

# A novel design of a unitized curtain wall with a timber only frame – basic mechanical, moisture, and fire tests and hygrothermal simulations

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## Highlights

- A new unitized curtain wall with a timber only frame was developed
- The bond between of Accoya and spruce glulam was proved by several tests
- The timber mullion deformation caused by the changing moisture was insignificant
- Both of the criteria for wood decay were safely met by the hygrothermal simulations
- The fire test showed no fire propagation on or within the timber curtain wall

## Abstract

The paper is focused on a newly developed unitized curtain wall with a timber only frame and how it deals with the general disadvantages of timber curtain walls, such as fire resistance or the effect of a high moisture content. The curtain wall is unique because the glued laminated timber frame is made from two different materials - spruce and acetylated (Accoya) wood. The Accoya and the pressure plate create an effective weather barrier because the Accoya is able to deal with a high moisture content. Three mechanical and two moisture tests proved that the connection of these two different types of wood is sufficient and that the deformation of the whole timber mullion, due to the different level of moisture content, is insignificant. The long-term effect of moisture on the potential for the development of wood-decay fungi was investigated using hygrothermal simulations. Several material properties of the Accoya wood required for the simulations were measured. The simulation results for the critical detail of the new timber curtain wall revealed that both defined criteria for the wood-decay fungi development were safely met. The results from the fire test showed that fire propagation does not occur on or within the timber curtain wall even in the 90th minute of the test.

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# 1. Introduction

## 1.1. State of the Art

Curtain walls came into use as exterior walls at the end of the nineteenth century, along with the spread of skyscrapers [1]. Since then, two main types of curtain walls have evolved: stick and unitized systems. Stick curtain walls are assembled piece by piece (or stick by stick) on the construction site and therefore require scaffolding during the assembly process. Stick curtain wall systems are only suitable for low-rise buildings [1]. Unitized curtain wall systems are used for high-rise buildings, as curtain wall units are prefabricated in a factory and then the units are hung on a supporting structure on the building site, see Fig. 1.



Fig. 1. Photo of a final unitized curtain wall unit being hung.

There are two sub-variants of stick and unitized curtain wall systems, depending on the attachment of glazing or opaque panel units. In the pressure plate method, an external plate or cap is used to hold the glass in place with screws or by EPDM gaskets. The second method is structural silicon glazing, in which the glass is adhered to the frame using high-strength silicone instead of an exterior pressure plate and cap [1]. All these curtain wall variants are plotted and described in Fig. 2. This article is focused only on the unitized curtain wall system with the pressure plate.

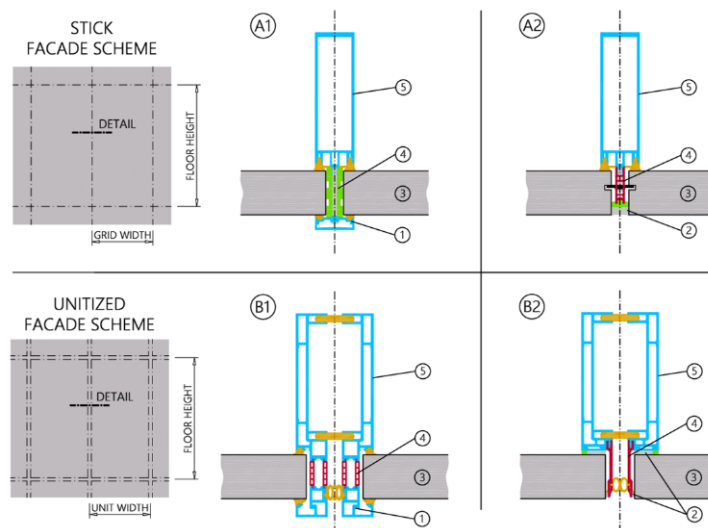


Fig. 2. Scheme of curtain wall systems and frame details: A1) stick system with pressure plate, A2) stick structural glazing system, B1) unitized system with pressure plate, B2) unitized structural glazing system; 1) pressure plate and cap, 2) structural silicon, 3) glazing, 4) plastic thermal break, 5) aluminium bearing part

Extruded aluminium is the framing material of choice for most curtain walls [1],[2],[3] and the steel framing is the second option [2],[3]. Timber, although very popular today for its environmental impact, energy efficiency and appearance, is unfortunately still rarely used for curtain wall systems. The possibility of timber framing for curtain walls is not even mentioned in these studies 2017 [2] and 2018 [4]. One of the first prefabricated wall with timber framing was presented as a case study in 2015 [5] and detailedly described in [6]. Today, there are only a few timber-framed unitized curtain walling products in the world [7], [8], [9], [10] and [11]. All these examples combine timber with an aluminium alloy into one frame called a hybrid frame. Some of these examples are plotted in Fig. 3. All these hybrid frame systems are made up of the same main parts: timber and aluminium support parts, plastic thermal break and aluminium pressure plate and cap. These systems differ slightly in the proportion of wood and aluminium parts, dimensions and the shape of the EPDM gaskets, plastic thermal breaks, etc. A different hybrid frame system was proposed in this study [12]. It is also composed of aluminium and timber but there is no plastic thermal break probably due to the mild weather in Australia. We are currently unaware of any unitized systems with timber only frame, so we decided to develop one.

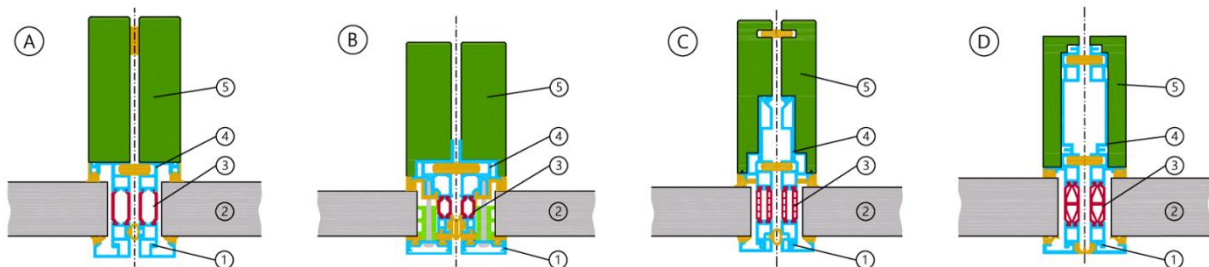


Fig.3. Different hybrid curtain wall frame details: product A [8], product B [7], product C [9], product D [10]; 1) pressure plate and cap, 2) glazing, 3) plastic thermal break, 4) inner bearing aluminium part, 5) inner bearing timber part.

The advantages of timber only or hybrid curtain walls are very well known. The environmental impact of timber frames is very low compared to classic aluminium curtain wall frames [13] and a timber curtain wall has better thermal properties than an aluminium curtain wall with plastic thermal breaks [14]. The main disadvantages of timber or hybrid framed curtain walls compared to metal frame curtain walls are moisture control and fire resistance. Therefore, the article is focused on a new design of the unitized curtain wall with a timber only frame and how the mentioned disadvantages for timber curtain walls are dealt with.

## 1.2. New Frame Design

Since 2021 we have been developing a unitized curtain wall system for multi-storey buildings with a timber frame basis only. There are a variety of timbers, which could be used in the curtain wall frames – laminated timber, LVL, glued laminated timber, etc. [7]. The glued laminated timber (glulam) was finally chosen based on our experience and its advantageous material properties – high structural capacity, dimensional stability, and decades of proven use in window frame systems [15].

