Traditional timber frames

WCTE 2014 Quebec City Canada August 10-14
World Conference on Timber Engineering

TRADITIONAL TIMBER FRAMES

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ABSTRACT: Due to new possibilities traditional timber framing has become increasingly popular since the beginning of the 21st century. Although traditional timber framing has been used for centuries, the expected mechanical behaviour is not dealt with in great detail in building codes, guidelines or text books. Especially the behaviour of the connections is of great importance, since the stiffness of the individual members is higher than the connection stiffness. Consequently, the connections govern the stiffness (and stability) behaviour of traditional portal frames.

A mechanical model is developed to describe and predict the behaviour of a portal frame. The stiffnesses used in this model are based on test data. The theoretical analysis is based on the work energy method.

KEYWORDS: timber, connections, energy, equilibrium

1 INTRODUCTION

This research is conducted to investigate the behaviour of portal frames. Firstly, the history of traditional timber framing is discussed followed by the questioned to be answered by this research. Thirdly, the motivation and finally the objective of the research are given.

1.1 HISTORY

Traditional timber structures have been built for centuries. At the beginning of the 20th century traditional timber framing became less common, due to increased labour costs and a lack of a high skilled labour. As a result, traditional timber framing was almost extinct at the middle of the 20th century. During the 70s, however, a revival took place. This started with the application of traditional timber framing in renovation and restoration projects. After several years also entirely new frame structures were built. Currently several companies in the Netherlands are specialised in the production and design of new timber frame structures. Due to CNC (Computer Numerical Control) production techniques the craftsmanship requirements and production costs reduce. Consequently, traditional timber framing is again competitive.

Despite the described positive developments and the fact that these type of structures last for centuries traditional framing is still regarded as a so-called niche industry.

As a result, structural design codes and guidelines are incomplete regarding the mechanical behaviour of these structures. This lack of knowledge results into confusion, which negatively influences the popularity of traditional timber structures. It also causes problems with the local building authorities in relation to building permits. Referring back to tradition including the structural design of realisations in the past is logically not sufficient. Nowadays building officials require a proper design calculated based on known material properties, loads, and predictable structural behaviour. Especially the knowledge about the structural behaviour lacks and, consequently, more research is needed to fill this knowledge gap.

1.2 MOTIVATION

Timber structures are in most cases characterized by a high degree of adaptability. Main elements can be reused in new structures. Waste can be recycled to produce paper or cardboard or it can be used as biomass to produce energy. Recycling of complete timber products is, although perfectly possible, still rare at the moment. Furthermore, wood is a renewable and sustainable material.

Only a small but increasing percentage of timber structures is realised with the traditional timber framing method. Due to the CNC controlled production process traditional timber framing is increasingly competitive to currently more common timber framing methods. The highly appreciated aesthetics of traditional timber structures might also positively affect the compatibility of traditional timber framing.

1.3 OBJECTIVE

Traditional timber structures are characterized by elements with relatively large cross-sections. These elements are connected by carpentry connections, which locally reduce the strength and stiffness. Consequently, the overall strength, stiffness and stability might be governed by these connections. The lateral stability of most traditional timbers structures is provided by portal frames. These frames exist of two columns and one beam, with diagonal corner braces as shown in figure 1 (top right). Both sides of the frame are referred to as beam-column connections, which include the diagonal brace. The column and beam are connected by so called wedge connections as figure 1 shows. The connections with the brace are referred to as brace-connections for which a mortise hole is cut in the column and beam. The notched end of the brace, which is referred to as a tenon, fits in the mortise hole and is fastened by a wooden peg. The structure of a beam-column connection is shown in figure 1.

