

THE INFLUENCE OF TIMBER DECAY ON THE LOAD-BEARING CAPACITY OF CLT ELEMENTS IN BELGIUM

Word count: 27549

Hannes Renette

Student number: 02410941

Supervisor(s): Prof. Dr. Ir. Nathan Van Den Bossche, Prof. Dr. Ir. Jan Belis and Ir. Anke Blommaert

A dissertation submitted to Ghent University in partial fulfilment of the requirements for the degree of Master in science
in Civil Engineering

Academic year: 2025 – 2026

PREFACE

This thesis presented in this document marks the completion of my master program in Master of Science in Civil Engineering at Ghent University.

This research was conducted between August 2025 and June 2026 partly at Lund University in Sweden and partly at Ghent University in Belgium.

After writing a first thesis at KU Leuven and Vilnius Tech, a deep fascination for biobased materials grew and lead to a second thesis about timber and a second exchange to a renowned university for advanced timber structures.

This time I specialised more in the material timber rather which allowed me to encounter the material from a lot of different perspectives and expanding my knowledge remarkably.

This was not possible without the help of several important people in this process.

I firstly want to thank Prof. Jan Belis for aiding me with the structural calculations, inspiring brainstorming and all the help.

I also want to thank Anke Blommaert for helping me and supporting me through this whole journey with all the hygrothermal simulations and the freedom she gave me to interpret this topic to the final product.

I want to express my gratitude to Prof. Nathan Van Den Bossche as well for the freedom and help with the hygrothermal simulations.

From Lund university I would like to appreciate the help of Dr. Jonas Niklewski for the aid and discussions about decay processes.

I also would like to acknowledge the aid of engineering office Houtvast from Belgium for sharing their plans, calculation notes and expertise in modelling CLT structures with me.

And finally, I want to thank my parents, brothers, partner Trees and friends for aiding and supporting throughout this journey by making the last six years the most beautiful, interesting and enlightening period of my life where I grew and expressed myself to the person I am today .

APPROVAL FOR LOAN

The author gives permission to make this master dissertation available for consultation and to copy parts of this master dissertation for personal use. In all cases of other use, the copyright terms have to be respected, in particular with regard to the obligation to state explicitly the source when quoting results from this master dissertation.

Hannes Renette 25/05/2026

EXPLANATORY NOTES ON THE ORAL PRESENTATION

This master's dissertation is part of an exam. Any comments formulated by the assessment committee during the oral presentation of the master's dissertation are not included in this text.

THE INFLUENCE OF TIMBER DECAY ON THE LOAD-BEARING CAPACITY OF CLT ELEMENTS AND CONNECTIONS IN BELGIUM

Author: Hannes Renette

Student number: 02410941

Supervisors: Prof. Dr. Ir.-Arch. Jan Belis, Prof. Dr. Ir.-Arch. Nathan Van Den Bossche, Ir.-Arch. Anke Blommaert

A dissertation submitted to Ghent University in partial fulfilment of the requirements for the degree of Master of Science in Civil Engineering.

Academic year: 2025–2026

Abstract

This master's dissertation investigates the influence of fungal decay on the load-bearing capacity of Cross Laminated Timber (CLT) elements and connections under Belgian climatic conditions. The study combines four established models in a single workflow: hygrothermal simulations in Delphin to obtain layer-wise moisture and temperature profiles, the daily-dose model of Brischke & Rapp (2008) with the logistic parameters of Isaksson et al. (2013) to quantify cumulative exposure, the mass-loss and strength-loss models of Hradil & Fortino (2023) and Bollmus et al. (2020) to translate the cumulative dose into reduced characteristic strengths, and a structural verification according to EN 1995-1-1. The workflow is applied to the reference building of engineering office Houtvast in Boortmeerbeek, considering two limit states (SLS and ULS), three structural elements (wall panel, roof panel, screwed wall–roof connection) and 48 configurations combining rot type, exposure duration, layup and wall and roof insulation.

The results show that the Serviceability Limit State of CLT floors is significantly affected by decay: a moderate loss of roughly 10 mm of the outer lamella or a 36% reduction of the modulus of elasticity is already sufficient to exceed the $L/300$ deflection limit. The Ultimate Limit State of CLT wall panels is only mildly affected, with the utilisation ratio increasing from 0.71 to 0.77 in the worst case, and the governing layer shifting from the outer lamella in three-layer panels to the central lamella in five-layer panels because vapour-tight MUF adhesive layers trap moisture inside the cross-section. The ULS of CLT roof panels remains essentially unaffected (utilisation 0.46 in all scenarios) since the outer governing lamella is protected by the bitumen roof finishing. The screwed wall–roof connection is the most decay-sensitive component, with a design-capacity loss of up to 15 % under brown rot and long-term moisture exposure, exceeding the available design margin of a standard EN 1995-1-1 detail. A One-At-a-Time sensitivity analysis ranks the design factors as follows: rot type ($S = 0.0677$), exposure duration ($S = 0.066$), number of CLT layers ($S = 0.0286$, but conditional), wall insulation ($S = 0.006$) and roof insulation ($S = 0$). The study concludes that durability assessment of Belgian CLT structures should focus primarily on the SLS of floors and the ULS of the wall–roof connection, rather than on the panel ULS that currently dominates design practice.

Keywords — Cross Laminated Timber (CLT), timber decay, hygrothermal simulations, load-bearing capacity, dose-response model, sensitivity analysis

The influence of timber decay on the load-bearing capacity of CLT elements in Belgium

Hannes Renette

Supervisor(s): Prof. Dr. Ir. Nathan Van Den Bossche, Prof. Dr. Ir. Jan Belis, Ir. Anke Blommaert

Abstract— This master’s thesis investigates the influence of fungal decay on the load-bearing capacity of Cross Laminated Timber (CLT) elements and connections under Belgian climatic conditions. Hygrothermal simulations in Delphin provide layer-wise moisture and temperature profiles for a reference single-family CLT building. These profiles are translated into a cumulative decay dose, a reduction of the timber’s characteristic strengths, and finally a structural verification according to EN 1995-1-1. Two limit states are considered (Serviceability and Ultimate Limit State) for the element verification and 48 configurations are compared for the wall-to-roof connection. The Serviceability Limit State of the floors is the most decay-sensitive limit state, the panel Ultimate Limit State is only mildly affected, and the screwed wall–roof connection is the governing component for the durability check. A One-At-a-Time sensitivity analysis identifies rot type and exposure duration as the dominant design factors, while the choice of insulation has essentially no effect on the connection capacity.

Keywords— Cross Laminated Timber, timber decay, hygrothermal simulations, EN 1995-1-1, dose-response model, sensitivity analysis

I. INTRODUCTION

The use of CLT as a structural material for low- and mid-rise residential buildings is growing rapidly in Europe. CLT combines a high strength-to-weight ratio, extensive prefabrication and acts as a carbon sink. However, CLT panels are susceptible to long-term moisture exposure and to the fungal decay that follows it. Belgium has been identified as one of the European regions with the highest decay risk for above-ground timber [1] and recent local most notably the residential balconies in Sint-Truiden cases as illustrated in Figure 1 that

had to be demolished after only seven years of service , confirm that this risk is not merely theoretical.