The main challenge was to find out an effective moisture control to avoid excessive moisture accumulation in the timber frames which will cause wood degradation and shorten the service life of the whole timber curtain wall. There are two main sources of moisture that affect moisture content in the timber curtain wall frames. One source is rain penetration through the first weather curtain wall barrier. The weather barrier is made up of a pressure plate with EPDM gaskets and water leakage through the barrier is unfortunately a common occurrence for curtain walls [16]. The second source of moisture is moisture load due to adsorption from the surrounding outdoor and indoor environments. A typical commonly used protection against both these sources of moisture for timber window frames

is a wood coating [17]. According to our experience wood coating is not suitable for timber curtain wall frames as a protection against moisture because there is a high risk of water penetration through the coating due to the often-used elements such as fasteners, fixing elements, corner connections and joints. In addition, any coating renovation for timber curtain wall frames used in high-rise buildings would be very costly.

The final patented timber only frame for unitized curtain walls is shown in Fig. 4. The frame is divided into two parts. The interior part is created by a common spruce glulam and the exterior part of the frame is made of acetylated wood (Accoya) glulam. The timber curtain wall design is innovative because the timber only frame does not need any coating against water leakage at all. The first barrier against driven rain and sun radiation is composed of a common aluminium pressure plate with EPDM gaskets. Accoya is used for the exterior part of the frame only where water will penetrate the first barrier because the use of the Accoya wood for the whole timber frame is not cost effective. The Accoya wood is able to deal with high moisture content compared to natural woods [18], and has already found a significant market in window joinery due to its 50-year service life and high dimension stability [19].

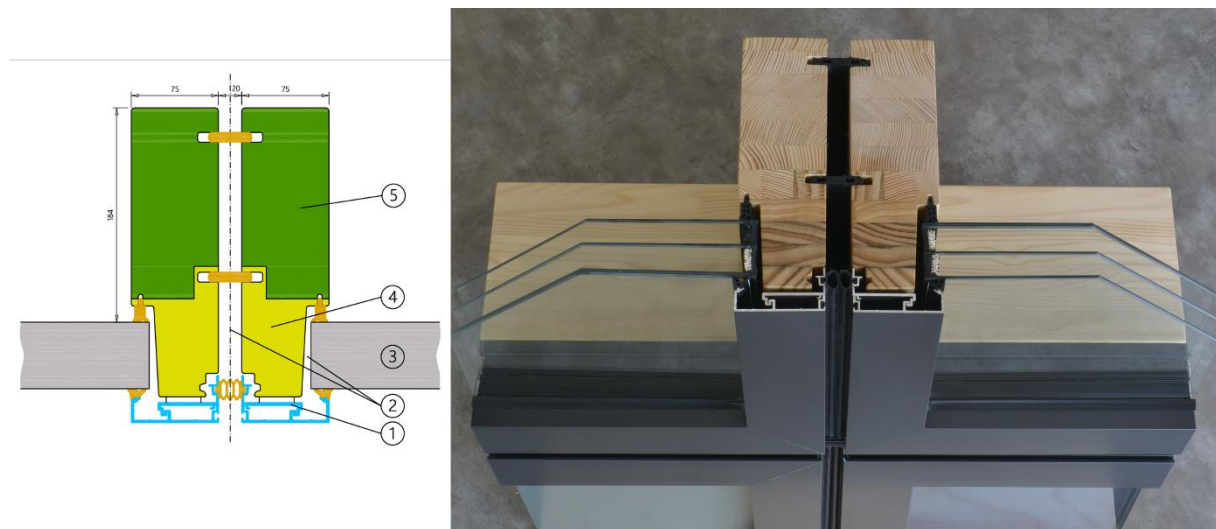


Fig. 4. Cross section of the timber only curtain wall frame and photo of the connection of four curtain wall units. 1) aluminium pressure plate, 2) cavities with possibility of leakage, 3) glazing, 4) Accoya glulam, 5) spruce glulam.

The new timber only curtain wall frame was designed as an alternative to the aluminium unitized curtain walling frame. As a result, the unitized timber curtain wall can be similar in size to aluminium curtain walls, i.e. curtain wall units can be 1.2 to 3.0 m wide and 3.5 to 4.5 m high.

### 1.3. Objectives and engineering challenges

The innovative design of timber only frame for unitized curtain walls raises several engineering challenges. The following challenges need to be addressed to demonstrate that the new timber frame design is functional and can be an alternative to commonly used aluminium curtain wall frames.

- 1) To prove that the connection of two different types of wood in one timber frame is fully functional.

The Accoya slats are bonded in the same manner and with the same polyurethane glue as the rest of the glulam wood. As two different types of wood (spruce and Accoya) are combined in one timber frame, three mechanical and one moisture tests should be done to prove that the connection of these two materials is satisfactory, (see section 2.1 to 2.4).

- 2) To demonstrate that the deformation of the entire timber frame due to differences in moisture content would be insignificant.

As the frame is made of two types of wood with different moisture sorption, it is important to know its deformation in different climatic conditions. To obtain this knowledge, the frame must be exposed to different conditions for several months, (see section 2.5).

- 3) To check the critical moisture content in the timber frame to prevent wood degradation

The long service life of any timber curtain wall requires moisture content in the timber frames to be under critical limits because high moisture content in wood will cause an attack of fungi decay and wood rot [20]. The hygrothermal simulations and the WUFI software tool [21] were used to check the critical moisture content in wood over a long period of time. This approach is similar to studies [8], [22], (see section 2.6)

- 4) To demonstrate that there will be no fire propagation on or within the curtain wall during the specified time period.

The new curtain wall frame design is made of the glued laminated timber which is a combustible material. The use of combustible materials for high-rise building is restricted in many countries because the facade can be one of the quickest spreading pathways for a fire [23]. To prove that there is no fire propagation during specified time period is critical for the new curtain wall design. The semi-scale standard test [24] was performed to prove no fire propagation would occur in the timber curtain wall, which would be in direct contact with the flames, (see section 2.7).

## 2. Methods and Materials

### 2.1 Bendig Test

The first test was the four-point bending test to verify the shear connection of two different types of wood in the new curtain walling frame. The measurement setup for the test was prepared according to the standard [25] and is shown in Fig. 5. Lateral restraint was provided to prevent buckling of specimens. The midspan deflection was continuously measured by two linear variable differential transformers (LVDT). The test is the typical universal test to simulate the bending load on a beam, which is typical for the wind load on the curtain wall mullion. All these mechanical tests were conducted indoor at ambient air temperature of 22°C.

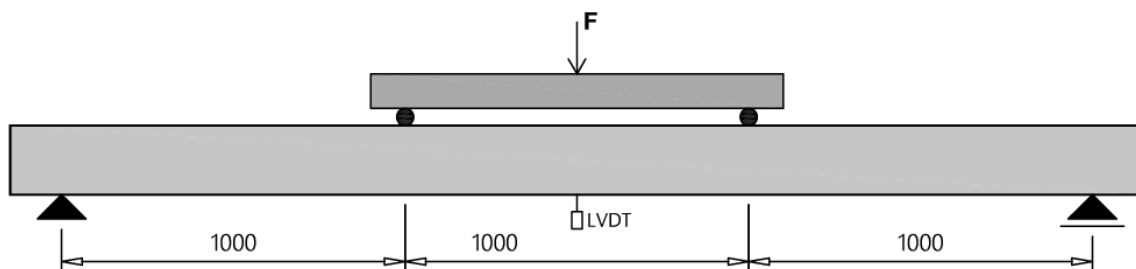
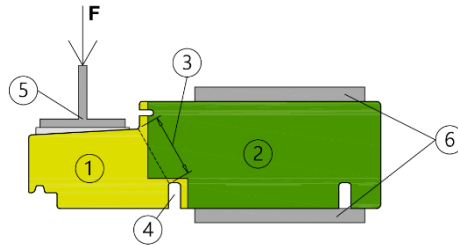


Fig. 5. Measurement setup for the four-point bending test.