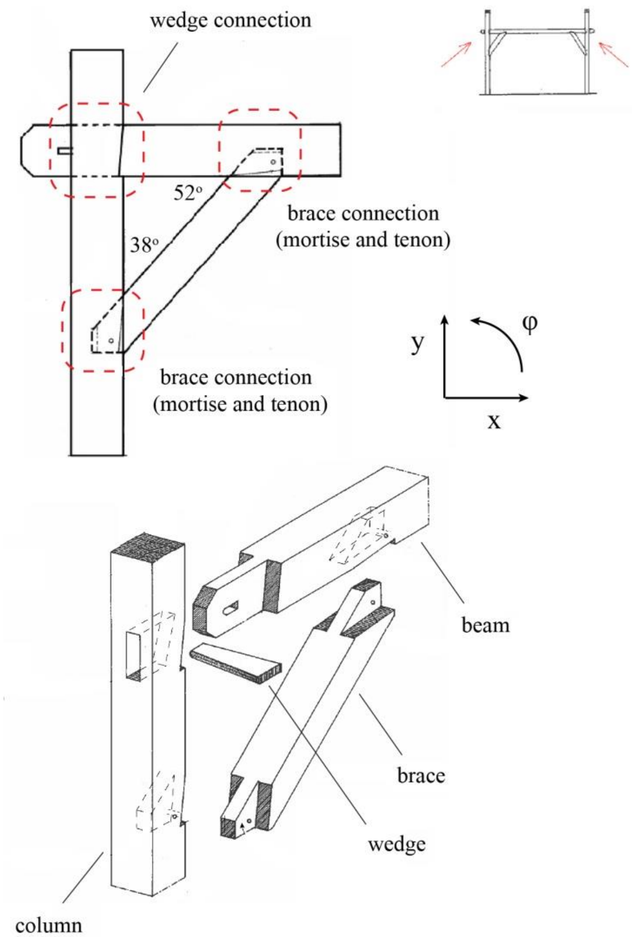

Figure 1: *Beam-column connection*

Although the strength of a beam-column connection can be predicted using available design codes and guidelines [1] usually no information is presented regarding the stiffness of this connection. Consequently, the stiffness of a portal frame remains unknown. Several research projects, e.g. [2] and [3], have investigated the mechanical behaviour of beam-column connections. This resulted in a mechanical model to approximate the behaviour of a portal frame. This mechanical model is shown in figure 2. Unfortunately, the stiffness values for the springs are not provided. The mechanical model therefore does not serve any practical use. The research described in this paper shows a method by which the stiffness can be determined.

This stiffness in combination with the proposed mechanical model result into an accurate model to approximate the mechanical behaviour of a portal frame.

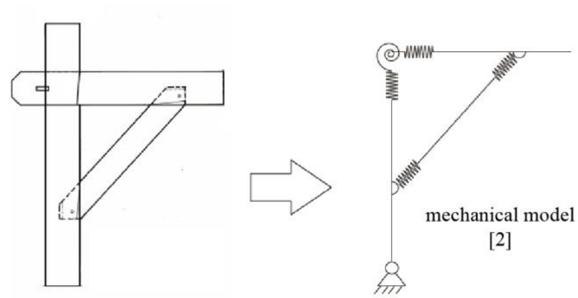

Figure 2: *Mechanical model proposed in [2] and [3] for a braced beam-column connection*

2 LITERATURE REVIEW

A literature review was conducted to gain knowledge regarding the behaviour of traditional framed timber structures. Traditionally they use green wood. The wood dries in the months and years after the erection of the structure until equilibrium moisture content is reached.

The drying process results in creep of especially the beam. Furthermore, the drying results in shrinkage, affecting mainly the connections and a change in the mechanical properties of the wood itself. Consequently, two situations exist within the life-time of such a structure. The first situation is referred to as ‘green’ state, which describes the situation in the first months or years after the erection of the structure. This state is characterized by a moisture content which is higher than the fibre saturation point. The second situation is referred to as ‘dry’ state, which describes the situation in which the moisture content of the wood has reached equilibrium. Several theories are developed to describe the relation between the moisture content and the physical- and mechanical properties of wood, see 2.1 and 2.2. Finally, how these affect the behaviour of the entire portal frame is discussed in 2.3.

2.1 PHYSICAL PROPERTIES

When the moisture content drops below the fibre saturation point, drying results in shrinkage. It is a known fact that the shrinkage value is different in longitudinal- (ignorable), radial and tangential directions.. The shrinkage in tangential direction is about twice the shrinkage in radial direction which causes cracks. The inner core of the elements dries slower than the outside region, especially when dimension are considerable as for this type of traditional frame structure. This causes a gradient in moisture content, which even further enlarges the risk of longitudinal cracking. Shrinkage also results into loosening of connections. This negatively influences the stiffness of a structure. Furthermore, the strength of the structure might be affected by internal drying stresses.

2.2 MECHANICAL PROPERTIES

Below the fibre saturation point strength and stiffness properties increase with decreasing moisture content. Kühne [4] investigated the mechanical properties of European Oak. The conclusion of this research is that the strength and stiffness properties at 0% moisture content are almost double compared to a moisture content of 50%.

2.3 RESEARCH QUESTION

The mechanical properties of wood increase while the timber shrinks during drying. Shrinkage results in a decrease of the connections stiffness. The magnitude of both effects on the stiffness of a portal frame is unknown. Consequently, either the green state or the dry state is governing. This situation is illustrated in figure 3.