Figure 1: Decay –deteriorated balcony
<https://www.vrt.be/vrtnws/nl/2022/05/10/appartementen-met-houtrot-in-sint-truiden-worden-best-afgebroken/>

Current design practice in Belgium nevertheless lacks a transparent framework that links the moisture exposure of a CLT element to its residual structural capacity. EN1995 covers neither CLT specifically nor decay-related strength reductions. This thesis addresses that gap by building an end-to-end methodology that translates a realistic Belgian moisture exposure into a quantified loss of load-bearing capacity, both for CLT panels and for the wall–roof connection.

II. METHODOLOGY AND MATERIALS

The workflow of the dissertation, summarised in Figure 2, runs as a chain. A hygrothermal simulation in Delphin produces the daily-average moisture content and temperature of every CLT lamella under encapsulated building-moisture conditions and a Moisture Reference Year representative of Brussels. The moisture and temperature time series feed the daily-dose model of Brischke-Rapp [2] with the logistic parameters of Isaksson et al. [3] to obtain a cumulative decay dose per lamella. The cumulative dose is translated into a mass loss using the model of Hradil and Fortino [4] and into reduced bending and compressive characteristic strengths using the model of Bollmus et al. [5]. The reduced properties are then introduced into a structural verification of the CLT panel and the screwed wall-to-roof connection according to EN 1995-1-1 [6].

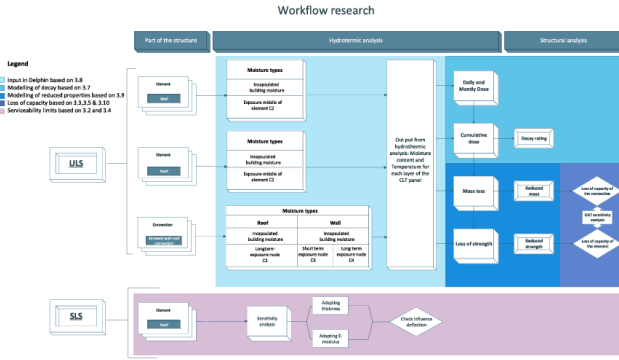


Figure 2: Workflow research

A. Reference building and elements

The reference building, see in Figure 3 is a single-family CLT structure designed by the engineering office Houtvast in Boortmeerbeek (Belgium).

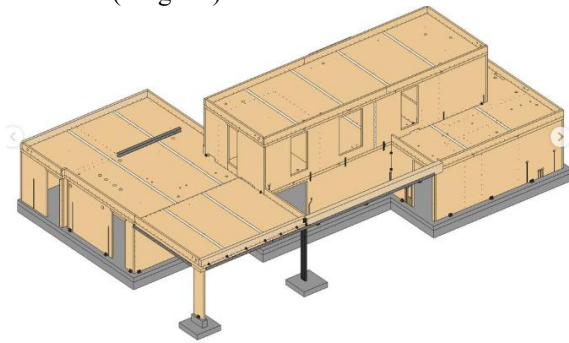


Figure 3: Reference building

Three CLT elements are considered and presented in Figure 4:

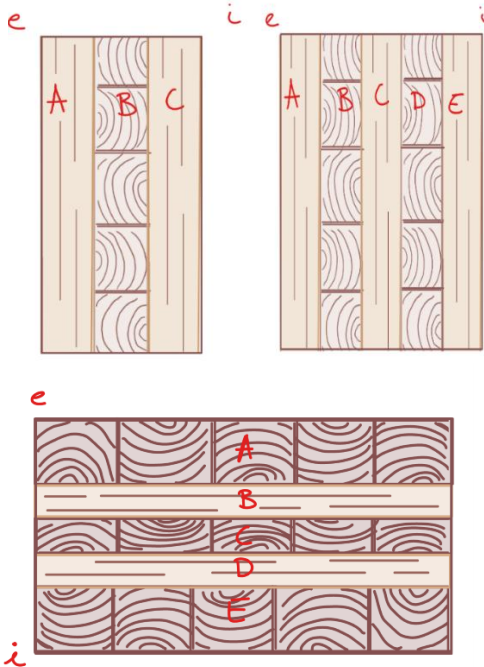


Figure 4: a) CLT100L3S b) CLT100L5S c) CLT140L5S

a three-layer wall panel CLT100-L3s with lamella thicknesses 30/40/30 mm, a five-layer wall panel CLT100-L5s with five lamellae of 20 mm, and a five-layer roof panel CLT140-L5s.

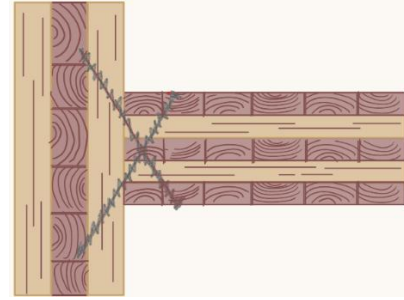


Figure 5: Wall-Roof connection

The wall-to-roof joint is a platform-frame connection executed with crossed self-tapping TBS Ø 12 × 240 mm screws at 160 mm spacing as displayed in Figure 5. This joint was designed by the author to find the influence of decay on the load-bearing performance of the connection better.

B. Moisture exposure

Two moisture sources were initially considered: encapsulated building moisture and leakages through the cavity. Preliminary simulations showed that realistic cavity leakages do not produce a measurable reduction of the load-bearing capacity, so the analysis was restricted to the encapsulated-building-moisture scenario. The initial moisture profiles per lamella are based on in-situ measurements from [7] on a CLT building exposed to Belgian outdoor conditions for more than three years and are clustered as shown in Figures 6 and 7. Cluster 2 represents the moisture content in the middle of a panel (panel verification), Cluster 3 the short-term exposure at the wall–roof joint, and Cluster 4 the long-term exposure at the same joint for the wall element. The roof is only exposed to one exposure level in the connection, namely Cluster 3.

Average Moisture per Cluster and Layer

Cluster	MC_A	MC_B	MC_C	MC_D	MC_E
4	120.2	66.6	142.1	50.2	159.5
3	32.9	33.1	122.1	30.2	31.7
2	22.7	25.8	31.1	30.1	22.8
1	20.1	18.7	17	17	17.7

Figure 6: Moisture contents wall

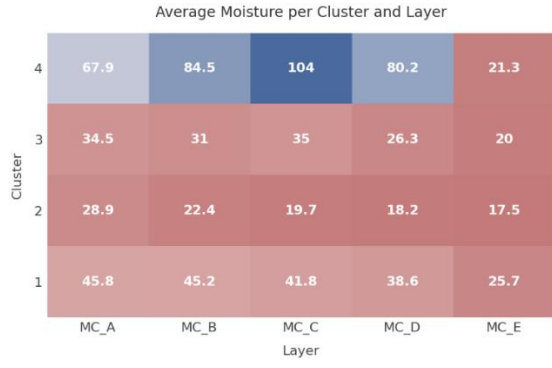


Figure7 : Moisture contents roof

C. Insulation configurations and design variables

For the wall, three insulation materials are compared: polyurethane (PUR, vapour-tight), mineral wool (MW, vapour-open and non-capillary) and cellulose (CEL, vapour-open and capillary). For the roof only PUR and MW are considered. Forty-eight connection configurations are constructed by combining five design variables: rot type (brown, white), exposure duration at the joint (short-term, long-term), wall layup (3 vs 5 layers), wall insulation (PUR, MW, CEL) and roof insulation (PUR, MW). The relative loss of design capacity $F_v, Rd, decay/F_v, Rd, 0$ is the engineering response.

