Structural behaviour of lateral load-carrying capacity of timber frame walls filled with hemp concrete : experimental study and numerical analysis

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Structural behaviour of lateral load-carrying capacity of timber frame walls filled with hemp concrete: Experimental study and numerical analysis.

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Abstract

Construction projects nowadays face significant challenges to reduce the large amounts of daily energy usage for utilities such as heating, electricity and hot water in residential and commercial buildings – especially in Europe. Many building regulations encourage the use of bio-based materials with superior physical properties for energy efficiency in the construction sector. The use of low-carbon material in structures such as hemp concrete, improves the insulation level and sound absorption and simultaneously decreases the weight of the building structure, as this natural material provides low-density aggregate.

This study aimed to investigate the mechanical behaviour of timber frame walls against lateral loads. Cross-laminated timber walls (CLT) and Oriented Strand Board (OSB) were used in this study in order to examine the global lateral strength of timber walls. A theoretical approach has been proposed to predict the lateral performance of CLT wall against lateral loads and a comparison between the theoretical and experimental results has been conducted.

Experimental testing was undertaken on a full-size example of two different designs of timber walls to investigate and highlight the parameters that significantly affect the lateral resistance of hemp concrete as infill material. Vertical studs and diagonal bracing elements under compression were used in this study, with dimensions of 2.5m height and 1.25m length. The results showed that hemp concrete makes a slight contribution against lateral loads in vertical stud timber wall of length 1.25m, which means that decreasing the length of timber wall significantly decreased the hemp concrete contribution against lateral loads.

Three timber walls with different lengths (1.2m, 1.6m and 2.4m) filled with hemp concrete have been examined numerically in this study. Based on the numerical results, it was obvious that the length of the timber wall plays a major role in the lateral strength of hemp concrete, as increasing the wall length significantly increased the lateral strength of hemp concrete. Also, the contact and bonding between hemp material and timber studs significantly affected the lateral load carrying capacity of hemp concrete as infill material in timber frame walls.

Keywords

Timber frame walls, hemp concrete, cross-laminated timber, racking strength, materials contact.

Résumé

Les projets de construction sont aujourd'hui confrontés à des défis importants pour réduire la grande quantité d'énergie employée quotidiennement pour les utilisations tels que le chauffage, l'électricité et l'eau chaude dans les bâtiments résidentiels et commerciaux, en particulier en Europe. De nombreux règlements de construction encouragent l'utilisation des matériaux biosourcés puisqu'ils semblent avoir des propriétés physiques supérieures en terme d'efficacité énergétique dans le secteur de la construction. L'utilisation de matériaux à faible teneur en carbone dans des structures telles que le béton de chanvre améliore le niveau d'isolation ainsi que l'absorption acoustique et diminue le poids de la structure du bâtiment, car ce matériau naturel fournit un agrégat à faible densité.

Cette étude concerne le comportement mécanique de murs en bois, réalisés avec des planches croisées en bois CLT et des murs à panneaux d'OSB, sous l'effet de forces horizontales de cisaillement. Une approche théorique a été proposée pour prédire la performance latérale de la paroi CLT par rapport aux charges latérales ainsi qu'une comparaison entre les résultats théoriques et expérimentaux a été effectuée.

Des essais expérimentaux ont été réalisés sur des murs de bois ayant deux formes différentes pour étudier et mettre en évidence les paramètres qui affectent significativement la résistance latérale du béton de chanvre en tant que matériau de remplissage. Des montants verticaux et des éléments de contreventement diagonaux de 2,5 mètres de hauteur et 1,25 mètres de largeur soumis à une compression ont été réalisés dans cette étude . Les résultats ont montré que le béton de chanvre apporte une légère contribution contre les charges latérales dans les murs verticaux de 1,25 mètres de largeur, ce qui signifie qu'une diminution de la largeur du mur de bois diminue significativement la contribution du béton de chanvre contre les charges latérales. Trois murs en bois de différentes longueurs (1,2 mètres, 1,6 mètres et 2,4 mètres) remplis de béton de chanvre ont été étudiés numériquement dans cette étude. D'après les résultats numériques, il était évident que la largeur du mur en bois joue un rôle principal dans la résistance latérale du béton de chanvre : lorsque la largeur du mur augmente, la résistance latérale du béton de chanvre s'accroît considérablement. De plus, le contact et la liaison entre le chanvre et les montants en bois affectent totalement la capacité de la résistance latérale du béton de chanvre en tant que matériau de remplissage dans les murs en bois.

Mots-clés

Murs en bois, béton de chanvre, résistance contre les charges latérales, contact des matériaux.

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$F_{l,Rd}$	Design racking load-carrying capacity.
α	Rotation angle of the board in OSB.
γ	Rotation angle of vertical studs in OSB.
h	Height of timber wall.
K_{ser}	Slip modulus of the fastener.
n	Total number of fasteners in the wall of OSB.
x_i	x-coordinate of fastener number i.
y_i	y-coordinate of fastener number i.
F_d	Design capacity of the fastener.
Δ	Horizontal displacement of a timber unit.
OSB	Oriented Strand Board.
CLT	Cross-Laminated Timber.
F	External horizontal force applied on the top of cross-laminated wall.
$M_{y,Rk}$	Characteristic value of the yield moment for the fasteners.
$F_{ax,Rk}$	Characteristic axial withdrawal capacity of the fastener.
t_1	Headside thickness in a single shear connection for nails.
t_2	Pointside penetration in a single shear connection for nails.
H	External horizontal force applied on the top of oriented strand board.
N	Total number of layers in cross-laminated wall.
N_v	Number of layers with vertical planks.
N_H	Number of layers with horizontal planks.
N_{px}	Number of vertical planks.

N_{py}	Number of horizontal planks.
e	Width of plank.
y	Thickness of plank.
a	Width of timber wall.
b	Thickness of timber wall.
d	Diameter of fastener.
N_{m1}	Number of meshes in two layers of the wall.
S_h	Distance between fasteners in OSB.
N_m	Total number of meshes in the whole cross-laminated wall.
$F_{v,Rk}$	Characteristic load-carrying capacity per shear plane per fastener.
β	Ratio between the characteristic embedment strengths.
$f_{h,1,k}$	Characteristic embedment strength in plywood elements.
$f_{h,2,k}$	Characteristic embedment strength in timber elements.
r	Distance from the fastener to the centre of the intersection plane.

Dedications

This study is wholeheartedly dedicated to my family who has been my source of inspiration and gave me strength when I thought of giving up.

To my brothers, sisters, friends and classmates who shared their words of advice and encouragement to finish my study.

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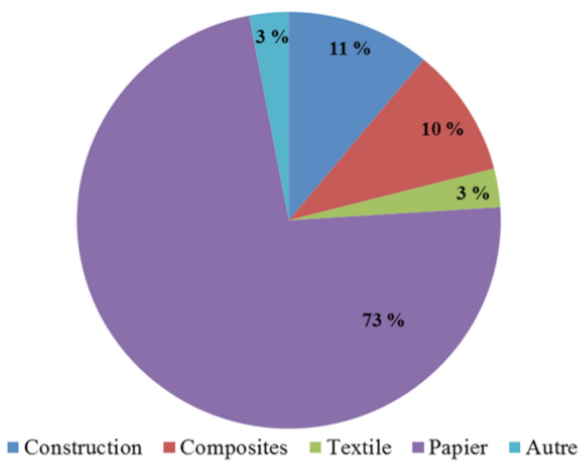
General Introduction

General Introduction

The use of eco-materials from agricultural products has increasing adoption as a solution in the field of construction. Indeed, like any other field (transport, aeronautics, etc.), this sector must deal with the issue of greenhouse gas emissions, as well as the scarcity of raw materials, the problems of recycling and development of sustainable methods. At present, the use of plant-based products as a raw material is a solution that is increasingly applied in many industries. In the field of construction, aggregates of mineral origin are substituted by aggregates of plant origin. Examples of this include sunflower grinds or wood and, even more widely, the use of hemp as an aggregate. Currently, French production of hemp comes from a cultivation area of about 10000 ha as compared to 120000 ha in the 19th century. According to the current trend of the use of aggregates of plant origin and given the advantages of hemp (favourable CO_2 balance, easy end-of-life management, etc.), its production is expected to increase in the coming years. Therefore, it is important to have good quality control of this product and how it is used to support it. Due to the low density associated with the high porosity of hemp particles, the combination of hemp and a mineral binder creates a natural building material whose mechanical, thermal and acoustic properties differ from those of traditional concrete. The strengths, thermal conductivity and acoustic properties of this agro-concrete are low. No regulations currently exist to allow design offices to take into account the properties of this material in their structural calculations. However, hemp concrete has mechanical properties, including dynamic damping, which should reduce the number of structural sections, and thus limit the costs and environmental impact of building materials[1].



Graph 1. Usage of hemp fibre.

Wood is also common natural material associated with lightweight structures, it has ubiquitous uses as a building material in many countries around the world. The pros of wood lie mainly its abilities to form ductile joints, its physical properties and being environmentally friendly. Timber walls are the frequently used structural system in the buildings designed to withstand lateral loads and transfer these forces to the foundations with ductile behaviour. According to the European Norm EN 594, [2] a timber shear wall consists of a timber frame and sheathing board, connected by fasteners. The sheathing board may be made of a variety of materials, such as gypsum, plywood, fibre board or OSB.

Hemp concrete was initially used as natural infill material in timber frame walls in construction. This filling material proved excellent physical properties in terms of isolation and acoustics. This material was also able to allow the building to breathe and did not shrink. The major purpose of using this natural material in construction was achieving the optimal physical properties. Nowadays, this material is considered as a natural, sustainable and carbon neutral infill timber wall material in construction. Figure 2 below shows the renewable house that has been constructed at the Building Research Establishment (BRE) to showcase the material in the UK.

Figure 2. The renewable house at BRE.

Problem statement

Although hemp concrete has proved to have some excellent characteristics such as thermal and acoustic properties, this material still has poor mechanical properties such as compressive strength. In addition, the structural design practice of wood frame construction does not assume any contribution of green concrete to lateral strength. Several studies have been carried out on the mechanical behaviour of hemp concrete in order to investigate its lateral contribution against horizontal loads – especially when used in timber walls, as infill materials. To date, there have been limited studies on the lateral load-carrying capacity of hemp concrete. These studies also did not explain or introduce any parametric design for using hemp concrete in structural functions.

As matters currently stand in relation to hemp-based materials, it is obvious that there is a lack of knowledge and a need for further studies in racking performance of hemp concrete – particularly in timber frame walls. For this purpose, this research highlights the parameters that could play a main role in the lateral strength of hemp concrete, and also opens the door for the parametric design for this filling material to make it contribute to the lateral performance. The main objective of the presented study is firstly, to investigate the lateral behaviour of timber walls according to the Eurocode 5 standards and, secondly, investigate the lateral strength of two different designs of timber frame walls filled in with hemp concrete. The length and overall rigidity of the timber hemp wall have been investigated in this study to describe their effects on lateral load-carrying capacity.

Aims and objectives of this research

The main aims of this study are firstly, to investigate and understand the lateral behaviour of timber frame walls according to the Eurocode 5 and secondly, to highlight the most important parameters that can play a main role on the lateral strength of timber walls filled with hemp concrete.

The aims and objectives of this research will be arranged in four sections:

1- Reviewing the applicability of Eurocode 5 to the lateral load carrying capacity of timber walls.

2- Investigate the lateral strength of timber frame walls (CLT) using experimental study.

3- Investigate the lateral strength of hemp concrete as infill material in timber frame walls using experimental tests.

4- Studying the parameters that affect the lateral strength of hemp concrete as infill material in timber frame walls using numerical study (Finite element method).

Outline of this thesis

In an attempt to fulfil its aims and objectives, this thesis is divided into four main chapters as follows:

Chapter 1: Literature review

This chapter gives some background information to wood material with its behaviour, particularly the mechanical properties. Also, this chapter describes the source of bio-based material, especially hemp shives, while presenting its mechanical properties. This chapter also shows the practical design for timber walls according to the Eurocode 5 recommendations. At the end of this chapter, there is in-depth description about the lateral load carrying capacity of timber walls filled with hemp concrete according to the previous studies.

Chapter 2: The lateral strength of cross-laminated timber walls

This chapter includes an extensive discussion about the principles of Eurocode 5 and reviewing of the design parameters for timber frame walls subjected to the lateral loads. This chapter also presents an experimental test for Cross-laminated timber walls (CLT). An analytical prediction has been proposed in this chapter to describe the performance of CLT walls subjected to lateral loads, which also could be used in the design recommendations. This chapter then examines the feasibility of using unclassified timber for constructing timber frame-walls in cross-plank form, and the lateral resistance of these walls to horizontal loads without the addition of extra, expensive materials.

Chapter 3: The lateral strength of hemp concrete as infill material in timber frame walls

This chapter focuses on the racking behaviour of hemp concrete as infill material in timber frame walls, investigating and highlighting the parameters that significantly affect the lateral resistance of hemp walls. This chapter presents two different timber design as a wall unit, also show the results of Digital Image Correlation (DIC) relate to determine and track local displacement and shear-strain fields of hemp concrete as infill material in the timber wall.

Chapter 4: Numerical analysis of timber frame walls filled with hemp concrete

This chapter presents the validation of the experimental tests of the previous chapter and reviews some important parameters that play a major role in determining the lateral load carrying capacity of hemp concrete as infill material. This chapter highlights some design considerations for hemp timber walls.

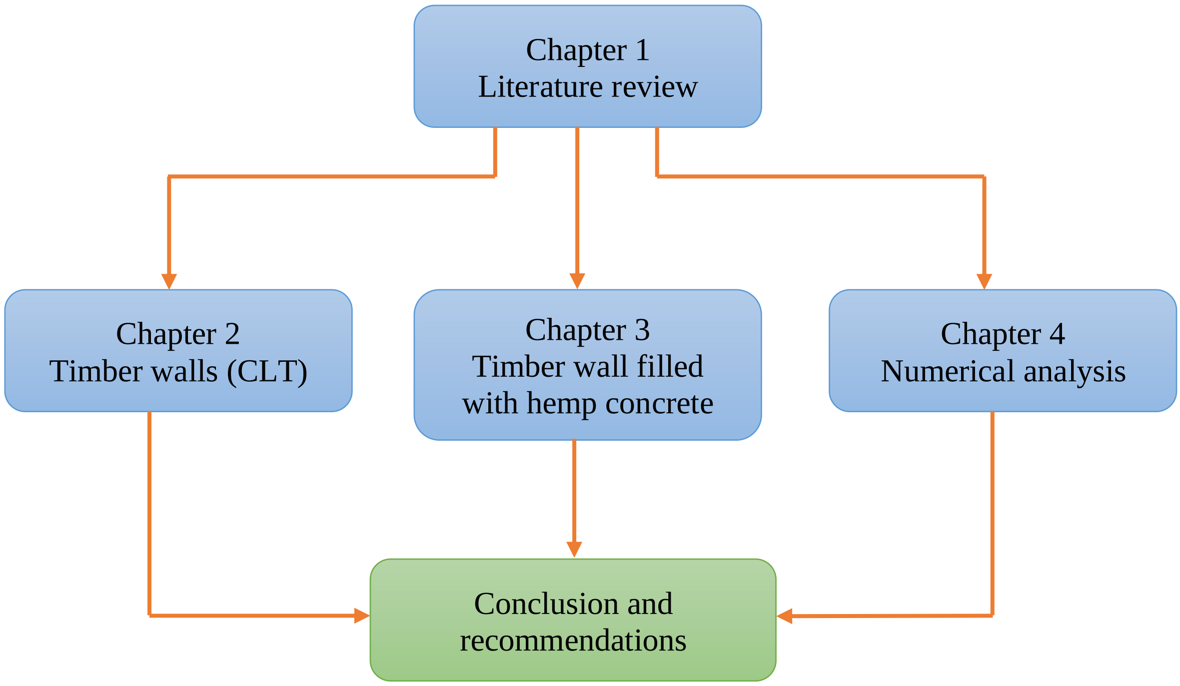


Figure 3. Schematic presentation of the thesis outline

Chapter 1 Literature Review

1 Literature Review

1.1 Introduction

Construction projects nowadays face significant challenges to reduce the large amounts of daily energy usage for utilities such as heating, electricity and hot water in residential and commercial buildings – especially in Europe. For this purpose, many building regulations now encourage the use of bio-based materials with superior physical properties for energy efficiency in the construction sector. The use of bio-based material in structures improves the insulation level and decreases the weight of the building structure, as this natural material provides a lightweight, low-density aggregate. In response to this need, the use of bio-aggregate such as hemp, flax and sunflower products is increasing in Europe – particularly in France [3]. Bio-aggregate-based building materials offer a route to more sustainable construction by reducing energy consumption and simultaneously achieving energy efficiency without causing additional environmental pollution [4]. Hemp concrete has been one of the most commonly used bio-aggregate-based building materials since the 1980s [5]. Although hemp concrete has proved to have some excellent characteristics such as thermal and acoustic properties, this material still has poor mechanical properties such as compressive strength. In addition, the structural design practice of wood frame construction does not assume any contribution of green concrete to lateral strength [6]. Several studies have been carried out on the mechanical behaviour of hemp concrete in order to investigate its lateral contribution against horizontal loads – especially in timber walls, as infill materials. To date, there have been limited studies on the lateral load-carrying capacity of hemp concrete. As matters currently stand in relation to hemp-based materials, it is obvious that there is a lack of knowledge and a need for further studies in racking performance of hemp concrete – practically in timber frame walls. For this reason, the literature review in this chapter highlights the mechanical behaviour of hemp concrete and also the lateral performance of timber frame walls.

The first chapter of the dissertation presents a comprehensive review of the current knowledge of the mechanical properties of hemp concrete, in addition to the lateral structural strength of hemp concrete as infill material in the timber frame walls. This chapter is consisting of three main parts: (I) timber as a structural material, (II) natural building material, (III) lateral structural behaviour of timber walls.

1.2 Timber as a structural materials

Trees and forest products have been used by companies around the wold for thousands of years. Wood is commonly associated with lightweight structures, it has ubiquitous uses as a building material in many around the world. The pros of wood lie mainly its abilities in ductile joints, its physical properties and being environmentally friendly[7]. Timber walls are the frequently used structural system in the buildings designed to withstand lateral loads and transfer these forces to the foundations with ductile behaviour[8].

1.2.1 Tree growth and structure of wood

The growth of the tree trunk is happened by two types of processes, each process controlled by a specific parts of the plant. The first process is mediated by (apical meristem), this part is responsible for predominantly upwards primary growth and located at the top part of the tree. The secondary growth of the tree can introduce thicker stems and make the oldest part of the tree in the centre of the trunk. Young xylem is the water conducting tissue (sapwood) and if the tissue dies and wood cells become hollow it forms heartwood. Phloem is tissue responsible for transfer the nutrients and situated on the outside of the trunk. Resinous materials and polyphenols are responsible about protecting these dead cells from fungal attack[9]. Wood material considered as non-uniform within sapwood and heartwood layers.

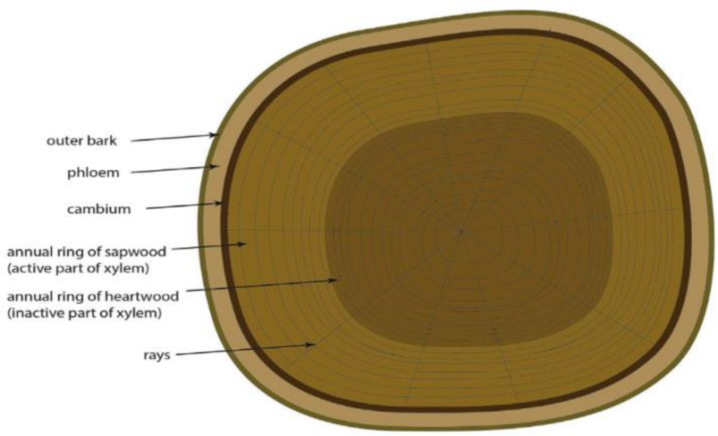


Figure 1. 1: Tree cross section.

1.2.2 Forests as a main source of timber

Forests are the main supply chain for softwood and hardwood wood in the world and particularly in Europe. Since 1990 until now, the area of forests in Europe increased approximately about 6%[10]. The main source for the other construction materials such as steel, concrete and cement became quite limited. As presented in the map below, much of Europe locate predominately in the northern latitudes or on the periphery of the mountains region of Europe. These region are always have a high rainfall which increase the area of forests without any fundamental concerns[11]. Valentini et al in his investigation concluded that the forests in Europe normally act as carbon sinks with an annual balance around 6.6 tonnes of carbon per hectare[12].

Forests also have a positive effects on the society and ecology, also have a main role in participating in climate change by balancing part of the global carbon budget. These advantages of increased forestry in Europe come with a huge need to use the natural material which forests supply wisely, ensuring that timber is increasingly used in a way which maximises its life time and permits environmentally sound disposal.

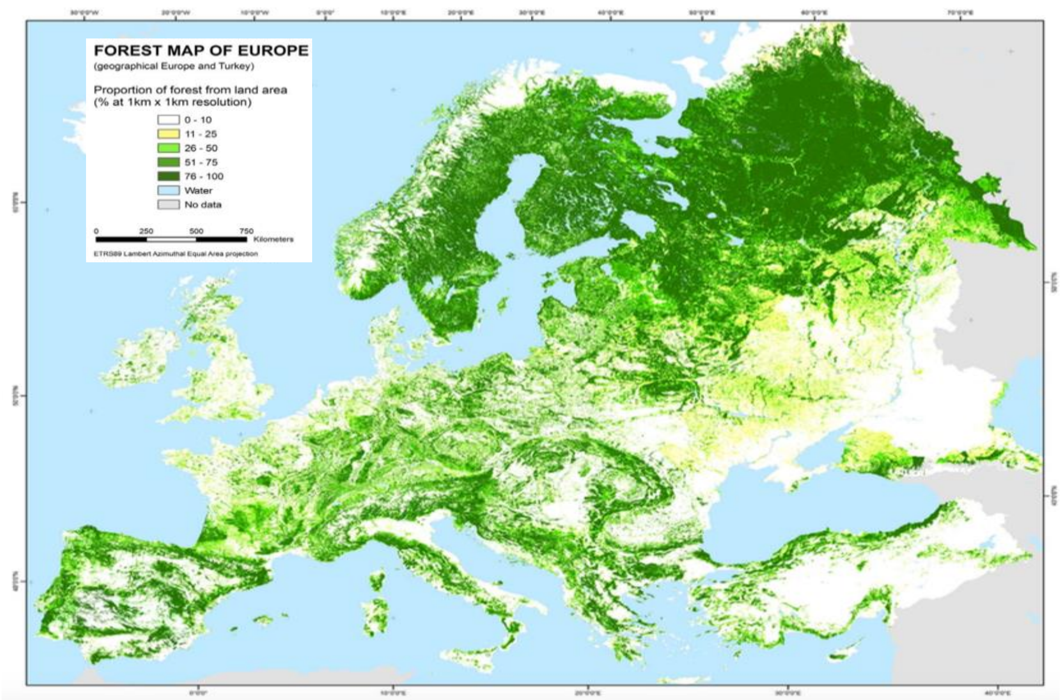


Figure 1. 2: Map showing the distribution of forests within Europe.

1.2.3 Processing timber products

Since 2013 the European Union Timber Trade Regulation put the processing timber products such as harvesters and distributers under legal obligations and roles particularly for materials used in constructions. In Europe, the sustainably manged coniferous forests are the main most commonly used as a structural timbers[13]. Although softwoods are not dense like hardwood but the first one is considered as a cheap material and available in many useful forms and can be more helpful for construction purposes.

The first step of timber processing is called “Roundwood” this step is related to removing trees branches and cut the trunks in a specific length for the transportation. According to the European standards wood should dry below 20% moisture content for “dry graded” timber in order to define the strength grading for the timber materials[14]. This process of drying will make the material lighter for transportation and also more receptive substrate for gluing. In addition, timber is a hygroscopic material which affected by the surrounded environmental so drying process will make the timber material more suitable and match the moisture within the building atmosphere with a good service conditions. The percentage of moisture in this step is called the dry weight in timber and the moisture content which wood tends towards in a given temperature and humidity is represents the equilibrium moisture content. The natural drying of reducing the natural moisture content will significantly increase the mechanical properties of wood. Kiln drying is one of many methods used for moisture removing from timber specially for sawn softwood industry. This kiln is usually around 30-100 m_3 with indirect steam or hot water. Previous studied[15] showed that the required energy for kiln dry radiata can be around 3GJ/m_3 specific heat.

Using timber as structural materials means that this material will be within a dry building conditions but could be exposed to excess moisture during construction stage. To ensure a balance moisture content during construction phase, the structural timber material is dried to between a 12-20% moisture content. This moisture content is defined clearly in European Standards[2] and indicates the “service classes” values. Un-protected structural timber in construction will indeed exposed this material of higher levels of moisture however keeping structural timber in an isolated case or enclosed it within finished building will decrease the moisture content from 20% to 12%. During the processing of round-wood as illustrated in figure below, around 50% is recovered as viable plank products and the remaining fibre and dust used as biomass fuel[16].

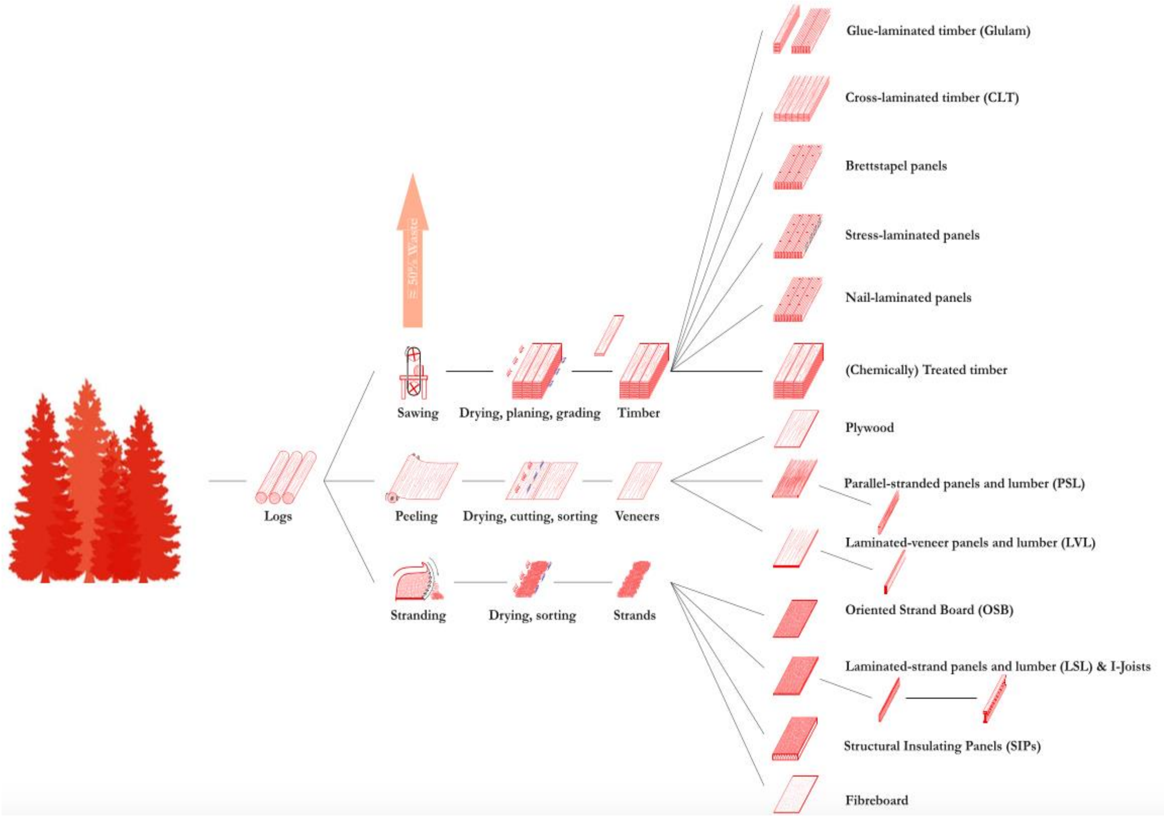


Figure 1. 3: The processing chain of engineered timber products.

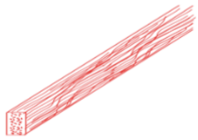
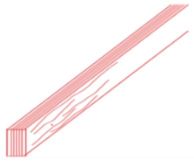
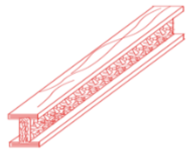
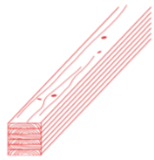
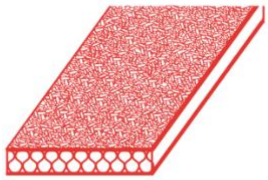
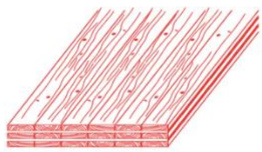
1.2.4 Strength grading of timber material

As mentioned before in the previous sections, wood is a natural material which means that this material exhibits inherent variation in terms of the mechanical properties even the same wooden samples, this difference in properties is related to the interaction of characteristics at the molecular and macro scale[17]. To ensure that this material can satisfy the structural functions in buildings and achieve the design maximum load in construction, it is necessarily to classify and strength grade[18] these pieces according to BS EN 14081. This grading standards will be useful and more accurate for the engineers and designers to choose the suitable strength class and consider these characteristics in their calculations.

There are two types of strength grading according to BS EN, the first one is called visual strength grading (VSG) and the second one is called machine strength grading (MSG). The visual strength grading is defined by noticing the weakness features such as knots on timber and also for splits or defects that could happened during the drying process. The machine strength grading is defined by a set of tests related to the characteristics values of stiffness and density for the strength classes by feeding individual timber length through calibrated rollers. The wood is classified by a letter “C” which indicates to softwood and also a letter “D” which indicates hardwoods, each letter followed by a number indicates the value of bending strength in unit N/mm2. For instance C16 is weak compared to C50 which is strong as defined by European standard, BS EN 338. Softwoods are known as “engineered timber” and considered as a structural building material. The advantage of this composite-manufactured from laminated timber and other materials is increasing dimensional stability and introduce a homogenous mechanical properties and also greater durability. Seven types of timber lie on this this family of wood as illustrated below:

1- **Glulam:** is defined as a structural timber member consists of at least two parallel laminations which can comprise of one or two boards with a thickness vary from 6 mm to 45 mm. this type of wood used normally long and curved beams.
2- **Laminated Veneer Lumber (LVL):** is defined as a reconstituted dimensional timber which is commonly twice the strength of timber of the same samples manufactured from rotary peeled veneers of spruce, pine or Douglas fir 3 mm thickness[19]. The veneer grain is usually oriented in a single direction and length of short veneer are jointed end to end with a scarf joint producing un limited dimensional lengths.
3- **Structural Veneer Lumber (SVL):** this type of timber is consists outer plies of LVL laminated together to form linear structural components. Douglas fir veneers of 2.5 mm laminated in the direction of grain parallel to the direction of the board or beam[20].
4- **Cross-Laminated Timber (CLT):** this type of panels consists of at least three layers of swan softwood each layer is perpendicular to the other with cross planks in a right angle. These layers are connected together by glue or fasteners to form a total thickness of a range 50-500 mm. Cross laminated timber panels are more suitable for floors roofs and wall elements [21].
5- **I-Joists:** these timber are considered more expensive comparing to solid timber joists for an equivalent strength and stiffness. This kind of timber can be more stable due to their homogeneous.
6- **Structural Insulating Panels (SIPs):** is defined as a structural prefabricated sandwich panels consisting of an insulating layer encased between two skins of fiber [22].
7- **Brettstapel:** this is a solid wood panels manufactured from softwood planks connected by hardwood dowels.

Table 1. 1: Common structural engineered timber products in Europe.

Engineered Timber product	Application	Usage	Details
Parallel Strand Lumber (PSL)	- Beams - Columns	Interior	
Laminated Veneer lumber (LVL)	- Beams - Columns - Cord	Interior	
I-Joist	- Joist - Beam	Interior	
Glulam	-Beam(long span) - High loading	Interior/Exterior	
Structural Insulating Panel (SIP)	- Roof - Wall - Floor	Interior	
Cross Laminated Timber (CLT)	- Roof - Wall - Floor	Interior/Exterior	
Brettstappel	- Roof - Wall - Floor	Interior/Exterior	

1.2.5 Mechanical Properties of wood

Wood is a natural material manufactured from the trees, these trees are subjected to many changing influences which means that the there is a variation in properties in this material. This section presents the most common mechanical properties of wood and also the effect of growth features on its characteristics.

In the literature review, many researchers described the wood material as an orthotropic nature material, which mean that this material has a specific and unique mechanical properties in each direction of three perpendicular axes: Longitudinal (L), radial (R) and tangential (T). the longitudinal axis is always parallel to the grain of the wood pieces. However, the radial axis is perpendicular to the grain in the radial direction. The tangential axis is perpendicular to the grain but tangent to the growth of rings in the wood as illustrated in Figure below[23].

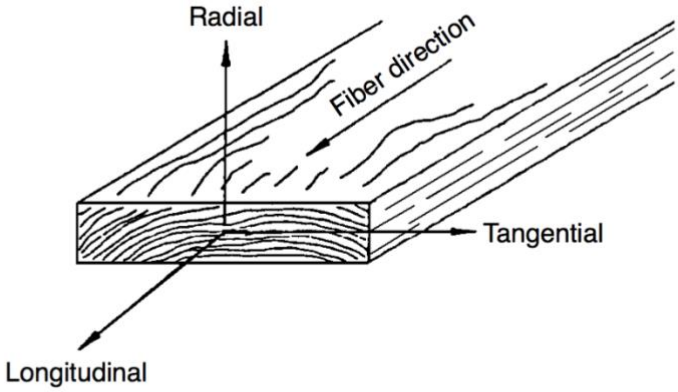


Figure 1. 4: Three principal axes of wood with respect to the grain direction.