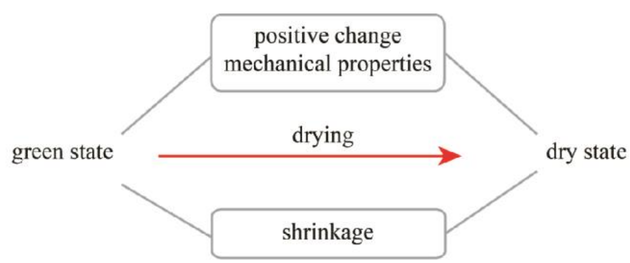

Figure 3: *Effects of a decrease in moisture content during drying from green to dry state*

3 EXPERIMENTAL RESEARCH

Tests were conducted to investigate the mechanical behaviour of full-size beam-column connections, individual mortise and tenon connections, and the wood itself.

3.1 SPECIMENS

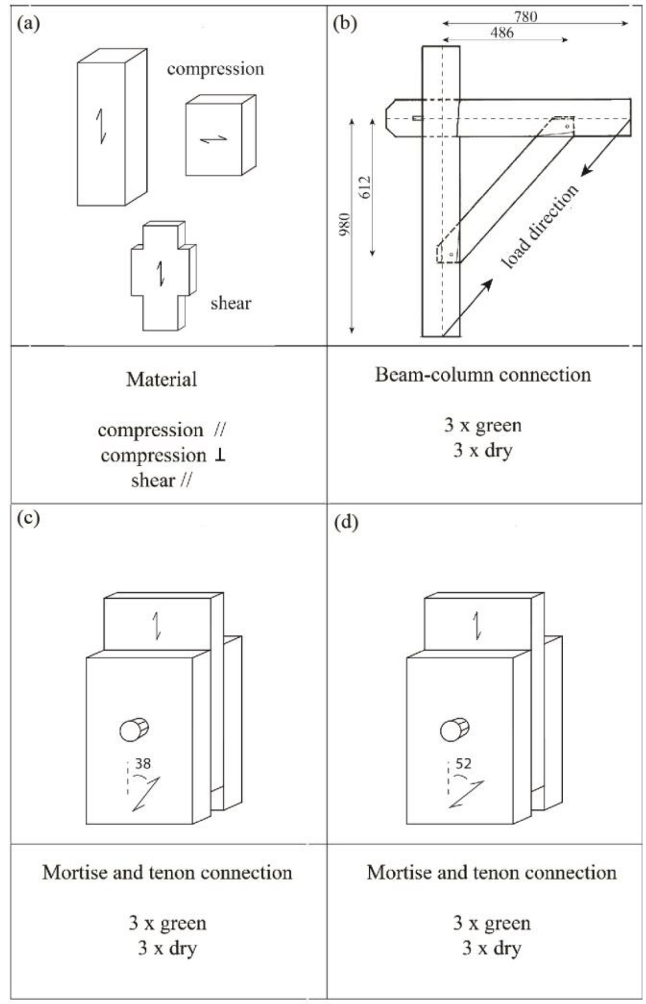

Figure 4: *Tested specimens*

In total six beam-column connections were tested. Three specimens were tested in green state and three in dry state for each of the specimens shown in figure 4. Additionally, 12 individual mortise and tenon connections were tested, simulating the behaviour of the brace to column and brace to beam connections. The diameter of the wooden pegs d = 22 mm. Six of these mortise and tenon connections were loaded at 38 degrees to the grain, simulating the behaviour of the brace to column connection. The other six mortise and tenon connections were loaded at 52 degrees to the grain, simulating the behaviour of the brace to beam connection. Both the angles of 38^o and 52^o are indicated in figure 1.

An overview of the types of specimens is presented in figure 4. After the tests the shear strength parallel to the grain and the compression strength and stiffness parallel and perpendicular to the grain were determined from uncracked sections cut from the beam-column connections.

3.2 TEST METHOD FOR THE BRACED CONNECTION

The beam-column connections were subjected to an closing mode load until failure. The load direction is shown in figure 4 (top right) and figure 5. The load was introduced by a hydraulic actuator. The test setup is shown in figure 5. The load and displacement of the actuator were monitored during the test using a load cell and a LVDT. Deformations within the wedge-connection were measured in the direction parallel to the column and parallel to the beam. Furthermore, the rotation between the column and beam was measured at the intersection centre. Displacements in both brace connections were measured parallel to the brace together with the rotation between the brace and the other main element (column or beam). The dimensions of the beam and column were 150*150 mm^2; the dimensions of the brace were 75*125 mm^2.