Three samples of 3 m long beams were prepared with all grooves and folds in the timber curtain wall frame. Two positions of the frame were tested. One sample in the positive direction (wind pressure) and two samples in the negative direction (wind suction). Load was applied at a constant rate until the samples were destroyed.

## 2.2 Test of bearing capacity of the frame nose

The second mechanical test was designed to prove the load-bearing capacity of the frame nose and the quality of the connection between the two different types of wood. The test setup is shown in Fig.6. The load was distributed by a steel T-profile on the frame nose. The whole frame was fixed by two steel plates. The measured setup was designed to simulate the load from glazing on the frame nose.



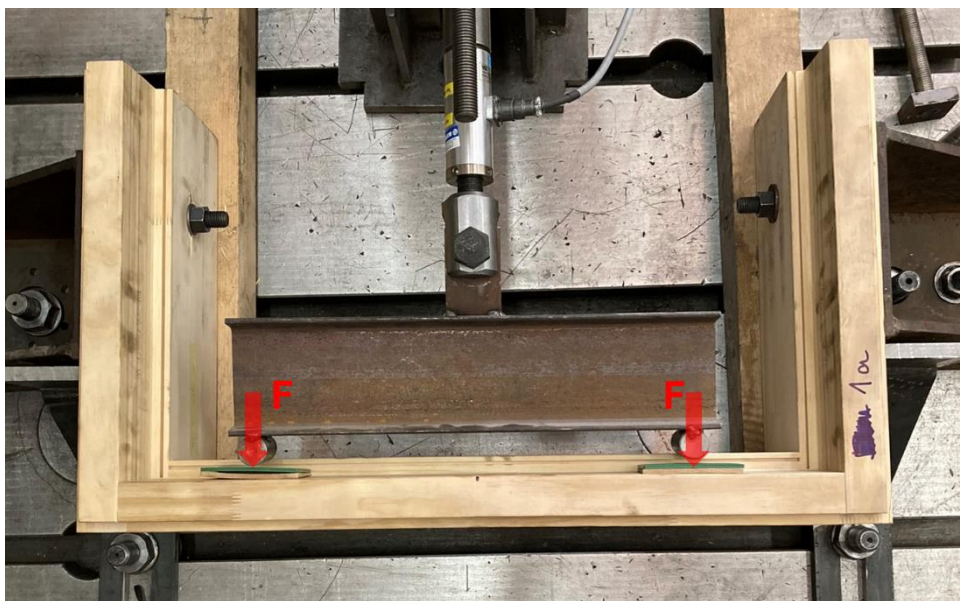
*Fig. 6. Measurement setup for bearing capacity of the frame nose. 1) Accoya glulam, 2) spruce glulam, 3) cracking distance, 4) groove with different position, 5) steel T-profile, 6) two fixing points*

Nine samples with all grooves and folds with a length of 300 mm were cut from the timber profile in three groups of three identical samples. The cracking distance was different for each group (A = 45 mm, B = 41 mm, C = 38 mm) depending on the location of the groove in the frame. Load was applied at a constant rate until the samples were destroyed. The deflection of the nose was continuously measured at each end of the sample by one LVDT.

## 2.3 Determination of the strength of sheared connection

The third mechanical test was done according to technical standard EN 16758 [26]. The test simulates the load (two points) from the glazing to the bottom transom of the unitized curtain walling frame and verifies the load capacity of the frame nose but also the load capacity of the corner joint. The test setup is shown in the photo, see Fig. 7.

Three U-shape samples were assembled from the timber only curtain wall frame with all grooves and folds. The axial distance of the mullions was 750 mm. Again, the load was applied at a constant rate until the samples were destroyed.



*Fig. 7. The measurement setup with the U-shape sample to simulate the glazing load to the bottom part of the unitize curtain wall.*

## 2.4 Delamination test

The delamination test was chosen to gain knowledge about the performance of the timber only frame in a rapidly changing moisture environment. There are many modifications of the delamination test [27], so the following procedure was used for the test. Four test pieces with a length of 50 mm were sawn out of the full cross-section of the glulam timber profile. The profile did not contain the grooves and folds typical for the curtain wall frame. The samples were placed in boiling water for four hours then put into an oven with the temperature at  $60 \pm 2$  °C to dry out until the initial weight had been reached. The percentage of open glue joints of the samples was assessed within 2 hours after reaching the initial weight.

## 2.5 Wood Warping Test

As the timber frame is made from two types of wood with different moisture sorption the knowledge of its behaviour in different climate conditions is important. The following test was designed and prepared. One 2.5 m long mullion of Accoya/spruce glulam was prepared with all grooves but without any coating. The mullion was placed successively into several different environments. Temperature and relative humidity of the environments were monitored continually, and the average values are shown in Tab.1. After each period of different environmental conditions, dimensions of the mullion were measured and different types of wood warping (bow, crook, cup, twist), cracks and delamination of open glue lines were recorded.

<i>No.</i>	<i>Environment</i>	<i>Time [days]</i>	<i>Air Temp. [°C]</i>	<i>RH of Air [%]</i>
1	Initial period	2	23.3	44.4
2	Wet period	33	17.9	98.0
3	Standard office period	33	24.5	47.5
4	In a water bath	32	N/A	N/A
5	Standard office period	32	25.2	53.8
6	Standard office period	44	24.2	51.2

*Tab. 1. Environmental conditions for the wood warping test*

## 2.6 Simulation of heat and moisture transport within the timber curtain wall frame

Moisture transport in building materials is a very slow phenomenon and therefore hygrothermal simulations appear to be a good tool to determine the critical moisture content in the materials for a specific location. The first step is to define the critical level of moisture in the wood.

### 2.6.1 Critical level of moisture in wood

Limiting moisture conditions for timber curtain walls must be defined. There are two phenomena – mould growth and decay fungi that can greatly shorten the lifetime of curtain walls. The critical moisture conditions for mould growth and how to calculate it are already well described in the technical standards, for example [28]. These assessments have long been performed for aluminium curtain walls and the same procedure is used for timber curtain walls.

The risk of wood decay is something new for curtain walls. The level of 20 % moisture content in wood as the critical limit for decay fungi development for timber structures has been defined for decades in (ASHRAE handbook, Wood handbook). It is generally known that wood will decay above 30 % moisture content and will not decay below 20 % moisture content. Moisture contents between 20 % and 30 % represent a grey area [20]. Many authors disagree with the 20 % limit and have tried to establish a new

critical level for wood decay depending on wood products and fungi species, for example [20], [29], [30], [31]. The limit defined by Kehl [31] later appeared in the technical WTA bulletin [32].

The WTA rule [32] is defined for solid wood and glulam and a critical 10 mm wood layer is assessed. The relative humidity of air in the pores inside the wood product must not exceed the line between 95 % at 0 °C and 86 % at 30 °C on a daily average, see Fig.8. More detailed information can be found in [31], [32].

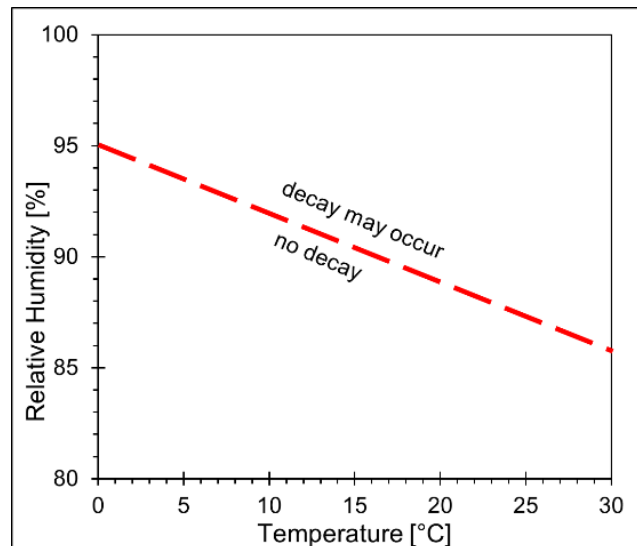


Fig.8. The WTA [32] rule for decay fungi development. No decay will occur below the conditions defined by the red dashed line.