D. Sensitivity analysis

A One-At-a-Time (OAT) sensitivity analysis in the sense of [8] is carried out on the 48 connection results. For each design factor X with discrete levels ℓ , the mean absolute deviation from the undamaged state is computed per level, and the sensitivity index S_x is defined as the gap between the worst and best level means. This sensitivity index is used to order the most important influence factors. OAT was preferred chosen because the response is reported in the same engineering units as in EN 1995-1-1 and because the partial-factor logic of EN 1995 (k_{mod} , k_{def} , k_{svs} , γ_m) is itself an OAT-style decomposition.

III. RESULTS

A. Serviceability Limit State of the roof

A sensitivity analysis was carried out on the CLT140-L5s roof panel by independently varying the thickness of the most-exposed outer lamella and the modulus of elasticity of the layers most affected by decay. Deflection was computed with both the Timoshenko beam theory and the gamma method (EN1995 Annex B); the difference is negligible.

Table 1: SLS sensitive analysis

Simplified Timoshenko method							Gamma method						
Modulus of elasticity for outer and centre layer E_o and E_c [MPa]	wfin	thickness outer floor layer t_0 [mm]					wfin	thickness outer floor layer t_0 [mm]					
	SC1	40	30	20	10	0	SC1	40	30	20	10	0	
	11000	15.5	19.8	26.6	40.0	79.4	11000	15.5	19.7	26.6	39.8	79.3	
	10000	16.2	20.7	28.0	42.2	83.9	10000	16.2	20.7	27.9	42.0	83.7	
	9000	17.1	21.9	29.7	44.9	89.3	9000	17.1	21.8	29.6	44.6	89.1	
	8000	18.1	23.3	31.7	48.2	95.8	8000	18.1	23.3	31.6	47.9	95.6	
	7000	19.5	25.1	34.3	52.3	103.9	7000	19.4	25.0	34.2	52.0	103.6	
	6000	21.2	27.4	37.7	57.7	114.4	6000	21.1	27.4	37.6	57.4	114.0	
	5000	23.6	30.7	42.4	65.1	128.2	5000	23.5	30.6	42.2	64.8	127.8	

The results in Table 1 show that a reduction of only 10 mm of the outer lamella is already sufficient to violate the $L/300$ deflection limit in service classes 1, while a 36 % reduction of the modulus of elasticity is required to produce the same outcome. The thickness enters the moment of inertia at the third power and the modulus of elasticity only linearly, so decay that physically removes timber is much more damaging for the SLS than decay that merely softens it.

B. Ultimate Limit State of the CLT panels

The wall-panel ULS verification under encapsulated building moisture produces a utilisation ratio of 0.71 for all six three-layer configurations (governed by the outer lamella A), and 0.71–0.77 for the five-layer panel (governed by the central lamella C). The shift in governing layer is a direct consequence of the moisture-trapping behaviour of the five-layer cross-section: the central longitudinal lamella is enclosed by two essentially vapour-tight MUF adhesive layers and retains its elevated moisture content much longer than the outer lamellae, which are free to dry inwards. PUR is the worst-performing insulation because it is the only fully vapour-tight option considered. The five-layer roof panel yields a utilisation ratio of 0.46 in all four configurations, with the outer lamella E governing the verification. Decay has no measurable effect on the ULS of the roof panel because the governing lamella is protected by the impermeable bitumen finishing ($\mu \approx 15\,000$) and never reaches a moisture content high enough to trigger a significant strength reduction.

C. Ultimate Limit State of the wall–roof connection

The 48-configuration matrix for the screwed wall-roof connection summarised in Figure 8 and Figure 9 with the legend in Table 2.

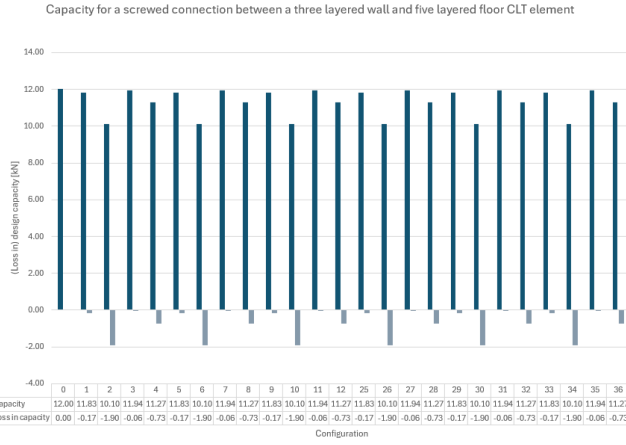


Figure 8: Capacity for the 3 layered wall and 5 layered roof connection

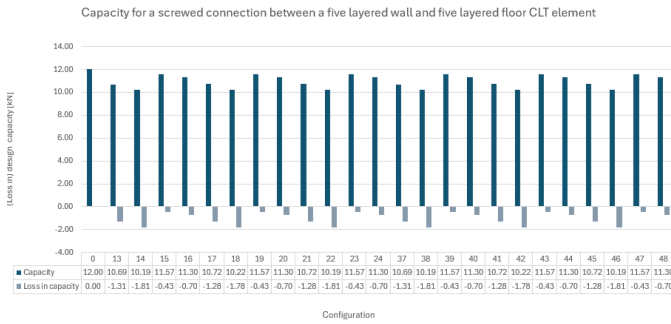


Figure 9: Capacity for the 5 layered wall and 5 layered roof connection

Table 2: Legend for Figure 8 and Figure 9

Roof PUR insulation				Roof MW insulation			
1	Wall PUR ST Brown 3L	13	Wall PUR ST Brown 5L	25	Wall PUR ST Brown 3L	37	Wall PUR ST Brown 5L
2	Wall PUR LT Brown 3L	14	Wall PUR LT Brown 5L	26	Wall PUR LT Brown 3L	38	Wall PUR LT Brown 5L
3	Wall PUR ST White 3L	15	Wall PUR ST White 5L	27	Wall PUR ST White 3L	39	Wall PUR ST White 5L
4	Wall PUR LT White 3L	16	Wall PUR LT White 5L	28	Wall PUR LT White 3L	40	Wall PUR LT White 5L
5	Wall MW ST Brown 3L	17	Wall MW ST Brown 5L	29	Wall MW ST Brown 3L	41	Wall MW ST Brown 5L
6	Wall MW LT Brown 3L	18	Wall MW LT Brown 5L	30	Wall MW LT Brown 3L	42	Wall MW LT Brown 5L
7	Wall MW ST White 3L	19	Wall MW ST White 5L	31	Wall MW ST White 3L	43	Wall MW ST White 5L
8	Wall MW LT White 3L	20	Wall MW LT White 5L	32	Wall MW LT White 3L	44	Wall MW LT White 5L
9	Wall CELL ST Brown 3L	21	Wall CELL ST Brown 5L	33	Wall CELL ST Brown 3L	45	Wall CELL ST Brown 5L
10	Wall CELL LT Brown 3L	22	Wall CELL LT Brown 5L	34	Wall CELL LT Brown 3L	46	Wall CELL LT Brown 5L
11	Wall CELL ST White 3L	23	Wall CELL ST White 5L	35	Wall CELL ST White 3L	47	Wall CELL ST White 5L
12	Wall CELL LT White 3L	24	Wall CELL LT White 5L	36	Wall CELL LT White 3L	48	Wall CELL LT White 5L

This figures show that the connection is markedly more sensitive to decay than the panel.