4 THEORETICAL ANALYSIS

The theoretical analysis discussed in this chapter is based on the Energy method as described by El Naschie [5]. Stiffness functions are determined based on energy-equilibrium and proposed energy-deformation functions.

4.1 ENERGY ANALYSIS

The energy introduced by the hydraulic actuator is referred to as the external energy. This causes connections and other elements to deform.

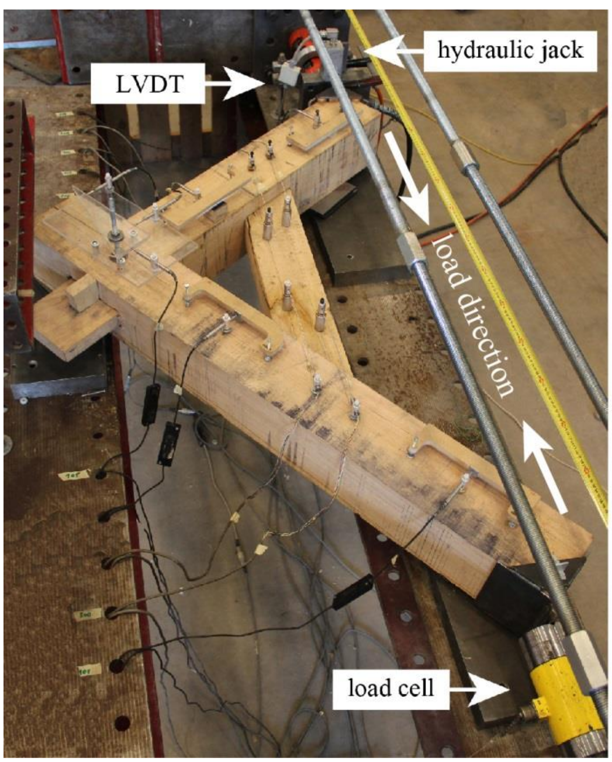

Figure 5: *Test setup beam-column connection*

The energy required for the deformation is referred to as the internal energy. The amount of energy stored in each of the connections and elements, the internal energy, is approximated using energy-deformation functions. These functions are based on theories presented by Leijten et al. [6] and El Naschie [5].

Energy losses are ignored and therefore the internal energy stored in the different elements must equal the external energy delivered by the hydraulic actuator: energy equilibrium. Consequently, comparison of the internally stored energy with the external energy indicates the accuracy of the proposed energy-deformation functions. These are subsequently used to derive the stiffness functions to be used in the mechanical model.

4.1.1 ENERGY STORED WITHIN THE WEDGE CONNECTION

The wedge connection is indicated in figure 1. The beam with the hole for the wedge is shown in figure 6. The forces caused by the column are indicated by the arrows. The opposite but corresponding forces in the column hardly lead to any deformation compared to the perpendicular to grain deformation in the beam. The derivation of the energy-deformation function is based on the area which is loaded in compression perpendicular to the grain, which is shown in figure 6.

Due to the difference in stiffness perpendicular and parallel to the grain, almost all of the energy is absorbed by beam. Two springs connected in series are used to simulate the behaviour of the contact surface. The stiffness of each spring is equal to the modulus of elasticity of the material it represents. The corresponding amount of energy is given by equation (1), assuming linear elastic material behaviour.

$$E_p = \frac{1}{2} F\,\Delta = \frac{1}{2} k\,\Delta^2 \quad \text{[mJ (Nmm)]} \tag{1}$$

In which
E_p = internal energy [mJ (Nmm)]
k = spring stiffness [N/mm]
F = load [N]
Δ = deformation [mm]

About 97% of the energy is stored in the material loaded perpendicular to the grain. Consequently, the energy stored in the column (loaded parallel to the grain) is ignored.

The energy is assumed to be solely stored by a rectangular volume within the beam. Depth'd' and length 'l' of the volume are dependent on the deformation and are described by (2) and (3). The width of the volume remains constant.

$$= 0{,}35 \cdot h_{beam} - \delta \tag{2}$$

$$l = l_{start} + 2 \cdot 1{,}5 \cdot \delta \tag{3}$$

The initial depth of the volume (0,35 h) is based on the stress spreading model [6]. The increase in length and the decrease in depth follow the line (with slope 1:1,5) indicated by van der Put [7], shown in figure 6 (dashed line).