Two moisture limits for fungi decay in wood were defined for the hygrothermal calculations: 1) the 20 % moisture content limit and 2) the WTA rule [32].

### 2.6.2 Simulation tools, model and materials

The WUFI 2D simulation tool [21] was used to simulate moisture and heat transport through the curtain wall over a long time period. The WUFI 2D was developed based on the work [33].

The model for a timber frame is shown in Fig. 9 with a description of materials and boundary conditions. Only one half of the unitized curtain wall frame is modelled due to the axis of symmetry. Most of the material properties used in the hygrothermal simulations are from the WUFI database [21]. If the WUFI database did not have the necessary material (e.g. aluminium) these properties were taken from the standard EN ISO 10456 [34]. One exception was for the modified wood Accoya.

### 2.6.3 Accoya material properties

The sorption isotherm data for Accoya wood were taken from the study [35] where measured sorption isotherms were compared for different wood species. The maximum free water saturation was measured as  $568 \pm 4.1 \text{ kg/m}^3$  and the point was added to the sorption isotherm. The water absorption coefficient (the A-value) of the Accoya was measured by this test procedure [36]. The mean A-value for four samples was  $0.0074 \pm 0.0015 \text{ kg.m}^{-2}.\text{s}^{-0.5}$ . The data set for dependence of the water vapour resistance factor on moisture content was taken from the WUFI database for Eastern White Pine as the data were close to our water vapour measurement. The spot value for the Accoya diffusion resistance factor (dry cup method: 23°C and 50/93 % RH) was measured as  $302 \pm 26$ . The other hygrothermal values for the Accoya were taken from the original data sheets [37].

#### 2.6.4 Indoor and Outdoor Climate Conditions

The outdoor climate conditions were taken from the WUFI database [21] for Stockholm city. The data set was provided by Lund University. The city of Stockholm was chosen because the average annual outdoor air temperature is only 6.8 °C (winter minimum -18.6 °C and summer maximum 29.4 °C) and the average annual relative humidity is 78.6 %. Radiation data were not applied on the exterior curtain wall surface. These conditions, without radiation, are on the safe side because the curtain wall may face north or be shaded by another building. Rain was simulated as the penetration of the EPDM gaskets only, no rain absorption was applied on the exterior surface due to materials (glass, aluminium, EPDM) with no water absorption. The leaking exterior EPDM gaskets are a common occurrence for curtain walls [16]. Rainwater leakage through the first curtain wall barrier was incorporated in the same way as the water leakage in the study [38]. In the simulations, the surface of timber nose absorbs 0 %, 1 % and 5 % of the rain precipitation.

Indoor conditions were taken from the standard [39] for the normal moisture load +5 % RH for residential and office buildings. All simulations were done for five years with a one hour step.

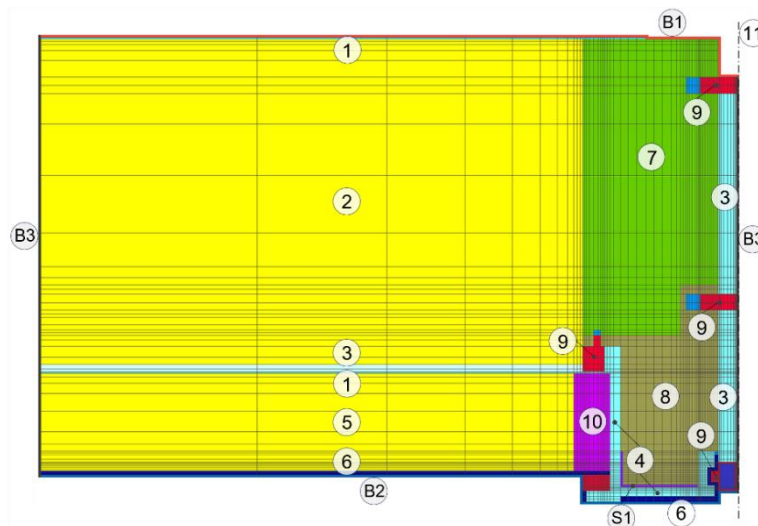


Fig.9. The model of a curtain wall mullion with an opaque panel. Legend: B1 – indoor conditions, B2 – outdoor conditions, B3 – adiabatic boarder, S1 – source of moisture, 1 – steel sheet, 2 – thermal insulation, 3 – unventilated air cavity, 4 – ventilated air cavity, 5 – thermal insulation, 6 – aluminium sheet, 7 – spruce glulam, 8 – Accoya glulam, 9 – EPDM gaskets, 10 – hard board, 11 – axis of symmetry

#### 2.7 Fire Propagation Test

There are not many published studies that focus on fire testing of whole curtain walls, e.g. [40], [41]. Fire tests mainly focus on individual curtain wall elements such as glazing [42] or spandrel panels [43]. Furthermore, there is no international ISO or EU standard for testing fire propagation on or within curtain wall systems [44], [45], [46]. There are several technical standards (for example ISO 13785 or BS 8414-2) that describe fire propagation test methods but only for claddings or for external wall insulation systems. In the mentioned study [41], a three-storey fire test facility was developed to provide full-scale fire propagation tests. In the study [40], the standard fire method EN 1364-3 was applied to test fire-resistant curtain walls, but the method is not suitable for testing fire propagation. Taking into account all the above information, the ISO 13785-1 standard method [24] was finally selected for the test because the method can give a very good overview of curtain wall performance when exposed to heat from a simulated external fire with flames impinging directly upon the curtain wall.

### 2.7.1 Specimen and materials

Four curtain wall units (EL1, EL2, EL3, EL4) were manufactured to represent the unitized curtain wall system. The units were fixed to a steel support frame and formed an L-shaped nook of the curtain wall with a total height of 2.4 m and a total width of 1.2 m plus 0.6 m. The photo of the specimen is shown in Fig. 10 with the units and thermocouples marked. The EL1 and EL2 units (0.69 m x 1.2 m) were straight with a typical triple insulation glazing for the EL1 and for the EL2 unit with opaque assembly (double glazing, 30 mm and 140 mm of rock wool thermal insulation, 1.5 mm steel sheet and 12.5 mm gypsum board). The EL3 and EL4 units were similar. Both were a corner L-shape with dimensions of 0.51 m plus 0.6 m x 1.2 m. The assembly of the units EL3 and EL4 was from the exterior: 2.0 mm aluminium sheet, 190 mm of rock wool thermal insulation, 1.5 mm steel sheet and gypsum board. The mullions and transoms were made from the Accoya and spruce glulam in the same way as in the previous mechanical and moisture tests but with one difference. The recommendations for not spreading fire through wooden facades [23] have been implemented and all surfaces of timber frames were treated with a fire-retardant coating, which was used in the study [47].



Fig. 10. The specimen of the timber curtain wall during the 46<sup>th</sup> minute of the fire test. The marking of thermocouples and the curtain wall units were added to the photo.