The relative capacity loss reaches 16 % in the most adverse configuration (brown rot, long-term exposure, three-layer wall), which exceeds the available design margin of the original detail. Four qualitative findings emerge.

- Brown rot is roughly four times more damaging than white rot, with mean absolute deviations of 0.1076 and 0.0399 respectively. The biological reason, discussed by [9] is that brown-rot fungi

depolymerise wood carbohydrates well in advance of the actual hyphal growth, so the mechanical degradation runs ahead of the visible mass loss.

- The effect of exposure duration is strongly conditional on the rot type: for brown rot the move from short-term to long-term raises the average deviation from 0. to 0.143, while for white rot it only rises from 0.020 to 0.030.
- The number of layers in the wall matters in early life but not in the long term: under short-term brown-rot exposure the five-layer panel produces a 9 % capacity loss while the three-layer panel produces only 2 %; under long-term exposure both layups converge on 14 %.
- Insulation has essentially no effect on the connection capacity.

D. OAT sensitivity ranking

The five design factors are ranked by their OAT sensitivity index S_x (units of fractional capacity loss): rot type ($S_x = 0.0677$), exposure duration ($S_x = 0.0660$), number of layers ($S_x = 0.0286$), wall insulation ($S_x = 0.006$) and roof insulation ($S_x = 0$). Rot type and exposure duration together explain the bulk of the observed variability and, because they interact strongly, the design conversation should be framed in terms of the joint “brown-rot long-term” scenario rather than in terms of either factor alone. The insensitivity of the connection capacity to the insulation material is counter-intuitive but robust: the bulk decay rate of the panel itself depends on the insulation [7], but the connection sits at the joint between two elements, where the moisture profile is set by the geometry of the joint rather than by the insulation behind it.

IV. DISCUSSION

The methodology combines four established models in a way that is directly compatible with the partial-factor logic of EN 1995-1-1. The hygrothermal step is calibrated against in-situ measurements on a Belgian CLT building [7], which gives the moisture inputs a realistic provenance. The strength-loss step, however, relies on laboratory data [5] obtained from small clear specimens decayed under monoculture conditions, which are known to be more aggressive than natural above-ground exposure. The predicted capacity losses reported here are therefore likely conservative and should be interpreted as upper bounds rather than expected service-life predictions.

A second limitation concerns the way decay is translated into a mechanical effect. The dissertation models decay as a reduction of the characteristic strengths, in line with one of the two approaches proposed by Bollmus et al. [5]. The alternative approach, namely a reduction of the cross-section thickness, is mechanically equivalent for the ULS verification of a panel but not for the SLS, because thickness enters the moment of inertia at the third power. A check based on strength reduction alone is therefore non-conservative for the SLS. A third caveat

concerns the moisture profiles themselves: Cluster 3 and Cluster 4 are reconstructed from long-term measurements rather than measured in situ at two distinct times, and the extrapolation introduces an uncertainty that has not been propagated through the present analysis.

V. CONCLUSION

Three conclusions stand out. First, the SLS of CLT floors is the limit state most sensitive to decay; a moderate cross-section reduction of about 10 mm of the outer lamella is sufficient to violate the L/300 deflection limit, and the cross-section-reduction modelling approach is required to capture this effect. Second, the ULS of CLT wall and roof panels is essentially safeguarded by the cross-laminated redundancy of the panel and by the impermeable finishing of the roof, with utilisation increases of at most 0.06. Third, the Ultimate Limit State of the screwed wall–roof connection is the governing component for the durability assessment of CLT structures, with a design-capacity loss of up to 15 % under brown rot and long-term moisture exposure.

Practical recommendations for Belgian design practice follow directly: durability checks should prioritise the SLS of floors and the ULS of the wall–roof connection; the cross-section-reduction approach should be adopted for the SLS; an explicit decay-related modification factor $k_{dec} \approx 0.85$ should be applied to F_v, R_d of CLT wall–roof screwed connections whenever the brown-rot dose threshold cannot be guaranteed to remain below 229 days over the service life; and joint detailing rather than insulation choice should be the focus of durability-driven design decisions.

ACKNOWLEDGEMENTS

The author wishes to thank Prof. Dr. Ir. Jan Belis for his guidance on the structural calculations, Prof. Dr. Ir. Nathan Van Den Bossche and Ir. Anke Blommaert for their support throughout the hygrothermal modelling, Dr. Jonas Niklewski (Lund University) for the discussions on decay processes, and the engineering office Houtvast for sharing their design documents.

REFERENCES

- [1] H. VIITANEN ET AL., “TOWARDS MODELLING OF DECAY RISK OF WOODEN MATERIALS,” EUROPEAN JOURNAL OF WOOD AND WOOD PRODUCTS, NO. 3, PP. 303–313, 2010, DOI: 10.1007/s00107-010-0450-xi.
- [2] C. BRISCHKE AND A. O. RAPP, “DOSE-RESPONSE RELATIONSHIPS BETWEEN WOOD MOISTURE CONTENT, WOOD TEMPERATURE AND FUNGAL DECAY DETERMINED FOR 23 EUROPEAN FIELD TEST SITES,” WOOD SCI. TECHNOL., VOL. 42, NO. 6, PP. 507–518, AUG. 2008, DOI: 10.1007/s00226-008-0191-8.
- [3] T. ISAKSSON, C. BRISCHKE, AND S. THELANDERSSON, “DEVELOPMENT OF DECAY PERFORMANCE MODELS FOR OUTDOOR TIMBER STRUCTURES,” MATERIALS AND STRUCTURES/MATERIAUX ET CONSTRUCTIONS, VOL. 46, NO. 7, PP. 1209–1225, JUL. 2013, DOI: 10.1617/s11527-012-9965-4.
- [4] P. HRADIL AND S. FORTINO, “INTEGRATED APPROACH TO PREDICT DETERIORATION OF MECHANICAL PROPERTIES OF DECAYING WOOD,” IN 13TH WORLD CONFERENCE ON TIMBER ENGINEERING, WCTE 2023, WORLD CONFERENCE ON TIMBER ENGINEERING (WCTE), 2023, PP. 536–541. DOI: 10.52202/069179-0073.
- [5] BOLLMUS S., BESTER VAN NIEKERK P., AND BRISCHKE C., “IMPACT OF FUNGAL DECAY ON THE BENDING PROPERTIES OF WOOD,” PROCEEDINGS IRG ANNUAL MEETING 2020 THE INTERNATIONAL RESEARCH GROUP ON WOOD PROTECTION, 2020.
- [6] EN1995, “EUROCODE 5 DESIGN OF TIMBER STRUCTURES PART 1-1: GENERAL-COMMON RULES AND RULES FOR BUILDINGS FOR PUBLICATION CONTENTS PAGE,” 2005.
- [7] A. BLOMMAERT, M. STEEMAN, AND N. VAN DEN BOSSCHE, “MODELING MOISTURE ACCUMULATION AND DECAY POTENTIAL IN CROSS-LAMINATED TIMBER WALL ASSEMBLIES EXPOSED DURING THE CONSTRUCTION PHASE,” BUILDINGS, VOL. 15, NO. 7, APR. 2025, DOI: 10.3390/BUILDINGS15071075.
- [8] A. SALTELLI, P. ANNONI, AND B. D’HOMBRES, “HOW TO AVOID A PERFUNCTORY SENSITIVITY ANALYSIS,” IN PROCEdia - SOCIAL AND BEHAVIORAL SCIENCES, 2010, PP. 7592–7594. DOI: 10.1016/J.SBSPRO.2010.05.133.
- [9] B. GOODSELL, Y. QIAN, AND J. JELLISON, “FUNGAL DECAY OF WOOD: SOFT ROT-BROWN ROT-WHITE ROT,” 2008.