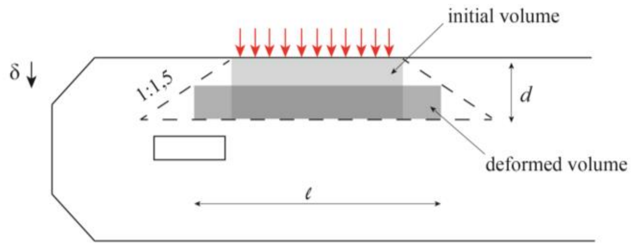

Figure 6: *Compressed volume model*

Individual pieces of wood (70 x 90 x 45 mm^3) were subjected to compressive loading perpendicular to the grain. The mean load-deformation diagram of these tests is shown in figure 7 (a) The integral of this function results into the energy-deformation diagram, which is shown in figure 7 (b).

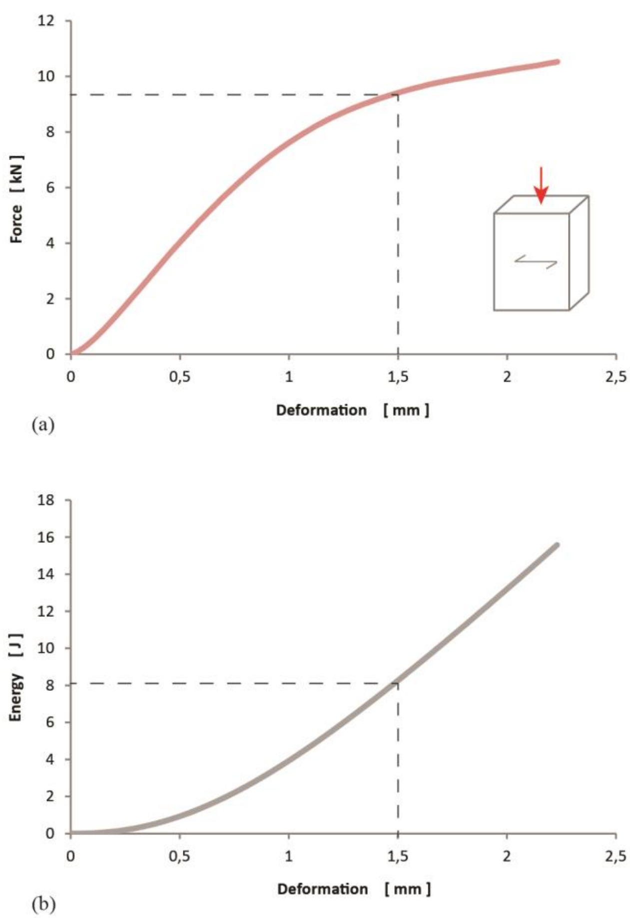

Figure 7: *Diagrams of individually tested wood pieces, loaded perpendicular to the grain: (a) load-deformation diagram, (b) energy-deformation diagram*

The amount of energy stored by the volume inside the beam (shown in figure 6) at a certain deformation is subsequently derived from the energy-deformation diagram of the individually tested wood pieces, the differences in dimensions are thereby taken into account. Consequently, an energy-deformation function is derived by which the internal energy in the wedge connection is determined. E.g. if the individual test at a displacement 1,5 mm relates to an energy of 8 J, it is assumed that in the wedge connection this energy is connected to the same deformation (corrected for dimensions).

4.1.2 ENERGY STORED WITHIN THE BRACE-CONNECTIONS

The brace is connected to the beam and to the column by ‘brace-connections’ as indicated in figure 1. The amount of energy stored by rotation is assumed to be negligible. Deformations parallel to the brace were observed during testing; the specimens and test set-up are shown in figures 4(b) and 5. The load transferred by the connections, the normal force in the brace, could not be measured directly. Nevertheless, the brace force has to be calculated. When the moment rotation resistance of both wedge connection and brace connections are ignored, the system is statically determined and the brace force can be calculated. The corresponding load-deformation graph is represented by the grey line shown in figure 8. It is at this stage unknown if the rotational stiffness of the wedge can indeed be neglected. Therefore, a certain correction factor “a” is introduced. At a= 1,0 no moment is transferred by the wedge connection and the axial force in the brace is maximal. At a= 0,0 the axial force in the brace is zero and the moment transferred by the wedge is maximal.

Individual mortise and tenon connections were tested, see figure 4(c) and (d) to simulate the behaviour of the brace-connections. The individually tested mortise and tenon connections should show a similar behaviour as the brace-connections during clearance removal. The mean load-deformation diagram of the mortise and tenon connections (figure 8, dashed red line) is compared to the behaviour of the brace-connections. At a = 0,6 the brace-connections (figure 8, black line) show similar behaviour during clearance removal as the individually tested mortise and tenon connections. Different behaviour is observed for higher loads, due to direct contact between the brace and the other element (column or beam). Direct contact does not apply to the individually tested mortise and tenon connections; therefore its stiffness remains relatively low.