1.2.6 Properties parallel to the grain of timber

The strongest and stiffest part in the timber pieces is the parallel to grain direction. The average tensile strength of clear and straight grained timber samples parallel to the grain is generally between 70 to 140 MPa at 12% of moisture content.

The compressive strength for clear and straight grained timber samples is approximately between 30 to 60 MPa which is less that the tensile strength. The defects and knots effects are playing a main role in the mechanical properties of timber and significantly reduce the strength of timber by a factor of as much as 10. The common failure mode is load dependent with brittle tension failure while the compression failure is normally ductile. The typical moisture content value for softwood and hard wood is around 12% in the range of 7 to 14 GPa.

1.2.7 Properties perpendicular to the grain of timber

The mechanical properties of timber samples in case of perpendicular to the grain of wood are significantly lower than the equivalent properties in case of parallel to the grain. The average tensile strength in tangential and radial direction are less as 3 to 5% and 5 to 8% respectively. According to these values in differences between parallel and perpendicular to the grain, the design timber standards and designers recommend in such a way that tensile stresses in perpendicular are minimized or even do not happen[24]. In terms of compressive strength, the previous studied concluded that the a average values for compressive strengths perpendicular to the grain is normally around 10 to 20% of the parallel to the grain values. The elasticity modulus for timber specimens perpendicular to the grain is basically around 4 to 9% of the parallel grain values for softwood but there is no differences in values between radial and tangential directions for Elasticity modulus.

1.2.8 Factors that influence mechanical behaviour of timber

Since wood material has manufactured from natural trees, indeed a lot of natural parameters will significantly affect the characteristics of this material particularly the mechanical behaviour. In this section Five parameters presented below[24] that play a main role in the mechanical properties of timber.

(a) - Natural defects:

Many natural and visual characteristics can be observed during the normal trees growth such as Knots and spiral grain. The existence of these defects increase the variability of wood and will not produce an accurate mechanical properties as clean wood[25].

Figure 1. 5: Live and Dead Knots in Timber.

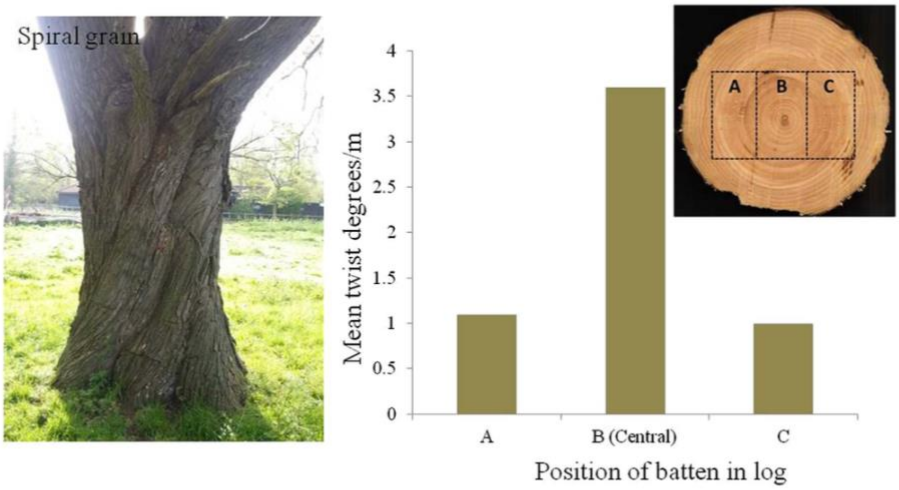


Figure 1. 6: Knots and twist in timber.

(b) – Moisture:

The moisture content in timber vary linearly with the mechanical properties of clean timber. Increasing the moisture content will affect negatively on the tensile and bending strength. For this purpose, design standards in Europe and around the world propose stress modification factor for considering the effect of moisture in structural timber.

(c) – Duration of load:

The duration of load affect significantly the stiffness and strength of structural timber. The strength will decrease with increasing the duration of a given magnitude load. The decreasing in strength value could arrive to 40% which indeed will affect the long-term strength of timber.

(d) – Cyclic load:

A reduction of strength calculation has been considered in case of timber elements subjected to cyclic or repeated load. This value of reduction depends on the amounts of Knots, for instance, about 50% of strength reduction should consider in case of small Knots with a static clear samples, however about 70% of strength reduction should considered in case of the Knots and sloping is present.

(e)- Temperature and fire:

In the normal rate of ambient temperature, the strength of timber will not be affected and can be stable. Subjecting the structural timber to a huge and permanent temperature will significantly reduce the strength of material.

1.3 Natural building Materials

Natural building materials are used widely nowadays in public and private construction sectors due to its renewability and availability on the global scale. These materials such as hemp, flax and sunflowers represent the aggregate part of the concrete. The heterogeneous mix between these bio-aggregates and the mineral binder will consist agro-concrete. On other words; agro-concrete can be defined as a mix between aggregates from lignocellular plant matter coming from agriculture and a mineral binder. The needs of lignocellular matter is for three reasons: reinforcement of structure, lightweight aggregate and insulating purposes. Recently, many researches work on the methods of integration between lignocellular substances and mineral binders to form lightweight aggregate. Research carried out to many plants of lignocellular substances with the suitable binder to consist the final mix of lightweight concrete with a dry density of less than 1000kg/m3. Table 1.2 below[3] illustrates some examples of these substances.

Table 1. 2 : Examples of ligncellular and binder materials of lightweight concretes.

No.	Plant	Material	Sources	Binders used
1.	Hemp	Hemp shiv	Agricultural co-product	Tradical PF70, hydraulic lime,methacholine, lime mix
2.	Flax	Shiv, tow	Agricultural co-product	Portland cement, cement + Sucrose
3.	sunflower	Stem	Agricultural co-product	Methacholine/ lime mix

1.3.1 Hemp aggregates

Hemp plants is growing nowadays specifically for the industrial and commercial uses and is a variety of Cannabis sativa plant. This plant is intended for the cultivation of industrial hemp. It is distinguished from other species (Cannabis indica-plant and Cannabis ruderalis-plant) by its low concentration of tetrahydrocannabinol (THC), less than 2%. This plant is more popular and commonly use in Europe and Central Asia. The agricultural hemp plant (Figure 1.7) is grown to a height around to 2-4 and with an average diameter ranging from 1 to 3 centimetres. The hemp stalk is composed of several layers from its centre to the outside, also there is hollow space or a hole in its centre as illustrated in Figure1.9 below[26].

Figure 1. 7: Morphology of the hemp plant.

Figure 1. 8: The hemp plant stalk.

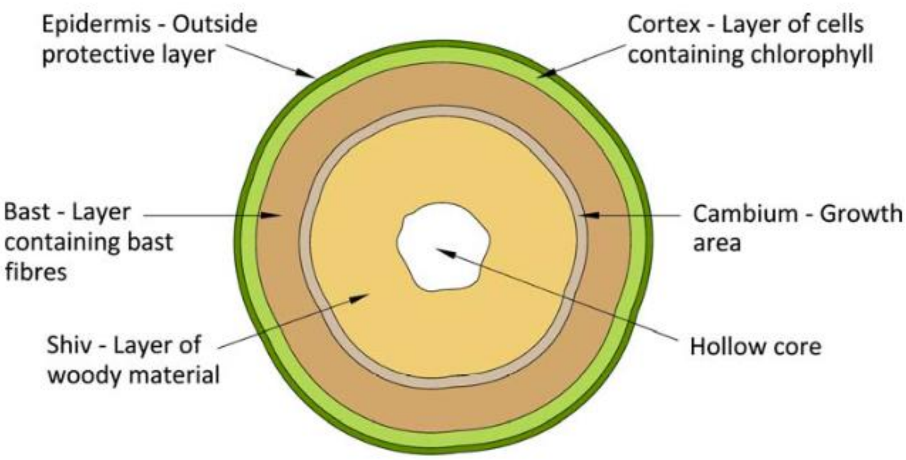


Figure 1. 9: Cross section through hemp plant stem.

The cross section through hemp plant stem consists of five different parts[27] as illustrated in previous Figures:

1- The epidermis: this part represents the outside protective layer of the stem and consisting of cells with a cellulosic material.
8- The cortex: this part contains chlorophyll.
9- The bast: this part represents a layer containing bast fibers.
10- Shiv: this part of the stem produces the woody material used in construction.
11- Hollow core: this part is totally empty and sometimes can occupy more than the half of the stem diameters in some older plants.

1.3.2 Hemp concrete

Hemp concrete is a concrete made by mixing a hemp shiv, mineral binders and water to create material mostly in a wooden structures with a good properties of thermo-hydric performances. there are two methods of hemp concrete implementation, the first method is casting in to a framework and the second method is compacting to make building block. Hemp concrete can be used in a lot of various applications in building such as walls, roof and floor as shown in Figure 1.10 and 1.11 below [28]. This concrete is environmentally friendly and also lightweight material with a densities between 200-600 kg/m3, depending on the application used. The required apparent density for using hemp concrete in timber walls is around 400 kg/m3 with heat conductivity 0.1 W/(m.k) however the apparent density of hemp concrete used as a roofing insulation is at the range of 200-250 kg/m3 with heat conductivity of 0.06 W/(m.k). other mechanical properties should be consider with the application of hemp concrete, for instance, when hemp concrete used in timber wall the Elasticity modulus should be greater than 15 MPa with a compressive strength greater than 0.2 MPa however using hemp concrete as roof application require modulus of elasticity greater than 3 MPa with a compressive strength greater than 0.05 MPa. The most popular mixing proportion between the mass of hemp shiv and the mass of binder for wall application is around 1:2 and consider 1 for the roof application[3].

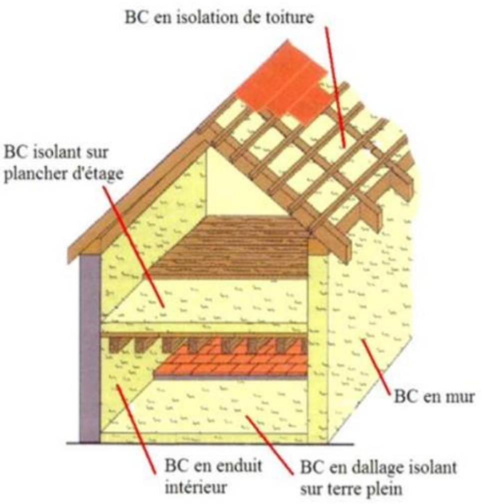


Figure 1. 10: hemp concrete applications.

Figure 1. 11: House of hemp concrete.

1.3.3 Binder material of agro-concrete

Generally, any type of concrete mix contains binder material which hold the other material together to form the mechanical and chemical properties of mixing as an adhesive. The choice of the binder type and proportion of mixing depend on the two factors: usage (insulation, support) and location (outdoor, indoor). Portland cement and hydraulic lime are the most popular binders used in concrete mix.

A hydraulic binder: is a ground mineral material, which form a paste and hardens by a lot of chemical reactions and hydration process when mixed with water, after hardened, retains its strength even mixed with water again (for example: *Portland cement*). In some agre-concretes you may use one or more binder, for instance, in hemp concrete different compounds in mixing: 70% slaked lime, 15% hydraulic lime and 15% pozzolana.

I. Portland cement

Portland cement is a hydraulic binder (mineral material mixed with water to form a paste which set and hardens by reaction and hydration process and once hardened, retains its strength even xhen faced to water again). Portland cement consists of base oxide (CaO) and acid oxides (SiO_2 or Fe_2O_3), the production of this cement can be made in a clinker with (80%) of limestone which produces calcium oxide and (20%) clay which produces silica, iron oxides. According to environmental impact of Portland cement, the studies observed that the consumption of energy resources (CEM l - type for example) is 5950 MJ/T, and the greenhouse gases is 866 equivalent Kilos of CO_2 per ton of product.

The cement plant may produce many different types of Portland cement according to the fineness and the type and content of other materials such as lime stone admixture, fly ash and blast furnance slag.

Portland cement classified to Five types according to its contents as follow:

- **CEM l**: Portland cement with at least 95% clinker.
- **CEM ll**: Portlant cement which may contain between 6% – 35% of other than clinker (blast furnace slag, silica fume, fly ash and lime stone)
- **CEM lll**: Blast furnace cement with 36% - 95% blast furnace slag.
- **CEM lV**: Pozzolanic cement which may contain between 11% - 55% of pozzolanic components.
- **CEM V**: blast furnace slag (18% - 50%), pozzolanic compound (18% - 50% mainly fly ash)

Portland cement offer great mechanical properties mainly compressive strength (compressive strength 10 times greater than flexural strength). These strength change rapidly over time 40% of final strength obtained after 2 days, 70% after 7 days. Mortar specimens can obtained 32.5 MPa, 42.5MPa and 52.5MPa. The addition of pozzolanic materials (blast furnace slag, fly ash, etc) can improve the durability of cement.

II. Lime

Lime has been used from ancient times, this material come from **calcination** and **decarbonation** of a limestone rock from the basic reaction

$$CaCO_3 \longrightarrow CO_3 + CaO \text{ (quicklime)}$$

Slaked process (add water) made with quicklime to create **calcium hydroxide**, depending on the water amount, this slaked lime will be in the form of lime paste or a powder.

$$CaO + H_2O \longrightarrow Ca(OH)_2$$

Types of lime, depend on to the limestone nature are summarized below:-

- **Calcic lime**: made of calcium hydroxides or oxides without adding pozzolanic or hydraulic materials.
- **Dolomitic lime**: made of calcium hydroxides or oxides and magnesium without adding pozzolanic or hydraulic materials.

- **Hydraulic lime:** made of natural hydraulic or natural hydraulic with pozzolanic materials, hydraulic limes are called **(HLs)** and natural hydraulic lime **(NHLs)**

Types of lime, depend on to the reaction with water existence are summarized below:-

- **Aerial lime:** made of calcium hydroxides or oxides, hardens in air by carbonation under the effect of carbon dioxide present in the air, no harden in reaction with water, non-hydraulic properties, the mechanical strengths are very poor (3-5 MPa) after 6 months kept in presence of CO_2, relative high thermal conductivity (0.65-0.84 W/mK) in the dry state.

- **Natural hydraulic lime (NHL):** made of calcium hydroxides, also include calcium silicate, rapid reaction with water, the mechanical strength change gradually in terms of time (from 1.0 MPa at 7 days to 3.6MPa at 28 days), it depends on the hydraulicity of lime and W/L ratio, high thermal conductivity (0.3 – 1.0 W/m.K), during its production a total of 635 kg of CO_2 per ton of NHL and fuel consumption of 75 kg of coal per ton of NHL.

Hydraulic limes may called HLs and natural hydraulic limes NHLs. Hydraulic limes are classified by their compressive strength at 28 days:

NHL 2: for strength between 2 - 7 MPa.

NHL 3.5: for strength between 3.5 – 10 MPa.

NHL 5: for strength between 5 – 15 MPa.

The setting of hydraulic lime occurs in two steps, the first step results from the hydration of C_2S and C_3S which cause to formulation of calcium silicate hydrate, the second step slower hardening around year results from carbonation of calcium silicate hydrate on contact with atmosphere CO_2. The mechanical properties of hydraulic lime mortars change gradually over time which may be very poor at the early stage (before 7 days). The environmental impact of hydraulic lime is similar to cement in terms of causes CO_2 emission, in the process of NHL 5 product, 635 kg of CO_2 per ton of cement.

III. Lime-pozzolan mixtures

Most bio-based concrete created from mineral binders like aerial or hydraulic lime, pozzolanic admixtures and may be Portland cement for enhancing the mechanical properties of concrete in the short and medium term, most of these admixture can be consider as natural pozzolan such as pumice, or calcinated natural pozzolans such as metakaolin or industrial by product such as fly ash or silica fume or Blast furnace slags. The mechanical properties of metakaolin at fresh state decrease the workability (adding superplasticizer or adjust W/l ratio to solve the problem) and at harden state improve the compressive strength.

IV. Plaster

This kind of binder can be obtained by dehydration of gypsum (calcium sulfate hydrate) in to hemi-hydrate and anhydrite, adding water to these materials give them hardens forming gypsum, and this binder is not hydraulic. Regarding to the view point of standardization, plaster binder shows flexural strength greater than 1 MPa (B1-B6) or 2 MPa (B7) and compressive strength greater than or equal to 2 MPa (B1-B6) or 6 MPa (B7). The heat conductivity of this binder is around to (0.18 – 0.56 W/m.K), and there is no specific advantages for plaster at acoustic side. In addition, this binder has low effects on the environment and CO_2 emissions because the low firing temperature at industry.

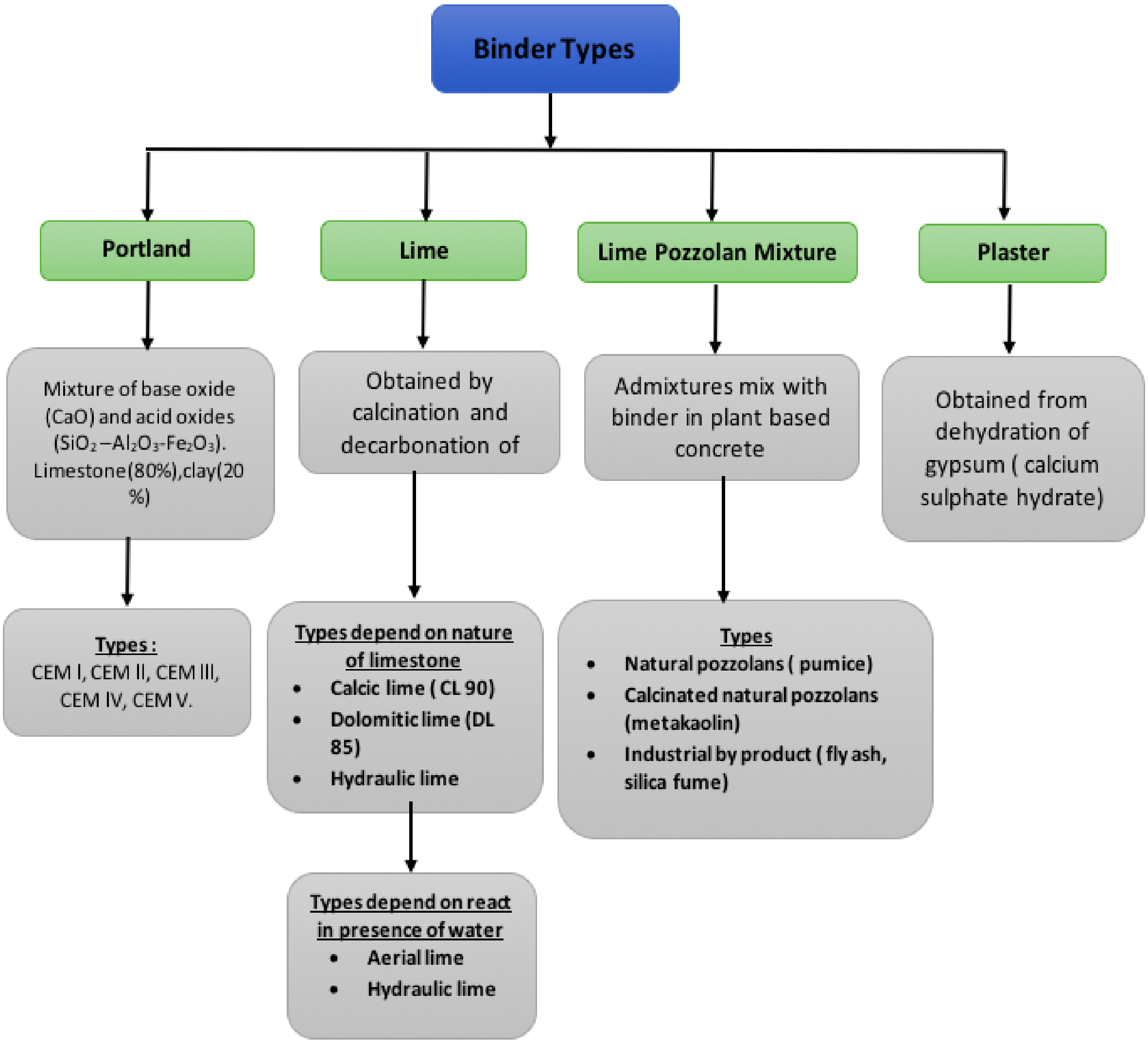


Figure 1. 12: Binder types used in concretes.

1.3.4 Compressive strength of hemp concrete

As mentioned before, hemp concrete contains particles of hemp shiv-as an aggregate materials-with high degree of porosity and capacity to deform which indeed play a main role on the mechanical performance on hempcrete, that is the main reason for using this material as a filling material with high level properties of insulation and without any contribution to the structural performance in building i.e. not used as a load bearing material. However currently there is some trend toward examining the possibility for some structural contribution for hemp concrete with timber structure. Furthermore the general behaviour of hemp concrete can be considered as elasto-plastic with a very possibility for strains, on the other hand, the porosity existence has a main role of low compressive strength because air bubbles represent weak point in materials. The existed previous studies concentrated on the compression tests of hemp concrete samples and more rarely on flexural, tension and shear tests. It is obvious from the literature review that there is a lack of knowledge related to these tests and also to the standardization in building code for mechanical behaviour and contribution of hemp concrete in structures.

R. Walker in 2014 investigated the effect of binder type uses on the mechanical behaviour of hemp concrete. Three different binders have been used in this study, a hydrated lime (CL90s-clcium lime) and a hydraulic lime (NHL 3.5) and Portland cement (CEM I). in this research a comparison has carried out between hemp-lime concretes made with a hydrated lime and pozzolan binder to those including hydraulic lime and cement. The results showed that the maximum compressive strength of hemp concrete samples at the first 5 days was around 0.04 MPa however after one year the compressive strength was around 0.39 MPa. This study also proved that most compressive strength of hemp samples was at the early stage (first 28 days) due to the hydration and drying processes. After three and six months, the metakaolin proved the highest compressive strength, then between six month and one year a slight reduction in the compressive strength observed with metakaolin with water retainer. The metakaolin pastes have been shown similarly the strength reduction as illustrated in figure 1-13 below. The commercial binder with biggest binder hydraulicity showed the highest compressive strength at early stages. Pozzolan concretes introduced similar compressive strength at 12 months to those including hydraulic lime and cement. Also the results showed the enhancement in early strength of lime due to using water retainers[29].

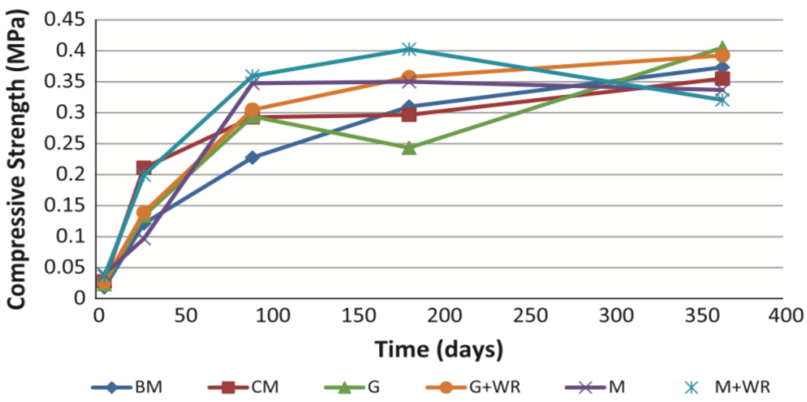


Figure 1. 13: Compressive strength of hemp-lime concretes over time.

BM – builder's mix; CM – commercial mix; G – GGBS mix; G + WR – GGBS binder with water retainer; M – metakaolin mix; M + WR – metakaolin with water retainer.

P. Bruijn studied the effect of using hemp shives and fibres on the mechanical properties of lime-hemp concrete under a hypothesis that fibres could improve the mechanical properties. The final results of this study showed that using shives and fibres in the hemp concrete mixing had not a positive effects on the compressive strength of hemp concrete and did not improve the mechanical properties. The average compressive strengths of all hemp concrete samples was ranged from 0.15MPa to 0.83 MPa. The author concluded in his study that lime-hemp concrete with unseparated fibres and shives did not show a great improvement in compressive strength and the average compressive strength in this study is similarly to values found in the previous literature review[30]–[32].

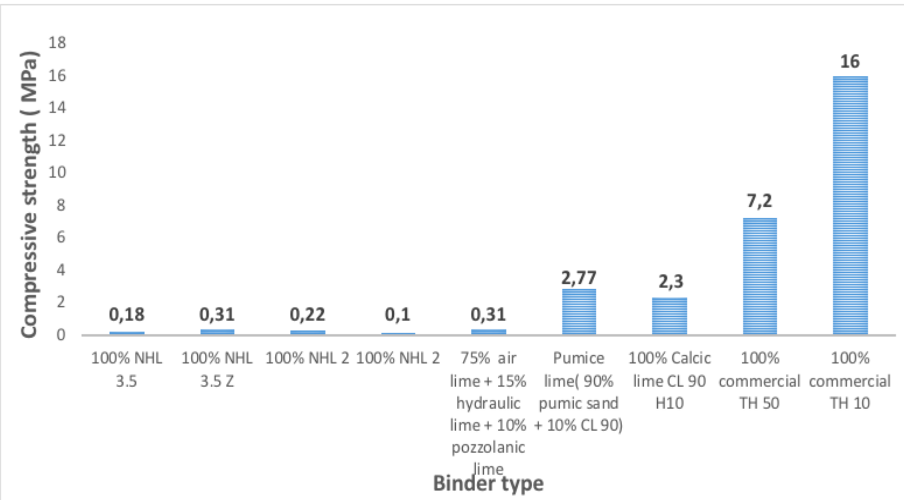


Figure 1. 14: Compressive strength values after 28 days.

L. Arnaud in 2012 investigated various parameters influencing the mechanical properties of hemp concrete. Curing conditions, age of concrete, content of binder and hemp shive characteristics have been studies in this research.

The hemp concrete samples showed the highest compressive strength at relative humidity of 50%RH. Also this study confirmed that the compressive strength enhanced from 0.35 MPa to 0.85 MPa between 21 days and 24 months of setting. In addition, using hemp particle size (3mm in length) reduced the porosity and the hemp particles coated in a better way by the binder and produced better compressive strength comparing to large particles of hemp shiv (9mm in length). This study concluded that increasing the content of binder will increase the surfaces contact between hemp shives and binder which improved the compressive strength of hemp concrete[33].

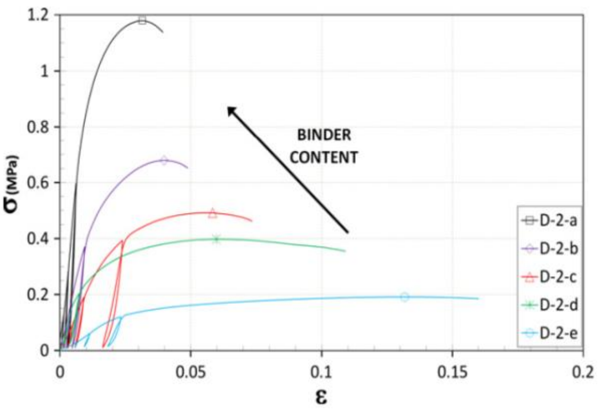


Figure 1. 15: Compressive strength tests of different binder content.

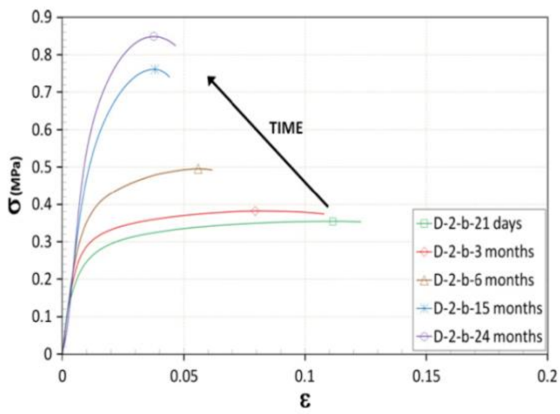


Figure 1. 16: Compressive strength of hemp samples for increasing ages.

V. Nozahic studied the morphological and mechanical performance of two different types of agro-aggregates; hemp and sunflower stems. The main outlines of his study was on the first hand, that hemp stem and sun flowers presents large similarities in terms of morphology and mechanical behaviour for the final introduced concrete. On the second hand, this study proposed using compaction device to cast the agro-concrete in layers and form orthotropic mechanical behaviour which leads to increase greatly the compressive strength of bio-based concrete without increasing the density of material in the same proportions[31].

S. Elfordy in 2008 examined the effect of a projection process of hemp concrete on the mechanical properties of hemp concrete blocks. The influence of the projection distance has been investigated and varied from 0.5m to 3m. the results of this study confirmed that the projection process induced a better compaction of hemp particles and higher density from a distance 1m which helped to increase the compressive strength of hemp blocks. The authors suggested to use hemp blocks manufactured by a projection process in case of using the filling concrete in a structural contribution in constructions[34].

A compression device of lime hemp concrete has been design by P. Tronet in 2016 to improve the compressive strength of hemp samples by exploring factors controlling stiffness and strength of lime hemp composite. This study concluded that compaction of blocks shape is a perfect method to increase the compressive strength of hemp lime concrete. This method will reduce the volume of particles and make shiv contribute in better way during the casting process[35].

P. Walker et al investigated the compressive strength of hemp-lime composite building material at three different densities and different ages up to 91 days using three binder of different composition. Hemp tradicalTM HF and was used in this study.
This study concluded that the percentage of wet binder and the density used during mixing were played a main role in increasing the ultimate strength of the material as illustrated in figure below[36].

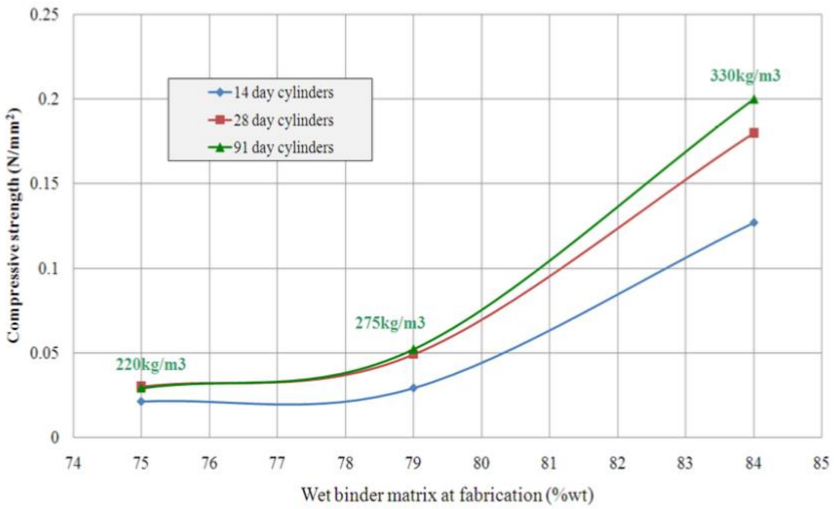


Figure 1. 17: Compressive strength vs. wet binder percentage of THB (TradicalTM Binder) specimens.

Treatments, chemical modifications and additive materials were another method for researcher to improve the mechanical properties of green concrete. A. Sellami et al, in 2013 investigated the effect of two types of diss-based fibres on the mechanical properties of green concrete. The authors extracted the sugar by distillation then waterproofing the Diss fibres to prevent water absorption. This study proved that on the first hand, removing sugars helps the fibres to react satisfactorily with cement. On the second hand, the compressive strength of green concrete significantly improved by boiled water treatment[37].

Using clay as a binder of hemp composite has been investigated by B. Mazhoud[38] in 2017. This research studied also the effect of hemp to binder ratio on the compressive strength of hemp composite. The conclusion remark was hemp stabilized clay composite (compressive strength ranged from 0.39 to 0.48 MPa) showed better mechanical properties than hemp clay composite (compressive strength ranged from 0.47 to 0.68 MPa) also depend on the hemp to binder ratio.

S. Pantawee et al in 2017 investigated the mechanical performance of hemp concrete by using chemical treatment of Aluminium sulphate and hydrated lime. The results of this study showed that using these chemical additive improved the compressive strength of hemp four times comparing to the control samples with a density of 1420-1470 kg/m3 and water absorption of 14.5-16.5%. the compressive strength of the hemp composite was between 15.0-17.0 MPa after 28 days of testing[39]. U. Sandrine investigated also the mechanical behaviour of hemp-starch concrete by using alkaline treatment with NaOH and silane treatments. These treatment improve the mechanical properties of hemp composites[40]. A. Bourdot et al mentioned in their study that increasing 0-5mm hemp shiv proportion for 15-30%leads to a significant improvement of the compressive strength of hemp[41].

1.3.5 Flexural strength of hemp concrete

S. Elfordy et at in 2008 [34] studies the mechanical properties of hemp concrete blocks with different densities of mixing. The hempcrete blocks have been fabricated in this study by using the projection method at a distance 1 m. the authors concluded that increasing the density of samples using projection methods leads to decrease the porosity in hemp shives and increase the bending strength of hemp blocks as illustrated in Table 1.3 below.

Table 1. 3 : Measured flexural strength of hempcrete blocks with various densities.		
Density (kg/m^3)	Flexural strength (MPa)	Standard deviation (MPa)
430	0.832	0.102
503	0.955	0.144
522	0.749	0.098
581	1.209	0.089
607	1.191	0.143

Other research done by R. Walker in 2014, the aim of this study was to investigate the effect of binder type on the strength of hemp concrete, flexural strength in particular. Hemp lime concrete made with a hydrated lime and pozzolan binder and also hemp concrete included hydraulic lime and cement were used in this study. Crack between the underline of the sample and the prism's main axis developed as illustrated in figure 1.18 below. The flexural strength of hemp samples for builders, commercial and lime; pozzolan with water retainer concretes were ranged between 0.11MPa and 0.13 MPa after 3 months of testing however, the lime pozzolan concrete yielded lower values ranging between 0.06 and 0.09 MPa. The flexural strength increased in the commercial binder concrete between the period 3 months and 12 months due to the exist of water retainers in hemp concretes[29].

Figure 1. 18: Typical deflection of hemp-lime concrete in bending.