### 2.7.2 Test apparatus

The geometry of the test apparatus was designed according to the technical standard [24]. The 100-kW burner was placed 250 mm below the bottom edge of the tested curtain wall. Twenty-seven thermocouples (type K) for continual monitoring of temperature were placed on the exterior surface and inside of the specimen, see Fig.10. The heat flux meter was placed at the top of the specimen. The temperature and heat flux were monitored after the ignition of the burner. A video recording was made of the entire test. The test was interrupted after 30 minutes for the standard evaluation. After a 30-minute pause, the test resumed, and the burner intensity was increased to 167 kW. The test was terminated after a net 90 minutes of time. The test was conducted indoors at 23 °C and 35 % relative humidity.

## 3 Results

### 3.1. Results of four-point bending test

The results of the test are:

- The timber mullion collapsed at a maximum load of 35-49 kN, see Fig.11. These values were expected from pre-calculated results.
- Tension crack failures were observed on all three samples, see Fig. 12. No shear cracks appeared in the glued lines between the two different types of wood.

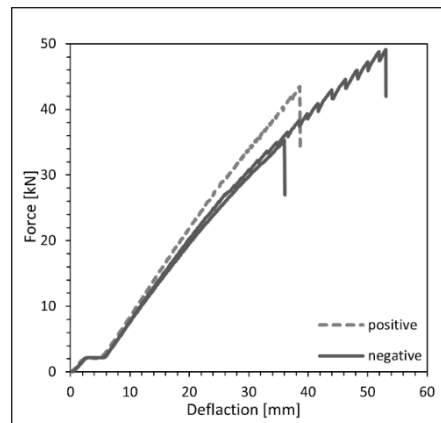


Fig. 11. Results from the bending test. Positive simulates wind pressure, negative is for wind suction.



Fig.12. The four-point bending test - destruction of timber mullion.

3.2. Bearing capacity of the frame nose

The results of the test are:

- None of the nine specimens had a failure at the connection between the two types of wood. The cracks of the samples had the expected shape, see Fig. 13.
- Maximum power before collapse for the frame nose was 3.5-5.5 kN depending on the cracking distance, see Fig.14.

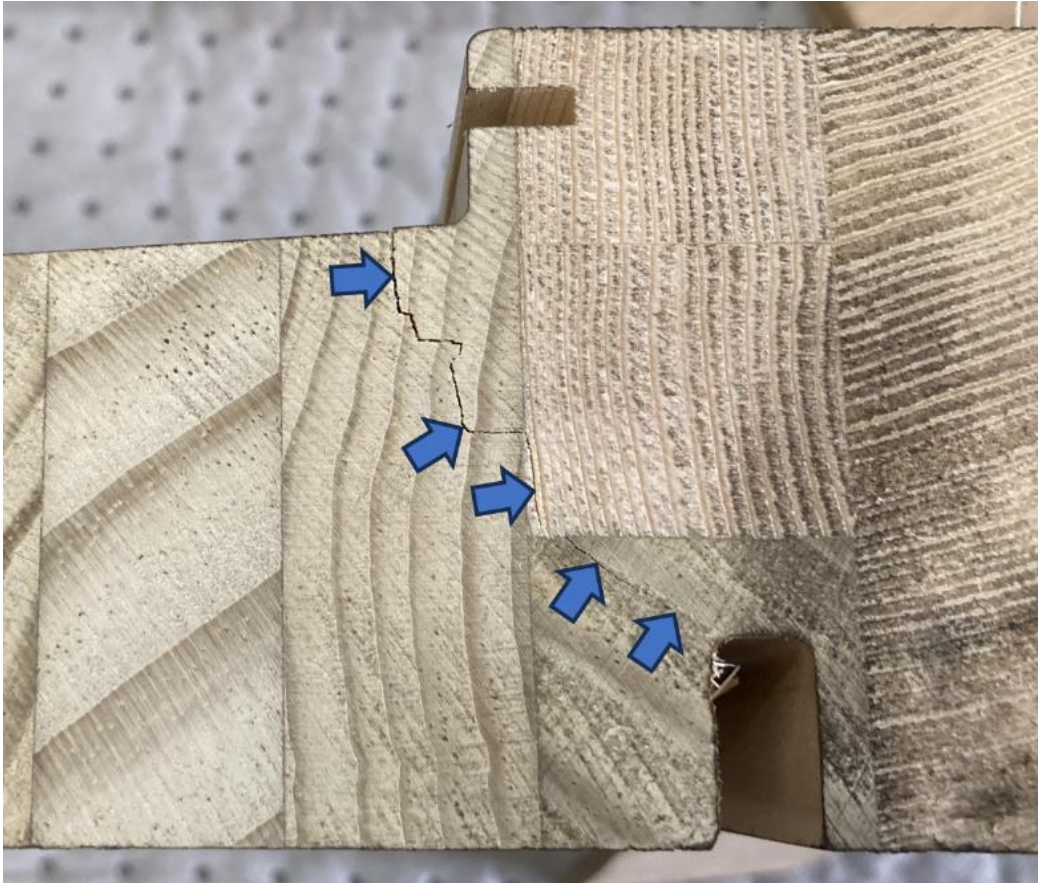


Fig. 13. Typical cracking pattern shown by arrows.

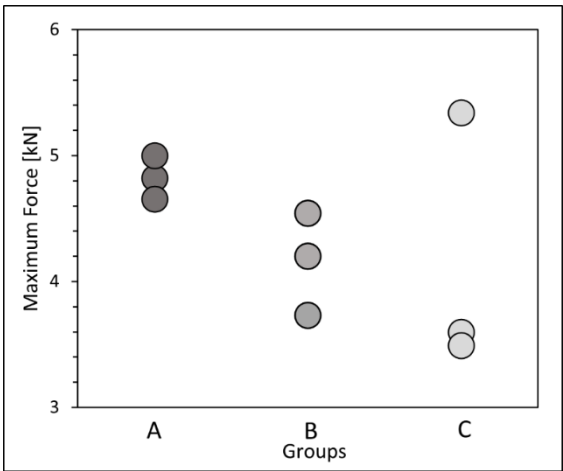
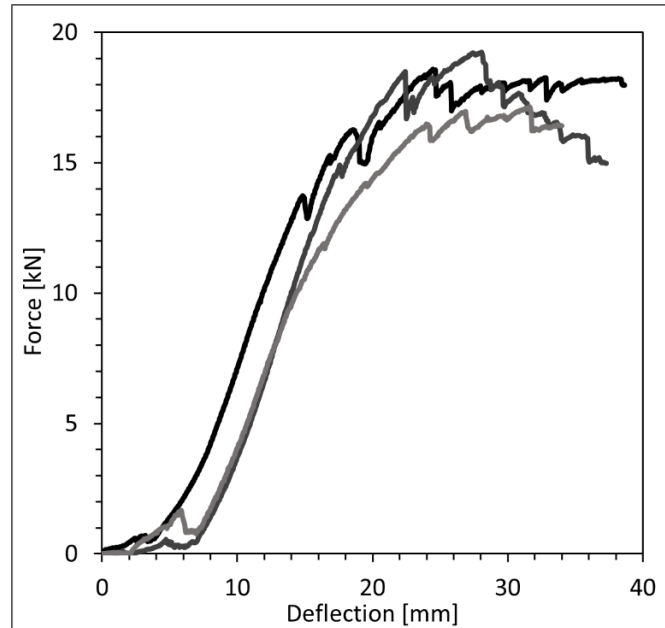


Fig. 14. Maximum force before the collapse of the nine samples. Group A: cracking distance 45 mm, group B: 41 mm, group C: 38 mm.

### 3.3. Measurement results of the strength of sheared connection

The results of the tests are shown in Fig. 15. The main highlights are:

- The test results were not satisfactory. The weakest part of the system was the corner connection and not the nose of the timber profile. Based on the results, the corner connection was redesigned (not the subject of this article)
- None of the specimens had a crack at the connection of the two types of wood.
- The nose of the profile sustained a much greater load than in the previous test



*Fig. 15. Results of the sheared connection test for the three samples.*

### 3.4. Delamination test results

The result of the test was that all four samples after the boiling cycle had shown no glue line opening, as can be seen for one sample in Fig.16. Accoya wood showed a significantly strong resistance to rapid changes in moisture content compared to spruce wood, as is clearly shown in Fig. 16.