TABLE OF CONTENTS

Preface	II
Approval for loan	II
Explanatory notes on the oral presentation	II
Table of contents	9
1 Problem statement	15
2 Literature review	17
2.1 Cross laminated timber	17
2.2 Beam theory	18
2.3 Shell theory	32
2.4 Design in Serviceability Limit State (SLS)	34
2.5 Design of the connection in ULS	35
2.6 Timber decay	36
2.7 Modelling decay	38
2.8 Modelling moisture	40
2.9 Modelling the loss of mechanical properties	43
2.10 One-At-a-Time Sensitivity Analysis	45
3 Methodology	47
3.1 Workflow	47
3.2 Reference building	50
3.3 Load-bearing system	52
3.4 Loads	52
3.5 Environmental conditions	55
3.6 Processing of data	55
3.7 Assumptions	56
3.8 Limitations	56
4 SLS sensitivity analysis	57
5 Loss of capacity in a panel	59
5.1 Wall element	59
5.2 Roof element	67
6 Loss of capacity in the connection	70
6.1 General information	70

6.2	Three layered CLT connection	70
6.3	Five layered CLT connection	74
6.4	Exposure of Roof panel	78
6.5	Loss of design capacity	80
6.6	OAT- sensitivity analysis	83
7	Conclusions and recommendations	85
7.1	General synthesis	85
7.2	Serviceability Limit State	85
7.3	Conclusions on the Ultimate Limit State of CLT panels	86
7.4	Conclusions on the Ultimate Limit State of the wall–roof connection	87
7.5	Conclusions from the OAT sensitivity analysis	88
7.6	Answer to the research question	88
7.7	Recommendations for design practice in Belgium	89
7.8	Future research	90
8	Social reflection	91
9	Use of Artificial Intelligence in this research	91
	References	92
	Attachments	95

LIST OF TABLES

Table 1: Definition properties	19
Table 2: Properties CLT for each direction	20
Table 3: Geometric properties CLT	20
Table 4: Properties Timoshenko's beam theory	21
Table 5: Reference length	23
Table 6: Formulas 3-layer CLT	23
Table 7: Formulas five-layer CLT structure	24
Table 8: Different options if bending in the transverse layers	27
Table 9: Properties layer shear	30
Table 10: kdef based on Service Class from (Zoltán I. Bocskai, 2019):	34
Table 11: variables dose-response function above ground applications(Isaksson et al, 2013)	39
Table 12: Rating decay according to (EN 252, 2014)	40
Table 13: leak categories	42
Table 14: Modelling mass loss for above ground applications	44
Table 15: parameters by (Brischke & Meyer-Veltrup, 2016)	44
Table 16: Strength loss properties decay (Bollmus S. et al, 2020)	45
Table 17: Properties of the wall in the simulations	50
Table 18: Properties of the roof in the simulations	51
Table 19 : Loads acting on the roof	52
Table 20: Properties of the connection	54
Table 21: comparison in deflection using the Timoshenko beam theory and the gamma method for the CLT140L5S roof ..	57
Table 22: Capacity check wall 3-layered element in case of exposure	59
Table 23: Moisture mass density MMD (left) and temperatures T(right) of the CLT-lamellae of a three-layered wall element to verify the capacity of a wall panel with PUR, MW and CEL insulation	60
Table 24: Capacity check wall 5-layered element in case of exposure	63
Table 25: Moisture mass density MMD(left) and temperatures T(right) of the CLT-lamellae of a five-layered wall element to verify the capacity of a wall panel with PUR, MW and CEL insulation	64
Table 26: Capacity check roof element	67
Table 27: Moisture mass density MMD (left) and temperatures T (right) of the CLT-lamellae of a five-layered roof element to verify the capacity of a roof panel with PUR and MW	67
Table 28: Moisture mass density MMD (left) and temperatures T(right) of the CLT-lamellae of a three-layered wall element to verify the capacity of a connection in case of short term exposure with PUR, MW and CEL insulation	71
Table 29: Moisture mass density MMD (left) and temperatures T(right) of the CLT-lamellae of a three-layered wall element to verify the capacity of a connection in case of long term exposure with PUR, MW and CEL insulation	73
Table 30: Moisture mass density MMD (left) and temperatures T(right) of the CLT-lamellae of a five-layered wall element to verify the capacity of a connection in case of short term exposure with PUR, MW and CEL insulation	75
Table 31: Moisture mass density MMD (left) and temperatures T(right) of the CLT-lamellae of a five-layered wall element to verify the capacity of a connection in case of long term exposure with PUR, MW and CEL insulation	77
Table 32: Moisture mass density MMD (left) and temperatures T(right) of the CLT-lamellae of a five-layered roof element to verify the capacity of a connection in case of exposure with PUR and MW insulation	79
Table 33: Legend for Table 34	80
Table 34: Legend to Figure 52 and Figure 53	81
Table 35: factors in the OAT analysis	83
Table 36: Results OAT sensitivity analysis	83
Table 37: Ranking of influence factors	83
Table 38: Visualisation of the influences	84

Figure 38: self-weight for each layer for a three-layer CLT wall in case of encapsulated building moisture	62
Figure 39: bending strength for each layer for a five layered CLT wall in case of encapsulated building moisture.....	65
Figure 40: parallel compressive strength for each layer for a five layered CLT wall in case of encapsulated building moisture.....	65
Figure 41: perpendicular compressive strength for each layer for a five layered CLT wall in case of encapsulated building moisture.....	66
Figure 42: self-weight for each layer for a five layered CLT wall in case of encapsulated building moisture.....	66
Figure 43: bending strength for each layer for a five layered CLT roof in case of encapsulated building moisture	68
Figure 44: parallel compressive strength for each layer for a five layered CLT roof in case of encapsulated building moisture.....	68
Figure 45: perpendicular compressive strength for each layer for a five layered CLT roof in case of encapsulated building moisture.....	69
Figure 46: self-weight for each layer for a five layered CLT roof in case of encapsulated building moisture.....	69
Figure 47: Self-weight per layer for a three layered CLT wall panel in case of short-term exposure	72
Figure 48: Self-weight per layer for a three layered CLT wall panel in case of long-term exposure.....	74
Figure 49: Self-weight per layer for a five layered CLT wall panel in case of short-term exposure.....	76
Figure 50: Self-weight per layer for a five layered CLT wall panel in case of long-term exposure	78
Figure 51: Self-weight per layer for a five layered CLT roof panel in case of exposure.....	79
Figure 52: Capacity for a screwed connection between a five layered wall and five layered roof CLT element	82
Figure 53: Capacity for a screwed connection between a three-layered wall and five layered roof CLT element.....	82

1 PROBLEM STATEMENT

The usage of cross-laminated timber (CLT) as a structural element in low-rise and mid-rise buildings is growing. It offers an intriguing substitute for conventional building techniques and has outstanding carbon storage and prefabrication possibilities. Nevertheless, CLT panels are susceptible to degradation if exposed to long-term moisture.