1.3.6 Tensile strength of hemp concrete

As mentioned before that most of the previous studies related to the mechanical properties of hemp concrete, focused on the compressive strength of samples and there is a lack of knowledge in the literature review for studies related to the tensile and shear strength of hemp concrete. At the research of studying the effect of using different binders (hydrated lime and hydraulic lime) and using hemp shiv and fibres studied by P. Bruijn[30], the tensile strength of hemp concrete was measured. The results of this study showed that the splitting tensile strength of hemp concrete without cement was around 22.55 × 10-3 MPa. the authors explained the reasons of low value of tensile strength were related to the weak bond between binder and hemp and also could be cause to lower tensile strength of binder. However, using cement in hemp concrete mixing improved the tensile strength to 113 × 10-3 MPa. B. Mazhoud et al [38] in 2017 investigated the effect of hemp to binder ratio on the mechanical properties of hemp concrete and also comparison between hemp stabilized clay composites (HSCC) and hemp clay composite (HCC). This study showed that hemp stabilized clay composites have better mechanical properties than hemp clay composites. The values of tensile strengths of hemp clay composites ranged between 0.021 to 0.026 MPa however for hemp stabilized clay composites the tensile strength was between 0.026 to 0.059 MPa.

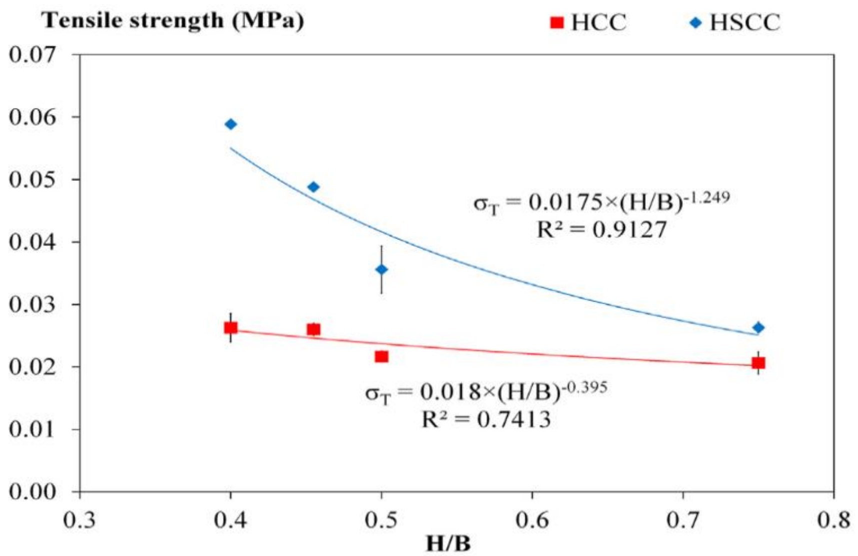


Figure 1. 19: Variation of tensile strength versus hemp to binder ratio(H/B).

1.3.7 Shear strength of hemp concrete

M. Chabannes et al in 2017[6] evaluated the shear strength parameters (peak friction angle and cohesion) for two different bio-based concrete (Lime-hemp concrete LHC and Lime and rice husk concrete LRC). The triaxial shear test was performed after two months of curing at confining pressure ranged between 15-150 kPa by using the device illustrated below in Figure 1-12. The results of this study concluded that the modes of failure of hemp samples was a combination of bulging and shear banding localized at the lower part of samples as illustrated in figure 1-13 below. The authors explained the bulging phenomena in LHC as a result of non-uniform pore distribution along the length of the specimen and assumed that the shear behaviour was anisotropic. The second key finding of this study was that both bio-aggregates have same cohesion of value 0.36 MPa. However they have a different values of peak friction angle. The peak friction angle of lime-hemp concrete LHC was around 46° which is higher than the estimated value for Lime and rice husk (29°) which indicated that the cohesion value is correlated to the binder strength used in hemp concrete mixing.

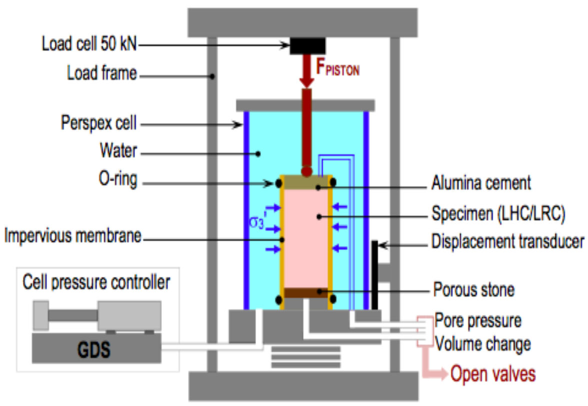


Figure 1. 20: Device of triaxial shear test on plant-based concrete.

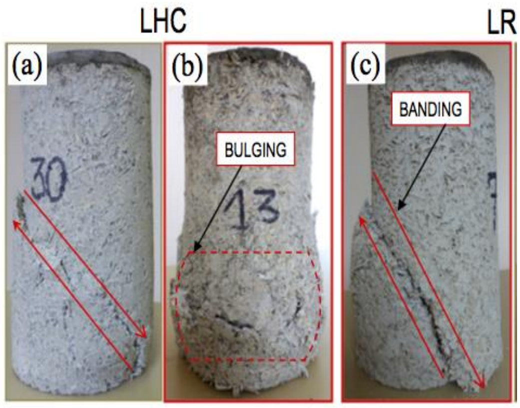


Figure 1. 21: Shear banding (a) and (c), bulging failure (b).

Alice et al [28] supposed that the behaviour of a commercial hemp blocks in shear strength should be able to take a part of the load and participate in the bracing as infilling material with timber walls, this results would reduce the sections of wood and save the structural materials. The results in terms of shear strength showed in figure 1-22 below that when shear is applied perpendicular to the direction of compaction with vertical load 0.2 MPa, and figure 1-23 when shear is applied perpendicular to the direction of compaction with vertical load 1 MPa.

The researchers noticed that it was no sudden break occurred during the test and a change in the slope appeared when the deformation reaches 2%. The authors supposed that this is may be corresponded to a transition between elastic to plastic shear. This study concluded that the absence of a brittle phase in the shear response for each material tested, allows to consider certain structural applications: it can help to dissipate large amounts of energy deformation in the event of an earthquake, even for slightly compacted materials, can play important role in earthquake resistant construction. As mentioned in the results, shear stress correlated to the vertical applied load. This phenomena is well known from soil mechanics, the coherence parameter by tracing the boundaries flow in a mohr diagram (shear stress/Normal stress).

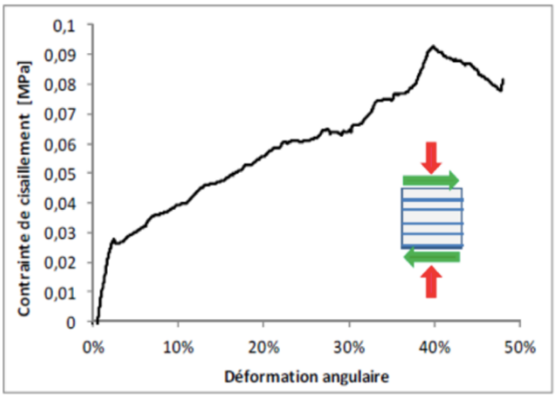


Figure 1. 22: shear perpendicular to the direction of fabrication with vertical load 0.2 MPa.

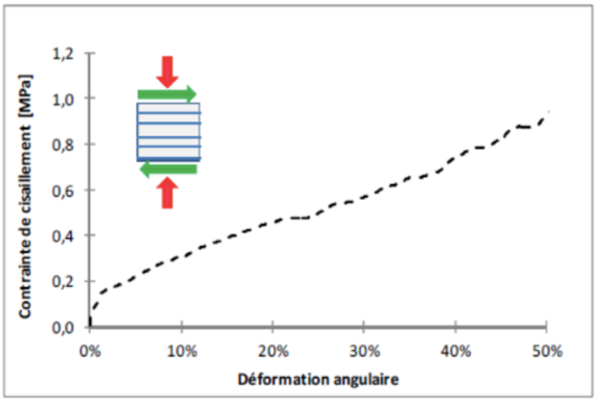


Figure 1. 23: Shear perpendicular to the direction of fabrication with vertical load 1 MPa.

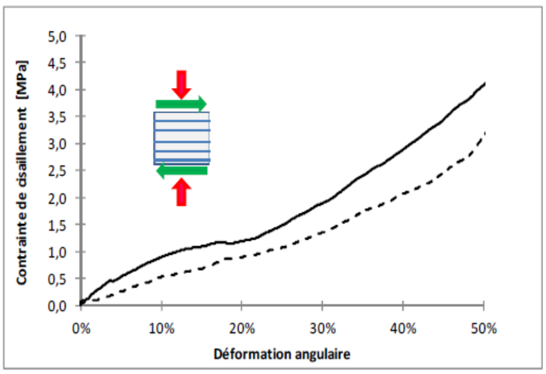


Figure 1. 24: shear applied perpendicular to the direction of fabrication with vertical load 1MPa dotted line and 2 MPa solid line.

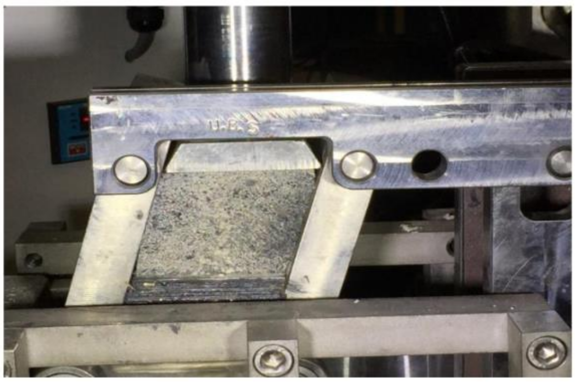


Figure 1. 25: Experimental proposed device for shear strength investigation.

1.3.8 Elasticity modulus of hemp concrete

The influence of cement and using different binding agents on the modulus of elasticity of lime hemp concrete have been examined by P. Bruijn et al. [30]. The specimens were cured for 3 months at a room temperature and 40 days in a carbonation room. The finding of this results concluded that the mixture with only hydrated and hydraulic lime (no cement) showed the lowest value of modulus of elasticity (average 13 MPa) however adding cement between 27-50% improved the modulus of elasticity to around 22.7 MPa. The samples that contained only cement (100%) showed the highest value of elasticity modulus a round 49.4 MPa. The authors concluded that modulus of elasticity appeared to be higher for those mixtures with a great proportion of cement.

A statistical analysis on hemp concrete properties has been investigated by C. Niyigena et al[42] in 2016 in order to investigate statistically the variabilities of the these properties. Two size of cylindrical specimens have been considered in this research 110 × 220 mm and 160 × 320 mm. The statistical analysis has been applied for the material properties and the results compared with the experimental tests. The study concluded that the modulus of elasticity of hemp specimens showed a large margin of variability with results varying from poor to excellent quality. In addition, the authors presented an accurate definitions for four different types of elasticity modulii that can be calculated as illustrated in figure below, the initial tangent modulus E_{ini} and secant modulus E_{sec} and tangent modulus E_{tan} and cyclic loading modulus E_{CYC}. Fig 1.26.

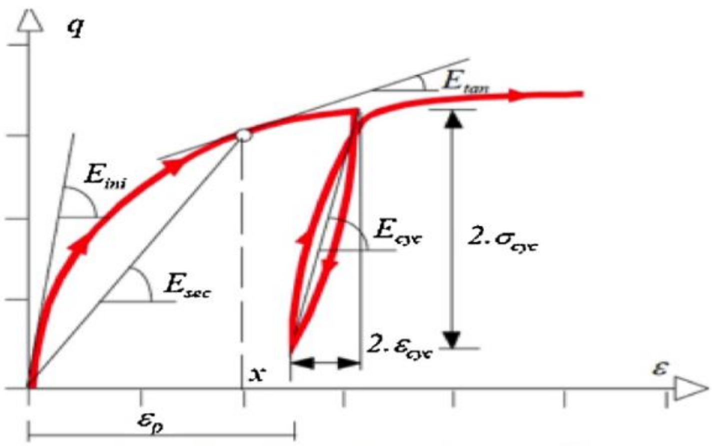


Figure 1. 26: Modulus of Elasticity definitions.

P. Tronet et al[35] also studied the modulus of elasticity of hemp concrete specimens. The authors were argument that the binder to shiv ratio is not the only key parameter that can play a main role in increasing or decreasing the modulus elasticity of lime hemp concrete. The author said that in Nguyen et al[43] study, the binder to shiv ratio was the same for two different mixes with a results of two different of modulus of elasticity. The main finding of this study concluded that increasing the compactness has also a main role in increasing the elasticity modulus of hemp concretes. P. Tronet has investigated five samples after 28 days with different compactness values varying from 0.37 to 0.5. with a compaction stress of casting 1.1 and 6.3 MPa. the results showed that the values of elasticity modulus improved from 43 to 122 MPa. According to these results the authors recommended to use compacted block hemp to increase the strength and stiffness of hemp concrete.

1.4 Lateral structural behaviour of timber walls

Wood is commonly associated with lightweight structures, it has ubiquitous uses as a building material in many around the world. The pros of wood lie mainly its abilities in ductile joints, its physical properties and being environmentally friendly[7]. Timber walls are the frequently used structural system in the buildings designed to withstand lateral loads and transfer these forces to the foundations with ductile behaviour[8].

1.4.1 Eurocode (5) Wall diaphragms – Method (A) and Method (B)

Eurocode 5 has a lot of considerations for the timber wall diaphragms particularly for resisting the horizontal loads. The Eurocode recommended for the walls design to consider both the horizontal and vertical loads in the calculations. Also this code consider three methods for resisting the lateral loads; boarding material, diagonal bracing or moment connections.
According to the European Norm EN 594,[2] a timber shear wall consists of a timber frame and sheathing board, connected by fasteners. The sheathing board may be made of a variety of materials, such as Gypsum, Plywood, Fibre board or OSB[44]. Two different methods for calculating the lateral resistance of timber walls are presented in Eurocode 5. The first is a very simple analytical approach, based on the assumption that the fasteners transmit the same ultimate force along the perimeter of the panel, and the second is an experimental approach based on the test procedures set out in EN 594.

- Simplified analysis of wall diaphragms – Method (A)

In this method, it was assumed that the spacing between fasteners is constant along the perimeter of every sheet or board and also the width of each sheet should be at least around h/4.

With a timber wall of height h and a width b_i and also assuming that a horizontal load $F_{i,v,Ed}$ applied at the top of the wall, and the (s) is the spacing between the fasteners, then the design load carrying capacity $F_{v,Rd}$ can be easily calculated using the following formula:

$$F_{i,v,Rd} = (F_{f,Rd}\ b_i\ c_i\ ) / s$$

The Eurocode (5) recommended also that panels contains opening such as doors and windows should not consider in the contribution of lateral resistance of the wall. In case of existing two boards with one panel, the total ranking load carrying capacity should take the sum of them in case of same spacing in their fasteners.

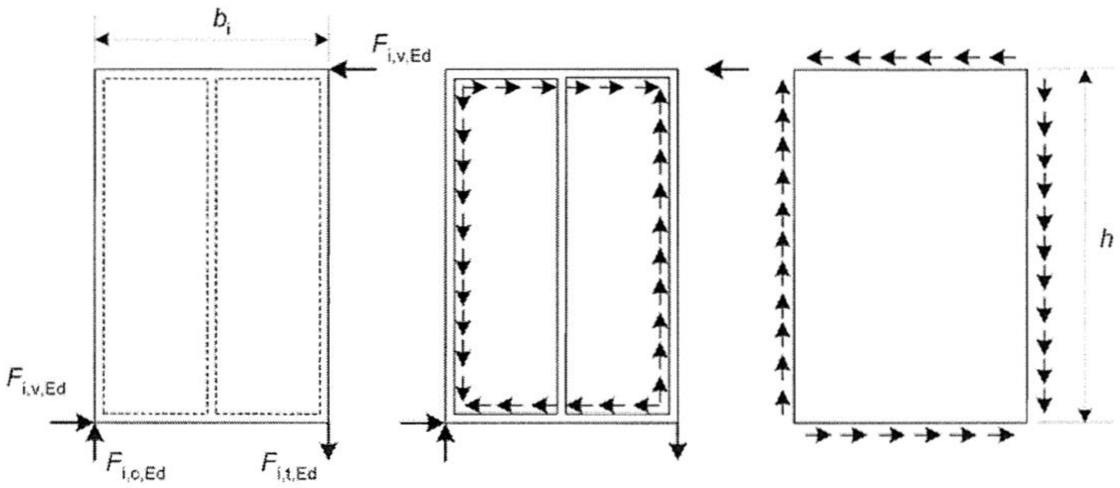


Figure 1. 27: Forces distribution on wall panels according to Eurocode (5).

It was assumed that the internal forces distributed equally according the fasteners. The external forces $F_{i,c,Ed}$ and $F_{i,t,Ed}$ can be calculated by using the following formula:

$$F_{i,c,Ed} = F_{i,t,Ed} = (F_{i,v,Ed}\ h / b_i)$$

- Simplified analysis of wall diaphragms – Method (B)

In this method, the width of each panel should be at least the panel height divided by 4 if this panel will be for resisting the racking loads. In case that board used as an element for lateral loads, the fasteners should be nails or screws with conserving the same spacing between each fastener. The design racking strength $F_{v,Rd}$ in this method against a horizontal force $F_{v,Ed}$ can be calculated with the same formula as method (A) with additional factors as below (Fig. 1.28):

$$F_{i,v,Rd} = (F_{f,Rd} \times b_i)/s_0 \times k_d\, k_{i,q}\, k_s\, k_n$$

Where

$F_{f,Rd}$ is the lateral design capacity of an individual fastener.

b_i is the length of the wall.

s_0 is the fastener spacing

k_d is the dimensional factor for the wall.

$k_{i,q}$ is the uniform distributed load.

k_s is the fastener spacing factor.

k_n is the sheathing material factor.

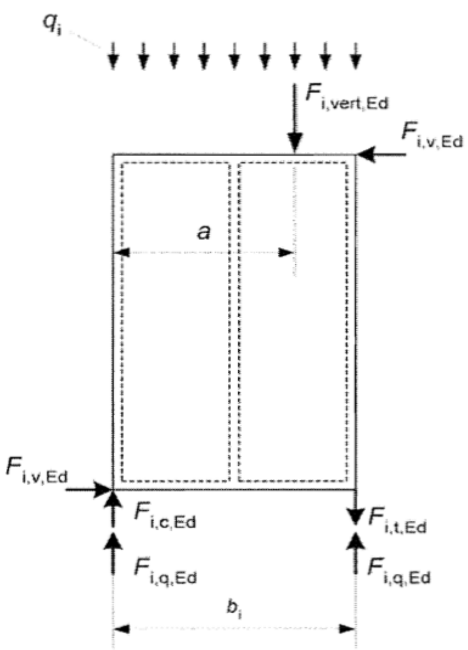


Figure 1. 28: Determination of equivalent vertical action q_i in method (B).

1.4.2 Oriented Strand Board (OSB)

A number of studies have been conducted by various authors, to investigate the load-carrying capacity of a timber frame wall, based on modelling and experimental tests. Most of these studies have been carried out on OSB walls, as these walls are very widely used. However OSB walls have lower in-plane stiffness than fibre-plaster boards (FPB)[45].

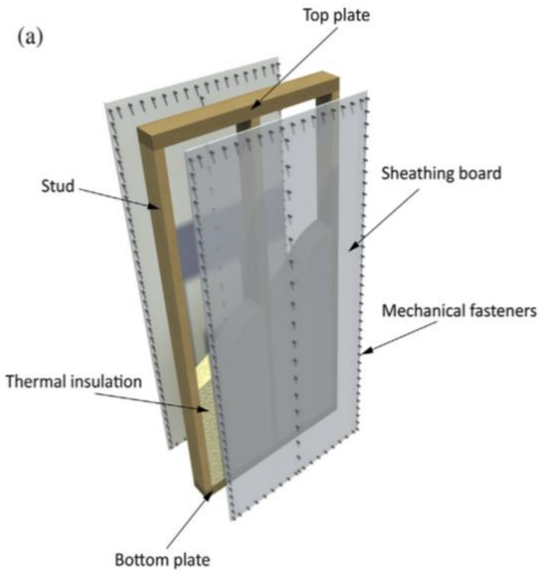


Figure 1. 29: Composition of single panel wall element.

An elastic analysis model is presented by Girhammar and Kallsner [46] to investigate the lateral load resistance and determine the horizontal displacement at the top of the timber wall against static forces, this model pertains to fully anchored sheathed timber frame.

K. Vogrinec et al. [45] proposed another model based on static and dynamic analysis to investigate horizontal loads on timber walls and study the effect of openings and the diameter of the diagonal strut on the load-carrying capacity. N. Gattesco et al. [47] examined the effect of different base connections of timber walls on the stress distribution of the fasteners in sheathing board, their model and experimental study confirm that different types of base arrangement influence the shear distribution on sheathing nails. Another analytical model was devised by D. Casagrande [48] to study the elasto-plastic behaviour of shear walls, on the one

hand, and to find a genuine relation between the properties of the structural elements of the wall, such as fasteners, and the structural properties of the whole wall, on the other hand.
Many parameters have been investigated experimentally in timber shear walls which play a crucial role in the overall behaviour of the wall, such as the connections between the wall and foundation [49], the type of fasteners used and the effect of openings.

The aforecited studies confirm that increasing the opening size in OSB timber shear walls will create concentrated stresses at the corners points of the opening, with resultant shear cracks which decrease the strength and stiffness of walls [50], [51]. Also, the strength of ring shank nails connections is 1.75 greater than that of smooth nails in timber shear walls, also staples exhibited brittle behaviour in Italian OSB panels [52], [53].

Other approaches are used by authors to improve the lateral resistance of timber frame walls, such as using stones and earth infill [54] , or the addition of diagonal steel strips fixed to the timber frame, which increase the lateral resistance by 77% [55] or adding concrete core with cross laminated timber for skyscraper applications [56].

1.4.3 Cross laminated timber walls (CLT)

Cross-laminated timber (CLT) is a prefabricated solid timber wall made of at least three orthogonal layers and bonded using adhesive material or fasteners such as nails. These walls were introduced in the early 1990s in Germany and Austria, and have been recently been gaining increased popularity for multi-story timber construction in North America and Europe in form of roof, floor, or wall applications. CLT has many benefits as a structural element. The first benefit is that it provides excellent in-plane strength. The second benefit is that it decreases the time of construction[57]. Some studies have been carried out recently by various authors to study the structural behaviour of cross-laminated timber (CLT) and these studies have focused mainly on the mechanical properties of CLT and also fire resistance[58].

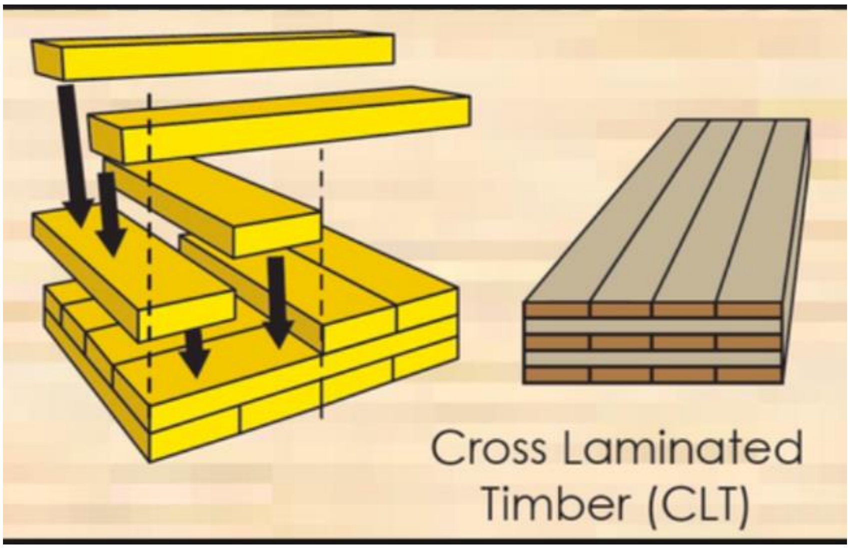


Figure 1. 30: Cross laminated timber principle.

F. Wiesner et al.[59] examined the structural response of cross-laminated timber compression elements exposed to fire. Wiesner tested eight walls of two different configurations and exposed them to thermal radiation sufficient to cause sustained flaming combustion. The lateral and axial deformation of the wall was investigated and compared with predictions calculated using a finite Bernoulli beam element analysis. Z. Wang et al. [57] investigated the mechanical properties of laminated stand lumber and hybrid cross-laminated timber (HCLT), this study confirms that HCLT has better bending and shear properties compared to generic CLT. Y. Shen et al. [60] studied the hysteresis behaviour of brackets connection in cross-laminated timber walls, with three kinds of connection for CLT shear wall subjected to cyclic and monotonic loading protocol used in this study to investigate its structural performance. The test results have been compared to two hysteretic models (saws model and Pinching4 model). The study confirms that the Pinching4 model has a better performance than the saws model, while using Simpson bracket as a connection shows the best connector with excellent seismic behaviour and ductility. R. Tomasi proposed a new connection system between wood frame shear wall and foundation under cyclic loads with high values of strength and stiffness and also confirmed that using a hold down connector does not induce differences in terms of stiffness. By contrast, angle brackets have some differences in performance depending on the type of fasteners used [49].

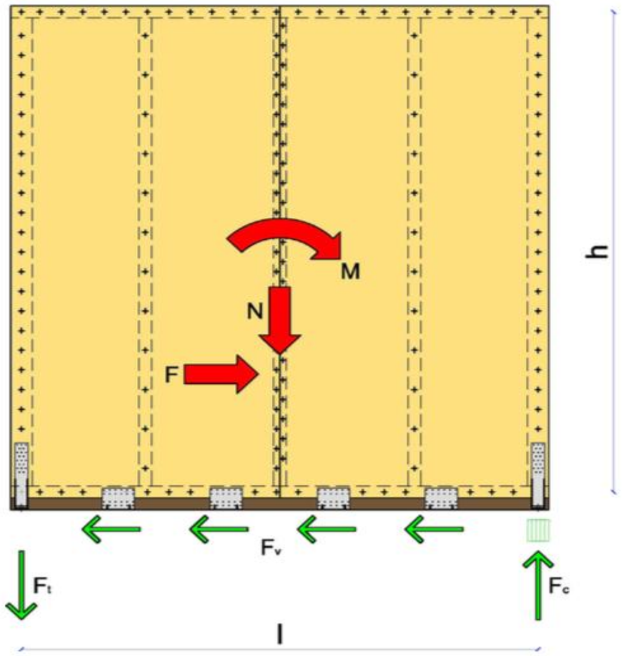


Figure 1. 31: Role of the connection system between vertical panel and horizontal diaphragm.

K. Vaivade et al. [61] verified experimentally the design procedures for elements subjected to flexural forces in cross-laminated timber under static load, using K-method, gamma method, shear analogy method and transformed section method all compared analytically. The deflection was calculated using the transformed section method and compared with the experimental results, the differences did not exceed 7%.

1.4.4 Timber frame walls filled with hemp concrete.

Munoz and Pipet in 2009 evaluated the contribution of hemp concrete as mentioned in S. Amziane book[3] installed by shotcrete to resist the horizontal loads (wind brace test) in timber panel as shown in figure below:

The test was related to the wall in timber structure filled with hemp concrete in a panel of a vertical plane with dimension of 4.56 m in length and 2.48 m in height. The main aim of this test was to determine the comparison between the behaviour of the panel with bracing strut only and others with same properties of the panel with hemp concrete material (without strut member).

The panel was tested on the flat to limit the friction on the panel in horizontal plane. A horizontal force of 50 KN applied to the panel by manual jack, reading of strain took at 13 points on the panel.

The research teams noticed that along the “x” axis the movements recorded at the level of points 8 and 10 are similar and are less than 0.4 mm, however, along the “y” axis. There was a great displacement downwind of the lower HEB at point 7 which moved back by 1.5 mm.
Compression force acting on the upwind strut and traction to the downwind strut after strain application. There was also rotation at intermediary uprights when great movement of the upper crosspiece occurred and causes the struts lock at uprights, which indicate that uprights have the apart role in bracing the structure. No rupture occurred during this test.
The second panel tested with hemp concrete wall with total thickness of 28 cm without strut bracing, the hemp properties were as binder content of 220 kg/m^3 and an apparent density of 300-350 kg/m^3. The same force applied to this panel and the movement measured by resistive sensors (50mm) and by inductive sensor (150 mm). The researcher team noticed a network of cracks caused by shear stress due to displacement and bending of uprights, in addition to separation between uprights and hemp materials.

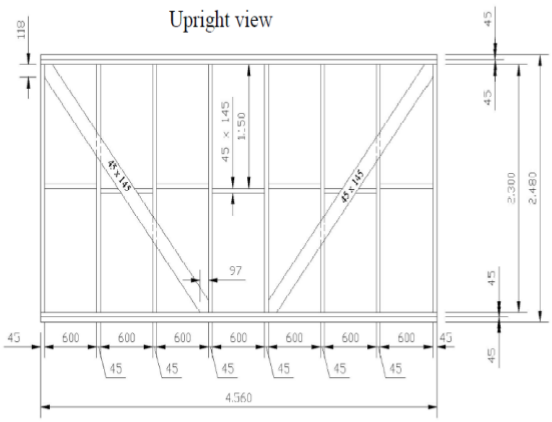


Figure 1. 32: Wood panel of the structure.

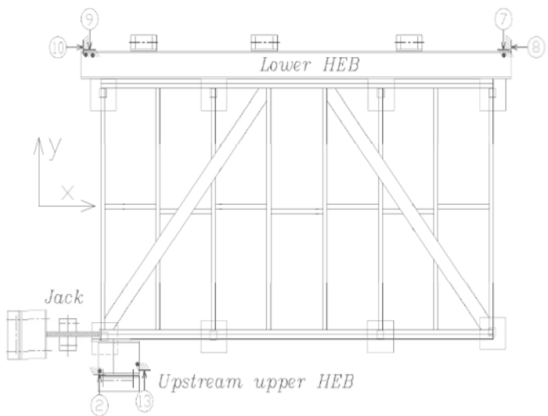


Figure 1. 33: Movements measurement during the test.

Figure 1. 34: Cracks of hemp material after the test.

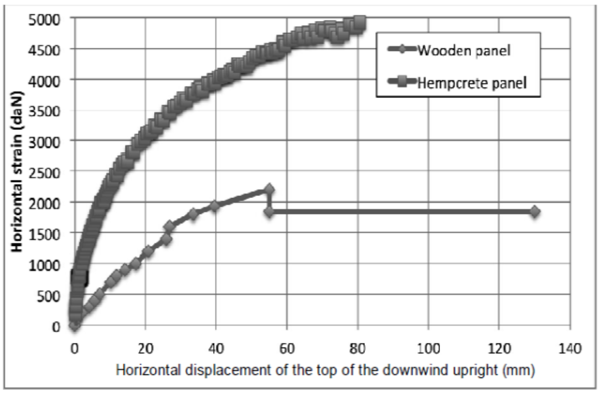


Figure 1. 35: Movements measurement during the test.

The conclusion of this study was that the results showed that hemp concrete substituted in the bracing strut panel and also improve the mechanical behaviour regarding to bracing, also the peak change 2.2 times higher, and the bracing rigidity increased also. This material also present a degree of ductility to limit any risk of stability.

Gross and Walker[62] in 2014 studied the performance of composite hemp lime to the plane racking strength of timber studwork framing. Five full size wall panel were tested, 4 with hemp concrete and one with timber studwork frame only. On sample R5 included a magnesium silicate sheathing (covering) board fixed to the studs. 5 KN vertical constant load to the top of studs and also 0.1 F_{max}. stiffness and strength cycles applied to the samples. The samples properties were as the table 1.4 below:

Table 1. 4 : Wall panels details.

Wall No.	Hemp Lime	sheathing
R1	30 cm thickness	None
R2	30 cm thickness	None
R3	Frame only	None
R4	30 cm thickness	None
R5	30 cm thickness	Multi- pro XS sheathing

The results observed after testing that all the walls have the same behaviour with initial high stiffness and then reduced as mentioned in the figure below, the reductions almost according to the element failed, for instance R1, R2 the failure corresponded to the stud connectors, R4 the failure corresponded to the crack in hemp concrete, R5 the failure corresponded to the pull of screws through the sheathing board.

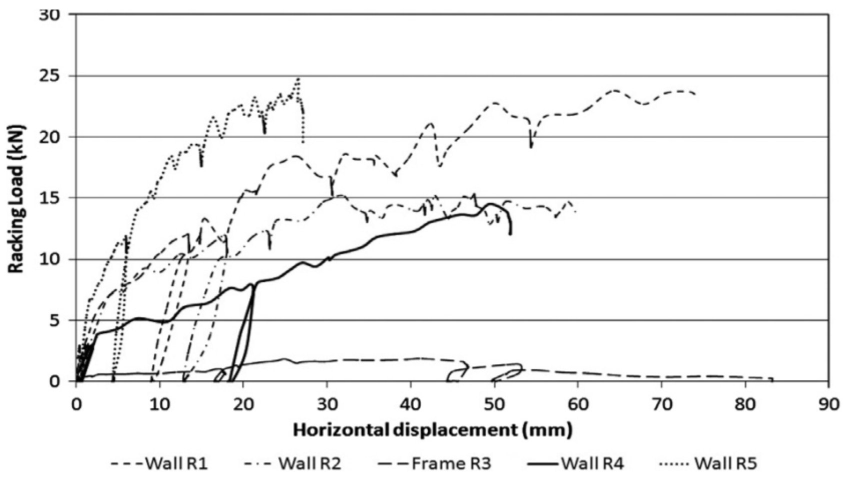


Figure 1. 36: Racking test results.

The results showed that R5 has the best performance with the highest stiffness and highest racking load due to the improve leading stud connection and Multi- pro sheathing board. R1 and R4 have similar performances during the second stage of testing because they have similar construction.