*Fig.16. One sample of glulam timber before (left) and after (right) the boiling test. The other three samples looked very similar.*

### 3.5. Results of wood warping test

The following dimensions of the mullion were measured in the centre and at ends after each period of different environmental conditions, see Fig. 17. The average values for shrinkage and swelling of the mullion in longitudinal and perpendicular to grain directions are given in Tab. 2. Different types of wood warping (bow, crook, cup, twist), cracks and delamination of open glue lines were observed. Wood warping values were measured in the middle of mullion (bow, crook) and at the end of the mullion (cup, twist). The values are also given in Tab. 2.

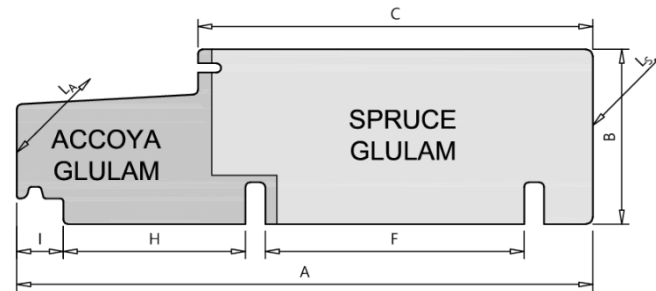


Fig. 17. Measured dimensions in the wood warping test.

No.	Direction/measurement	Measurements related to environment numbers					
		1	2→1	3→1	4→3	5→3	6→3
Shrinkage (-)/Swelling (+) in [%]							
Ls	Longitudinal, Spruce side	0	0.04	0	0,04	0	0
La	Longitudinal, Accoya side	0	0.04	0	0,08	0,04	0,02
A	Cross-grain, Spruce + Accoya	0	1.3	-0.1	2.9	1.0	0.2
B	Cross-grain, Spruce	0	1.2	-0.4	2.9	0.4	0
C	Cross-grain, Spruce	0	1.8	-0.3	4.6	1.1	0.1
F	Cross-grain, Spruce	0	2.0	-0.2	4.8	1.3	0.1
H	Cross-grain, Accoya	0	0.2	0	0.5	0.2	0
I	Cross-grain, Accoya	0	0.7	0.5	0.2	0.5	-0.3
Wood warping [mm]							
	Warping – bow (middle)	0	0	0	1.5	1.0	0
	Warping – crook (middle)	0	1.5	<0.5	2.0	2.8	1.0
	Warping – cup (bottom end)	0	0	0	<0.5	2.0	<0.5
	Warping – twist (bottom end)	0	0	0	0	0	1.0

Tab. 2. Results of wood warping test.

The main results of the test are:

- The swelling of the mullion after the wet period was insignificant - less than 1 % in the longitudinal direction and up to 2 % in the perpendicular to the grain direction. A 1.5 mm wood crook appeared in the middle of the mullion. No delamination or cracks were observed.
- Almost all dimensions of the mullion and wood warping returned to their initial values after the first standard office period. The spruce part of the glulam showed even lower than the initial values. Twelve drying cracks were observed in the spruce part of the glulam. The Accoya part showed no drying cracks.
- The swelling of the mullion after the 32-day water bath was insignificant for longitudinal direction (less than 1 %). Swelling for cross-grain directions was up to 5 % for the spruce part of the glulam. The Accoya part had much lower values up to 0.5 %. Wood warping (bow, crook, cup) appeared. One crack was observed in the Accoya part.

- The mullion was dried for 32 days in a vertical position (the second standard office period) and then turned over and dried for another 44 days. Changes in dimensions of the mullion and in the wood warping were insignificant at the end of the whole drying period. One crack in the Accoya part was observed and several others drying cracks were found in the spruce part of the glulam. Also, five 5-25 cm long delamination cracks in glue lines were found in the spruce part.

### 3.6. Results of hygrothermal simulations

- 1) First, several hygrothermal simulations were done for various details of the curtain wall such as: a frame with two triple glazing insulation units, a frame with one triple glazing insulation units and with an opaque insulation assembly and a frame with two opaque insulation assemblies. These initial simulations showed that maximum moisture accumulation in the timber frame is in the detail with two opaque assemblies and this is the critical detail, see Fig. 18. The details with one or two glazing units have lower moisture content due to drying moisture out of the timber frame to the interior environment. Therefore, all the following simulations were done for this critical detail only.

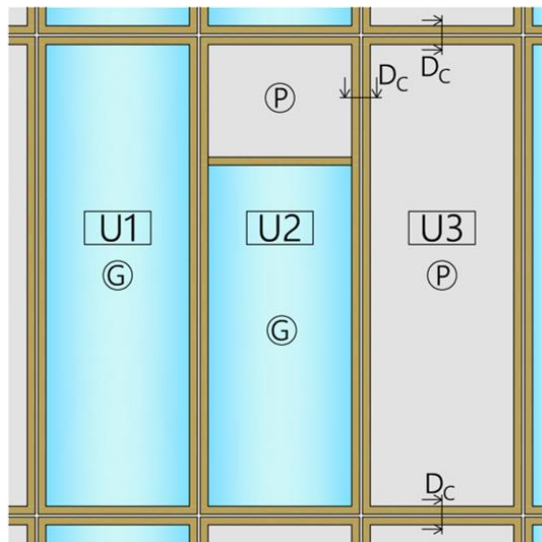


Fig. 18. Front schematic view of the unitized curtain wall with three different units. Unit U1 – all-glass unit, U2 – partially glass unit, U3 – fully opaque unit, G – glazing, P – opaque panel, Dc – critical detail.

- 2) The critical detail was calculated with a different fraction (0 %, 1 %, 5 %) of precipitation which hit the nose of the timber profile. Differences in the amount of moisture content in the spruce glulam were insignificant. The next calculations were done only with the penetration of 5 % fraction of rain.
- 3) The critical area in the timber frame is the area in the spruce glulam close to the material connection with the Accoya wood. Fig.19 shows the three resulting curves: 1) the total moisture content in the spruce glulam; 2) the mean value of the moisture content at the intersection line of Accoya and spruce glulam; 3) the mean value of moisture content in a 10 mm spruce layer next to the connection Accoya/spruce wood. All three curves are significantly below the 20% moisture content limit for the whole calculation period and the trend for all three curves is decreasing therefore the 20% criterion is met.
- 4) Fig. 20 shows relative humidity in the spruce pores in the 10 mm layer next to the material intersection during the five-year period. This approach is according to the WTA [32]. The relative humidity in spruce pores is significantly below the red dashed line, so the WTA rule for wood decay is also met.

- 5) Both criteria for the decay development in the wood are fulfilled during the calculation period as no decay will occur in the spruce glulam.
- 6) In addition, Fig. 21 shows moisture content in  $\text{kg}/\text{m}^3$  for the materials used and for the whole curtain wall detail. All the curves are degressive, meaning that moisture is drying out of the detail. The peaks in the Accoya curve are caused by precipitation.