A CLT is typically subjected to mechanical loads, temperature changes and moisture loads, which can result in degradation of performance and durability of specific materials or the assembly as a whole, in addition to normal ageing phenomena such as lignin degradation and erosion of fibres. A comprehensive risk analysis should ideally be carried out when a structure's durability is put to the test. This study started based on the design details, precise evaluation of the materials used, high-resolution data on boundary conditions and a trustworthy numerical simulation and performance model.

However, this ideal is frequently difficult to achieve and impractical (Vanderschelden et al., 2022). Therefore, statistical data is combined with expert judgement (e.g., appraisal of concrete structures). Unlike strength requirements, durability problems associated with moisture only become apparent over an extended period and no clear rules govern the use of numerical models in this field (Vanderschelden et al., 2022).

This research creates a link between the durability of CLT elements and long-term capacity of the elements and connections when the structural elements are degraded due to different types of moisture which results in the initiation of decay.

The capacity is checked in several ways: The capacity of a panel is checked in Serviceability Limit State (SLS) and in Ultimate Limit State (ULS) and the capacity of a connection is verified in ULS.

To find the most influential factors a One-At-a-Time (OAT) sensitivity analysis is performed.

The workflow on which this research is based is visualised in Figure 1, where also the most influential authors are mentioned and the work environment where the specific component is researched.

The methodology is explained in detail in §3.

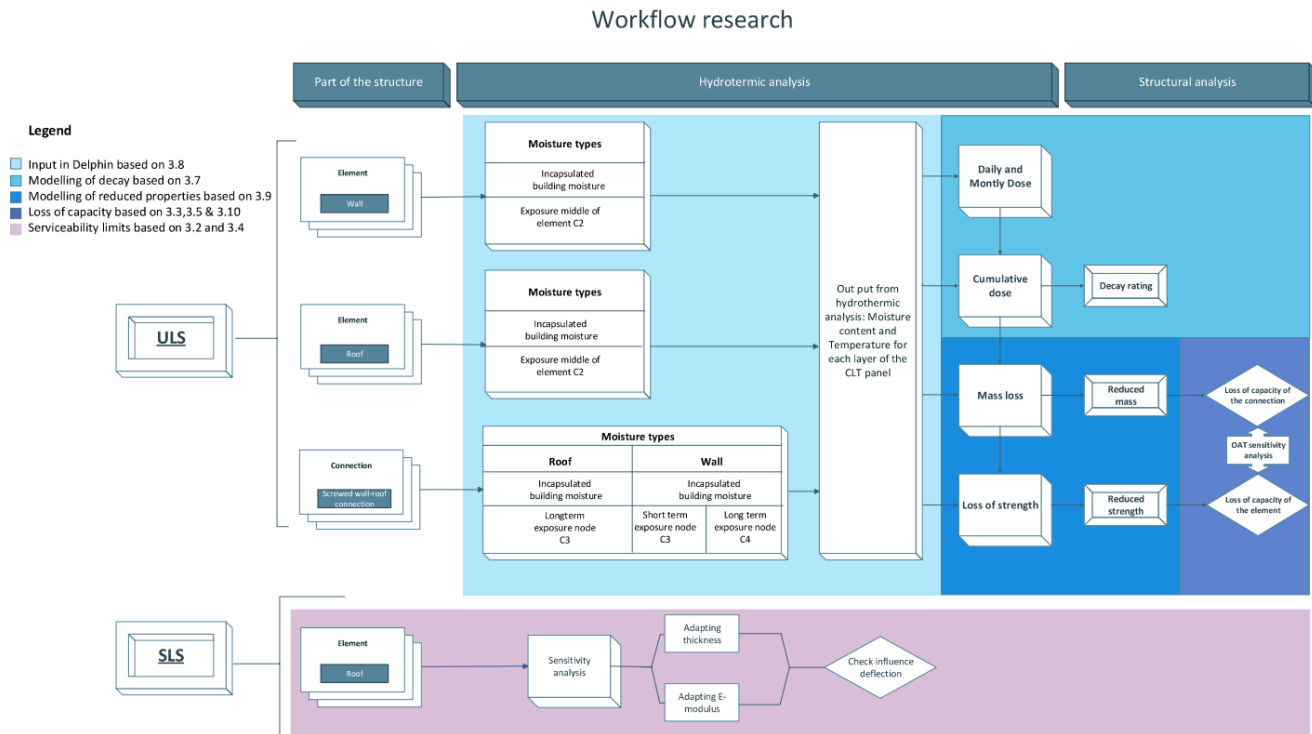


Figure 1: Workflow master dissertation

2 LITERATURE REVIEW

2.1 Cross laminated timber

Cross Laminated Timber (CLT) is a structural component made of glued boards or planks layered alternately at right angles that can be used in the frames of multi-storey buildings, houses and special structures such as bridges. CLT is a versatile product that can be used in a broad range of applications but it is used most in floors and walls (Fröbel & Gustafsson, 2022).

It is usually built up in a three-, five-, seven- or eight-layered configurations resulting in a thickness going from 60 to 320 mm. The length can go up to 16 m and the width to 3.5 m (CLT by Stora Enso Technical Brochure, n.d.).

Typical layouts can be found in Attachment 1.

CLT is a highly engineered wood product (EWP). "Engineering wood is created by combining natural wood fibres or particles with adhesives and other additives to enhance its strength, durability, and dimensional stability. The resulting material exhibits improved properties compared to traditional solid wood, such as a higher strength-to-weight ratio, resistance to moisture and pests, and reduced warping or shrinking." (Bayat, 2023)

EWP were developed around 1990 to compensate limitations of traditional timber construction and increase the efficiency of timber construction methods. During the last 50 years timber materials underwent strong technological advances, making them increasingly suitable for meeting contemporary construction requirements (Fröbel & Gustafsson, 2022).

The distinguished features of CLT are that it is often used as large surface panels which results in a high load-bearing capacity and stiffness that can help stabilise the building due to the sizeability of cross-sections.

CLT elements can be connected to each other or other elements in several ways: By using (wood) screws, dowels; metal plates and metal brackets (Fröbel & Gustafsson, 2022).

CLT combines a high strength-to-weight ratio with extensive prefabrication. Its low weight reduces transport, assembly and foundation costs, while tight manufacturing tolerances maintain dimensional stability. Timber resists fire through a predictable charring layer that protects the inner core, and the layered build-up improves thermal performance (Fröbel & Gustafsson, 2022). This has led to an increase in the demand for and production of CLT worldwide, including in Europe.