R2 was weaker than the others three walls because hemp lime had not fully cured, even though all walls were stronger and stiffer than R3. Finally the researchers conclude that low density of hemp lime increasing the racking resistance of timber studwork frame, also the racking stiffness is improved significantly by using permanent shuttering that act as sheathing board such Multi-pro XS boarding.

S. hans et al in 2017 studied the contribution of a sprayed hemp concrete in the mechanical behaviour of building with wood structure. Five walled were test and each wall was subjected to horizontal force at the top of walls and also a constant vertical load was applied. The length of all walls was around 3 m with a height of 1.6 m. the geometry of the timber walls was a combination of vertical studs and diagonal bracing. Different values of horizontal force were used in this study starting from 2.5 kN to 30 kN and the comparison was made between empty timber frames and timber frames filled with hemp concrete.

The results and the comparison showed the importance of using hemp concrete as infill material. The authors concluded that hemp concrete as infill material in the timber frame walls showed a significant enhancement in the bracing timber walls in terms of strength, rigidity and also durability.

Figure 1. 37*: *Filling the timber frame with hemp.

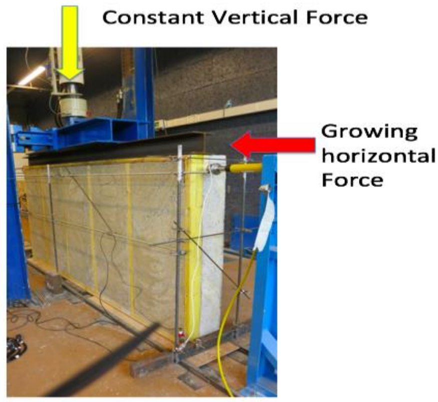


Figure 1. 38: Mechanical test of the wall.

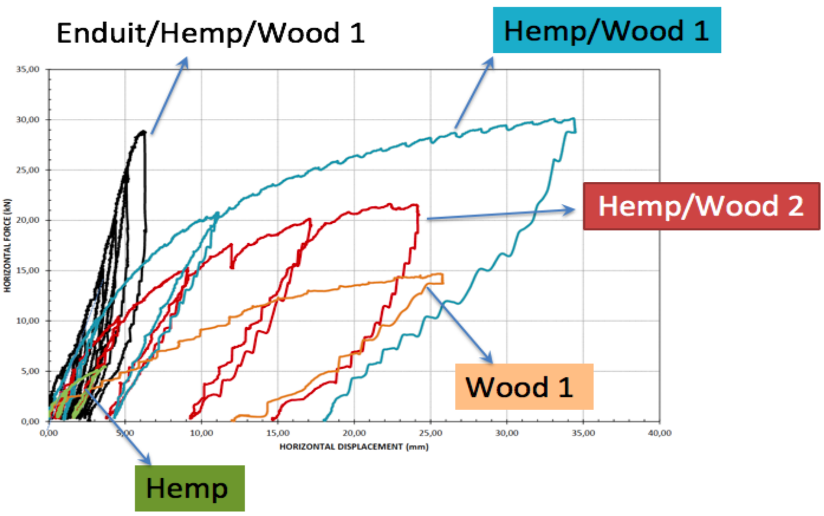


Figure 1. 39: Racking Strength of tested walls.

1.5 Conclusion

It is obvious from the previous literature review that the design procedures of Oriented Strand Board have been covered in detail in Eurocode 5 and also a number of models have been proposed by many authors. The main aspects of previous studies focused on the modelling and experimental tests of Oriented Strand Board walls [63], [64]. The modelling studies concentrated on the theoretical approaches related to the lateral displacement and the total horizontal force applied on the wall. The experimental studies focused on the effect of many parameters such as base connections and opening on the lateral resistance of the wall.

By contrast, there is a gap of knowledge in Eurocode 5 and state of the art for the design procedures related to cross-laminated timber walls especially subjected to lateral loads.

On the second hand, it was clearly that hemp concrete used in new construction as natural and sustainable material according to its benefits related to the insolation, light weight and acoustical behaviour. Most of the previous studies were concentrated on the mechanical properties of hemp concrete in terms of densities, mix design and binder effects. The structural design does not assume any contribution of hemp concrete to the structural performance of timber walls.

As matters currently stand in relation to hemp-based materials, it is obvious that there is a lack of knowledge and a need for further studies in racking performance of hemp concrete – practically in timber frame walls. For this purpose, this research highlights the parameters that could play a main role in the lateral strength of hemp concrete. The main objective of the presented study is to investigate the lateral strength of two different designs of timber frame walls filled in with hemp concrete. The length and overall rigidity of timber hemp wall have been investigated in this study to describe their effects on lateral load-carrying capacity.

Chapter 2 The lateral strength of cross-laminated timber walls

2 The lateral strength of cross-laminated timber walls

Article (A)

(Article published in Engineering Structures journal in 26 March 2018)

The lateral load resistance of unclassified cross-laminated timber walls: Experimental tests and theoretical approach

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Abstract

This paper focuses mainly on the mechanical behaviour of unclassified cross-laminated timber walls under lateral loading (seismic and wind loads). Unclassified wooden planks were used to construct the wall unit with an odd number of layers (three) for each wall, with the planks in each layer in a perpendicular relative orientation. In this research, an experimental study of large-scale timber walls was carried out with a view to determining the lateral load resistance. Diagonal struts, under tension and compression were employed on the cross-laminated walls to investigate the effects of these elements on the lateral resistance of the wall. A theoretical approach has been developed to describe the overall behaviour of the cross-laminated wall and to investigate the internal forces on the fasteners. The present work is then compared to Oriented Strand Board (OSB) panel designs. Based on the data and results obtained from the experimental tests, this study confirms, firstly, that cross-laminated walls without a diagonal strut have approximately double the horizontal strength of (OSB) panels, secondly, that diagonal strut significantly increases the lateral load resistance of cross-laminated walls, particularly under compression conditions, and thirdly, the proposed theoretical approach shows similar performance to the average experimental test up to 100 mm of overall lateral displacement of cross-laminated timber wall.

2.1 Introduction

Wood is commonly associated with lightweight structures, it has ubiquitous uses as a building material in many around the world. The pros of wood lie mainly its abilities in ductile joints, its physical properties and being environmentally friendly. Timber walls are the frequently used structural system in the buildings designed to withstand lateral loads and transfer these forces to the foundations with ductile behaviour. According to the European Norm EN 594, a timber shear wall consists of a timber frame and sheathing board, connected by fasteners. The sheathing board may be made of a variety of materials, such as Gypsum, Plywood, Fibre board or OSB. Two different methods for calculating the lateral resistance of timber walls are presented in Eurocode 5. The first is a very simple analytical approach, based on the assumption that the fasteners transmit the same ultimate force along the perimeter of the panel, and the second is an experimental approach based on the test procedures set out in EN 594. The two methods in Eurocode 5 are not clearly expressed, leading to unsafe and imprecise structural design. Some of the obvious limitations of Eurocode 5 are that it does not consider the horizontal displacement of the wall, and assumes that fasteners under shear stresses are entirely within lower bound of the plastic state, which may lead to unlimited displacement and an overestimation of the wall's racking strength. Furthermore, the underlying assumption of Eurocode 5 is that the wall is blocked, the role of the layout of the fastenings is not taken into account. Clearly, Eurocode 5 has many design conflicts, and it is not advisable to consider its guidance absolute in terms of design.

It is obvious from literature review that the design procedures of Oriented Strand Board have been covered in detail in Eurocode 5 and also a number of models have been proposed by many authors. By contrast, there is a gap of knowledge in Eurocode 5 and state of the art for the design procedures related to cross-laminated timber walls especially subjected to lateral loads. For this purpose, an analytical prediction has been proposed in this present study to describe the performance of CLT walls subjected to lateral loads, which also could be used in the design recommendations. This present paper also examines the feasibility of using unclassified timber for constructing timber frame-walls in cross-plank form, and the lateral resistance of these walls to horizontal loads without the addition of extra, expensive, materials.

2.2 Analytical Model of Timber Wall Unit

Two basic theories are presented below for one unit of timber wall, to study the overall behaviour of the timber walls, the internal forces and the displacements under horizontal loads. The first analytical model is related to the timber frame wall consisting of one sheet on one side of the frame fixed to the three vertical studs and two rails (Figure 2.1), the second is concerned with cross-laminated walls of three layers of perpendicular strips of wood as illustrated in Figure 2.3.

2.2.1 Timber-frame wall with Oriented Strand Board (OSB)

Kallsner and Akerlund presented a theoretical elastic model to describe the internal and external behaviour of a timber-frame wall consisting of one side board fastened to the frame (Figure 2.1). Kallsner assumed that the board and elements of the frame are rigid, and also that there is a linear elastic relation between the board and the frame elements at joints.

The static equilibrium equation between external horizontal force (H) and hinge support forces Ft,Ed, Fc,Ed and Fx,Ed of the timber unit is given as in Figure 2.2:

$$F_{X,Ed} = H; \;\; F_{t,Ed} = -F_{c,Ed} = H\,(h/b) \tag{2.1}$$

The coordinates x and y of the fastener forces are given as:

$$F_{X,Ed,i} = Hh\left(\frac{y_i}{\sum_{i=1}^{n} y_i^2}\right); \;\; F_{y,Ed,i} = Hh\left(\frac{x_i}{\sum_{i=1}^{n} x_i^2}\right); \;\; i = 1, \dots, n \tag{2.2}$$

and:

$$F_{Ed,i} = \sqrt{F_{x,Ed,i}^2 + F_{y,Ed,i}^2} = Hh\sqrt{\left(\frac{y_i}{\sum_1^n y_i^2}\right)^2 + \left(\frac{x_i}{\sum_1^n x_i^2}\right)^2}; \;\; i = 1, \dots, n \tag{2.3}$$

The maximum fastener force $F_{Ed,max}$ is written as:

$$F_{Ed,max} = Hh\sqrt{\left(\frac{y_{max}}{\sum_1^n y_i^2}\right)^2 + \left(\frac{x_{max}}{\sum_1^n x_i^2}\right)^2} \leq F_{l,Rd} \tag{2.4}$$

The design racking load-carrying capacity $F_{l,Rd}$ of the timber wall can be calculated as:

$$F_{l,Rd} = \frac{F_d}{h\sqrt{\left(\frac{x_{max}}{\sum_{i=1}^{n} x_i^2}\right)^2 + \left(\frac{y_{max}}{\sum_{i=1}^{n} y_i^2}\right)^2}} \tag{2.5}$$

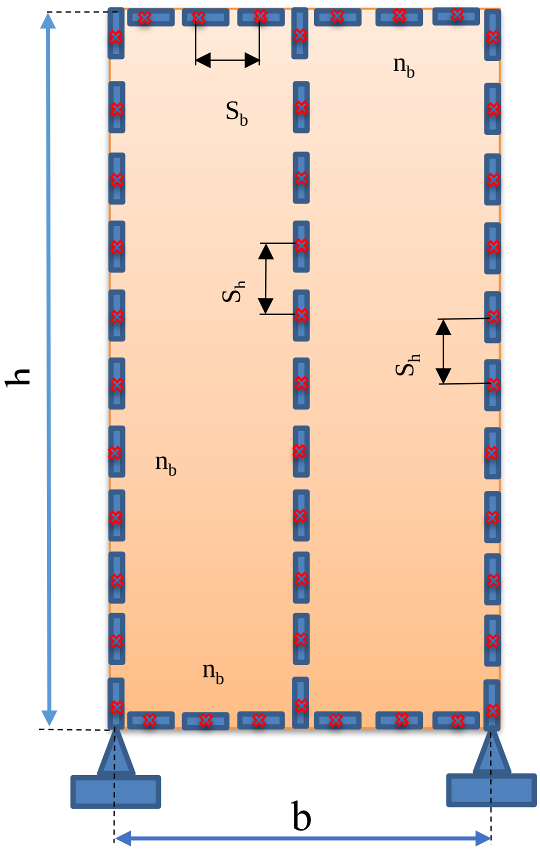

Figure 2. 1: Unloaded state of timber frame.

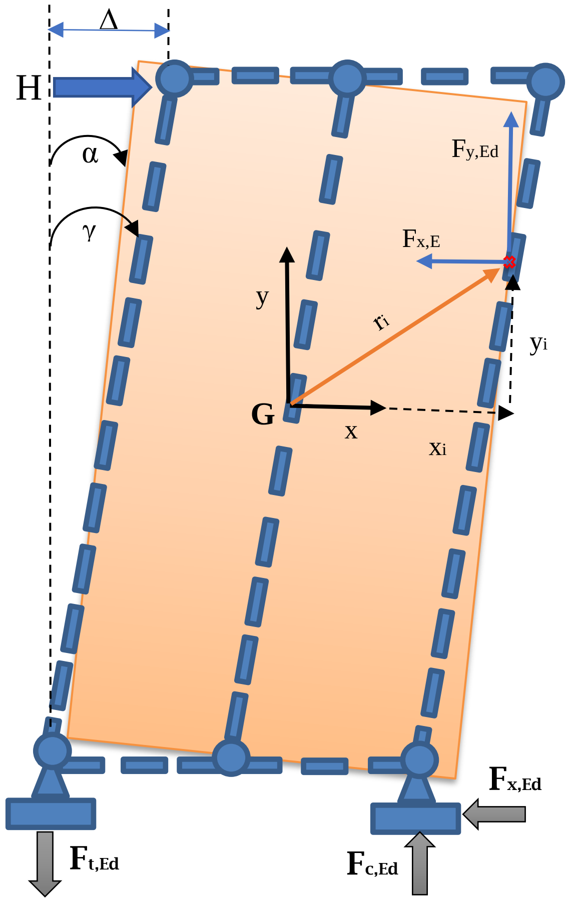

Figure 2. 2: Loaded state of timber frame.

In the loaded state (Figure 2. 2) of the timber-frame wall under horizontal forces, the vertical studs of the frame will rotate at an angle γ and the board also will rotate at an angle α. Considering that the origin of the coordinates x and y is located in the centre of gravity of the fasteners, the angles are written as:

$$\alpha = \frac{1}{Kser}\, Hh \left[\frac{1}{\sum_{i=1}^{n} x_i^2}\right] \text{ and} \tag{2.6}$$

$$\gamma = \frac{1}{Kser}\, Hh \left[\frac{1}{\sum_{i=1}^{n} x_i^2} + \frac{1}{\sum_{i=1}^{n} y_i^2}\right] \tag{2.7}$$

where:

H	is the external horizontal loads applied at the top of the wall.
h	is the height of the board.
K_{ser}	is the displacement (slip) modulus of the fastener.
n	is the total number of fasteners in the wall.
x_i	is the x-coordinate of fastener number i.
y_i	is the y-coordinate of fastener number i.
F_d	is the design capacity of the fastener.

The total horizontal displacement of a timber unit from the original position is calculated by the formula below:

$$\Delta = \gamma\ h = \frac{1}{Kser}\ Hh^2 \left[\frac{1}{\sum_{i=1}^{n} x_i^2} + \frac{1}{\sum_{i=1}^{n} y_i^2}\right] \tag{2.8}$$

2.2.2 *Cross-laminated wall unit*

The calculation model based on the principle of conservation of energy (internal work is equal to the external work) is presented below to investigate the structural behaviour of the wall and the internal stresses in the cross-laminated wall. Applying the external horizontal force on a cross-laminated wall will create internal shear forces from fasteners which resolve the internal moment for each two fasteners in each shear plane as illustrated in Figure 2.4.

This wall is formed by crossing vertical and horizontal planks, each layer forming a fold (horizontal or vertical). The assembly is always carried out in pairs of layers – one vertical and the other horizontal. The total number N of layers is constituted by an odd number N_V of the vertical layers and an even or odd number N_H of horizontal layers, as illustrated below:

$$\begin{cases} N_V = (N+1)/2 & (2.9) \\ N_H = (N-1)/2 & (2.10) \end{cases}$$

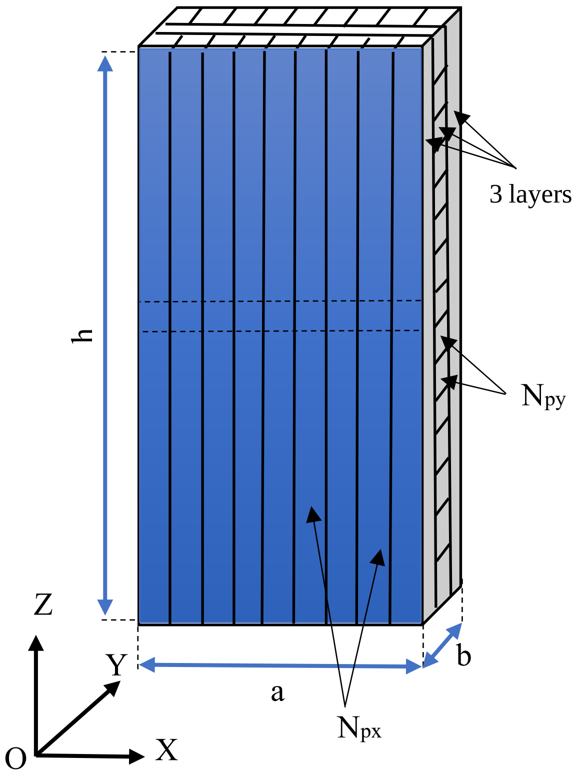

Figure 2. 3: Timber cross-laminated wall.

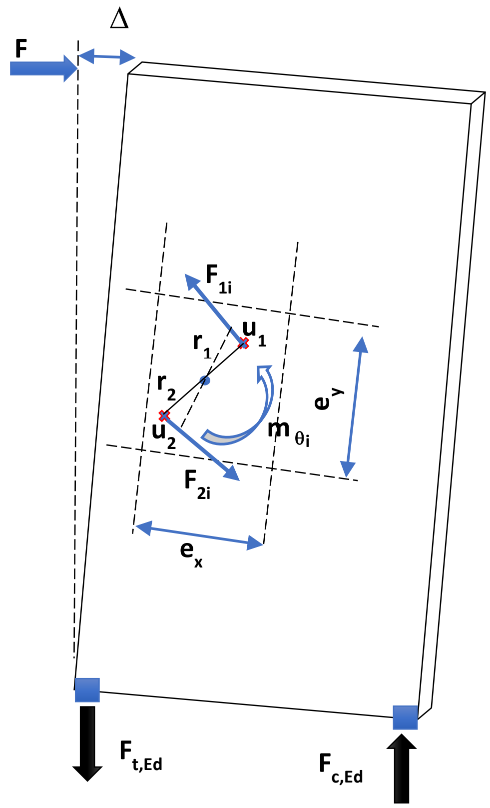

Figure 2. 4: Intersection plane of the fasteners.

Each layer in the cross-laminated wall is formed by a number of planks (N_{px} for the vertical planks and N_{py} for the horizontal planks). The number of horizontal and vertical planks is determined by the total width and height of the wall. One plank is characterised by a width e ($100 \leq e \leq 150$ mm) and a thickness y ($20 \leq y \leq 30$ mm) while, generally, the vertical and the horizontal planks have the same width as presented in Figure 5 ($e_x = e_y = e$).

$$\begin{cases} a \geq N_{px}\ e_x & (2.11) \\ b \geq N\ y & (2.12) \\ h \geq N_{py}\ e_y & (2.13) \end{cases}$$

The height of the wall (h) varies from 2 m to 3 m, the width (a) varies also from 1 m to 1.2 m and its thickness (b) depends on the total number N of the layers. Each area of intersection between the planks (mesh) is assembled and secured by two fasteners to ensure the connection between the vertical plank and the horizontal one. The fasteners are anchored at an edge distances of 5d as presented in the Eurocode (EC5); r_1 and r_2 are the distances from the fasteners to the centre of the intersection plane (Figure 2.5). By using the same plank width, $r_1 = r_2 = r$ with respect to the geometrical centre "o" of the mesh.

$$r_1 = r_2 = r = \sqrt{\left(\frac{e_x}{2} - 5d\right)^2 + \left(\frac{e_y}{2} - 5d\right)^2} = \frac{1}{\sqrt{2}}(e - 10d)\Big|_{e_x = e_y = e} \tag{2.14}$$

(where d is the diameter of the fastener).

The construction of the cross-laminated wall is generally automated and the configuration of the assemblies of all the meshes is practically homogeneous. The number of intersection planes (meshes) N_{m1} for two layers and total number of meshes in the whole wall N_m are given respectively by:

$$\begin{cases} N_{m1} = N_{px}\ N_{py} & (2.15) \\ N_m = N_{m1} N_V = N_{px}\ N_{py}\left((N+1)/2\right) & (2.16) \end{cases}$$

Each pair of fasteners in each intersection plane create two internal forces and an internal moment.

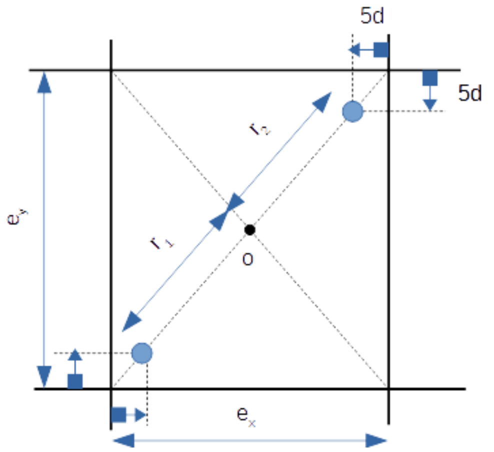

Figure 2. 5: Shear plane intersection.

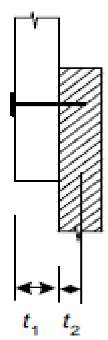

Figure 2. 6: Single shear of fasteners.

The total number of fasteners in the whole wall is equal to ($2 \times N_m$) and each fastener has an ultimate force $F_{v,Rk}$ in each plane of intersection.

The ultimate force can be calculated according to Eurocode 5 as given below:

$$F_{v,Rk} = \min \begin{cases} f_{h,1,k}\, t_1\, d & (a) \\ f_{h,2,k}\, t_2\, d & (b) \\ \dfrac{f_{h,1,k}\, t_1\, d}{1+\beta}\left[\sqrt{\beta + 2\beta^2\left[1+\dfrac{t_2}{t_1}+\left(\dfrac{t_2}{t_1}\right)^2\right]+\beta^3\left(\dfrac{t_2}{t_1}\right)^2} - \beta\left(1+\dfrac{t_2}{t_1}\right)\right] & (c) \\ 1.05\,\dfrac{f_{h,1,k}\, t_1\, d}{2+\beta}\left[\sqrt{2\beta(1+\beta)+\dfrac{4\beta(2+\beta)M_{y,Rk}}{f_{h,1,k}\, t_1^2\, d}} - \beta\right] + \psi\, F_{ax,Rk} & (d) \\ 1.05\,\dfrac{f_{h,1,k}\, t_2\, d}{1+2\beta}\left[\sqrt{2\beta^2(1+\beta)+\dfrac{4\beta(1+2\beta)M_{y,Rk}}{f_{h,1,k}\, t_2^2\, d}} - \beta\right] + \psi\, F_{ax,Rk} & (e) \\ 1.15\sqrt{\dfrac{2\beta}{1+\beta}}\sqrt{2M_{y,Rk}\, f_{h,1,k}\, d} + \psi\, F_{ax,Rk} & (f) \end{cases} \quad (2.17)$$

where:

- $\beta = f_{h,2,k}/f_{h,1,k}$ is the ratio between the characteristic embedment strengths ($\beta = 1$)
- $f_{h,1,k}$ is the characteristic embedment strength in first timber element (N/mm2)
- $f_{h,2,k}$ is the characteristic embedment strength in second timber element (N/mm2)
- $M_{y,Rk}$ is the characteristic value of the yield moment for the fasteners (N.mm)
- $F_{ax,Rk}$ is the characteristic axial withdrawal capacity of the fastener (N)
- t_1 is the headside thickness in a single shear connection (mm)
- t_2 is the pointside penetration in a single shear connection (mm) (see Figure 2.6)

The value of the slip modulus of assembly K_{ser} without pre-drilling holes can be calculated according to Eurocode 5 (EC5) as follows:

$$K_{ser} = \frac{1}{30}\,\rho_m^{1.5}\, d^{0.8} \quad (2.18)$$

where:

- ρ_m is the mean density of the wood (kg/m3)
- d is the diameter of the fastener used in the wall (mm)

The lateral load-carrying capacity of a cross-laminated wall is ensured by the rotational resistances of the intersection plane assemblies (Figure 2.7), which develop an internal moment (Figure 2.8) in ultimate resistance given by the following equation:

$$M_{v,Rk} = \sum_{i=1}^{N_m} \left[F_{v,\mathrm{R}k} \left(r_1 + r_2 \right) \right]_i = F_{v,\mathrm{R}k} \sqrt{2}\ N_m\ \left(e - 10d \right) \Big|_{e_x = e_y = e} \tag{2.19}$$

Since all planks have the same width, the area of intersection (mesh) form a square. The two nails were fixed with an angle 45 degrees to the timber grain to optimize the maximum arm of the moment. Optimizing the maximum arm of the internal moment will increase the overall resistance of the wall.

Each fastener anchor in the wood can be represented by a spring K-ser, and the equilibrium of crossing planks is ensured by a rotational stiffness Kθ.

The method applied was the energy conservation theorem, also, some simple mechanical models were considered that were similar to those suggested in [65], the rotational rigidity of each mesh of index "i" is represented as:

$$\frac{1}{2}\left(K_\theta\ \theta^2 \right)_i = \frac{1}{2} K_{ser}\ \left(u_1^2 + u_2^2 \right)_i = \frac{1}{2} K_{ser}\ \left(r_1^2 + r_2^2 \right)_i = \frac{1}{2} K_{ser} \left(e - 10d \right)_i^2 \Big|_{e_x = e_y = e} \tag{2.20}$$

$$K_{\theta_i} = K_{ser}\ \left(r_1^2 + r_2^2 \right)_i = K_{ser} \left(e - 10d \right)_i^2 \Big|_{e_x = e_y = e} \tag{2.21}$$

Consequently, the total rotational rigidity is obtained by summation over the set of cross planes of the intersection.

$$K_\theta = \sum_{i=1}^{N_m} K_{\theta_i} = K_{ser} \sum_{i=1}^{N_m} \left(e - 10d \right)_i^2 \Big|_{e_x = e_y = e} = K_{ser} N_m \left(e - 10d \right)^2 \tag{2.22}$$

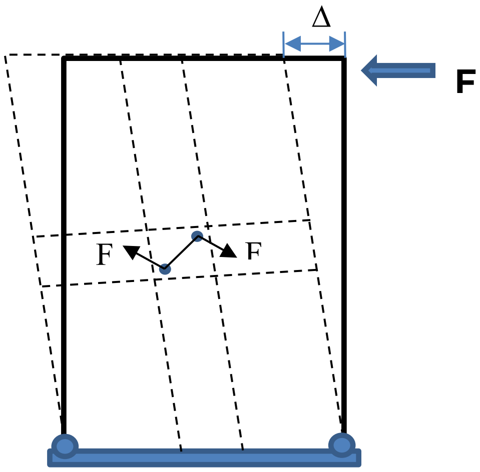

Figure 2. 7: The deformation of the cross-laminated wall.

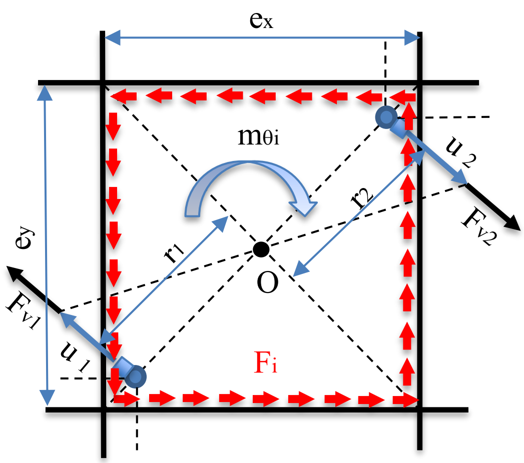

Figure 2. 8: The resistance in the intesection plane.

Proposition 1:

This proposition is based on the equilibrium of cross meshes of intersection. It can be assumed that the distribution of the external force on the crossover meshes is proportional to the rotational rigidities (see Figure 2.8) as follows:

$$F_i = \frac{K_{\theta_i}}{\sum_{i=1}^{N_m} K_{\theta_i}} F = \frac{K_{\theta_i}}{K_\theta} F; \quad \Rightarrow \quad M_{\theta_i} = F_i \left(e_x + e_y\right) = \frac{K_{\theta_i}}{K_\theta}\left(e_x + e_y\right) F = \left(e_x + e_y\right) \frac{F}{N_m}\bigg|_{K_{\theta i} = C^{const.}} \qquad (2.23)$$

In this case, each fastener must have a force F_{Vd} :

$$F_{Vd} = \frac{M_{\theta_i}}{\left(r_1 + r_2\right)} = \frac{M_{\theta_i}}{\sqrt{2}\left(e - 10d\right)\Big|_{e_x = e_y = e}} = \frac{\sqrt{2}\, e}{\left(e - 10d\right)}\bigg|_{e_x = e_y = e} \frac{F}{N_m}\bigg|_{K_{\theta i} = C^{const.}} \leq F_{V,Rd} \qquad (2.24)$$

Proposition 2:

The second proposition is based on the equilibrium of moments. Applying the static equilibrium of the wall by equality between the internal and external moments (taken from the base of the wall (Figure 2.4)), then:

$$\begin{cases} h\,F=\sum_{i=1}^{N_m}\left[F_{Vd}\ \left(r_1+r_2\right)\right]_i=F_{Vd}\ \sum_{i=1}^{N_m}\left(r_1+r_2\right)_i=F_{Vd}\ N_m\sqrt{2}\left(e-10d\right)\Big|_{e_x=e_y=e} & (2.25)\\ F_{Vd}\ =\dfrac{h}{\sqrt{2}\left(e-10d\right)\Big|_{e_x=e_y=e}}\dfrac{F}{N_m}\leq F_{V,Rd} & (2.26)\end{cases}$$

Proposition 3:

This proposition is created from the theorem of conservation of energy. The displacement at the top of the wall, as illustrated in Figure 2.7, is obtained by application of the law of conservation of energy between the work of the external force and those of the spiral springs of the different cross meshes. Then we can calculate the maximum displacement of the wall as presented below:

$$\begin{cases} F\,\Delta=\dfrac{1}{2}\sum_{i=1}^{N_m}K_{\theta_i}\theta_i^2=\dfrac{K_\theta}{2}\Bigg|_{K_{\theta_i}=C^{const.}}\times\left(\dfrac{\Delta}{h}\right)^2_{\theta_i=\theta} & (2.27)\\ \Delta=\dfrac{2h^2}{K_\theta}F & (2.28)\end{cases}$$

Proposition 4:

For calculating the ultimate force that can be applied on the cross-laminated timber wall, we consider, in the following formula, the ultimate characteristic force of the fastener. When considering the ultimate single shear strength of the fastener, the ultimate characteristic force that can be applied to the wall can be calculated using the formula below:

$$\begin{cases} M_{v,Rk}=F_{U,k}h=F_{v,\mathrm{R}k}\sqrt{2}\ N_m\ \left(e-10d\right)\Big|_{e_x=e_y=e} & (2.29)\\ F_{U,k}=\sqrt{2}\ N_m\ \dfrac{\left(e-10d\right)\Big|_{e_x=e_y=e}}{h}F_{v,\mathrm{R}k} & (2.30)\end{cases}$$

2.3 Experimental Study

2.3.1 Properties of materials

The purpose of this section is to characterise and investigate some measurements for the materials used in this study – firstly for unclassified wood, such as density and compressive strength, and secondly for fasteners, such as shear tests.

Mean density of timber specimens

Five unclassified specimens, with different dimensions have been chosen, to calculate the mean density of the material. The different samples of timber (with different densities) are characterised by the dimensions (a), (b) and (h) to represent height, length and width respectively. The mean density of all specimens was 463.4 kg/m3 as illustrated in Table 2.1.

Table 2. 1: Mean density of timber specimens.

No	a (mm)	b (mm)	h (mm)	V × 10-4 (m3)	M (kg)	ρ (kg/m3)
1	220	146	24	7.71	0.334	433.3
2	196	146	24	6.87	0.32	465.9
3	199	149	25	7.41	0.33	445.2
4	196	145	24	6.82	0.316	463.3
5	199	150	25	7.46	0.38	509.2
					ρ_{mean} (kg/m3)	**463.4**

Compressive characteristic tests of timber specimens

Nine samples of timber specimens were tested for compressive strength to classify the type of wood and to determine mechanical characteristics. Five samples were tested in a direction parallel to the grain (Figure 2.9) and four samples were tested transversally to the grain (Figure 2.10). The average compressive strength parallel to grain ($f_{c,0,k}$) was 29.9 MPa, as illustrated in Table 2.2, and the average compressive strength perpendicular to the grain ($f_{c,90,k}$) was 4.2 MPa, as illustrated in Table 2.3. Taking into account the compressive strength and the mean density of the material and comparing these three values with timber classification specified in **Eurocode (5) NF EN 1194**, the closest comparable class of this wood material is C30. The characteristic values parallel and transverse to the grain were calculated according to the standard (EN 14358).

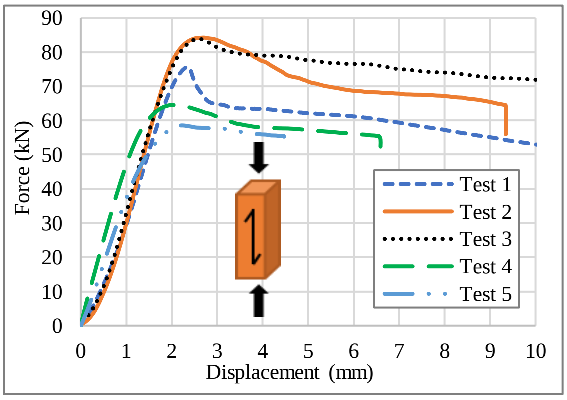

Figure 2. 9: Compressive timber behaviour parallel to the grain.