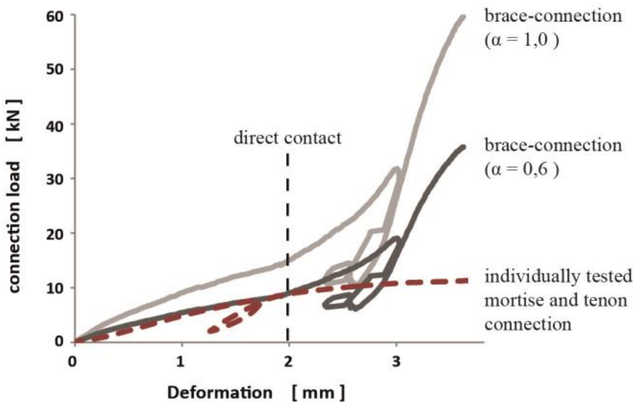

***Figure 8:** Comparison of the load-deformation diagrams*

Using a = 0,6 a load-deformation diagram is determined which describes the behaviour of the brace-connections. The corresponding energy-deformation function is found by taking the integral of the load-deformation function.

4.1.3 ENERGY STORED WITHIN THE BEAM AND COLUMN

According to El Naschie [5] the amount of energy stored within an element can be determined using its mechanical properties, the bending moment diagram, the shear diagram, and the axial force diagram. Deformations caused by axial forces are virtually zero; the corresponding amount of energy is therefore considered negligible. The bending moment diagram and the shear diagram are determined using the curvature test data. The material properties are determined by separate material tests; see figure 4(a). The energy stored within the beam and column is determined using these data and a Riemann sum used to evaluate (4). Eq. (4) is in principle an extension of equation (1), which is also presented by El Naschie [5].

$$E_p = \frac{1}{2}\int\left(\frac{M^2}{EI} + \frac{Q^2}{GA\kappa}\right)dx \qquad \text{[Nmm]} \qquad (4)$$

In which
M = bending moment [Nmm]
EI = bending stiffness (Nmm^2]
Q = shear force [N]
GAκ = shear stiffness [N]
x = length in beam/column direction

4.1.4 ENERGY INTRODUCED BY THE APPLIED LOAD

The energy introduced by the applied load (external energy) is determined using the applied load and the load displacement, which are both measured directly.

4.2 ENERGY EQUILIBRIUM

The internal energy must at all times equal the external energy. In this case the internal energy equals the energy stored in the connections and elements and the external energy equals the work done by the applied load. The analysis of the column and beam, described in 4.1.3, is based on linear elastic material behaviour and structural response. Consequently, the amount of energy stored by plastic deformation of the elements are theoretically not taken into account.

Figure 9 shows the energy equilibrium of one of the beam-column connections tested in green state (moisture content ≈ 65%). The energy stored in each of the connections and elements, the internal energy in each individual element and connection, is represented by the lines close to the bottom of the figure. The total energy stored within the connections and elements, the total internal energy, is shown by the blue line, which is obtained by summation of the internal energy stored in each individual element and connection. The external energy introduced by the applied load is represented by the red line. The internal energy agrees with the external energy rather well up to an applied load of approximately 40 kN. A certain deviation occurs for higher loads. This deviation is most probably caused by plastic deformations in the column and beam and crack development, which are not taken into account in the internal energy value. Visible cracks appeared at loads close to 40 kN.

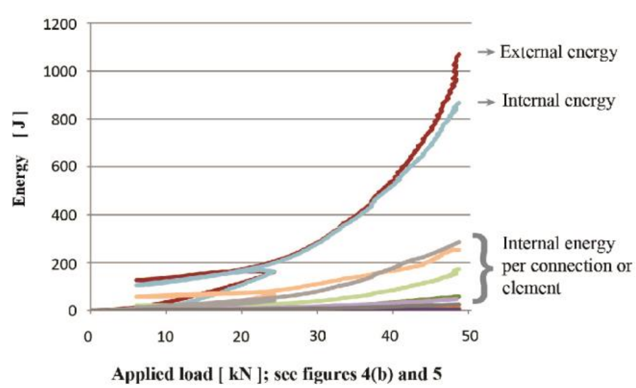

***Figure 9:** Energy equilibrium in green state (≈ ω 65%)*

The average energy values at failure for each of the connections and elements are presented in 10. Most of the energy is stored by bending deformation of the beam and column, deformations in both brace-connections, and deformations parallel to the column in the wedge connection. Much less energy is stored by shear deformation of the beam and column, deformation caused by rotational movement in the wedge connection, and deformation parallel to the beam in the wedge connection.
The individual energy values found for the test specimen shown in figure 4(b) are presented in table 1 and table 2.