Since 2015, European consumption of CLT has increased by an average of 15% per year, with more than 50 producers now operating in Europe. However, even though wood construction is increasingly being recognised as a structural building material, the speed of implementation varies from country to country. Belgium is certainly not among the fastest in Europe in this respect. This is partly due to a lack of knowledge among all actors in the construction process, but also partly because solid wood construction has not yet been embraced by building regulations such as Eurocode 5 (Houtinbois, 2022; Hyams et al., 2020).

A key aspect driving this knowledge gap is the structural complexity of CLT as a load-bearing element, particularly in floor-wall systems where the panels are subjected to distinct and demanding loading conditions. In floor applications, CLT panels primarily act as bending elements, resisting out-of-plane loads through flexure and shear along their major and minor strength axes — a behaviour governed by the orthotropic layup of the cross-laminated layers (Karacabeyli & Douglas, 2019). In wall applications, the vertically oriented outer laminations carry gravity loads predominantly as compression parallel to the grain, maximising the axial load-bearing capacity of the panel (Fröbel & Gustafsson, 2022). However, at the critical wall-roof interface, the floor panel beneath a bearing wall is loaded in compression perpendicular to the grain, a fundamentally weaker and more deformation-sensitive direction in wood, making this a governing limit state in multi-storey CLT construction (Brandner et al., 2016; NBN EN16351, 2021). Furthermore, when CLT wall panels are subjected to combined axial compression and out-of-plane bending, rolling shear in the transverse layers becomes a

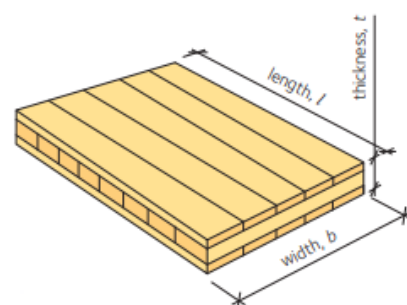


Figure 2 CLT panel (Fröbel & Gustafsson, 2022)

primary failure concern, creating a complex interaction that current design codes address through simplified interaction equations (Huang et al., 2022). Together, these loading mechanisms illustrate why CLT floor-wall systems require a dedicated and thorough structural assessment, which motivates the present study.

In this research the connection between the roof and the wall is considered to be a platform frame, making the connection interesting to investigate to find the influence of decay on the load-bearing capacity of the connection.

CLT has some complexities. Due to its wooden layers and adhesive layers, this material cannot be tackled as a regular solid timber material. Therefore, a literature review will be given, tackling the similarities and differences between the mechanical properties of CLT and solid timber, followed by two stability calculation methods for the capacity in ULS for an (see §3.2 and §3.3) and in SLS (see §3.4). Literature about the required calculations for calculating the capacity of a connection are presented in §3.5

In these standard calculation methods, a decay risk due to moisture is not implemented. An overview is given of what wood decay is (see §3.6). This will be followed by the state of the modelling decay (§3.7) and thus also modelling moisture (§3.8) and the resultant modelling the loss of mechanical properties (§3.9).

Finally, an OAT sensitivity analysis is performed to find the most important influence factors as described in §3.10.

2.1.1 Differences in calculations compared to normal timber

The main difference between solid timber elements and CLT panels is that CLT has a higher average strength and that there is a smaller dispersion in strength values. This is because CLT is a composed material and the risk that the weakest links of each cross-section coincide with each other in the same direction and layer is rather limited. This beneficial property of CLT is indicated by a system factor k_{sys} . Since there is not yet a standard, multiple calculation methods exist to calculate this effect. In this dissertation, it is opted to work with the conservative system factor that is also implemented in the FEM software used for this master thesis, FEM-Design: $k_{sys}=1$ (Bocskai, 2019).

The partial factor γ_M is influenced by both the level of control in design and manufacturing processes, as well as the homogeneity of the material. The partial safety factor γ_M is also considered as: $\gamma_M = 1.25$ (Bocskai, 2019).

As for normal timber calculations also the effects of the duration of the load, the timber type and the climatic conditions are considered via k_{mod} .

This is done to shift from the characteristic strength to the design strength:

$$f_{cd} = k_{sys} \cdot k_{mod} \cdot \frac{f_{ck}}{\gamma_M} \quad (1)$$

2.2 Beam theory

The global lack of standardisation in CLT design has led to significant regional disparities in calculation methodologies. While the German and Swiss National Annexes to the Eurocode provide explicit recommendations for stiffness assumptions and associated reduction factors also known as the Kappa method based on Timoshenko's beam theory, the Swedish National Annex offers no CLT-specific guidance beyond the "mechanically jointed beams" method detailed in Eurocode 5 or also named the gamma method. To bridge this regulatory gap, Swedish Wood expanded upon the Eurocode framework within the Swedish CLT Handbook (Fröbel & Gustafsson, 2022), proposing specific adaptations of the mechanically jointed beam method for CLT stiffness calculations.

2.2.1 Timoshenko's simplified beam theory

2.2.1.1 Definition of directions

CLT and CLT products can distribute loads in three directions; along the longitudinal (X-) axis, along the transverse (Y-) axis and perpendicular to the plane (Z-axis) as shown in Figure 3. The current product standard for CLT, EN-16351 (NBN EN16351, 2021) uses the following definitions:

The X-axis is parallel to the grain of the outermost panel.

The Y-axis is perpendicular to the grain of the outermost panel.

The Z-axis runs along the thickness of the board and is perpendicular to the XY-plane.

EN-16351 also assumes a symmetrical cross-section and a negligible influence of the modulus of elasticity perpendicular to the grain, i.e. $E_{90}=0$. This means that the contribution of the transverse layers to the element's capacity are neglected.

The modulus of elasticity parallel with the grain is denoted as E_0 .

2.2.1.2 Designations

Stresses for the beam theory can be visualised and expressed as shown in Figure 4.

It assumes that the cross-sections remain plane during deformation but not necessarily perpendicular to the beam axis:

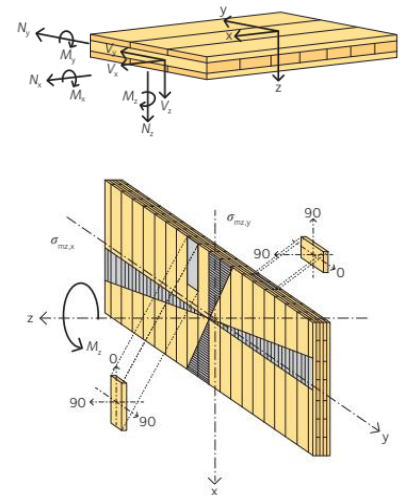


Figure 3: Load directions CLT (Fröbel & Gustafsson, 2022)