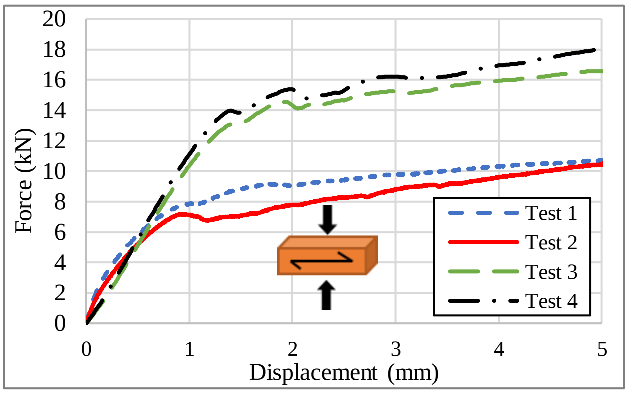

Figure 2. 10: Compressive timber behaviour transverse to the grain.

Table 2. 2 : Compressive characteristic strength parallel to the grain.

	Test 1	Test 2	Test 3	Test 4	Test 5
F_{max} (kN)	75.6	84.2	83.8	64.5	58.5
A (mm²)	1560	1520	1520	1560	1600
σ_{max} (MPa)	48.5	55.4	55.1	41.4	36.6
$f_{c,0,k}$ (MPa)			29.9		
C.O.V			0.05		
RH %	9.8	9.7	10.6	10.1	10.7
Average RH%			10.18		

Table 2. 3 : Compressive characteristic strength transverse to the grain.

	Test 1	Test 2	Test 3	Test 4
F_{max} (kN)	7.7	7.0	13.2	13.9
A (mm²)	1560	1520	1520	1560
σ_{max} (MPa)	5.0	4.6	8.7	8.9
$f_{c,90,k}$ (MPa)		2.4		
C.O.V		0.19		
RH %	9.9	10.5	11	9.6
Average RH%		10.25		

Load-carrying capacity tests for fasteners

Three tests were examined to determine the load-carrying capacity of fasteners as presented in Figure 2.12, double shear timber-to-timber with three pieces connected using two simple nails per side (Figure 2.11). The nails were of a rounded cross-section, 2.5 mm in diameter and 45 mm in length. Table 2.4 illustrates the calculations of the total maximum force F_{max} and the maximum force $F_{max/fastener}$ for each fastener in each shear plane. The mean value of the maximum load per fastener $F_{v,R,mean}$ was 1.59 kN.

Figure 2. 11: Shear test set up for fasteners.

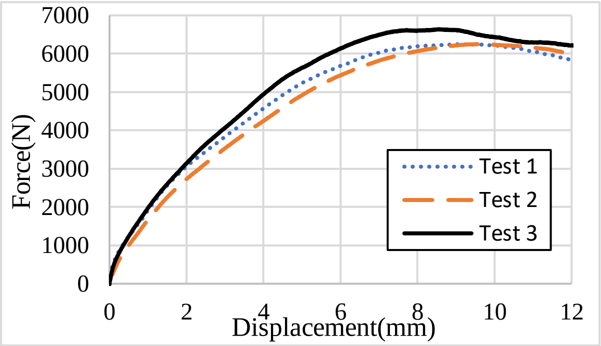

Figure 2. 12: Simple shear behaviour of nail fasteners.

Table 2. 4 : Test results of the double shear connections.

	Test 1	Test 2	Test 3
F_{max} (kN)	6.215	6.23	6.60
$F_{max/fastener}$ (kN)	1.55	1.56	1.65
$F_{v,R,mean}$ (kN)		**1.59**	
$F_{v,R,K}$ (kN)		**1.43**	

2.3.2 Lateral load-carrying capacity of the cross-laminated wall

Three groups of large-scale timber cross-laminated walls were used, each cross-laminated wall consisting of three layers, connected using rounded nails of 2.5 mm diameter and 45 mm length. The dimensions of all tested walls were 2.5 m height, 1.2 m width and 75 mm in thickness. The first group (S1) consisted of five panels without diagonal elements. The second group (S2) consisted of three walls with diagonal elements under compression conditions and the third group (S3) consisted of two walls with diagonal elements under tension condition. A horizontal racking load was applied to the top of each wall by a hydraulic jack as illustrated in Figure 2.13.

All panels were fixed to the floor at the Institut Pascal to ensure the stability of the panels and prevent sliding and uplift of the base of the walls. For these reasons a commercial type of angle bracket (with a height of vertical flange 135 mm) was fixed to the edges of the wall, the vertical flange of the angle bracket having four rows of holes (each row consists of five holes). Screws of a diameter 8 mm were used.

This angle bracket can transfer the force to the anchor bolt fixed centrally to the base flange. Both the loads and displacements for S1 were recorded as shown in Figure 14 and the wall weights illustrated in Table 2.5 below.

Figure 2. 13: **Timber wall of first group (S1) in test.**

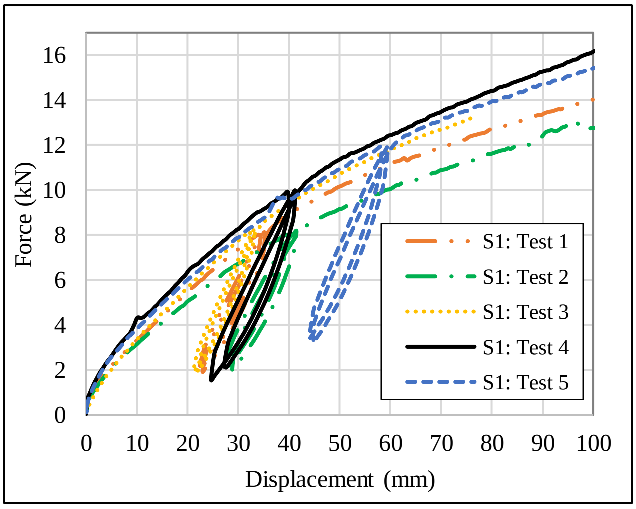

Figure 2. 14: Force-displacement behaviour for (S1)

Table 2. 5 : Wall weights in the first group (S1) without diagonal elements.

Wall No.	**1**	**2**	**3**	**4**	**5**
Mass (kg)	114.2	115.3	116	111	110

The second group (S2) of cross-laminated walls were timber walls with diagonal elements under compression. A horizontal racking load was applied to the top of the walls in the second group (S2) with the same setup and fixing on the floor as the first group as illustrated in Figure 15. Three walls were tested in this group, with the loads and displacements recorded as illustrated in Figure 2.16. The wall weights are also recorded in Table 2.6 below.

Table 2. 6 : Wall weights in second group (S2) with diagonal elements under compression.

Walls with diagonal elements under compression (S2)			
Wall No.	1	2	3
Mass (kg)	118	114.5	112

Figure 2. 15: Timber wall of the second group (S2) in test.

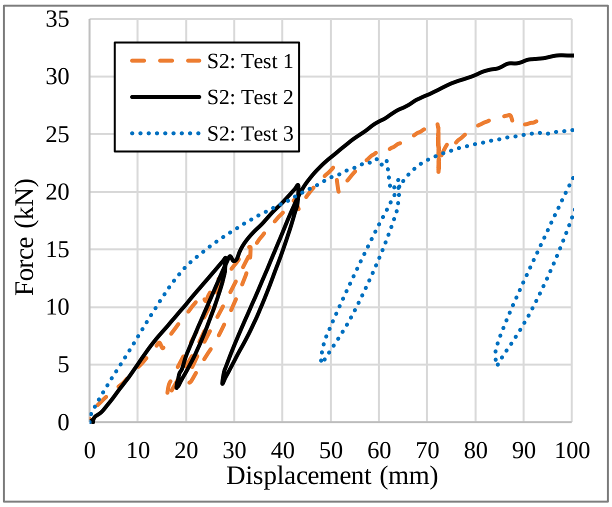

Figure 2. 16: Force-displacement behaviour for (S2).

The third group (S3) of the walls were timber walls with diagonal elements under tension as illustrated in Figure 2.17. The same protocol of the horizontal racking load was applied to the top of the walls with the same setup and fixing on the floor as the first and second groups. Wall weights have been measured as presented in Table 2.7. Two walls were tested in this group, with the loads and displacements recorded as illustrated in Figure 2.18.

Table 2. 7 : Wall weights in the third group (S3) with diagonal elements under tension.

Walls with diagonal elements under tension (S3)		
Wall No.	1	2
Mass (kg)	118	114.5

Figure 2. 17: Timber wall of third group (S3) in test.

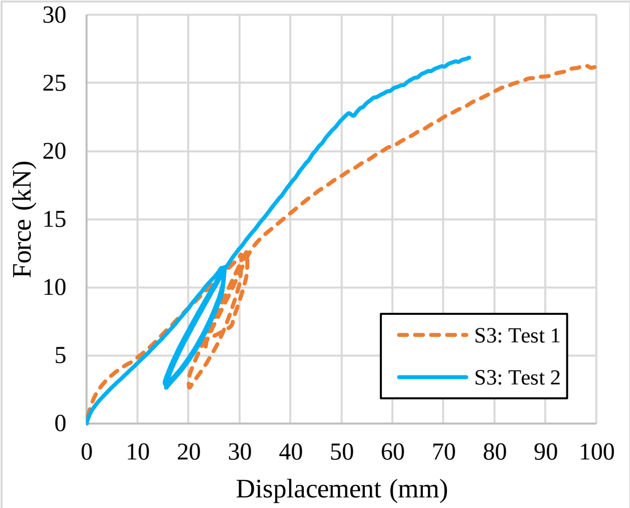

Figure 2. 18: Force-Displacement behaviour for (S3).

2.3.3 Racking tests of timber frame with oriented strand board (OSB)

One timber frame with oriented strand board was used, with the height 3 m, width 1.21 m and thickness 135 mm. The wall was fixed to the floor to avoid sliding, and a horizontal load was applied to the top of the panel using the same setup techniques as illustrated in Figure 2.19.

A hold-down connector was placed inside the thickness of the wall panel, the vertical flange is nailed to the external stud of the timber wall and the anchor bolt is connected to the foundation. Due to the difference between the wall length and the distances between foundation bolts, a steel beam was fixed by bolts to the floor to prevent wall sliding (Figure 2.19).

The wall consisted of three vertical columns (studs) and OSB3 board. The nails used were also a rounded cross-section, 2.5 mm in diameter and 45 mm in length. The distance between nails within external suds (outer perimeter) was 150 mm and within the middle stud was 300 mm. The loads and displacements were recorded as presented below in Figure 2.20. Monotonic loading was used in the test of this wall.

Figure 2. 19: OSB wall during test.

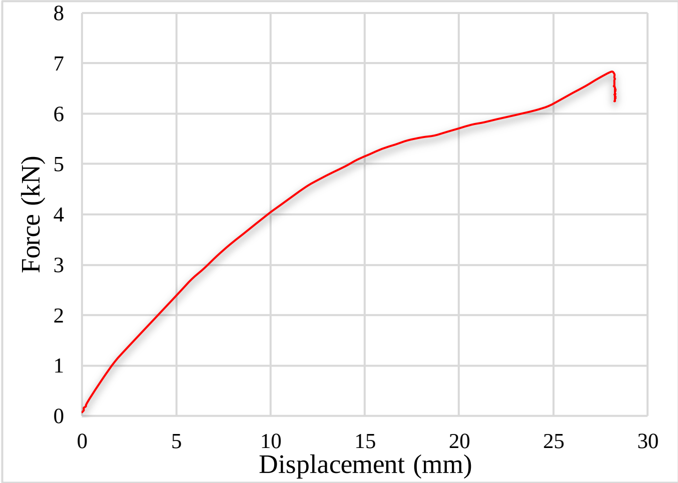

Figure 2. 20: Force-displacement behaviour for OSB wall.

2.4 Calculations and discussion

Calculation examples have been presented below to validate the proposed expressions and to make a comparison between results of experimental investigation and proposed theoretical approach as illustrated in Table 8. Data used in the mathematical example are taken from cross laminated walls and fasteners between layers (Figure 3). Number of wall layers (N) = 3, number of vertical planks (N_{px}) = 8, number of horizontal planks (N_{py}) = 16, thickness of plank (y) = 25 mm, the height of the wall (h) = 2.5 m, width of the wall (a) = 1.2 m, thickness of the wall (b) = 75 mm, the diameter of the nail (d) = 2.5 mm, the experimental mean density of the wood (ρ_m) = 463.4 kg/m^3 and the width of plank $e_x = e_y = e = 150$ mm.

The characteristic load-carrying capacity of the fastener is calculated based on Eurocode 5 as presented in equation (17) and the value was $F_{v,Rk} = 722$ N . This value was investigated experimentally as presented in Table 4 and the value was $F_{v,Rk} = 1430$ N. The minimum value has been used in this example which is $F_{v,Rk} = 722$ N. The value of slip modulus is calculated by formula (18) as illustrated below:

$$K_{ser} = \frac{1}{30} \rho_m^{1.5} d^{0.8} = 692.09 \text{ N/mm}$$

The rotational resistance of crossover assemblies is calculated based on formula (19)

$$M_{v,Rk} = \sum_{i=1}^{N_m} \left[F_{v,Rk} \left(r_1 + r_2 \right) \right]_i = F_{v,Rk} \sqrt{2}\ N_m \ \left(e - 10d \right)\Big|_{e_x = e_y = e} \quad = 32.67 \text{ kN.m}$$

The total rotational rigidity is calculated by using the formula (21) as presented below:

$$K_\theta = \sum_{i=1}^{N_m} K_{\theta_i} = K_{ser} \sum_{i=1}^{N_m} \left(e - 10d \right)_i^2 \Big|_{e_x = e_y = e} = K_{ser} N_m \left(e - 10d \right)^2 \quad = 2768.4 \text{ kN.m/rad}$$

Based on equation (28) the value of horizontal force is calculated at the displacement 50 mm

$$\Delta = \frac{2h^2}{K_\theta} F \quad \Longrightarrow \text{F = 11.07 kN}$$

The ultimate characteristic force that can be applied to the wall is calculated by equation (30)

$$F_{U,k} = \sqrt{2}\ N_m \ \frac{\left(e - 10d \right)\Big|_{e_x = e_y = e}}{h} F_{v,Rk} = 13.1 \text{ kN}$$

Table 2.8 below shows a comparison between the experimental and theoretical values. The value 50 mm of displacement has been considered as a benchmark of force comparison because it falls within the average linear behaviour of the wall as shown in Figure 21. The relative error of force values at 50 mm is calculated and was around 7.4%. Then the theoretical value of ultimate force was 13.1 kN and the observed experimental value (at displacement 100 mm) was 14.5 kN.

Table 2. 8 : Comparison between the experimental and theoretical wall results.

	Displacement (Δ) mm	Force (F) kN	Ultimate force ($F_{u,k}$) kN
Theoretical values	50	11.07	13.1
Experimental values	50	10.30	14.5 (at Δ=100 mm)

The behaviour of cross-laminated walls made from unclassified wood proved to have a greater resistance and more rigidity than the oriented strand board (OSB) panel as illustrated in Figure 21. This resistance is due to the number of internal rotational moments that were created in each shear area of intersection in the wall (Figure 2.22). However, the different conditions of the diagonal elements, under conditions either of tension or compression, did not offer a significant improvement for the overall strength of the wall.

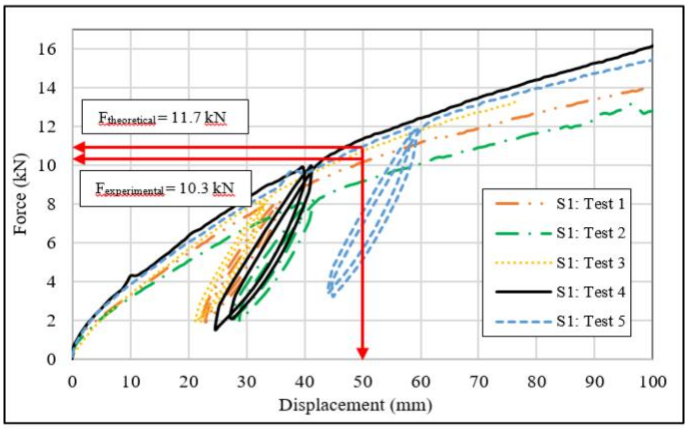

Figure 2. 21: Comparison between the experimental results and the proposed expressions.

On the other hand, the OSB design showed less resistance and less rigidity under horizontal force. In fact, the principle of Eurocode 5 to calculate the design racking resistance of the timber wall is based on the assumption of equal force distribution between the fasteners in the outer perimeter of the panel – particularly in method A (Figure 2.23). This assumption leads to the fasteners' behaviour being limited to the lower limit of the plastic state and causes the value of the load-carrying capacity of the timber frame wall to be overestimated.

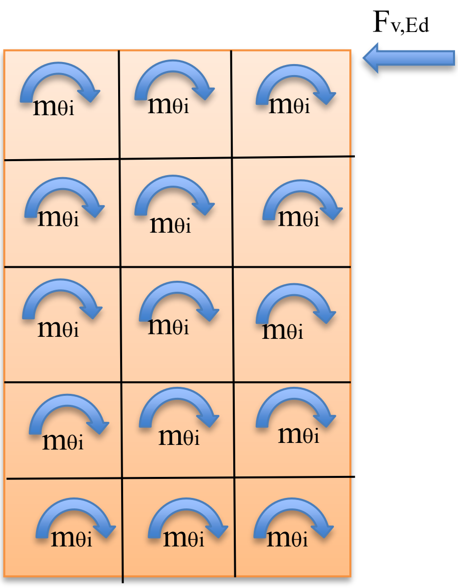

Figure 2. 22: Internal resistance of rotational moments for cross-laminated wall.

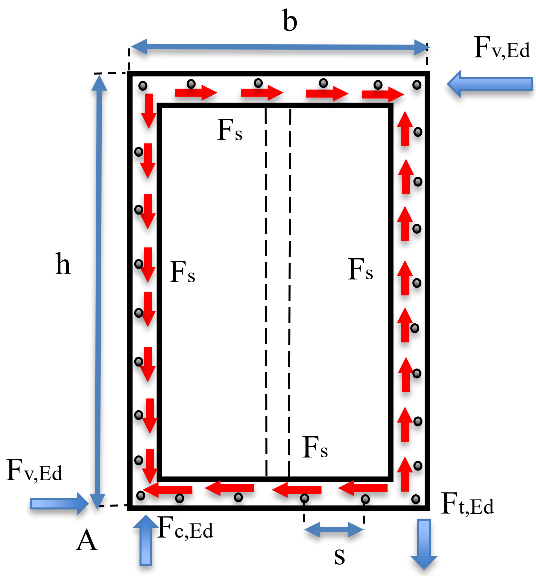

Figure 2. 23: fasteners behaviour as Eurocode 5 principle in OSB panel.

The forces for each fastener F_s are assumed the same in Eurocode 5, assuming that (s) represents the spacing between fasteners and, $F_{v,Ed}$ is the external horizontal force applied to the panel of width (b) and height (h). The equilibrium of the external forces will create the reactions $F_{v,Ed}$, $F_{c,Ed}$ and $f_{t,Ed}$ as shown in Figure 2.23.

$$\sum F\ y = 0$$

$$F_{c,Ed} - F_{t,Ed} = 0$$

$$F_{c,Ed} = F_{t,Ed}$$

$$\sum M\ A = 0$$

$$(-F_{v,Ed} \times h) + (F_{t,Ed} \times b) = 0$$

$$F_{t,Ed} = \left(\frac{h}{b}\right) F_{v,Ed}$$

Applying equilibrium of internal forces, then:

$$F_{t,Ed} = \left(\frac{h}{b}\right) F_{v,Ed}\ ,\quad F_{t,Ed} = n_1 F_s$$

Where n is the number of fasteners in the first right column of the panel:

$$n_1 = \left(\frac{h}{s}\right)\ ,\quad so \left(\frac{h}{b}\right) F_{v,Ed} = n_1 F_s$$

$$\left(\frac{h}{b}\right) F_{v,Ed} = \left(\frac{h}{s}\right) F_s$$

$$F_{v,Ed} = \left(\frac{b}{h}\right) \times \left(\frac{h}{s}\right) F_s$$

$F_{v,Ed} = \left(\frac{b}{s}\right) F_s$. This formula is compared to the Eurocode method (A), which is:

$$F_{i,v,Rd} = (F_{f,Rd}\ b_i\ c_i) / s \qquad (31)$$

2.5 Conclusion

During this study, an experimental investigation of the racking performance of timber frame wall (OSB) and cross-laminated timber walls has been conducted. A theoretical approach has been proposed to predict the performance of CLT wall subjected to lateral loads and also a comparison between the theoretical and experimental results has been conducted. Based on the results in this study, the proposed theoretical approach model exhibits similar behaviour to the average test curve up to 100 mm. The experimental value of the horizontal force (at displacement 50 mm) was approximately 93% of the calculated force and also the theoretical value of ultimate force (at displacement 100 mm) applied on the wall was 90% of the experimental value. This study also confirms that a diagonal strut significantly increases the lateral load resistance of cross-laminated walls, particularly under compression conditions. The diagonal strut can be applied in practice easily and be connected with the wall by using the same planks size. This strut can be fixed on one side on the cross laminated wall using the same type of nails between layers. Practically, it is better to connect the diagonal strut on the wall before installing the wall with the foundations.

According to the analysis of the Eurocode 5 formulas, this study concludes that these formulas are not very accurate, and need to be reformulated, especially for the parameter $F_{f,Rd}$ (lateral design load-carrying capacity per fastener). The behaviour of cross-laminated walls made from unclassified timber showed greater resistance to the lateral loads than OSB panel design, which is due to the number of internal rotational moments that are created in each shear plane of intersection in the wall. However, the diagonal elements enhance the load-carrying capacity of the wall and its performance under tension or compression does not show a significant difference for the load-carrying capacity of the wall. An analytical model has been created to represent the internal forces on each fastener and to calculate the ultimate force that can be applied to the top of the wall at the design stage. The cross-laminated wall could well be a suitable material for construction, given its strength and good performance under horizontal loads.

Chapter 3 The lateral strength of hemp concrete as infill material in timber frame walls

3 The lateral strength of hemp concrete as infill material in timber frame walls

Article (B)

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Lateral load-carrying capacity of hemp concrete as a natural infill material in timber frame walls

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Abstract

This study focuses on the racking behaviour of hemp concrete as infill material in timber frame walls, investigating and highlighting the parameters that significantly affect the lateral resistance of hemp walls. For this purpose, two different designs of timber frame walls are used as wall units, the first consisting of vertical studs and the second using diagonal bracing elements under compression. These two designs of timber frames are those most widely used as external walls in construction. In this research, an experimental investigation of large-scale timber frame walls with dimensions (2.5m height and 1.25m length), both with and without hemp concrete, was carried out to assess the contribution of hemp concrete as infill material against lateral loads. The hemp walls were then compared to empty timber frames to determine the real contribution of hemp concrete to lateral strength. Digital Image Correlation (DIC) was used in order to determine and track local displacement and shear-strain fields of hemp concrete as infill material in the timber wall. Based on the results obtained from the experimental tests, it is obvious that hemp concrete makes a slight contribution against lateral loads in a vertical stud timber wall of length 1.25m. However, hemp concrete did not improve the lateral strength in walls with diagonal bracing elements. This study confirms, firstly, that the length of timber wall plays a significant role in the lateral strength of the hemp concrete. In other words,

decreasing the length of the wall will significantly decrease the contribution of hemp concrete to lateral resistance. Secondly, the use of diagonal elements increases the overall rigidity of the timber wall, which negatively affects the contribution of hemp concrete and prevents hemp concrete from increasing the lateral strength of the wall.

3.1 Introduction

Private and public construction projects nowadays face significant challenges to reduce the large amounts of daily energy usage for utilities such as heating, electricity and hot water in residential and commercial buildings – especially in Europe. For this purpose, many building regulations now encourage the use of bio-based materials. with superior physical properties for energy efficiency in the construction sector. The use of low-carbon material in structures, firstly, improves the insulation level and sound absorption and, secondly, decreases the weight of the building structure, as this natural material provides a lightweight, low-density aggregate. In response to this need, the use of bio-aggregate such as hemp, flax and sunflower products is increasing in Europe – particularly in France. Bio-aggregate-based building materials offer a route to more sustainable construction by reducing energy consumption and simultaneously achieving energy efficiency without causing additional environmental pollution. Using materials with high moisture buffering capacity helps improve the hygrothermal behaviour of this material and increases the environmental benefits of the final construction. Hemp concrete has been one of the most commonly used bio-aggregate-based building materials since the 1980s.

Although hemp concrete has proved to have some excellent characteristics such as thermal and acoustic properties, this material still has poor mechanical properties such as compressive strength. In addition, the structural design practice of wood frame construction does not assume any contribution of green concrete to lateral strength.

As matters currently stand in relation to hemp-based materials, it is obvious that there is a lack of knowledge and a need for further studies in racking performance of hemp concrete – practically in timber frame walls. For this purpose, this research highlights the parameters that could play a main role in the lateral strength of hemp concrete. The main objective of the presented study is to investigate the lateral strength of two different designs of timber frame walls filled in with hemp concrete. The length and overall rigidity of timber hemp wall have been investigated in this study to describe their effects on lateral load-carrying capacity.

3.2 Theoretical analysis of timber wall units

Two different designs of timber walls are considered in this study: vertical stud and diagonal bracing walls (see Figures 3.1 & 3.2). The dimensions of all walls were 2.5m height, 1.25m length and 140mm in thickness. A linear elastic behaviour of the wall units is assumed in this approach, and the deformations are caused by external force alone. By applying the virtual work transformation theorem by the unit-load (F), the total top displacement of the wall unit (Δ) can be calculated as:

$$\Delta = \frac{\partial W}{\partial F} \tag{3.1}$$

where (w) is the elastic strain energy stored in the wall and provided by an external horizontal load (F) applied on the top of the wall unit. In the present case, the total strain energy consists of three internal forces: a normal force (*N*), shear force (*V*) and an internal moment (*M*) as illustrated in equation (3.2).

Considering the material characteristics, the total horizontal displacement (Δ_1) in vertical stud walls can be calculated as a function of the internal forces, as in equation (3.3). Moreover, the total horizontal displacement (Δ_2) in the diagonal bracing wall can be calculated by equation (3.4) using the same principle.

$$W = \frac{1}{2}\left[\frac{1}{E_{0.05}\,I}\int M^2\,(x)\,dx + \frac{1}{E_{0,mean}\,A}\int N^2\,(x)\,dx + \frac{1}{G_{mean}\,\acute{A}}\int V^2\,(x)\,dx\right] \tag{3.2}$$

$$\Delta_1(m) = \left[\left(\frac{0.964}{E_{0.05}\,I}\right) + \left(\frac{5.72}{E_{0,\,mean}\,A}\right) + \left(\frac{3.85}{G_{mean}\,A'}\right)\right]F(N); \quad A' = \frac{2}{3}A \tag{3.3}$$

$$\Delta_2(m) = \left[\left(\frac{1.26\times10^{-5}}{E_{0.05}\,I}\right) + \left(\frac{25.5}{E_{0,\,mean}\,A}\right) + \left(\frac{1.0\times10^{-4}}{G_{mean}\,A'}\right)\right]F(N) \tag{3.4}$$

$$\Delta_i(m) = (a_M + a_V + a_N)F(N) \tag{3.5}$$

where $E_{0.05}$ and $E_{0,\,mean}$ are: fifth-percentile values of stiffness property and parallel to the grain elastic modulus respectively, G_{mean} is the mean value of shear modulus, A' is two-thirds of the cross-sectional area of the element. Table 3.1 below summarises the analytical and numerical values of the internal forces for loaded states of walls caused by an external horizontal unit load of 1kN. Robot software is used to analyse the behaviour of the timber wall and to calculate the internal forces in the elements. Based on the results in Table 3.1, it is obvious that, on the one hand, normal and shear forces in the vertical stud walls are negligible compared to the value of the internal moments (1.2×10^{-4}). On the other hand, shear forces and internal moments are negligible in the case of diagonal bracing compared to the value of normal forces (3.5×10^{-7}), as presented in Figures 3.1 & 3.2, below.

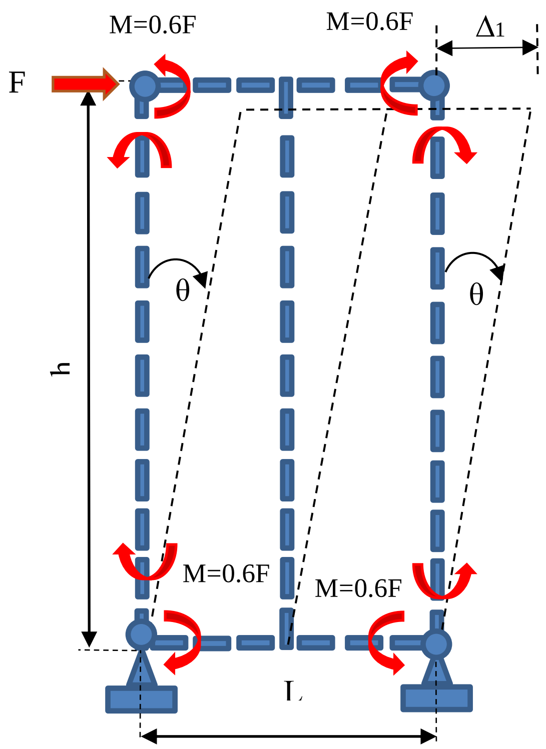


Figure 3. 1: Loaded and unloaded states of vertical stud wall unit.

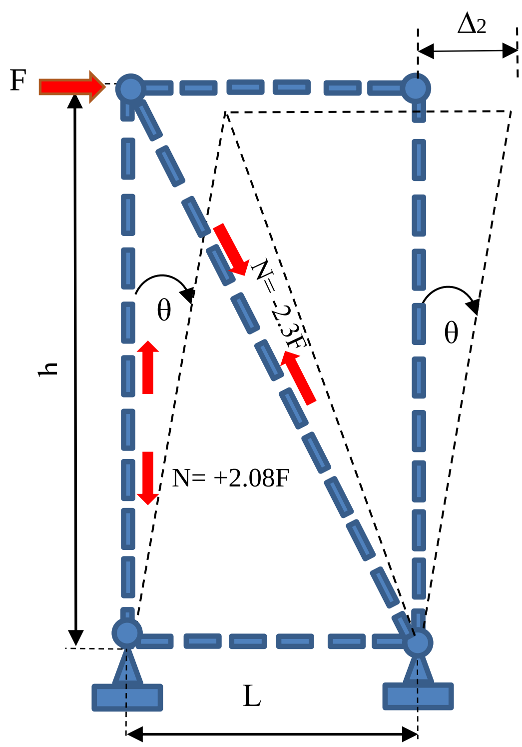


Figure 3. 2: Loaded and unloaded states of diagonal bracing wall unit.

Table 3. 1 : Analytical and numerical values of internal forces of timber frame walls.

	Analytical expressions			Numerical expressions $E_{0.05}$=7.4GPa, $E_{0,\,mean}$ = 11GPa, G_{mean} = 0.69GPa		
Wall type	$a_M \times (E_{0.05}\, I)$	$a_V \times (G_{mean}\, A')$	$a_N \times (E_{0,\,mean}\, A)$	a_M	a_V	a_N
Vertical studs	0.964	3.85	5.72	**1.2×10^{-4}**	1.3×10^{-6}	8.0×10^{-8}
Diagonal bracing	1.26×10^{-5}	1.0×10^{-4}	25.5	1.5×10^{-9}	3.3×10^{-11}	**3.5×10^{-7}**

Through this analysis, it becomes easier to predict the elastic behaviour of both designs of timber walls. Using equations (3) and (4), the force-displacement curves for both walls can be presented as below:

- For vertical stud timber frame: $F(kN) = 0.0083 \times \Delta_1\,(mm)$ (3.6)
- For diagonal bracing element: $F(kN) = 2.7 \times \Delta_2\,(mm)$ (3.7)

3.3 Experimental Study

3.3.1 Properties of materials

The purpose of this section is to characterise and investigate some measurements for the materials used in this study: firstly for wood materials, such as density and compressive strength, and secondly for hemp concrete samples, such as compressive strength.

Timber specimens

The type of wood used in this study to construct the timber frame walls is Class C 24 sawn timber, which is the type that is most readily available and common in the marketplace and used by construction companies in France.

Five wood specimens were selected, with different dimensions, to calculate the mean density of the wood. The different specimens are characterised by the dimensions (a), (b) and (h) to represent length, width and height respectively. The mean density of all specimens is 393.2kg/m^3 as illustrated in Table 3.2.

Table 3. 2 : Mean density of wood specimens.

No.	h (mm)	a (mm)	b (mm)	$V \times 10^{-4}$ (m^3)	M (kg)	ρ (kg/m^3)
1	99.5	44.4	44.8	1.9	0.078	393.9
2	99.8	44.7	45.1	2.0	0.077	383.1
3	100.1	44.4	45.2	2.0	0.079	393.0
4	99.8	44.9	44.8	2.0	0.081	403.0
5	99.9	44.6	45.1	2.0	0.079	393.0
					ρ_{mean} (kg/m^3)	**393.2**

Nine specimens of timber were tested for compressive strength to determine the mechanical behaviour of the wood. Five specimens were tested in a direction parallel to the grain and four samples were tested transversally to the grain (Figures 3.3 and 3.4). The dimensions of all specimens were 45mm × 45mm × 100mm. The maximum force (F_{max}) was recorded using a compression load cell; also the cross-sectional area (A) of each sample was calculated, as illustrated in Tables 3.3 and 3.4. Compressive strain is taken as change in height of the wood sample. The average moisture content of timber samples tested parallel to and transversally to the grain was about 10.18% and 10.25% respectively.

Table 3. 3 : Compressive strength of timber parallel to the grain.

	Test 1	Test 2	Test 3	Test 4	Test 5
F_{max} (kN)	82.0	68.5	74.1	78.5	72.9
A (mm²)	2021	2020	2017	2021	2013
σ_{max} (MPa)	40.5	33.9	36.7	38.8	36.2
RH%	9.8	9.7	10.6	10.1	10.7
Average RH%			10.18		

Table 3. 4 : Compressive strength of timber transversally to the grain.