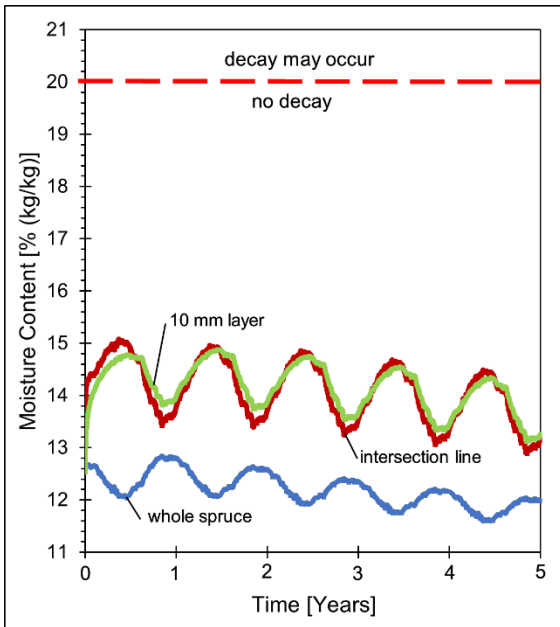


Fig. 19. Moisture content in spruce glulam over 5-year period and critical moisture limit

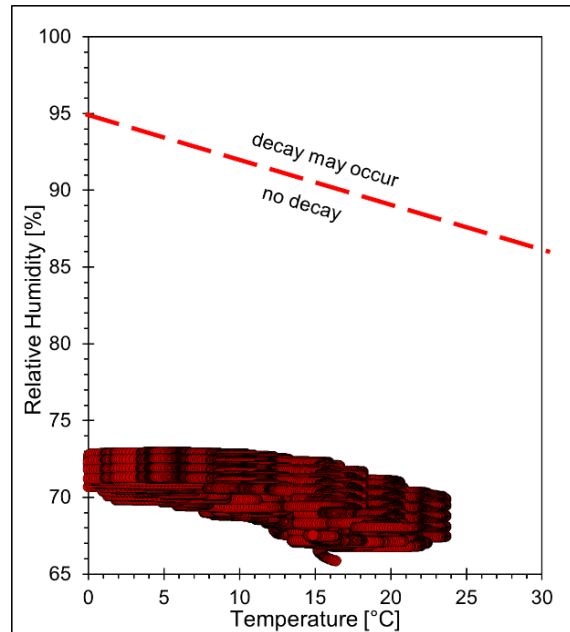


Fig. 20. Relative humidity in spruce wood pore over 5 years and critical moisture limit according to [32].

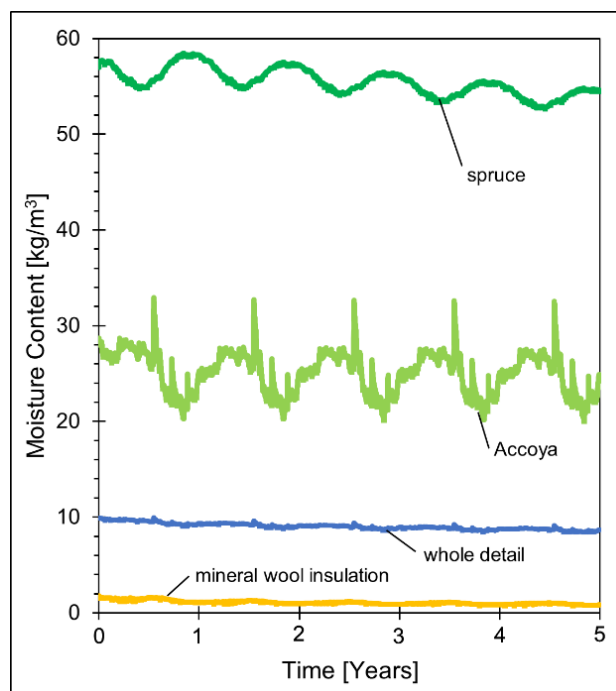


Fig. 21. Moisture content in materials and in the whole wall detail over 5 years.

### 3.7. Results of fire propagation test

The results of the test are shown for surface temperature in Tab.3. The temperatures measured in the middle of the cavity/insulation are in Tab.4. The main findings are:

- Fire propagation did not appear visually within the curtain wall for the whole period of the test. The bottom parts of the curtain wall (EL2, EL4) were heavily charred and the aluminium cover caps were melted. The glazing units were without any cracks and the metal sheets were without major deformation.
- Based on the results, the curtain wall meets the requirements of the Czech national standard [48] for fire propagation. The standard requires that the average temperatures for the surfaces, for the inner insulation layers and for the cavities at a height of 0.5 m on the back wall must not exceed 350 °C during the first 30 minutes of the test.
- The requirement of the standard in the 30<sup>th</sup> minute [48] was met even in the 90<sup>th</sup> minute of the test when the burner power was increased from 100 kW to 167 kW.

Net Time [min]	Surface Temperatures [°C]													Radiation [kW.m <sup>-2</sup> ]
	Back Wall						Side Wall							
	height of TC above bottom [m]													
	0,5			1,0	1,5	2,0	2,4	0,5	1,0	1,5	2,0	2,4		
TC <sub>20</sub>	TC <sub>21</sub>	TC <sub>22</sub>	T <sub>av</sub>	TC <sub>23</sub>	TC <sub>24</sub>	TC <sub>25</sub>	TC <sub>26</sub>	TC <sub>40</sub>	TC <sub>41</sub>	TC <sub>42</sub>	TC <sub>43</sub>	TC <sub>44</sub>		
0	24	24	24	24	24	24	24	24	25	24	25	24	24	0.0
10	44	64	104	71	48	45	40	43	117	80	71	60	61	0.7
20	53	82	152	95	59	53	46	44	149	104	90	80	73	0.6
30	53	82	157	98	61	53	46	44	144	104	90	81	73	0.6
40	78	134	281	164	84	69	57	61	242	144	122	102	98	1.7
50	115	192	350	219	116	93	73	70	291	184	149	129	117	1.4
60	144	204	353	234	127	101	81	74	265	178	145	129	115	1.4
70	120	152	427	233	104	80	68	63	298	195	159	135	120	1.5
80	182	183	467	277	121	94	77	73	385	259	203	169	150	1.9
90	188	235	540	321	145	108	88	82	363	253	200	178	159	2.3

Tab. 3. Surface temperatures for the back wall and the side wall of the specimen

Net Time [min]	Temperatures in the middle of cavity/insulation [°C]															
	Back Wall							Side Wall								
	140 mm of Insulation			Hor. Cav.	Win. Cav.	50 Insul.	Vertical cavity		Hor. Cav.	140 Insul.	50 Insul.	140 Insul.	50 Insul.			
	Height of TC above bottom [m]															
0.5			1.2	2.3	0.5	0.5	1.1	1.3	2.3	1.2	2.3	2.3	0.5	0.5		
TC <sub>27</sub>	TC <sub>28</sub>	TC <sub>29</sub>	T <sub>av</sub>	TC <sub>30</sub>	TC <sub>31</sub>	TC <sub>32</sub>	TC <sub>33</sub>	TC <sub>34</sub>	TC <sub>35</sub>	TC <sub>36</sub>	TC <sub>45</sub>	TC <sub>46</sub>	TC <sub>47</sub>	TC <sub>48</sub>	TC <sub>49</sub>	
0	25	25	25	25	25	26	26	25	25	25	26	24	25	26	24	26
10	25	26	25	25	25	26	27	25	25	25	27	24	25	26	25	27
20	25	26	25	25	25	27	32	26	25	25	27	24	25	27	25	32
30	25	26	25	26	25	27	37	28	25	25	27	25	25	29	25	38
40	27	29	28	28	26	28	53	40	26	27	29	27	26	31	30	54
50	27	30	30	29	26	28	81	51	26	27	31	28	27	34	33	81
60	28	31	32	30	27	28	84	58	27	28	31	30	27	37	36	89
70	30	34	36	33	29	30	98	76	28	28	31	31	28	40	41	90
80	33	37	41	37	30	31	134	87	30	29	33	32	29	44	45	100
90	37	43	49	43	30	32	238	100	32	30	34	33	29	48	53	100

Tab. 4. Temperatures in the middle of the insulation/cavity on the back wall and on the side wall.

