed to be 20 mm, in this case, the main stud size will be 90*150 mm, and the main three studs should be able to transfer the whole vertical loads See Figure 3.18.
The applied shear force on each wall is equal to 19.4 kN
By using screws of 5*50 mm, its capacity for a single shear case is 0.88kN
each OSB panelboard needs 20/0.88= 23 Nos of screws. See the table below.

For the shear buckling, adding the vertical supports to OSB at half of its width, the ratio between hw and bw will be less than 35, and there is no shear buckling risk.

Connection / first alternative				
Fastener	Single shear steel-timber			
l (mm)	d (mm)	fu (MPa)	fy (MPa)	D cc (mm)
	5	365	235	
Timber				
lt (mm)	t1 (mm)	t2 (mm)	ρk	
	30		550	
Myrk	10785	Nmm	γM	Kmod
f hk	29.6	MPa	1.3	0.8
Shear Capacity	Fv1rk	1776		
	Fv2rk	2055		
		Fvrk	1776	N
		Fvrd	1093	N

Connection / Second alternative				
Fastener	Single shear timber-timber			
l (mm)	d (mm)	fu (MPa)	fy (MPa)	D cc (mm)
	5	365	235	
Timber				
lt (mm)	t1 (mm)	t2 (mm)	ρk	
	20	30	440	
Myrk	10785	Nmm	γM	Kmod
f h1k	28.4	MPa	1.3	0.8
f h2k	22.3			
β	0.783138			
Shear Capacity	Fv1rk	2843		
	Fv2rk	3339		
	Fv3rk	5489		
	Fv4rk	1422		
	Fv5rk	1587		
	Fv6rk	1887		
		Fvrk	1422	N
		Fvrd	875	N

Capacity Hilti anchor bolt K1B1

Nominal anchor diameter in.	Effective embedment in. (mm)	Nominal embedment in. (mm)	Tension (lesser of concrete breakout / pullout) - ΦN_n			
			f'_c = 2,500 psi (17.2 MPa) lb (kN)	f'_c = 3,000 psi (20.7 MPa) lb (kN)	f'_c = 4,000 psi (27.6 MPa) lb (kN)	f'_c = 6,000 psi (41.1 MPa) lb (kN)
3/8	1-1/2 (38)	1-7/8 (48)	1,435 (6.4)	1,570 (7.0)	1,815 (8.1)	2,220 (9.9)
	2 (51)	2-3/8 (60)	2,070 (9.2)	2,130 (9.5)	2,230 (9.9)	2,380 (10.6)
1/2	2 (51)	2-3/8 (60)	2,205 (9.8)	2,415 (10.7)	2,790 (12.4)	3,420 (15.2)
	3-1/4 (83)	3-5/8 (92)	4,570 (20.3)	5,005 (22.3)	5,780 (25.7)	7,080 (31.5)