	Test 1	Test 2	Test 3	Test 4
F_{max} (kN)	13.6	12.9	13.0	13.0
A (mm²)	4500	4495	4505	4492
σ_{max} (MPa)	3.02	2.87	2.89	2.90
RH%	9.9	10.5	11	9.6
Average RH%		10.25		

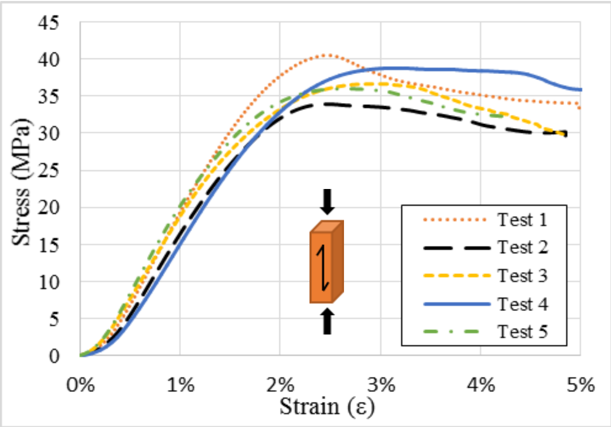


Figure 3. 3: Stress-strain diagrams of timber sample behaviour parallel to the grain.

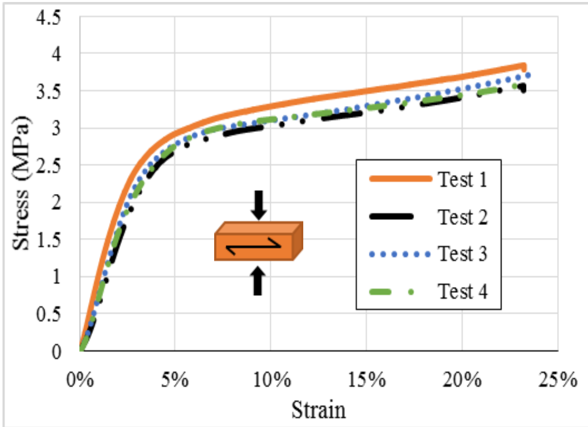


Figure 3. 4: Stress-strain diagrams of timber samples behaviour transversally to the grain.

Hemp concrete specimens

In this study, the same mix proportions were followed for both cylindrical hemp samples and timber frame walls using the same hemp shiv and binder (Prompt Natural Cement), with citric acid. This product (citric acid) is a retarder made of 100% food grade citric acid and is the most efficient setting retarder for prompt natural cement, its use is preferable for the workability of the cement laying. The ratios and quantities, in kilograms, for the manufacturing of hemp concrete for wall applications are illustrated in Table 3.5. The mix procedure for each batch of hemp concrete in this study is specified as follows: firstly, the full quantity of shiv was scattered into the mixer, and then the mixer was switched on for a couple of minutes. Secondly, half the quantity of water was then added to the mixer with one bottle of citric acid and the direction of mixing was changed periodically to ensure the batch was homogeneous. Thirdly, the full amount of cement (binder) was added to the mixer while continuing the mixing for two minutes. Finally, the second half of the water was added to the mixer gradually with another bottle of citric acid.

Table 3. 5 : Quantities in Kilograms of hemp concrete mix: proportions for one batch.

Shiv (kg)	Binder (kg)	Citric acid (kg)	Water (kg)	Ratio Water/Binder	Ratio Shiv/Binder
20	50	0.06	50	1	0.4

Cylindrical moulds of 110 mm × 220 mm were used for casting the specimens of hemp concrete and filled with five layers, each layer being 44mm thick. All specimens were kept in a specific curing room with a temperature of 20°C and a relative humidity (RH) of 55% to ensure equal drying conditions for all specimens. The specimens were tested in two groups. The first group was tested two months after casting (vertical stud hemp walls with their specimens) and the second was tested four months after casting (diagonal bracing hemp walls with their specimens). All specimens of hemp concrete were kept in an oven at a temperature of 50°C for 72 hours until reaching weight stability with a difference of (+/- 2%). Compression tests of specimens were performed using a 50 kN Zwick Roell machine (Figure 3.6).
Cyclic loading with a displacement control of 3mm/min was applied for all tested specimens. Three cycles of loading and unloading were achieved for each specimen with a strain difference of 1% between each cycle. Compressive stress was calculated as force divided by original cross-section of the cylindrical specimens of hemp concrete. Compressive strain was taken as the change in height of the hemp samples. The average compressive strength of the cylindrical specimens for vertical stud walls (after two months) and diagonal bracing walls (after four months) were 0.60 MPa and 1.07 MPa respectively, as presented in Figure 3.5 below.

It clearly appears that the compressive strength of hemp concrete specimens improved with time, which means that with time, the hydrates are connecting together and gradually create a continuous network in which the stresses are transmitted as reported in Arnaud and Gourlay study.

Table 3. 6 : Compressive strength of hemp concrete specimens 2 months after casting.

	Specimen 1	Specimen 2	Specimen 3
F_{max} (kN)	4.75	7.12	5.41
A (mm²)	9498.5	9498.5	9498.5
σ_{max} (MPa)	0.50	0.74	0.57
σ_{max} (MPa) average		0.60	

Table 3. 7 : Compressive strength of hemp concrete specimens 4 months after casting.

	Specimen 4	Specimen 5	Specimen 6
F_{max} (kN)	10.26	9.69	10.54
A (mm²)	9498.5	9498.5	9498.5
σ_{max} (MPa)	1.08	1.02	1.11
σ_{max} (MPa) average		1.07	

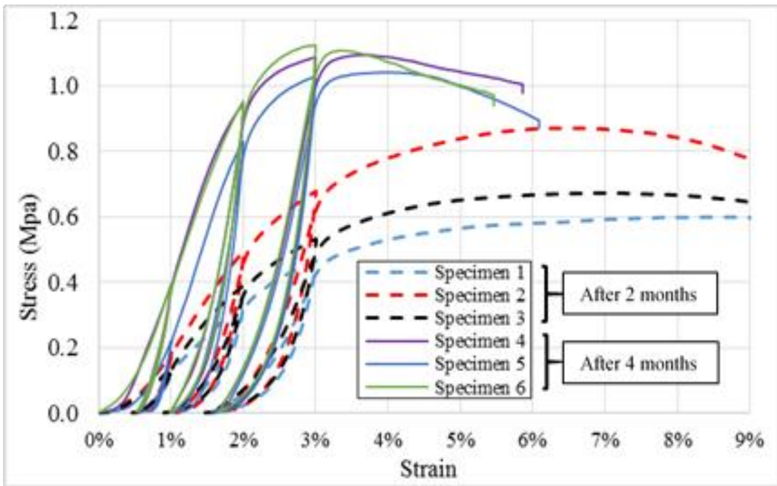


Figure 3. 5: Stress-strain behaviour of hemp concrete specimens.

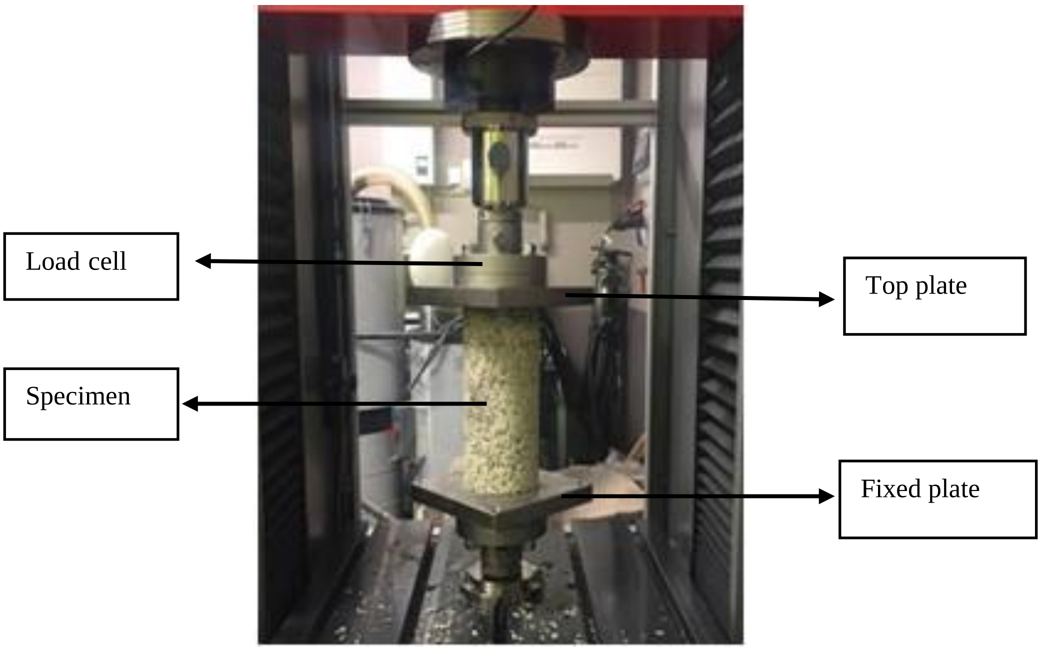


Figure 3. 6: Hemp concrete specimen in test.

3.4 Timber frame walls

Two different designs of timber frame walls were considered in this study to investigate the role of hemp concrete as infill material in lateral resistance. The first group of walls consists of three vertical studs and two rails, as shown in Figure 3.7. The second group consists of a frame reinforced by a diagonal bracing element (Figure 3.8). Eleven timber walls were tested against horizontal loads: one empty vertical stud wall, four walls of vertical stud filled with hemp concrete, three empty walls with diagonal bracing and three diagonally braced walls filled with hemp concrete. All timber walls tested had the same external dimensions: 2.50m in height by 1.25m in length by 145mm thick. The cross-sections of the studs and rails and also of the diagonal struts were 45mm by 145mm.

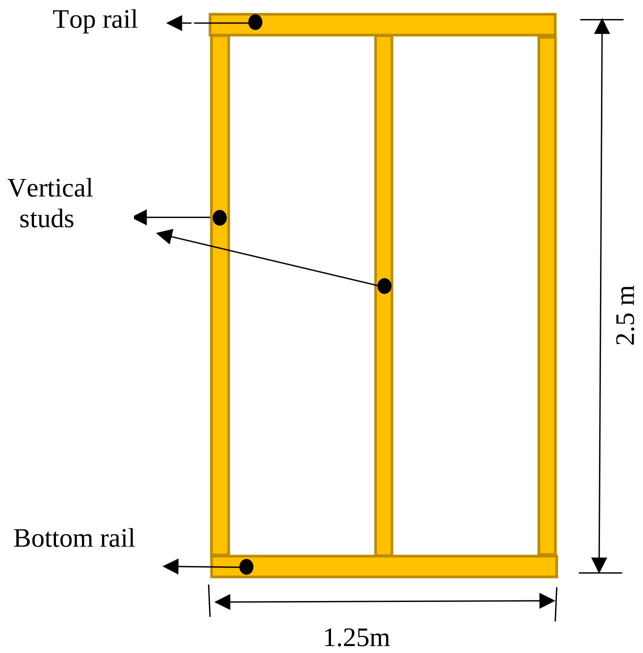


Figure 3. 7: ***Vertical stud wall details.***

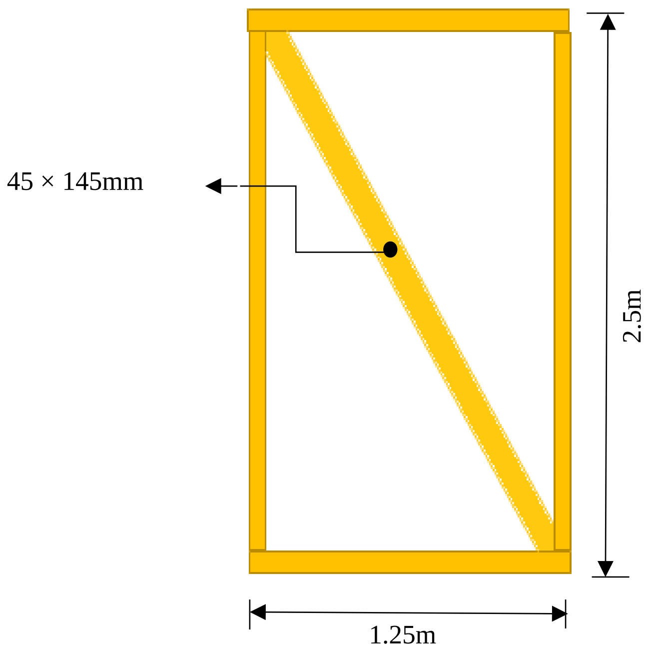


Figure 3. 8: Diagonal bracing wall details.

3.4.1 Casting of hemp concrete

Seven walls of hemp concrete were cast with the same mix proportion as mentioned before. Each wall was installed above a wooden box to keep it higher than the floor of the laboratory. The walls were fixed at the top to maintain stability during the casting.

All timber hemp walls followed the same process of casting, with two rectangular boards fixed on both sides, and the first board temporarily fixed to the frame during casting. The second board was removable for each layer of casting. Four clamps were used on each edge to avoid the buckling of the hemp concrete, as illustrated in Figure 3.9. After casting each layer, the removable rectangular board was moved to the next layer up. Each wall was cast in five continuous layers for both vertical studs and diagonal bracing walls.

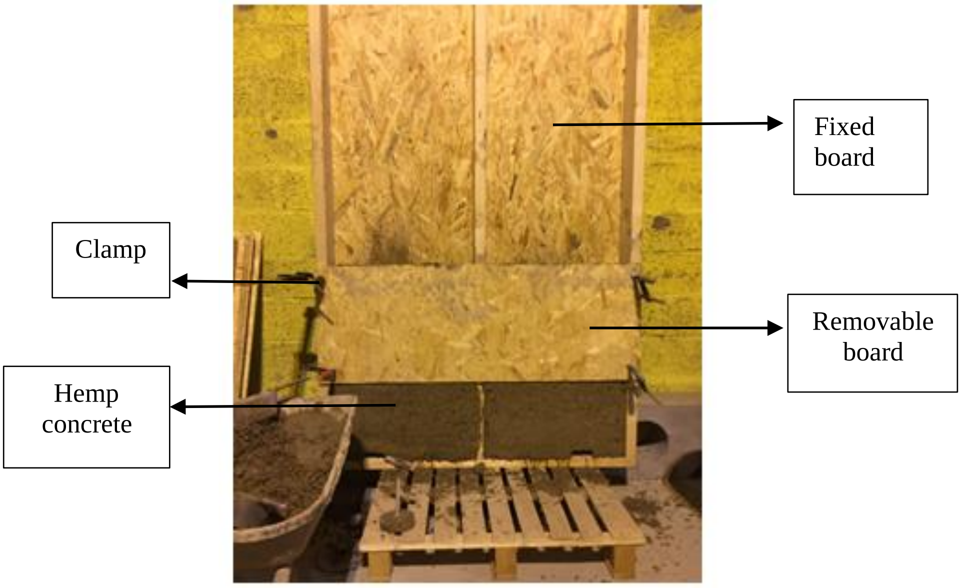


Figure 3. 9: Casting protocol of vertical stud timber wall.

3.5 Test setup

All timber walls with and without hemp concrete were tested in the same test setup to determine the lateral load-carrying capacity. Figure 3.10 presents the method by which the walls were fixed to the ground using two U-shaped steel beams. The U beams were fixed to the floor by two bolts, and the wall was securely connected by bolts to the steel plates. Two other steel beams were fixed to the top of the setup to prevent wall movement out of the plane and keep it in plane during the test. A hydraulic jack was fixed to the top corner of the wall to apply the horizontal force. Displacement and force sensors were installed at the top of the wall to measure the overall horizontal force and displacement. A lateral load was applied to all walls at a constant rate of displacement of 5mm/min with three-cycle loading (see Figure 3.11). The first cycle was a stabilising load cycle: a force was applied to the wall up to a value of approximately (0.1 F_{max}). This was followed by unloading after two minutes of force application and, after that, a 10-minute wait before starting the second cycle. The second cycle was a stiffness load cycle: a force was applied to the wall up to a value of approximately (0.4 F_{max}), followed by unloading after five minutes and waiting for 10 minutes before starting the third cycle. The third cycle was a strength test: a force was applied up to (0.4 F_{max}) and after five minutes, loading was continued until the failure point was reached.

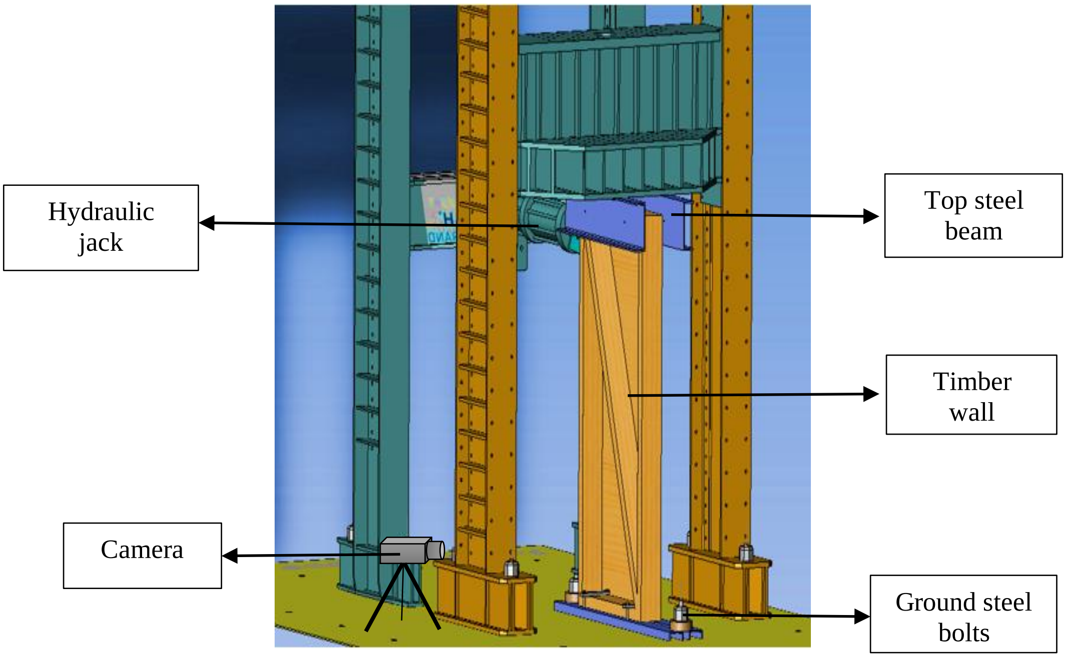


Figure 3. 10: The test setup for timber walls.

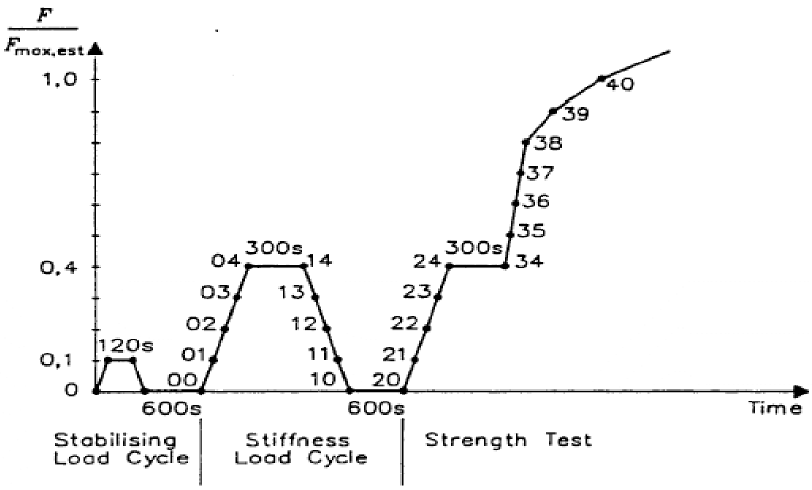


Figure 3. 11: Lateral load versus time for walls.

3.6 Measurement of kinematic fields

In order to measure local displacements and shear strains of the hemp concrete in the wall, the technique of Digital Image Correlation (DIC) was used. The purpose of this technique is to determine and track both displacement and shear strain fields from a set of images, taken every 10 seconds. A PCO 2000 camera featuring a 14-bit/2048 × 2048 pixel sensor was used and located to focus on the bottom left corner of the wall, as illustrated in Figure 3.12 below. The camera was equipped with a 105mm lens. The wall was sprayed randomly using black and white paint to obtain a speckle. The images were then processed after the tests using Ncorr software to deduce displacement and strain fields from the speckle images. The values of the parameters used for DIC analysis were: Subset size (SS) = 10 pixels, Zone of interest or Step Size (ST) = 5 pixels and Strain Window (SW) = 4 pixels, which represent standard settings for DIC. An estimate of the spatial resolution (distance between two independent points) can be calculated for DIC from these parameters by using the definition proposed in (SW - 1) × ST + SS = 25 pixels. The area covered by the camera is 0.65 × 1.0m, as illustrated in Figure 3.12 below:

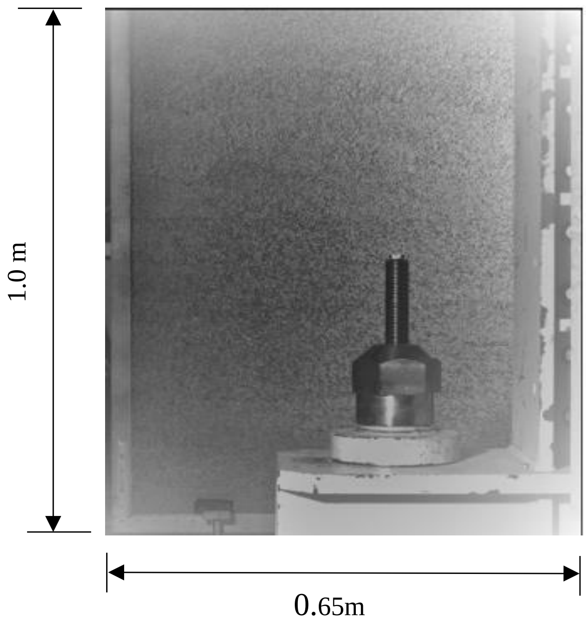


Figure 3. 12: The zone of measurements by camera in timber walls filled with hemp concrete.

3.7 Results

3.7.1 Vertical stud walls

The empty vertical stud wall is considered as a control frame for comparison with hemp walls (see Figure 3.13). The lateral load-carrying capacity of the empty vertical stud wall is presented below in Figure 14, in the form of the force-displacement graph. The maximum load-carrying capacity of the empty frame was around 0.18kN. It is obvious that the theoretical approach describes the elastic behaviour of the wall and matches the initial behaviour with experimental results as presented in Figure 3.14.

Vertical stud hemp walls (V-H) were tested with the same setup and method as illustrated in Figure 3.15. The force-displacement diagram is displayed to investigate the lateral load-carrying capacity of the walls, as in Figure 3.16. The average load-carrying capacity of the vertical stud hemp wall was around 2kN. Horizontal cracks appeared, as illustrated in Figure 3.15. A separation between the external vertical studs and the hemp concrete also appeared. An internal rotated steel bracket was fixed at the bottom of the wall to prevent the separation between the vertical stud and the bottom rail.

Figure 3. 13: Empty vertical stud frame in test.

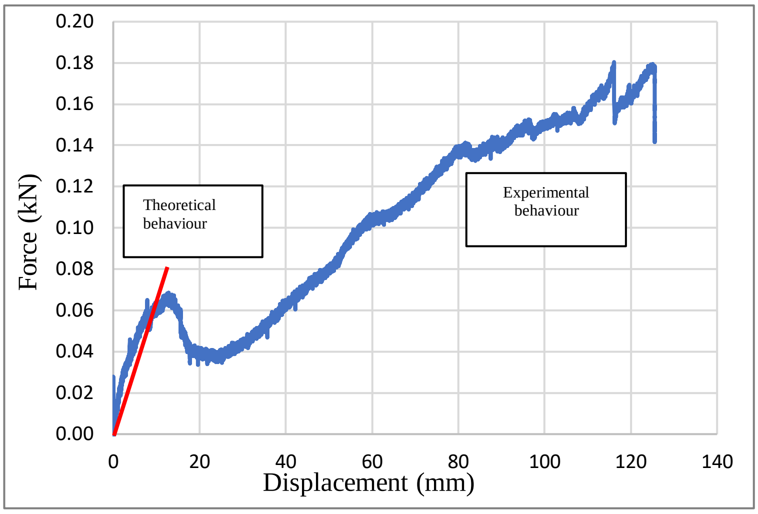


Figure 3. 14: Force-Displacement behaviour for frame only.

Figure 3. 15: Vertical stud hemp wall in test.

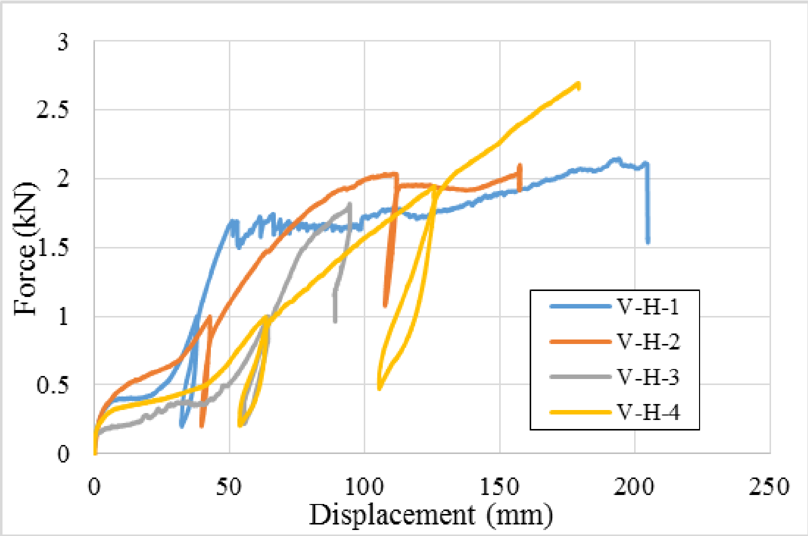


Figure 3. 16: Force-Displacement behaviour for vertical stud hemp wall.

3.7.2 Diagonal bracing walls

Three empty diagonal walls were tested against lateral loads, and the diagonal bracing struts were under compression conditions during the tests, as presented in Figure 3.17. The load-carrying of empty diagonal bracing walls is presented below in Figure 18 by force-displacement plots. The average maximum load-carrying capacity of a diagonal bracing wall was 10.78kN.

The theoretical behaviour of the diagonal bracing wall does not predict the behaviour seen in the experimental results. It is clear from the results that the experimental behaviour of the diagonal bracing wall is less rigid than predicted by the theoretical calculations. Figure 3.20 presents the lateral strength of diagonal bracing walls filled with hemp concrete (D-H) and, obviously, this shows the hemp concrete does not contribute to the lateral strength with the diagonal bracing wall and there is no significant contribution of the hemp concrete in either case to improved lateral resistance, when used as infill material in the diagonal configuration.

Figure 3. 17: Diagonal bracing walls in test.

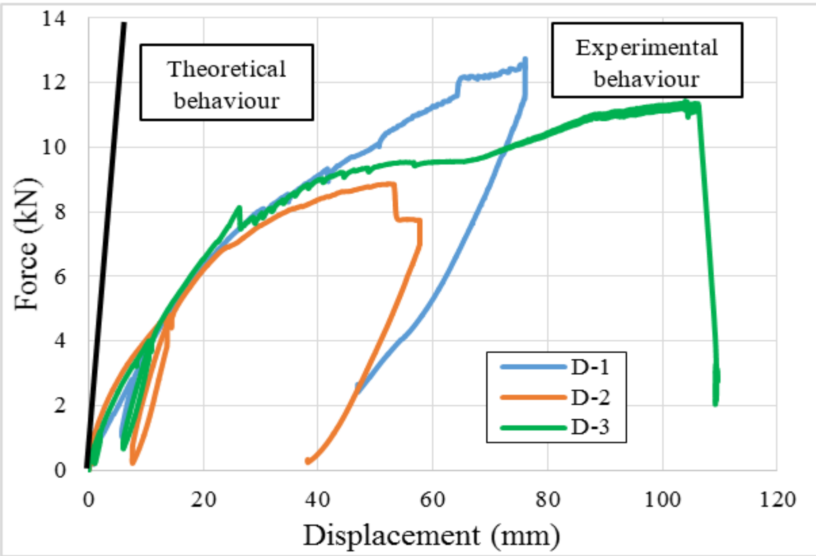


Figure 3. 18: Force-Displacement behaviour for diagonal bracing walls.

Figure 3. 19: Diagonal bracing hemp walls in test.

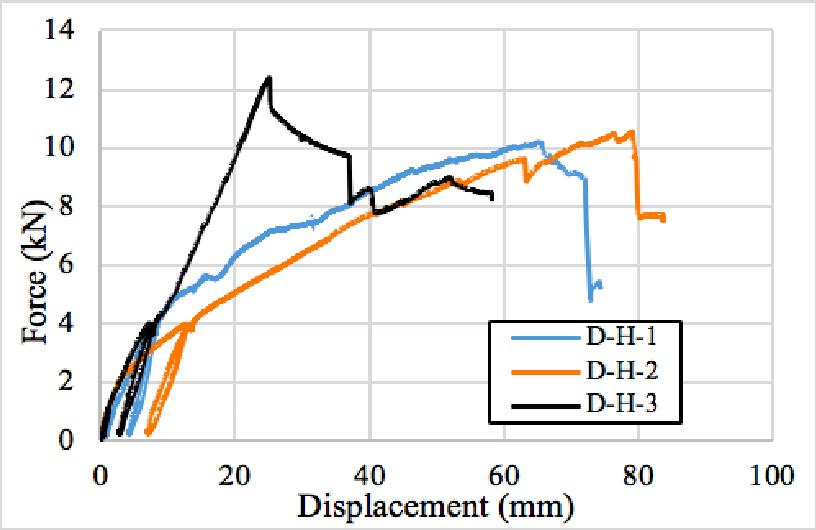


Figure 3. 20: Force-Displacement behaviour for diagonal bracing hemp walls.

3.7.3 DIC analysis

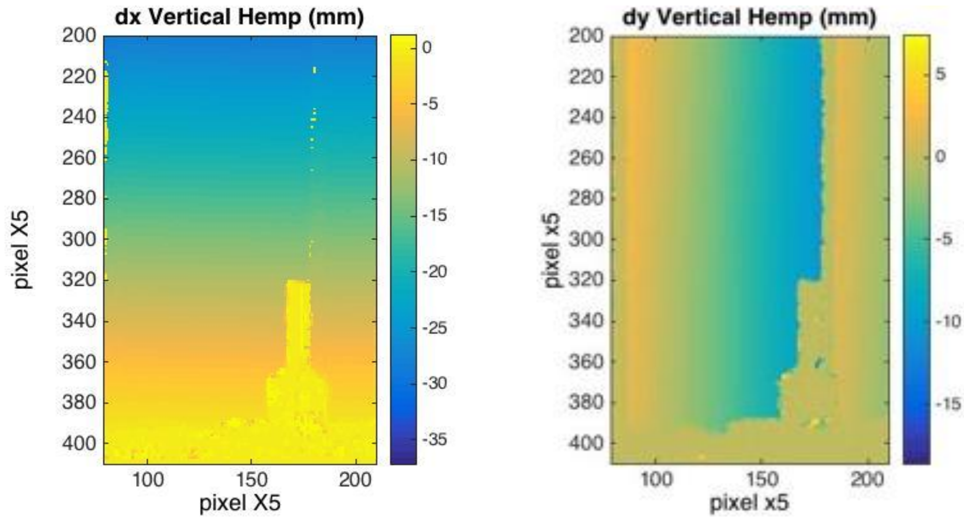
The results of the local displacement and shear-strain fields obtained with DIC for both vertical stud and diagonal bracing walls are presented in Figures 3.21 and 3.22 and 3.23. As illustrated in Figure 3.21 (a), the horizontal displacement of the wall is around zero at the bottom of the wall and gradually increases as we move towards the top.

However, the vertical displacement in Figure 3.21 (b) near the external stud is very small and increases nearer to the middle stud. Figure 3.23 (a) shows the shear-strain field of the wall and it is obvious that the higher values of shear strain are focused on the corner with average value of 0.0042 of the square zone visible in Figure 3.23 (b) above, which indicates that the hemp particles are deformed according to the external force applied on the top of the wall.

Figure 3.22 presents the displacement and shear strain fields of the diagonal bracing timber wall. As illustrated in Figure 3.22 (a), the value of horizontal displacement increases from the bottom to the top of the wall, and also the value of vertical displacement increases from the external stud to the middle area of the wall. The shear strain of hemp particles has an average value of 0.0021.

These results obtained using DIC show that the average shear strain value in the bottom left corner of the vertical stud wall is higher compared to average shear strain value of the bottom left corner of the diagonal bracing wall.

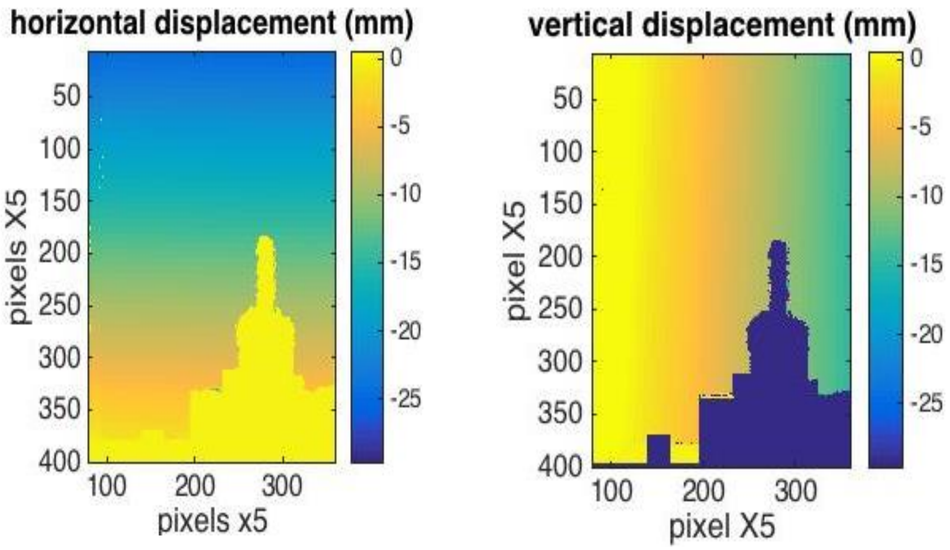
This clearly proves that the vertical stud geometry has less rigidity than the diagonal bracing. The high rigidity of the diagonal system prevents the infill material contributing to the horizontal resistance of the wall, which explains why the hemp concrete provides no increase in the strength in the diagonal bracing walls.