#### 4 Discussion and further work

All three mechanical tests were carried out as expected with a sufficient number of samples. No shear cracks appeared in the connection line between the two different woods. We expected a better result in the bearing capacity of the profile nose in the second mechanical test. This was caused due to the small sample width of only 300 mm. The following mechanical test showed much better results with the same loading method but with a sample width of 750 mm.

The delamination test showed surprisingly excellent moisture resistance of the Accoya wood compared to the spruce wood, see Fig. 16.

The warping test procedure was designed by us to obtain information about the behaviour of the timber profile under different moisture conditions. In hindsight and with more time, all testing periods could have been longer. Especially the initial period (2 days) was very short and before this the specimen was stocked in a hall with non-measured conditions. The water bath for the specimen mullion was an extreme situation which the curtain wall would never encounter but the test gave us knowledge of how the timber mullion would behave during these conditions. The presented deformation of the timber mullion after the bath period may be misleading as the specimen was held under water level by a weight placed in the middle of the specimen. The warping test was done with only one sample. This is not sufficient for any measurement, but given the previous results from the other tests, we expect that using more samples for the warping test would not produce significant different results. All samples for both moisture tests were without any coating. A wood coating would significantly reduce moisture absorption. The water absorption coefficient measured according to this procedure [36] for the Accoya wood without coating is  $A = 0.0074 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-0.5}$  and with a coating [47]  $A = 0.0029 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-0.5}$ . The results for spruce wood with the same procedure are for spruce without any coating  $A = 0.0070 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-0.5}$  and with a coating  $A = 0.0031 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-0.5}$ . These results show that the curtain wall timber frame with a coating absorbs less moisture over time than a timber mullion without any coating. Therefore, the deformation of the timber mullion with a coating should be lower than the results presented in Tab.2. It is good to mention that the presented values for the wood deformation are significantly lower than the expected values of deformation due to wind load.

The hygrothermal simulations appear to be a good tool to determine the critical moisture content in materials for a specific location but the hygrothermal simulations require the knowledge of material properties and the requirements for critical moisture content in wood must be clearly defined, as the building industry requires simple and precise results. For example, the widespread 20 % moisture content limit does not say if this is the average value for a whole timber beam, or if the 20 % limit must be met at every point in the wood during the whole service life. The WTA rule for wood decay [32] is more accurate as it evaluates the average value in a critical 10 mm thick layer over time. The moisture critical limits are still a huge opportunity for further work.

The simulation model of the curtain wall detail is simplified in the following main points:

- 1) A wood coating of the timber mullion is not considered in the hygrothermal simulations. The wood coating can significantly affect the absorption of water vapour and liquid water from the outer environment. The effect of the coating on water absorption has already been mentioned. Due to this affect the results are on the safe side. The study [8] shows that a very high diffusion resistance of a coating leads to a high level of moisture accumulation in wood and slows the potential for wood drying. The used fire-retardant coating has the water vapour diffusion thickness ( $s_d$ -value) of 0.59 m according to [47]. This  $s_d$ -value is quite low, very close to the reference value  $s_d = 0.5 \text{ m}$  from [8] for a coating, therefore neglecting the fire-retardant coating will not have a significant effect on the results.

- 2) Another inaccuracy in the model is the neglect of glue lines between timber slats. The glue line creates a very thin layer ( $\approx 0.1$  mm) of a different material and can reduce moisture transport [49]. The effect of the glue line is important for designing laminated products for exterior applications mainly in wet climates [49]. The results of the simulations while neglecting the effect of the glue line are on the safety side because moisture transport is not slowed down by the glue lines, and moisture can accumulate faster in colder parts of the timber frame. There is very rare experimental data on moisture diffusion properties of various adhesives [49], so there is room for the further work.
- 3) Moisture and heat transport in the timber curtain wall mullion is simulated in critical detail as it is two-dimensional only with the cross-grain direction of the glulam. In reality, moisture and heat transports are three-dimensional. Moisture vapour transport is faster in the longitudinal direction than in the cross-grain direction, therefore the critical detail of the timber mullion can dry out faster through the longitudinal direction of wood. This simplification is again on the safe side.
- 4) The hygrothermal simulations were done with water penetration through EPDM gaskets with 0 %, 1 % and 5 % fraction of the rain precipitation and the presented results are with a penetration of 5% fraction of rain. There is little data on water leakage through the first weather barrier of curtain walls. One measurement for a stick curtain wall was done in [16] and the results for other building walls and windows are presented here [50]. The results indicate that the infiltration rates for the flawless curtain wall was 0.2 % - 0.3 % but for a window-wall interface with a 90 mm slit in the sealant the rate jumped to 3 % - 5 %. Therefore, the used value of 5 % for the simulations seems to be a reasonable value because a popped EPDM gasket is a very common defect for curtain walls.

The presented results of the simulations of heat and moisture transport in the critical detail are significantly below both limits for wood decay. Several other calculations were done for the same detail but not all results were on the safe side. For example, the 20 % moisture content limit was exceeded for a hybrid timber system. It is a pity that the wood decay issue is not mentioned in the study [8] which is focused on a hybrid timber system. It is important to always provide the assessment of moisture accumulation in timber or in hybrid curtain wall systems to avoid wood decay. This assessment should be as common as the curtain wall assessment for the risk of mould growth on the interior surface.

Reality can differ from hygrothermal simulations therefore a wooden lab was built to provide measurements with real weather conditions. Several 2.5 m high curtain wall unit prototypes were made from different woods with different coatings and placed into the lab, see Fig.22. As moisture transport is a very slow phenomenon, results are expected within 3-5 years.



*Fig. 22. Interior view of the wooden lab with different timber curtain wall units.*

The fire propagation test for claddings or for external wall insulation systems was used to see the behaviour of the curtain wall during a fire as there is no standard fire propagation test for curtain walls. The use of this fire test method can be the way how to do fire propagation testing for curtain walls in the future.

Building on the findings of this study, our next research will focus on the development of a timber unitized curtain wall with the structural silicone glazing system.

## **5 Conclusions**

A unique timber unitized curtain wall system with the world-first timber only frame was developed. The frame is made from glued laminated timber and the protection barriers against weathering is done with acetylated wood (the Accoya) slats and an aluminium pressure plate.

The integrity of the glued laminated timber profile with two different woods (spruce and the Accoya) was tested by three mechanical tests. The results of the tests revealed good resistance of the timber mullion to loads – no shear cracks at glue lines appeared. The integrity of the profile was also tested by the moisture delamination test. The results from the test showed no drying cracks at the connection of the spruce glulam and the Accoya, and the Accoya wood showed a significantly strong resistance to quick changes in moisture content compared to spruce wood.

A warping test procedure was developed, and one 2.5 m long timber mullion was tested. The final deformation of the mullion caused by the different moisture conditions was insignificant compared to the expected timber deformation due to the wind load even though extreme moisture conditions were applied.

Hygrothermal simulations of heat and moisture transport through the building materials were made for the critical detail of the timber curtain wall to evaluate the risk of wood decay. The presented results revealed that both defined criteria for the wood-decay fungi development were safely met. The results from the simulations and moisture tests confirmed that the timber frame did not need any coating against water leakage.

There is not yet an international standard test for fire propagation on and within the curtain wall system. A medium-scale fire testing method for cladding and for external thermal insulation compact systems was used to test fire propagation within the timber curtain wall system. The results of the test showed that fire did not spread on and within the curtain wall with the timber only frame protected by the fire-retardant coating, even during the 90<sup>th</sup> minute of the test with increased power of the burner.

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