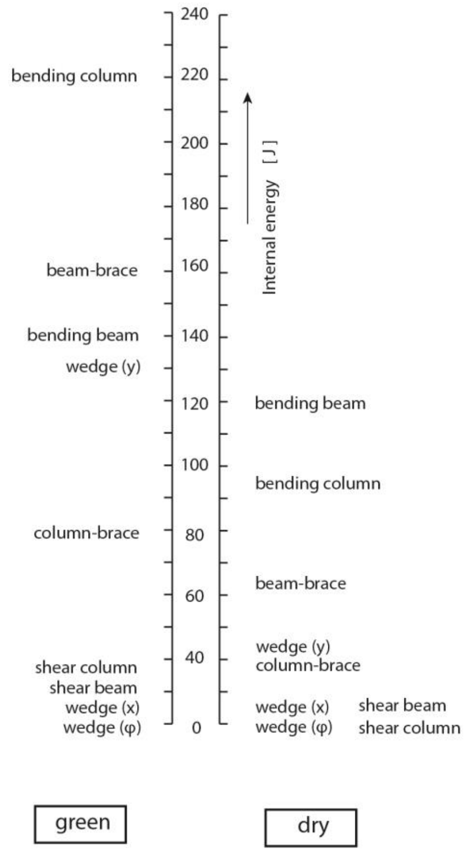

Figure 10: *Energy value per connection or element in green(≈ ω 65%) and dry (≈ ω 20%) state. The x- and y directions are indicated in figure 1.*

Table 1: *Internal energy per connection or element in green state(≈ ω 65%)*

	Energy value [J]	Percentage [%]
Bending column	220	28,1
Beam-brace	160	20,4
Bending beam	142	18,1
Wedge connection (// column)	130	16,6
Column-brace	77	9,8
Shear column	27	3,4
Shear beam	16	2,1
Wedge connection (// beam)	8	1,0
Wedge connection (rotation)	4	0,5
Total internal energy	784	100

Table 2: *Internal energy per element or connection in dry state($\omega \approx$ 20%)*

	Energy value [J]	Percentage [%]
Bending beam	124	31,0
Bending column	95	23,7
Beam-brace	63	15,7
Wedge connection (// column)	38	9,5
Column-brace	38	9,5
Shear beam	20	5,0
Shear column	10	2,5
Wedge connection (// beam)	7	1,8
Wedge connection (rotation)	5	1,3
Total internal energy	400	100

4.3 DERIVATION OF SPRING STIFFNESSES

As can be seen in figure 9, both the internal energy and the external energy show great similarity up to an applied load of 40 kN. The proposed energy-deformation functions used to determine the amount of internal energy are therefore considered valid. After differentiating the energy function twice, the stiffness is obtained. This follows from e.g. equation (1): $\frac{d^2E_p}{d\Delta^2} = k$ in which k represents the stiffness function. Consequently, a stiffness function is found for each of the elements and connections. As can be shown in figure 10 only a small amount of energy is stored by rotational deformations within the wedge connection and deformations parallel to the beam within the wedge connection. For this reason the number of spring can be reduced as indicated in figure 11.

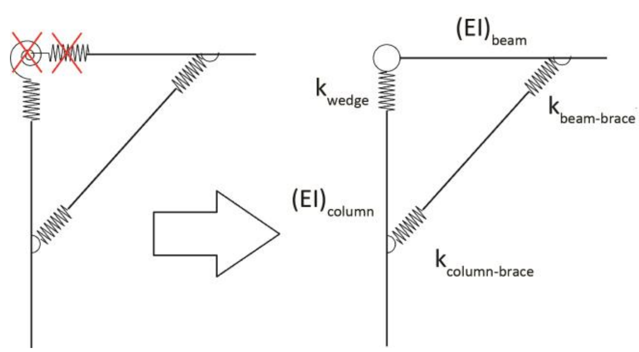

Figure 11: *Adjustments made to the mechanical model*

4.4 MECHANICAL MODEL

A portal frame consists of two beam-column connections (including two braces), one on either side. Consequently, the behaviour of a portal frame is suggested to be modelled as shown in figure 12. When a portal frame is subjected to in-plane lateral loading one brace is loaded in tension (opening mode) while the brace at the other side is loaded in compression (closing mode). Paragraph 4.2 presents a method to determine the spring stiffness of a beam-column connection for the closing mode situation. The stiffness values determined are consequently only valid for this mode.