(a) Horizontal displacement of hemp in vertical stud timber wall.

(b) Vertical displacement of hemp in vertical stud timber wall.

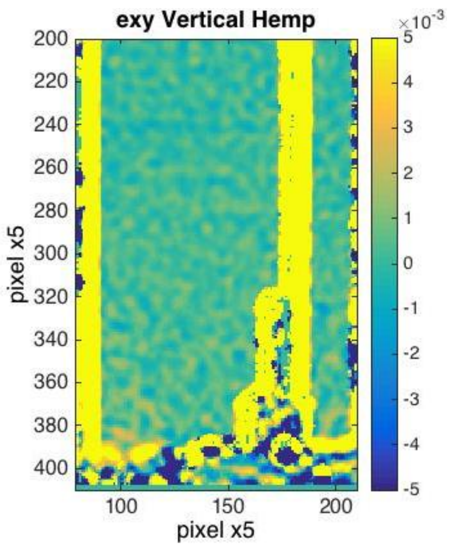
Figure 3. 21: Example of displacement fields of hemp concrete in vertical stud timber wall (V-H-2) for an overall horizontal displacement at the top of the wall equal to 50mm.

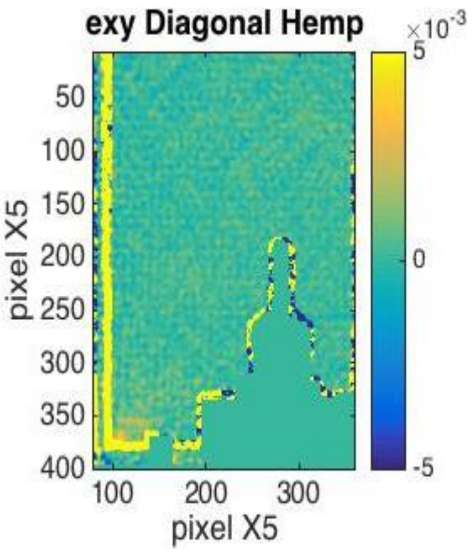


(a) Horizontal displacement of hemp in diagonal bracing timber wall.

(b) Vertical displacement of hemp in diagonal bracing timber wall.

Figure 3. 22: Example of displacement fields of hemp concrete in diagonal bracing timber wall (D-H-2) for a global horizontal displacement at the top of the wall equal to 50mm.





(a) Shear strain of hemp in vertical stud timber wall in (V-H-2).

(b) Shear strain of hemp in diagonal bracing timber wall in (D-H-2).

Figure 3. 23: Shear strain values of hemp concrete in vertical stud timber walls for an overall horizontal displacement at the top of the wall equal to 50mm.

3.8 Analysis of the experimental results

The experimental results show the advantages of hemp concrete in vertical stud wall against the applied lateral loads as shown in Figure 3.24 below. Obviously, hemp concrete makes a lesser contribution to the lateral load-carrying capacity in the vertical stud wall. The racking strength of the empty frame is around 0.18kN. In contrast, the average racking strength of vertical stud hemp walls is around 2kN, which indicates that hemp concrete increases the horizontal capacity nearly tenfold as compared with the empty frame and provides more rigidity. As shown in the representative curve of vertical stud hemp wall in Figure 3.25, the initial strength appears at the beginning of the curvature of the walls (Zone I) due to the existence of a rotated steel angle at the top of the wall to prevent separation of the vertical stud from the top rail. In Zone II, the strength of curves becomes constant with a continuous increase of displacement due to the gap between the hemp material and vertical timber studs. In Zone III, the strength increases with more rigidity compared to the first zone; this strength is due to the direct contact between the vertical studs and hemp concrete. The cracks appear as horizontal lines in the vertical stud hemp walls, as illustrated in Figure 3.15.

In the diagonal bracing walls, it is clear that the diagonal element alone increases the total rigidity of the wall. This high rigidity prevents the hemp concrete from contributing to improving the results when measured against lateral loads. The average displacement of a diagonally braced wall in linear behaviour in the experimental test is around Δ_{Exp} = 20mm. However, the theoretical average displacement is around Δ_{Theo} = 4mm (see Figure 18). The system coefficient can be calculated as: $(\Delta_{Theo}/\Delta_{Exp}) \times 100\% = 20\%$. The theoretical model can describe only 20% of the actual experimental behaviour of the diagonal timber walls. This comparison confirms that the diagonal bracing wall is complicated and its experimental behaviour shows it is not suitable for use with filling material.

Obviously, the two designs of timber walls behave differently with the same filling material. On one hand, the participation of hemp concrete provides more than ten times the strength in a vertical stud wall, compared to the empty frame. On the other hand, the contribution of hemp concrete is practically non-existent in the diagonally braced wall. Simply put, the forces did not transmit to the filling material in the diagonally braced wall due to the high rigidity of the whole system. However, in the case of vertical stud walls, which have less rigidity, the forces easily transmit to the filling material, and it has great impact on the lateral strength performance. The results obtained from the camera analysis also confirm this explanation, with the value of the shear strain in the vertical stud hemp wall being doubled, compared to the diagonal bracing. Despite the contribution of hemp concrete with vertical stud walls, this contribution is still insufficient. In fact, the dimensions of the timber wall (L/h) play the main role in making the filling material effective when loaded under shear forces.

Table 3. 8 : Racking performance of vertical stud hemp walls.

Wall no.	V-H-1	V-H-2	V-H-3	V-H-4	**Average**
Racking strength (kN)	2.14	2.03	1.80	2.60	**2.14**
Racking stiffness (kN/mm)	0.0540	0.0260	0.0430	0.0202	**0.0360**

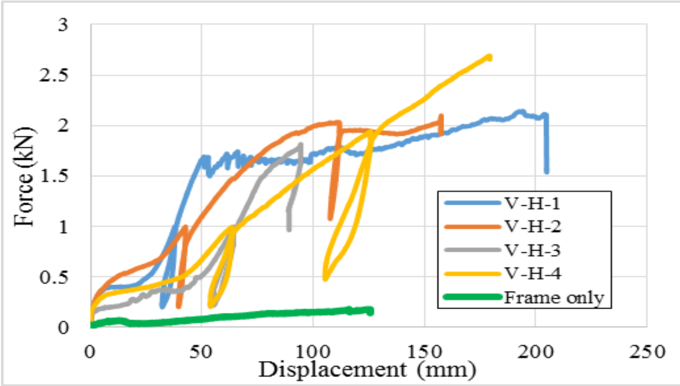


Figure 3. 24: Comparison between empty frame and vertical stud hemp walls.

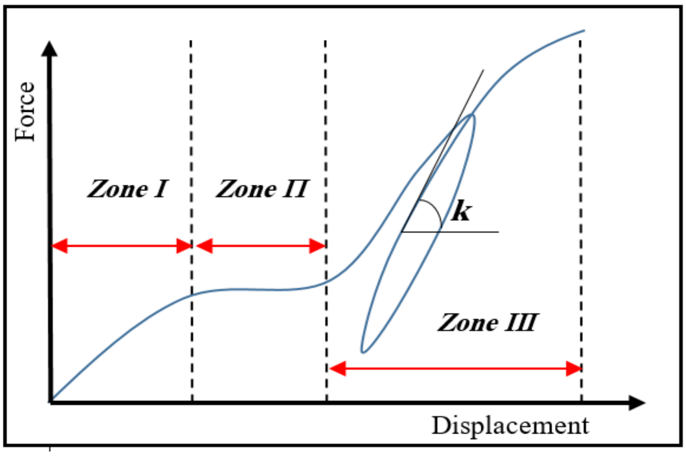


Figure 3. 25: Representative curve for the lateral load resistance of vertical stud hemp wall.

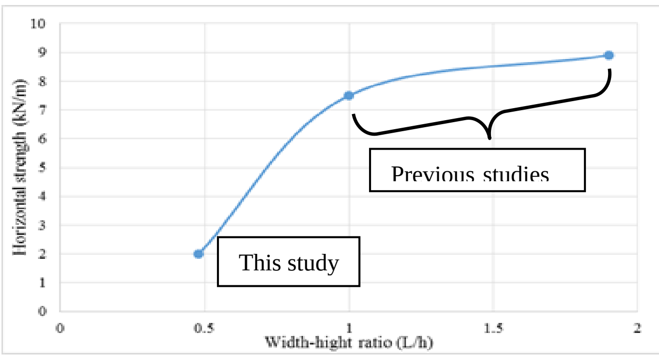


Figure 3. 26: Comparison of racking strength of timber hemp wall with different width-height ratios.

3.9 Conclusion

In this study, an experimental investigation of the racking performance of two different designs of timber walls (vertical stud and diagonal bracing) filled with hemp concrete was conducted. The hemp filling material increased the lateral resistance of vertical stud timber frame tenfold and the racking stiffness was improved. However, this filling material does not contribute to lateral strength in wall with diagonal bracing. Based on the results of this study, it is impossible to draw a generalised conclusion that hemp concrete always makes a significant contribution to strength in timber walls.

The filling material could not work mechanically against lateral loads without complete compression in the diagonal zone, which subjects the material to shear forces. This zone is related to the dimensions of the wall and is present when $L/h \geq 1$, approximately (see Figure 3.26). Within this limit, the material makes an appreciable mechanical contribution. Beyond this limit, the results are totally different. Also, the overall rigidity of the timber wall affects the contribution of hemp concrete against lateral loads. This study confirms that the contribution of hemp concrete in the lateral strength of the timber wall depends significantly on the length of the wall, since the height is fixed. Also installing hemp concrete in a very highly rigid system will prevent transmission of forces to the filling materials and thus decreases its improvement of lateral resistance measurements: the more rigid the wall is, the less resistant the hemp is.

Chapter 4 Numerical analysis of timber frame wall filled with hemp concrete

4 Numerical analysis of timber frame wall filled with hemp concrete

Article (C)

(Article under submission for Engineering Structures journal)

Simple modelling of timber frame wall filled with hemp concrete subjected to lateral loads

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Abstract

This study focuses on the numerical study of the lateral-load carrying capacity of hemp concrete as infill material in timber frame walls, investigating and highlighting the parameters that significantly affect the lateral resistance of hemp walls. For this purpose, the vertical stud timber frame walls with dimensions (2.5m height and 1.2m length) were used as the bench mark to validate the previous experimental work. A numerical study of three timber walls filled with hemp concrete has been conducted to verify the effect of wall length of the lateral load carrying capacity of hemp concrete. Three vertical stud timber frame walls with a standard height 2.5m and different lengths (1.2 m, 1.6 m and 2.4 m) were investigated using Abaqus software.

This study confirms, on the one hand, that the length of timber wall plays a significant role in the lateral load-carrying capacity of the hemp concrete. On the second hand, the contact and bonding between the hemp concrete and timber wall has a major role in affecting the lateral load carrying capacity of hemp concrete as infill material in timber frame walls.

Based on the numerical results, it was obvious that increasing the length of the wall will significantly increase the contribution of hemp concrete to lateral resistance. Good contact and bonding between hemp concrete and timber elements will also increase the lateral strength of the hemp wall.

4.1 Introduction

Timber walls are a common design component in the construction industry in many countries around the world. Prefabricated timber walls are considered as one of the most frequently used solutions for single and multi-storey buildings, with good performance in resisting the lateral loads (wind and seismic) [66]. Numerical modelling is an important tool for the analysis of this behaviour of structural elements when appropriately validated by the experimental results [67]. Timber frame walls have shown to be strong and effective when subjected to lateral loads, as testified by real case studies [68] and by experimental tests [54], [69]–[71].

Different approaches have been investigated in modelling these kinds of elements, starting from Complicated 3D modelling with accurate representing of timber to timber connection with nails to simplified 2D modelling, adopting linear and springs elements to represent timber elements and joints of timber connections. Kouris and Kappos [72] studied detailed and simplified non-linear numerical investigation of timber masonry structures. The simulation in this study was made using a plasticity model. The proposed finite element model considered orthotropic behaviour of timber elements and proper interface. However, the masonry infill was not considered in the model. The authors concluded that the proposed model can be used in a detailed displacement-focused, analytical assessment but was not intended for the analysis of full-scale buildings. Another study was performed by Santos et al [73] where the authors pre formed a 2-D detail modelling of the wall along with considering non-linear orthotropic properties of wood while the contact in timber elements was simulated by adopting interface elements. However, the infill material was not included in the proposed model but was able to be represented by the experimental tests at the laboratory showing the capacity of the timber walls.

Kouris et al [74] focused in their study on alternative modelling procedures, ranging from simple to rather complex and all models were applied to study the performance of full scale specimens of diagonally braced timber frame panels. The simple proposed model that was used in this study involved familiar beam column elements. The procedure was detailed and was found to lead to a reliable estimate slightly lower than the complex model, but still quite acceptable for all practical purposes.

In 2013 a study was carried out by Quinn and D’Ayala [75] for investigating the seismic performance of traditional Peruvian timber frame walls using 2-D beam elements and semi-rigid springs elements to the connection joint of the wall. A traditional technique consisting of a timber frame with infill of canes and mud was used in this study. The proposed finite element model in this research was only for the empty timer frame (without infill material). The proposed model was able to demonstrate an accurate performance of the timber frame before adding the infill of canes and mud material. The authors concluded that using semi-rigid springs with connection in the model with a calculated stiffness using a variation of the component method, gave a very similar results. A proposal for standard procedures to establish the seismic behaviour factor q of timber building was carried out by Ceccotti and Sandhaas in 2010 [76]. The method used in this study to simulate the timber building was combined of non-linear in the timber domain dynamic modelling of 2-D or 3-D building models. The models were spring and lumped mass models. The mechanical behaviour of the buildings was determined by springs and the springs were calibrated on reserve cyclic testing data of large-scale elements. Based on this method, a computational model was developed which covered many different geometrical setups or mass distributions.

A previous study carried out by Hicyilmaz [77] to establish whether the building type could be modelled analytically and to determine how a representative house performs when subjected to lateral loads. In this research, the timber elements and masonry infill pieces were modelled with and without nails. The results showed that it is possible to model the behaviour of traditional *dhajji dewari* buildings, this form of construction can safely withstand forces associated with earthquake in high seismic region hen built properly.

Three-dimensional finite element analysis of the Japanese traditional post and beam connection has been investigated by Hong et al in 2010 [78], using the wood foundation method which employed the concept of a beam on a nonlinear foundation. The wood foundation in the model was a three-dimensionally prescribed zone surrounding a nail shank in order to address the intricate wood crushing behaviour induced by nail slip. Materials were modelled based on the transversely isotropic plasticity on the ANSYS software. Finite element analysis with solid elements was considered in this study as the best approach to investigate the behaviour of connections under loads. Branco et al [79] proposed a model to study the behaviour of timber roof connections by using nonlinear moment rotation laws in order to represent the cyclic response of the timber joint.

The authors concluded that typical joints have a significant moment-resisting capacity and, therefore, they cannot be represented by common constraint models like perfect hinges. This study presented a model for interpreting the cyclic, semi-rigid behaviour of joints in timber structure, along the guidelines of the European Codes. The strength prediction of rounded dovetail connections has been studied also by Tannert et al [80].

Munoz and Pipet in 2009 investigated experimentally the contribution of hemp concrete [3] installed by shotcrete to resist the horizontal loads in timber panel. The tested walls were with dimension of 4.56 m in length and 2.48 m in height. A comparison was carried out between empty panel with bracing strut only and other with the same panel filled with hemp concrete material (without strut member). The thickness of hemp concrete was 28 cm. This study concluded that hemp concrete had contributed in the bracing strut panel and also improved the mechanical behaviour. In 2014 another experimental study was investigated by Gross and Walker [62] in order to determine the lateral strength of hemp concrete as infill material in a timber frame wall. The length of all tested walls was around 3 m with a height of 1.6 m. the authors in this research concluded that the low density of hemp lime increased the racking resistance of the timber studwork frame and also the racking stiffness. Also, using permanent shuttering acting as a sheathing board significantly improved the lateral load carrying capacity of the timber wall filled with hemp concrete.

S. Hans et al in 2017 studied the contribution of a sprayed hemp concrete in the mechanical behaviour of building with wood structures. The length of all tested walls was around 3 m with a height of 1.6 m. The geometry of the timber walls was a combination of vertical studs and diagonal bracing. The results of this study confirmed that hemp concrete provided an enhancement in lateral strength of timber wall. S. Hans studied the contribution of sprayed hemp concrete in timber walls of 3 m height and 1.6 m length. The results concluded the significant enhancement of hemp concrete in the bracing timber walls in terms of strength and rigidity. Obviously, several studies have been carried out on the lateral load carrying capacity of timber walls experimentally and numerically. To date, there have been limited studies on the lateral load carrying capacity of hemp concrete, especially as regards numerical analysis. As matters currently stand in relation to hemp materials, it is obvious that there is a lack of knowledge and a need for further studies in racking performance of hemp concrete, particularly in timber frame walls.

For this purpose, this present study investigates numerically the lateral load carrying capacity of hemp concrete as infill material in timber frame walls using the Finite element method, using

Abaqus software. This study highlights the parameters that could play a main role in the lateral strength of hemp concrete. The main objective of the presented study is to investigate numerically , on the one hand, the effect of the length of wall on the lateral strength of hemp concrete. On the other hand, it investigates the effect of contact between hemp concrete and timber frame on the racking strength of hemp materials. Two different models were proposed in this study to investigate the lateral strength of walls, both complete numerical analysis and then a simplified model.

As matters currently stand in relation to hemp concrete, it is obvious that there is a lack of knowledge and a need for further studies in numerical analysis of lateral load carrying capacity of hemp concrete as infill material in timber frame walls. For this purpose, this study highlights the parameters that could play a major role in the racking performance of hemp concrete in timber frame walls. The main aim of the presented study is investigate numerically the lateral strength of hemp concrete as infill material in different wall lengths, and also the effect of bonding between hemp material and timber studs on the global lateral strength of hemp concrete.

4.2 Geometry and Material properties

A vertical stud timber frame wall, designed to full scale, was considered in this study in order to validate the experimental study of empty and filled timber walls. The frame was composed of three vertical studs with two rails. The total dimension of the timber wall was 2.5m height and 1.25 m length as illustrated in the Figure 4.1 below. The cross sectional area of the studs and rails were 45 mm by 145 mm. The material properties of elastic behaviour of wood were defined (according to EC5) by the Young's modulus of 11000 MPa and Poisson's ratio 0.2 with Isotropic assumption. Also the nails' parameters were defined and represented in this model with isotropic behaviour, as per the following. According the supplier company information, nail diameter was 2.8 mm, head diameter was 6.5 mm, nail length was 90 mm, characteristic withdrawal parameter ($f_{ax,k}$) was 17.49N/mm2, characteristic yield moment ($M_{y,k}$) was 3235 N.mm and characteristic tensile capacity ($f_{tens,k}$) was 4.19 KN. The hinges in each connection timber to timber were considered as non-linear behaviour with the possibility of rotation. The properties of hinges were assigned according to the shear and the rotational stiffness respectively. The hemp concrete material also defined with a value of 37 MPa of modulus of elasticity and 0.1 Poisson's ratio. Linear and non-linear analysis were both used in order to define the capacity of timber frame wall.

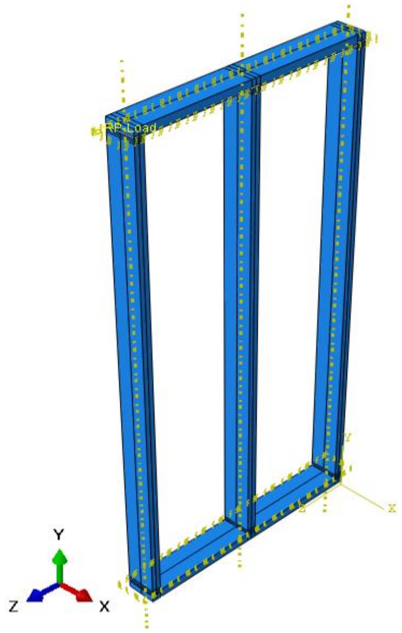

Figure 4. 1: Model geometry of the vertical stud timber wall.

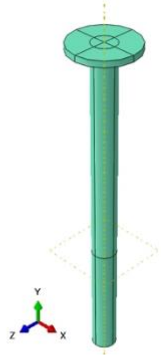

Figure 4. 2: The represented nail at the timber joints between rails and columns.

4.3 Loading and boundary conditions

The exact conditions followed during the experimental procedure in chapter 3 are simulated numerically. Thus, the applied loading condition is the application of a horizontal displacement at the top beam of the main timber frame equal to 100 mm for empty timber frame and 200 mm for timber frames filled with hemp concrete. This horizontal displacement represented a concentrated lateral load. The bottom joints of the timber frame were simulated as a hinge support and were restrained in vertical and horizontal directions. Moreover, another restraint was simulated at the top side of the wall (top rail). This part was restrained in the X-direction of movement in order to prevent the wall from moving out from the in-plane test. This simulation represented the two steel beams that fixed at the both edges of the top rail of the timber frame wall.

4.4 Contact interaction

General contact interaction using Abaqus can define contact between many or all regions of the model with a single interaction. In this simulation, the column was assumed as the master surface and the beam as slave surface in each timber-to-timber joint with a degree of smoothing for the master surface of 0.2. The discretization method considered in this analysis was Surface-to-surface. The normal behaviour of contact properties for timber to timber was defied as hard contact. The tangential behaviour was defined by the value of friction coefficient 0.8.

In case of nail-timber contact interaction, the nail surface was considered as the master surface and the timber part was consider as the slave surface with a degree of smoothing for master surface of 0.2. The discretization method used in this analysis was surface-to-surface standard. The normal behaviour of contact properties for nail to timber was defined as hard contact and the tangential behaviour was defined by the value of friction coefficient 0.5.
The joint for the empty timber frame wall was simulated as the real case in the laboratory tests. Each joint between column and beam considered of three ring nails with full rounded head as illustrated in Figure 4.3 below. The contact surface between the rounded surface of timber in each hole and the rounded surface of fastener was simulated as a general standard contact considering the fastener as the master surface and the wooden part as the slave one.

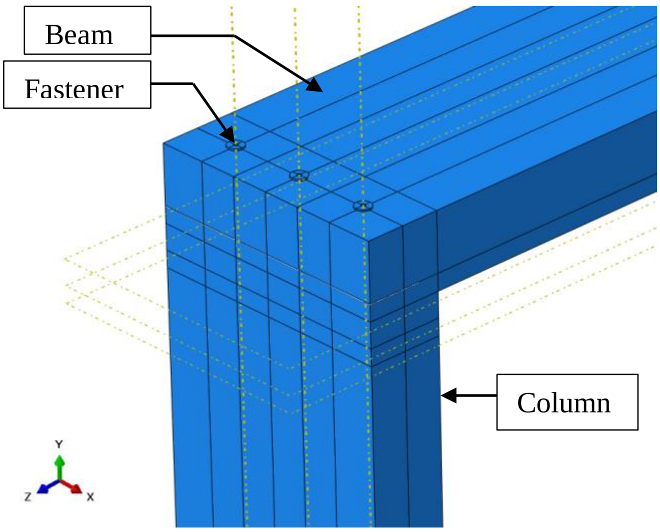

Figure 4. 3: Simulated timber joint with represented nails.

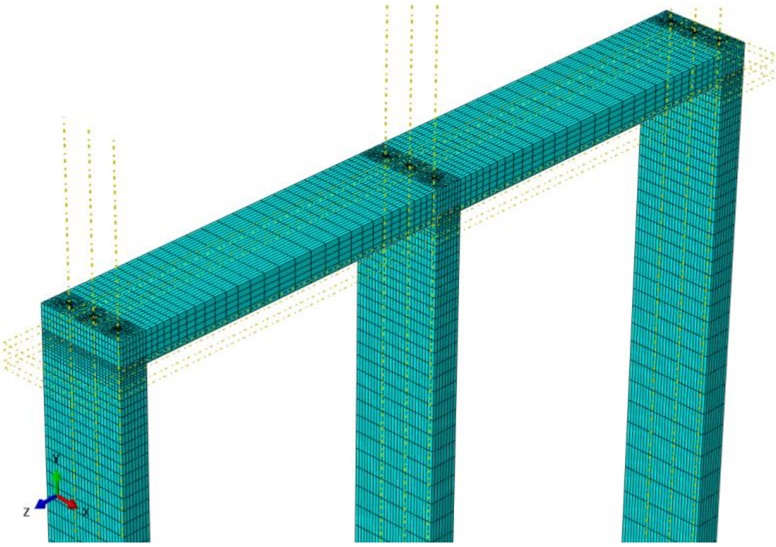

Figure 4. 4: Mesh of Finite Element Model for timber frame wall.

4.5 Complete numerical analysis of empty timber frame wall

Linear and nonlinear analysis were used in this model in order to define the capacity of the timber frame wall. Linear static analysis was checked on the model in terms of geometry, materials and loading. Nonlinear was used in order to check the capacity of the timber connections considered as plastic hinges. Abaqus 2017 software was used in an effort to validate the results from the experimental studies. The analysis was performed by means of a wall complete model where all nails at each joint were modelled by representative nails, these nails connected to the timber parts by contact surfaces. The timber frame wall was loaded with a horizontal displacement around 120 cm at the top of the wall.

The deformed shapes were illustrated below in Figures 4.5 and 4.6 due to the applied lateral load. Figure 4.5 below shows the displacement in z-direction (the same direction of the applied lateral load). The maximum horizontal displacement was at the top of the wall with a value of 1.2 m and it was also obvious that the horizontal displacement at the bottom of the wall was around zero. For the vertical displacement (y-direction) as shown in Figure 4.6 the global behaviour of the timber frame wall was taking a position of rotation as the left bottom side of the frame is going up and the right bottom side as going down.

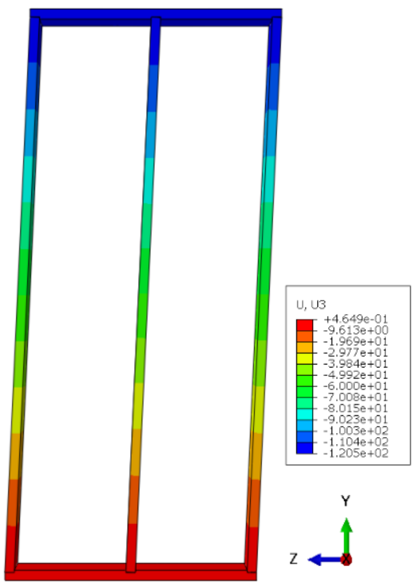

Figure 4. 5: The deformed shape showing the displacement in z-direction.

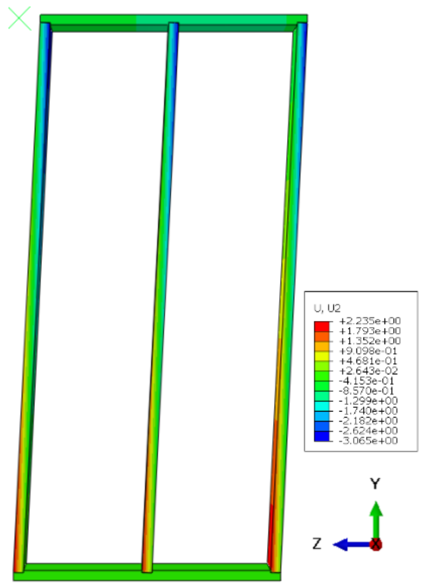

Figure 4. 6: The deformed shape showing the displacement in y-direction.

4.6 Validation of empty timber frame wall model

After checking the complete numerical model for the empty timber frame wall, a comparison with experimental tests on full scale wall results was developed. Figure 4.7 below illustrates that the lateral load carrying capacity of the timber frame wall was predicted by the complete numerical model and compared with load vs displacement curve. The results show a considerably good coincidence between the proposed numerical model and experimental results. According to the comparison below it is obvious that the preliminary stage of strength of the experimental result was slightly less than the numerical model result at a displacement of 45 mm in the elastic zone of the wall. This difference is due to the transport of the timber frame at the laboratory which decreased the rigidity of the joint, especially in that the frame is empty, which resulted in the joint being more affected with the movement. Two top steel beams were fixed on both sides of the timber wall at the laboratory before starting the test. The main objective of using these two beams was to keep the tested wall in-plane and prevent it from moving out of plane. These two beams were fixed at the set up and space of 2 cm were kept between the wall and the beam. During the test, the wall touched the steel beam from one side which created a slight friction between the top wooden rail and the steel beam. This friction added a small strength to the results and explain the difference between the experimental and the numerical results at the zone beyond 45 mm of global displacement.

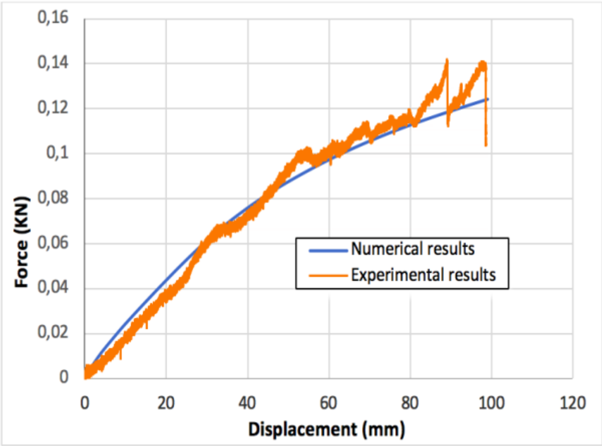

Figure 4. 7: Comparison between the experimental and the numerical results.

Figure 4. 8: Empty timber frame in test.

4.7 Simple numerical analysis of timber frame filled with hemp

A vertical stud timber frame wall of length 1.2 m and height 2.5 m at full scale was considered in this study in order to validate the experimental study of timber frame wall filled with hemp concrete. The timber frame consisted of three vertical studs with two rails as illustrated in Figure 4.9 below. An isotropic case was assumed for the elastic wood properties with modulus of elasticity 11000 MPa and a Poisson's ratio of 0.2. The yield stress and plastic strain of timber were taken from the experimental tests of timber samples and were considered in the numerical analysis.

Following the same method, defining the hemp material was conducted with the elasticity modulus and Poison's ratio for the elastic case, as well as the plastic strain and yield stress for the plastic behaviour. The hinges in each connection, timber-to-timber were considered as non-linear behaviour with rotation possibility as noted for the empty timber frame wall.

The properties of hinges were assigned according to the shear and the rotational stiffness respectively. Elasto-plastic analysis was used in this model in order to define the lateral load carrying capacity of the timber frame wall filled with hemp concrete.

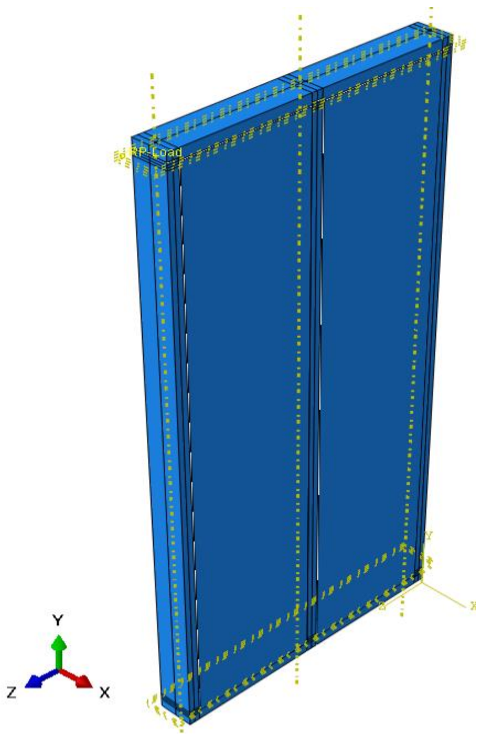

Figure 4. 9: Model geometry of the vertical stud timber wall filled with hemp concrete.

4.7.1 Calibration of the model

As the simulation of timber frame wall filled with hemp concrete is complicated, especially with infill material, a calibration has been done in this section to identify the exact parameters that could affect the final results of the load carrying capacity of the whole timber wall filled with hemp concrete. The calibration included the top and bottom boundary conditions and also the type of analysis (linear and non-linear). This calibration was made only on the timber frame wall filled with hemp concrete with two panels and the same conditions were used on the other timber frame wall with three and four panels.

- Linear analysis with fixed boundary condition at the bottom of the wall

A simple model of the timber frame wall filled with hemp concrete has been made as a first step of the calibration of the model. A linear analysis was applied in the Abaqus software and the boundary condition was defined as a fixed support which prevented the movement in the three directions. The mechanical properties of the wood material and hemp concrete material were defined in the software as mentioned in the previous section. Figure 4.10 below illustrate the global lateral load of timber frame wall with filled with hemp concrete in linear analysis with a complete fix to the foundation along the total length of the bottom timber beam of the frame.

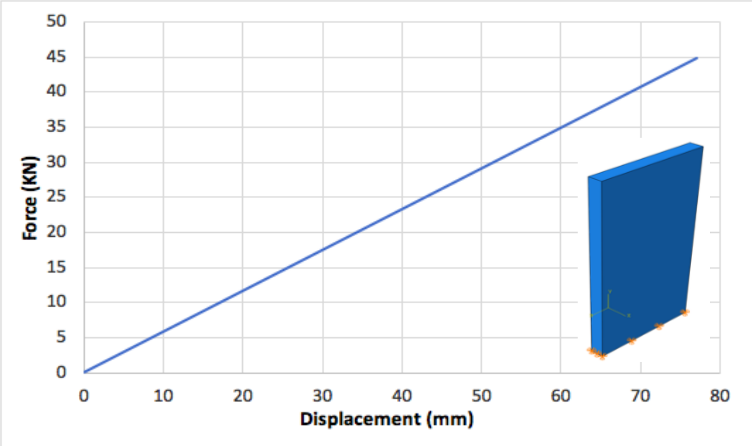

Figure 4. 10: Lateral resistance of wall in linear behaviour and fix support foundation.