The stiffness values for the opening mode are determined as follows:

- The stiffness of the wedge connection is assumed to be equal to closing mode stiffness.
- The stiffness of the brace to column and brace to beam connections are determined by testing using individual mortise and tenon connections loaded in tension,

Furthermore, a maximum allowable elongation is introduced. Tear-out failure of the weakest brace-connection occurs when this elongation is exceeded.

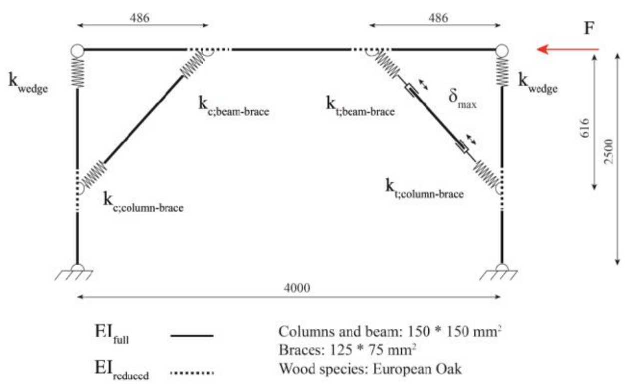

Figure 12: *Mechanical model of a traditional timber portal frame (not on scale)*

The behaviour of the mechanical model shown in figure 13 is simulated using Scia Engineer [8]. In addition to the stiffness values for the individual elements (beams and columns) and connections, a reduced beam c.q. column stiffness area is taken into account at the brace connections.

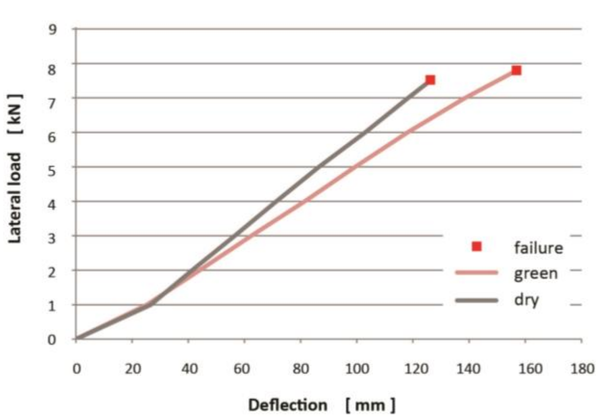

Figure 13: *Deflection of a portal frame in relation to the subjected in-plane lateral loading in green($\approx \omega$ 65%) and dry ($\omega \approx$ 20%) state.*

Two computer models are developed. One with stiffness values representing the green state of the material; the other the dry state. Both models are subjected to a lateral in-plane loading as indicated in figure 11. The load deflection graphs of both models are shown in figure 13. The model representing a frame in dry state shows smaller deflections and a slightly lower ultimate failure load in comparison to the green state. As a consequence, the green state is considered governing regarding the stiffness of a frame, while the dry state is considered governing regarding the strength.

5 SUMMARY AND CONCLUSIONS

The internal energy within a beam-column connection is determined using deformation data observed during testing and by proposed energy-deformation functions. The internal energy within the system is in good agreement with the external energy.

A beam-column connection in green state absorbs more energy before failure (average external value 950 J) in comparison to a frame in dry state (average external energy value 630 J).

Most energy is stored by bending deformation of the column and beam, deformations in both brace-connections, and deformations parallel to the column within the wedge connection. Much less energy is stored by shear deformations of the column and beam, deformations caused by rotation in the wedge connection, and deformations parallel to the beam in the wedge connection.

A mechanical model is developed to simulate the behaviour of a beam-column connection. The contributions of the connections which store less than 5% of the total internal energy are not taken into account. The stiffness values of the individual components (beam – column – brace connections) are obtained by differentiating the corresponding energy function twice. The behaviour of a complete closing mode corner connection can be described quite accurately, as indicated in figure 8, by taking these stiffness values into account.

The behaviour of a whole frame is modelled using these stiffness values for the closing mode corner of the frame. For the corner connection on the other side of the frame, the stiffness value used is that of the mortise and tenon connections loaded in tension. The stiffness is determined by the stiffness of the connection (in this case a connection with a wooden dowel). A maximal allowable elongation of the brace is taken into account to simulate tear-out failure of the weakest brace-connection. According to this model a frame in green state is less stiff than a frame in dry state, while a frame in dry state is slightly less strong.

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