It is obvious from the results in Figure 4.10 that the lateral load carrying capacity of the timber wall was much more than the experimental results (around 2.5 KN) with high rigidity. The extra resistance and rigidity were related to the secure fix at the bottom of the wall which added more strength to the total load carrying capacity of the global behaviour. Also, in this model, the top part of the wall was free which caused the wall to move out of the plane and added extra strength to the total performance of the timber frame. In contrast, the top part of the timber wall was fixed with two steel beams from both sides to prevent the movement of the wall in the third direction for measuring exactly the in-plane strength of the hemp wall. The total behaviour of the wall was far removed from the real findings, when compared to the experimental tests, so this case has been ruled out of the results analysis.

- Linear analysis with simple support boundary design at the bottom of the wall

A second linear, simple model of the timber hemp concrete wall has been made in this section as a second example of calibration. The type of the analysis was also linear and the boundary condition of the bottom part of the wall was designed as simply support on both sides.

The boundary fixing was removed along the bottom beam of the timber frame. Figure 4.11 below presents the lateral load carrying capacity of the timber frame wall filled with hemp concrete using the simple support boundary condition and linear behaviour. It was clear from the results that the total strength and rigidity of the hemp wall decreased due to changing the boundary condition from total fixation to the simple support. This will confirm that using the simple support is closer to the real case results, comparing to the experimental tests.

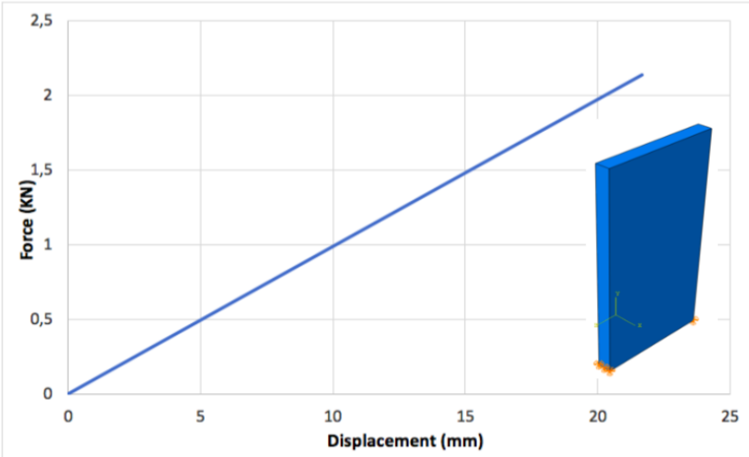

Figure 4. 11: Lateral resistance of wall in linear behaviour and simply support foundation.

- Elasto-plastic analysis-simply support model

In this proposed model, the material properties for both wood and hemp concrete in the plastic stage were defined in the Abaqus software. These results used in the program were extracted from the laboratory tests as mentioned in previous chapters. Lateral load carrying capacity of this model for the same wall dimension was formulated from Elasto-plastic analysis in Figure 4.12 below. As shown in Figure 4.12, the lateral strength of the timber wall filled with hemp concrete was around 2.7 kN at the point of 75 mm total horizontal displacement. However, this model was closer to the experimental results compared with the previous, it still showed higher rigidity and strength.

According to the numerical analysis, the global movement of the timber wall was in three directions (x,y and z). The movement in the third direction (out of the plane) play a main role in increasing the strength and rigidity of the total strength of the wall. Indeed, this extra strength was not taken into account for investigating the in-plane lateral load carrying capacity of timber wall filled with hemp concrete. For this purpose, the wall at the experimental tests was preventing from moving outside the plane by using top two steel beams on both sides of the top timber beam of the frame. To simulate the same case as the laboratory test, another proposed model was studied in the next section with the same parameters in addition to a boundary condition at the top of timber wall in order to keep the movement in the same direction as the total lateral load.

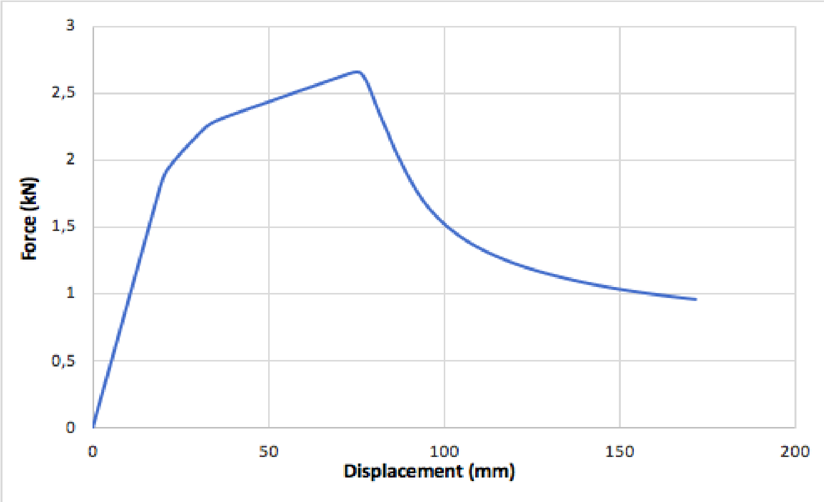

Figure 4. 12: Elasto-plastic behaviour of timber wall filled with hemp.

- Elasto-plastic analysis-simple support model with top boundary conditions

Elasto-plastic analysis for timber frame wall filled with hemp concrete was proposed in this section, taking into account the simple support boundary condition at the base of the wall and also top boundary condition to prevent the wall's movement in the x-axis during the test.
Figure 4.13 below illustrates the lateral load carrying capacity of the timber frame wall filled with hemp concrete considering the elasto-plastic analysis with two cases of boundary conditions. The first is simple support at the base of the wall and the second were hinges placed along both sides of the top timber beam in order to keep the horizontal movement of the timber wall in in-plane direction parallel to the main lateral force.

Based on the numerical results below, the top boundary conditions changed the global plastic behaviour of the wall compared to the previous case (without top boundary condition). In the case of this model, the plastic behaviour of the timber wall was closer to the experimental results. In terms of the elastic zone, in both case the behaviour was approximately the same with and without top boundary conditions.

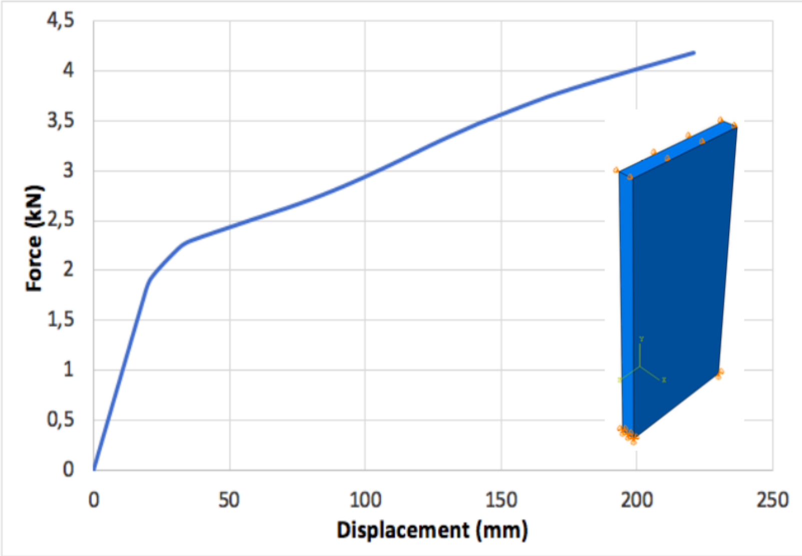

Figure 4. 13: Elasto-plastic behaviour of hemp wall with top boundary condition.

4.7.2 Comparison between the numerical and experimental results

According to the previous calibration, it was clear that the elasto-plastic model with top and bottom boundary condition was the most suitable one and closer to the experimental tests set up. In Figure 4.14 a comparison between the numerical and experimental results was plotted below. As mentioned in chapter 3, the experimental results consisted of three zones: the first one was related to the steel angle fixed on the timber joint; second was related to the gap between the hemp material and the timber stud; and the third was the real contribution of the hemp concrete. For this reason, the numerical curve was shifted to the right in order to compare the elastic linear behaviour between two cases. This distance was around 27 mm.

Considering the first wall (V-H-1) as a benchmark for the comparison, the elastic behaviour of the numerical model matched the behaviour of the wall in the laboratory. However, the plastic region was significantly beyond the 50 mm of the global lateral displacement. The reason behind the difference between the proposed model and the experimental tests is simple, the gap between the hemp material and the timber stud was playing a main role in decreasing the total lateral load carrying capacity of the wall during the experimental tests. In contrast, this gap in the proposed model did not exist and the two materials (timber and hemp) were assumed to behave as one piece. This assumption was factored into the proposed model on the one hand, to simplify the analysis and, on the other hand, studying the contact between two materials at large scale is a complicated analysis.

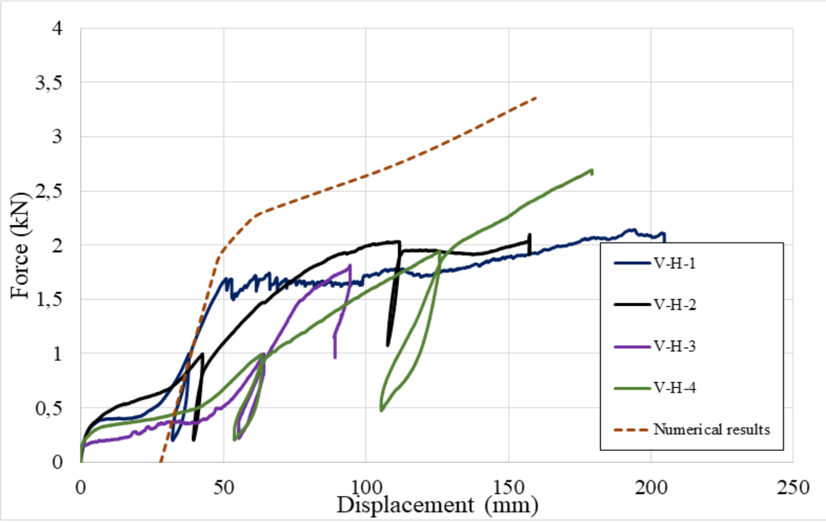

Figure 4. 14: Comparison between the experimental and numerical results.

4.7.3 Numerical analysis of timber frame walls more than two panels

A numerical study was conducted for the same geometry of the timber frame wall with different length to investigate the effect of the wall length on the lateral load-carrying capacity of hemp concrete. For this purpose, two different lengths of timber frame wall (1.8 m and 2.4 m) were considered in this study, just as the length of 1.2 m was investigated in the previous section. The first wall geometry consisted of three panels with height 2.5 m and length 1.8 m (length of each panel equal to 60 cm). The second wall geometry was consisting of four panels with height 2.5 m and length 2.4 m. The height of all walls was constant as the wall length is the parameter that is examined in this study.

- Timber frame wall of three panels with length 1.8 m.

Numerical analysis was carried out for the timber frame wall of three panels with height 2.5 m and length 1.8 m. The same conditions as the previous model were considered in order to determine the lateral load carrying capacity of the hemp concrete subjected to lateral loads and also to study the effect of wall length on the horizontal strength of the wall. Figure 4.15 below illustrates the force-displacement curve of three panels filled with hemp concrete. The results below show that the total lateral strength of hemp concrete in the elastic zone has been improved from 2.3 kN to 6.2 kN, due to the increase of the wall length from 1.2 m to 1.8 m respectively.

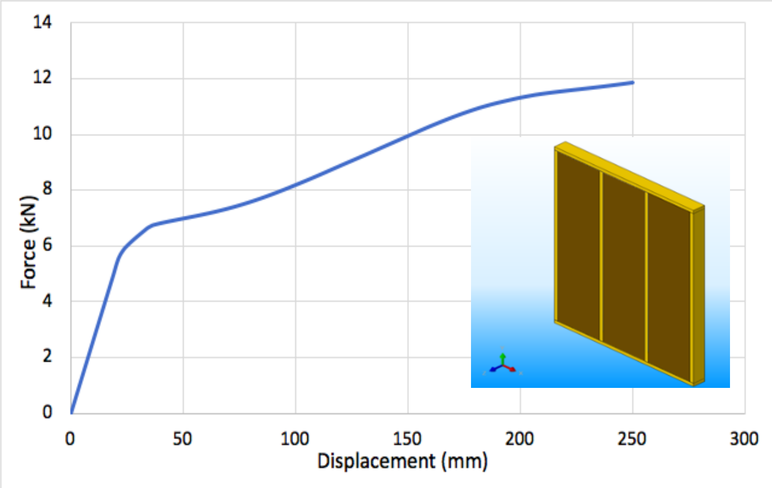

Figure 4. 15: Lateral strength of hemp wall three panels with length 1.8 m.

- Timber frame wall of four panels with length 2.4 m.

A timber frame wall of four panels filled with hemp concrete (length 2.4 m) was analysed with the same method as the previous walls. Figure 4.16 below presents the lateral behaviour of hemp concrete as infill material in the timber frame with four panels. The results below show that increasing the length of the wall to 2.4 m significantly improved the rigidity and the lateral load carrying capacity of hemp concrete as infill material. The lateral strength of the hemp wall was around 8.1 kN in the elastic zone of the global performance of the wall. The total resistance in the plastic zone was compared to the timber wall of 1.2 m length.

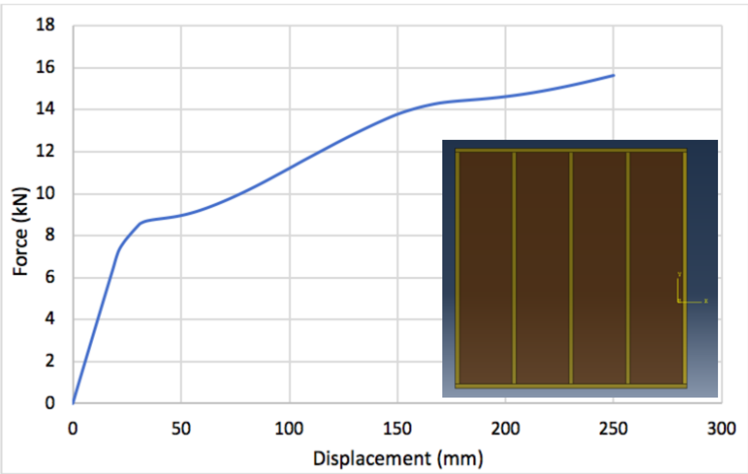

Figure 4. 16: Lateral strength of hemp wall four panels with length 2.4 m.

The global lateral and vertical displacements of the timber frame wall filled with hemp concrete are illustrated in Figure 4.17 and Figure 4.18 below.

It is obvious that the lateral displacement is increasing from the bottom until the maximum value at top of the wall. For the vertical displacement, it is noticeable that the left side of the wall (under the applied force) is raising up and the right side is going down. In other words, the wall rotates due to the applied lateral load at the top of the wall.

Figure 4.19 and Figure 4.20 show the stress distribution of the hemp wall. Concentrated stresses are located at the corners of the wall (joints).

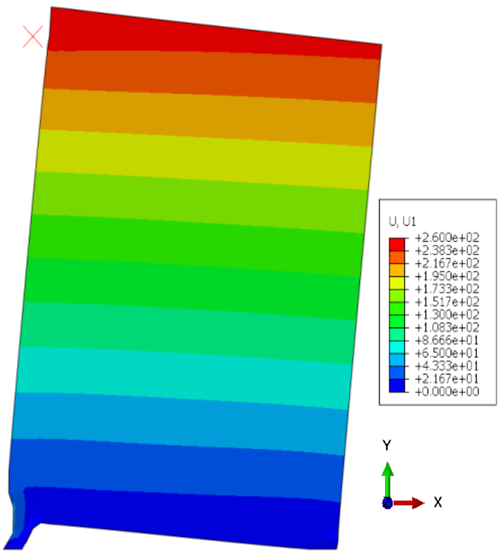

Figure 4. 17: Lateral displacement of hemp wall with four panels.

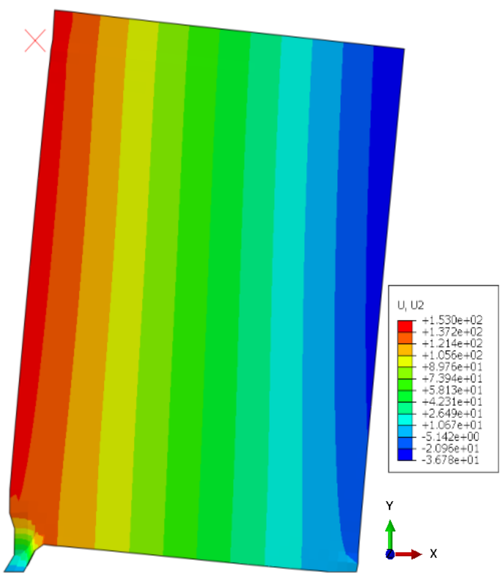

Figure 4. 18: Vertical displacement of hemp wall with four panels.

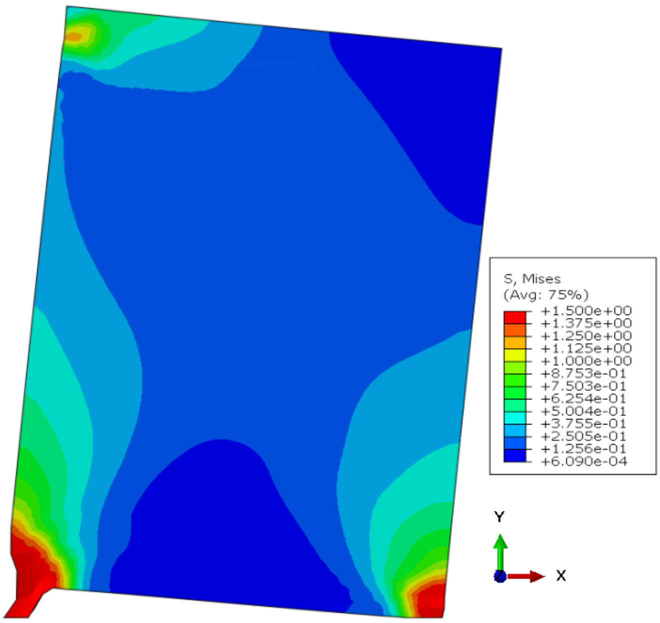

Figure 4. 19: Stresses distribution in hemp wall with four panels.

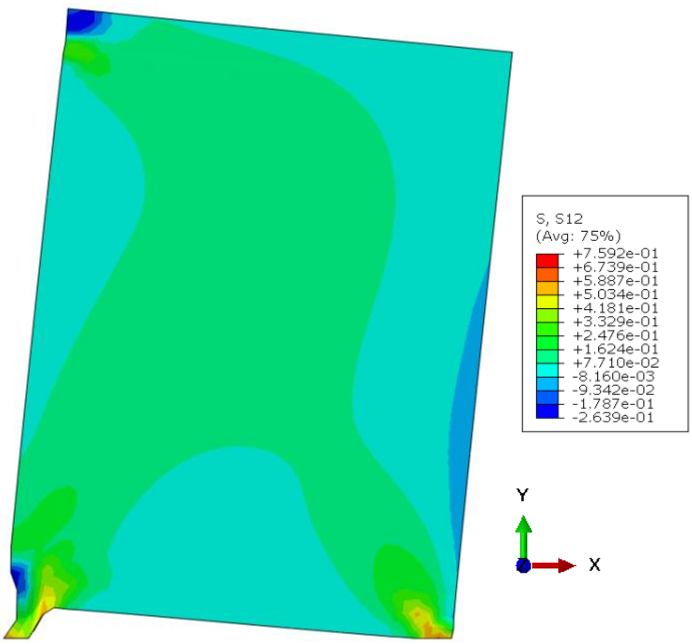

Figure 4. 20: Stresses distribution in x-y directions in hemp wall with four panels.

4.8 Analysis of the numerical results

The numerical results show the contribution of hemp concrete in vertical stud timber wall subjected to lateral loads as shown in figure 4.21 below. Obviously, hemp concrete participates as infill material in the lateral load carrying capacity of vertical stud wall. The in-plane strength of vertical stud hemp wall consists of two panels is around 2.1-kN in the elastic zone. As shown in the comparison between results for different wall lengths, the lateral strength of hemp concrete improves with the increasing the wall length. The total horizontal resistances (elastic zone) of wall length 1.2 m, 1.8 m and 2.4 m are about 2.1 kN, 6.2 kN and 9 kN respectively.
On the one hand, the contribution of hemp concrete provides more than three times the strength in the wall of three panels, compared to the two-panels wall. On the other hand, the contribution of hemp concrete in lateral strength in four panels is not as much as the improvement in the three panels wall. The results obtained from Abaqus software confirm that increasing the wall length will increase the capacity for transmitting the forces to the filling material. Figure 4.22 below presents the effect of the number of panels on the lateral strength of the timber wall filled with hemp concrete in the elastic zone. In fact, the length of the timber wall significantly enhances the hemp concrete contribution as infill material and also plays a main role in transmitting the hemp concrete from the insufficient zone (two panels) to an effective material when subjected to lateral loads.

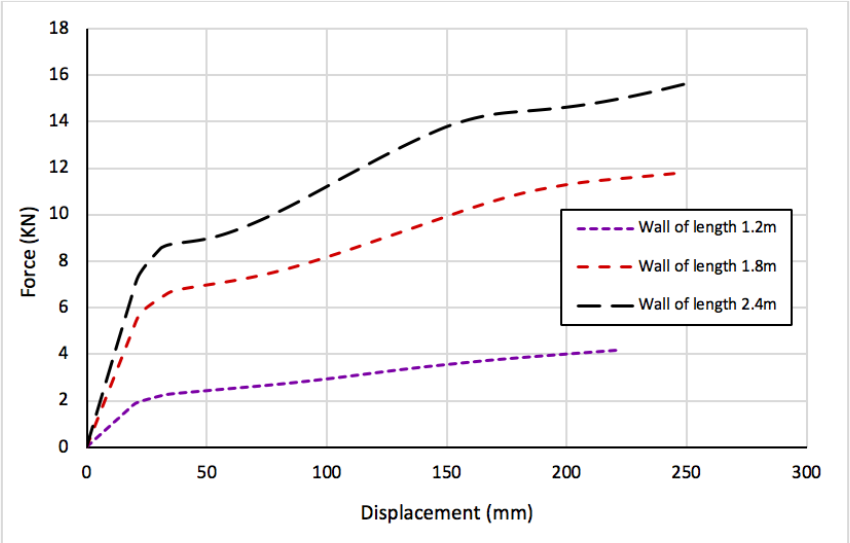

Figure 4. 21: Comparison between numerical results with different wall lengths.

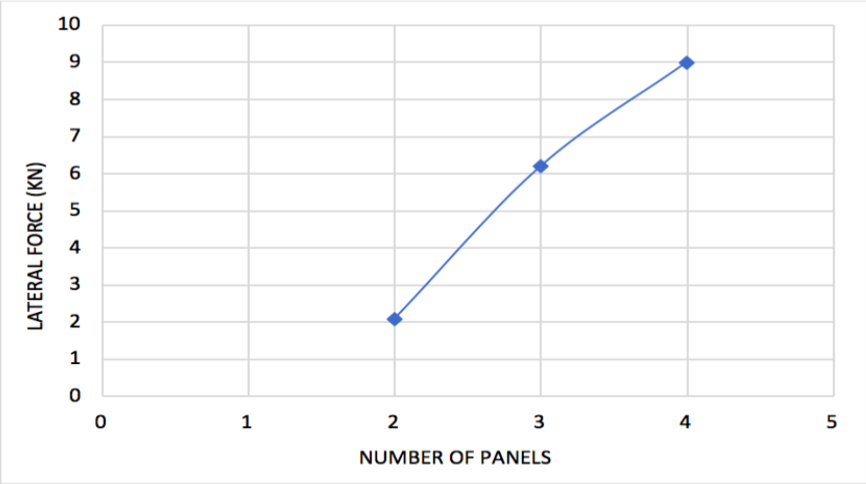

Figure 4. 22: Lateral strength vs number of panels in timber frame wall.

4.9 Conclusion

In this study, a numerical study of the racking performance of different lengths of timber walls (1.2 m, 1.8 m and 2.4 m) filled with hemp concrete was carried out. The lateral load carrying capacity of hemp concrete as infill material improved by increasing the total length of the wall. According to the numerical investigation, it is impossible to draw a generalized conclusion that the filling material always makes a significant contribution to lateral strength of the timber walls. The hemp concrete could show small mechanical contribution against horizontal loads without creating a complete compression zone in the diagonal position of the wall which subjects the hemp concrete to shear forces. This compression zone at the diagonal position of the wall is present when, approximately, the length of the wall is greater than or equal to the total height of the wall (see figure 4.22). Hemp concrete makes an appreciable mechanical contribution and improves the overall rigidity within these limits of dimensions. Beyond this limit the filling material becomes insufficient. The numerical results confirm the analysis of the experimental test in the chapter 3.

General conclusions and perspectives

5 General conclusions and perspectives

The aims of this study were set out at the beginning of the thesis in the general introduction with the main aim being investigating the lateral load carrying capacity of hemp concrete as infill material in timber frame walls. Other aims were to establish a theoretical model to predict the behaviour of cross-laminated timber walls subjected to lateral loads. An in-depth review of the applicability of Eurocode 5 was carried out in this study. In addition, an experimental and numerical analysis of hemp concrete performance as infill material in timber frame walls was conducted, including verifying the parameters that could play a major role in increasing or decreasing the lateral strength of hemp material.

The literature review in chapter 1 summarized the limited resources and studies related to hemp concrete as infill material when subjected to lateral loads, in particular, infill used in large scale of timber frame walls. To date there have been only a few limited studies of hemp concrete in timber walls and most of them are focused on the compressive strength of hemp material as infill in timber walls. This thesis has added and increased knowledge of the structural performance of hemp material inside timber structures. The thesis has also highlighted and further opened the door for some initial knowledge when lateral loads are applied.

This chapter of the thesis presents the conclusions that came out from the study. The conclusions of this thesis are drawn from theoretical, experimental and numerical investigations. Finally, recommendations for further studies will be made.

Lateral load carrying capacity of timber walls has been examined in this thesis. The first part in this research was related to a detailed understanding of European standards applying to the lateral strength of timber walls. Cross-laminated timber wall was investigated at the beginning of this study theoretically. The second part was investigating experimentally the lateral contribution of hemp concrete as infill material in timber frame walls. The third part was studying numerically the parameters that affect the lateral load carrying capacity of hemp concrete in timber walls.

5.1 Theoretical approaches

A theoretical approach has been proposed in this study to predict the global behaviour of cross-laminated timber walls (CLT) subjected to horizontal loads. The comparison between the theoretical approach model and the experimental tests showed that the theoretical model exhibits similar behaviour of the average test curve of experimental test up to 100 mm of the total horizontal displacement of the wall. The experimental value of the lateral force at 50 mm of the total displacement was around 90% of the experimental value. Based on the results, this study concludes that using diagonal elements under compression conditions in cross-laminated timber will significantly improve the lateral load carrying capacity of the wall. The diagonal element can be fixed on one side of the timber wall using the same type and size of nails between layers.

This study also confirms that the formulas in Eurocode 5 applied to the lateral load carrying capacity of timber frame wall are not very accurate and need to be reformulated, especially the lateral design load carrying capacity per fastener. Unclassified timber material used to construct the cross-laminated timber wall showed greater lateral strength than the oriented strand board (OSB) panel design. The number of internal rotational moments that are created in each shear plane of intersection of the cross-laminated wall was the main factor responsible for the global lateral strength. The existence of diagonal strut under tension or compression conditions does not present a significant difference in the lateral resistance.

The analytical model has been created to estimate the maximum force that can applied to the top of the wall at the design stage by representing the internal forces on each fastener in each shear plane. This model can be a particularly useful tool to design the cross-laminated wall particularly, estimating the lateral load carrying capacity of the wall. The study concludes also that using the cross-laminated timber wall in construction is a sufficient structural element and show good performance to resist the lateral loads such as winds and seismic loads.

5.2 Experimental testing

An experimental investigation of the racking performance of two different designs of timber walls (Vertical studs and diagonal bracing) filled with hemp concrete was conducted in this study.

The lateral load carrying capacity of hemp concrete as infill material in timber frame walls has been investigated in this study. The experimental results and data showed the contribution of hemp concrete against the applied lateral loads. The average racking strength of hemp concrete as infill material in the vertical stud wall of length 1.2 m was around 2kN. This value shows that hemp concrete contributes in the lateral strength tenfold as compared to the empty timber frame wall of resistance 0.18kN. The lateral load carrying capacity of hemp concrete as infill material inside the diagonal timber does not show any extra contribution compared to the results of the empty diagonal wall (both are with lateral strength around 10kN). The existence of the diagonal element in the timber wall increases the total rigidity of the wall. This rigidity is an obstacle to letting the hemp concrete to contribute in the lateral strength.

Based on the experimental results and data obtained from this study, it is impossible to draw a generalized conclusion that hemp material always make a significant contribution to the lateral load carrying capacity of timber frame walls subjected to the lateral loads. This study concludes that the filling material could not work mechanically without forming a complete compression area in the diagonal zone. The existence of this diagonal compression zone depends totally on the dimension of the timber wall and it is created typically when the length-height ratio (L/h) is greater than or equal to 1. This experimental test confirms that within this limit of wall dimensions ($L/h \geq 1$) the filling material will be able to show better contribution and performance in the lateral strength of the wall. Also, the gap between the hemp concrete and the timber elements decreases the mechanical contribution of hemp concrete in the horizontal strength of the timber wall. This problem of contact between the two different material was due to the drying of the hemp concrete.

This study concludes also that installing the hemp concrete in a very highly rigid timber system will prevent the filling material contribute to loading performance. In other words, the internal forces will transmit only to the diagonal element of the timber wall, the more rigid the wall is, the less strength the hemp provides. This study confirms the significant effect of timber wall length on the lateral resistance of hemp concrete as infill material.

5.3 Finite element analysis

Numerical analysis has been carried out in this study using Abaqus software for different wall lengths (1.2m, 1.8m and 2.4 m) with a standard height of 2.5 m.

The numerical results show that hemp concrete participates as infill material tin the lateral load carrying capacity of vertical stud wall. The horizontal strength of vertical stud hemp wall consists of two panels was around 2.1-kN in the elastic zone. The results of different wall lengths illustrate that the lateral strength of hemp concrete improves with increasing the wall length.

This study confirms that that increasing the wall length will increase the ability for transmitting the forces to the filling material. The length of the timber wall significantly improves the contribution of hemp concrete as infill material and also plays a main role in transmitting the hemp concrete from insufficient zone (two panels) to an effective material when subjected to lateral loads.

The hemp concrete could show small mechanical contribution against horizontal loads without creating a complete diagonal compression zone in the diagonal position of the wall, which subjects the hemp concrete to shear forces. This compression zone at the diagonal position of the wall is present when, approximately, the length of the wall is greater than or equal to the total height of the wall. Hemp concrete makes an effective mechanical contribution within this limit of dimensions. Beyond this limit the filling material becomes insufficient.

5.4 Perspectives

This study has shown that hemp concrete does improve the lateral load carrying capacity of timber wall under specific considerations. However, there is still further work on various aspects that could be undertaken. The contact performance between the hemp concrete and timber elements in the wall is one important point where further research could be developed. The contact between the timber and filling material would have a beneficial effect on the lateral load carrying capacity of the wall. This could be investigated by developing a new methodology of preventing the separation between the two materials or using an adhesive material between them.

During this study, the lateral load carrying capacity of hemp concrete has been investigated without using top vertical loads on the timber wall. Using the top vertical loads on the timber walls also requires further research to study the effect of this load on the infill material and on the global behaviour of the timber wall.

Further investigation is required for studying the effect of beam-column joint at timber walls. During this study, the failure of this joint significantly affected the results. Strengthening and improving the timber beam-column joints could be an important aspect in hemp concrete resistance against lateral loads.

In this study the thickness of hemp concrete used was around 14 cm so increasing the thickness of hemp concrete in timber frame wall could play a major role in producing different results of hemp concrete strength as infill material.

During this study, door and window openings have been ignored. These aspects could be considered to investigate the effect of these openings on the lateral load carrying capacity of the hemp concrete and also on the global performance of the timber wall. This is an area in which further investigations are necessary.

Further investigation is required for studying the effect of using precast blocks of hemp concrete. Using these blocks could be a perfect solution for the contact problem between hemp material and timber and could show better load carrying capacity against horizontal loads.

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Curriculum Vitae

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List of publications

International journals

- "*The lateral load resistance of unclassified cross-laminated timber walls: experimental tests and theoretical approach*" Accepted and published at "***Engineering Structures*" Journal**. 2018

- "*Lateral load-carrying capacity of hemp concrete as a natural infill material in timber frame walls*" accepted and published at "***Engineering Structures*" journal**. 2019.

Conference proceedings

- *" Mechanical behaviour of unclassified timber walls against horizontal forces" 35èmes Rencontres de l'AUGC, ECN/UN,* ***Nantes, 22 au 24 mai 2017****.*

- *" Experimental study of lateral load resistance of timber walls" 2nd International Conference on Bio-based Building Materials & 1st Conference on ECOlogical valorisation of GRAnular and FIbrous materials.* ***June 21th-23th 2017 Clermont Ferrand.***

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- *" Structural behaviour of lateral load bearing capacity of timber frame walls filled with hempcrete" 2018 world Conference on Timber Engineering,* ***August 20-23 Seoul, Republic of Korea.***

- *" Lateral load carrying capacity of timber walls filled with hemp concrete: experimental and numerical investigation" 3rd International Conference on Bio-based Building Materials.* ***June 26th-28th 2019 Belfast, UK.***