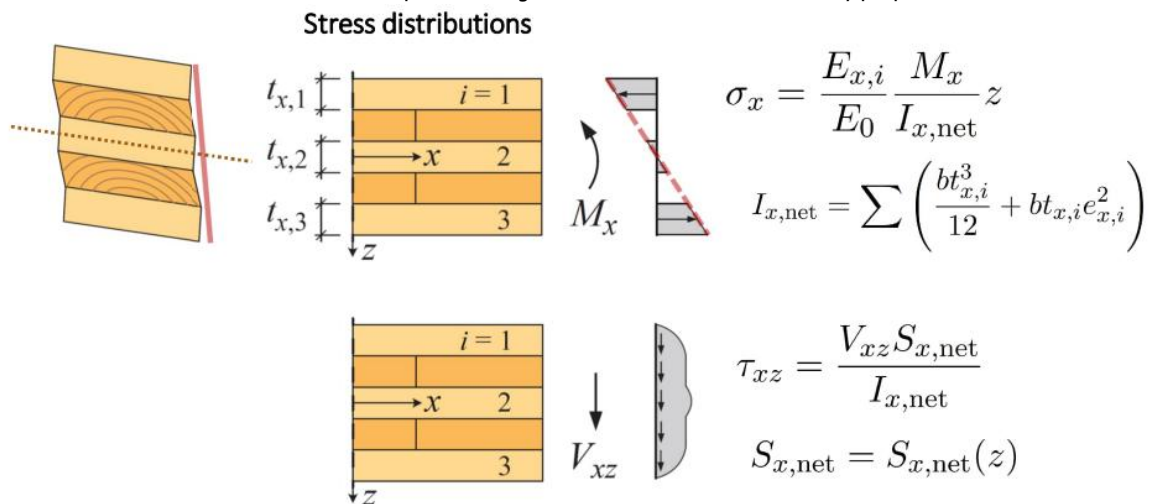


Figure 4: Stress distributions CLT according to the Timoshenko beam theory. (Danielsson, 2025)

The modulus of elasticity for each layer is formulated based on Figure 5.

The properties are summarised in Table 1 and Table 2 :

Table 1: Definition properties

E_0	Modulus of elasticity for a layer parallel with grain i
$E_{0,mean}$	Mean value according to SS-EN 338
$E_{x,i}$	Modulus of elasticity along X-axis for layer i
$E_{y,j}$	Modulus of elasticity along Y-axis for layer j
$G_{x,i}$	Shear modulus along X-axis for layer i
$G_{y,j}$	Shear modulus along Y-axis for layer j

Table 2: Properties CLT for each direction

$E_{x1} = E_{x3} = E_{x5} = \dots = E_{0,xlay,mean} = E_0$	$G_{x1} = G_{x3} = G_{x5} = \dots = G_{090,xlay,mean} = G_0$
$E_{y2} = E_{y4} = \dots = E_{0,ylay,mean} = E_0$	$G_{y2} = G_{y4} = \dots = G_{090,ylay,mean} = G_0$
$E_{x2} = E_{x4} = \dots = E_{90,ylay,mean} = 0$	$G_{x2} = G_{x4} = \dots = G_{9090,ylay,mean} = G_{90}$
$E_{y1} = E_{y3} = E_{y5} = \dots = E_{90,xlay,mean} = 0$	$G_{y1} = G_{y3} = G_{y5} = \dots = G_{9090,xlay,mean} = G_{90}$

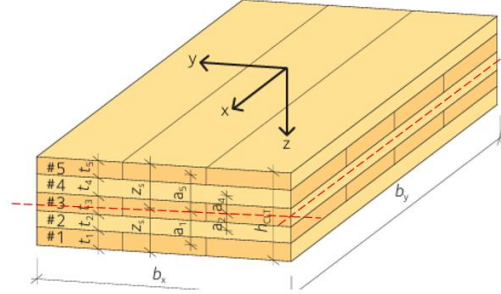


Figure 5: CLT structure (Fröbel & Gustafsson, 2022)

Properties related to geometry can be written as shown in Table 3.

Z_s represents the maximum distance from the neutral axis and h represents the height.

Table 3: Geometric properties CLT

$$\begin{aligned} h_x &= t_1 + t_3 + t_5 \\ h_y &= t_2 + t_4 \\ h_{CLT} &= h_x + h_y \\ Z_s &= \frac{h_{CLT}}{2} \end{aligned}$$

The shear capacity of the layer is mainly dependent on the rolling shear strength, $f_{r,i}$ of the transverse layer. The corresponding net static moment $S_{R,net}$ for a panel with m_L as the designation for the transverse layer nearest to the panel's centre of gravity and E_{ref} as the chosen reference value for the modulus of elasticity (often equal to the direction's modulus of elasticity, can be written as:

$$S_{R,x,net} = \sum_{i=1}^{m_L} \frac{E_{x,i}}{E_{ref}} \cdot b_x \cdot t_i \cdot a_i \quad (2)$$

$$S_{R,y,net} = \sum_{i=1}^{m_L} \frac{E_{y,i}}{E_{ref}} \cdot b_y \cdot t_i \cdot a_i \quad (3)$$

The other geometric properties are displayed in

Table 4 where:

- m_L is the designation for the transverse layer nearest to the panel's centre of gravity;
- b_x, b_y is the width of the board layer;
- t_i is the thickness of the board layer;
- a_i is the distance between the centre of the board layer and the CLT panel's neutral axis;
- E_{ref} is the chosen reference value for modulus of elasticity;
- E_{xi}, E_{yi} is the board layer's modulus of elasticity.

Table 4: Properties Timoshenko's beam theory

Property	Parallel with main direction of load	Perpendicular with main direction of load
Gross Area A_{bruto}	$A_{x,bruto} = b_x \cdot h_{CLT}$ (4)	$A_{y,bruto} = b_y \cdot h_{CLT}$ (5)
Net Area A_{net}	$A_{x,net} = b_x \cdot h_x$ (6)	$A_{y,net} = b_y \cdot h_y$ (7)
Net moment of inertia I_{net}	With rotation about Y-axis $I_{x,net} = \sum_{i=1}^{m_L} \frac{E_{x,i}}{E_{ref}} \cdot \frac{b_x \cdot t_i^3}{12} + \sum_{i=1}^{m_L} \frac{E_{x,i}}{E_{ref}} \cdot b_x \cdot t_i \cdot a_i^2$ $= \frac{b_x \cdot t_1^3}{12} + b_x \cdot t_1 \cdot a_1^2 + \frac{b_x \cdot t_3^3}{12} + b_x \cdot t_3 \cdot a_3^2 + \frac{b_x \cdot t_5^3}{12} + b_x \cdot t_5 \cdot a_5^2 + \dots$ (8) With rotation about Z-axis $I_{z,x,net} = \sum_{i=1}^{m_L} \frac{E_{x,i}}{E_{ref}} \cdot \frac{t_i \cdot b_x^3}{12}$ (9)	With rotation about Y-axis $I_{y,net} = \sum_{i=1}^{m_L} \frac{E_{y,i}}{E_{ref}} \cdot \frac{b_y \cdot t_i^3}{12} + \sum_{i=1}^{m_L} \frac{E_{y,i}}{E_{ref}} \cdot b_y \cdot t_i \cdot a_i^2$ $= \frac{b_y \cdot t_2^3}{12} + b_y \cdot t_2 \cdot a_2^2 + \frac{b_y \cdot t_3^3}{12} + b_y \cdot t_4 \cdot a_4^2 + \dots$ (10) With rotation about Z-axis $I_{z,y,net} = \sum_{i=1}^{m_L} \frac{E_{y,i}}{E_{ref}} \cdot \frac{t_i \cdot b_y^3}{12}$ (11)
Net section modulus W_{net}	$W_{x,net} = \frac{2 \cdot I_{x,net}}{h_{CLT}}$ (12)	$W_{y,net} = \frac{2 \cdot I_{y,net}}{h_{CLT}}$ (13)

If the shear force capacity of a longitudinal layer in bending needs to be calculated, the static moment should be written as follows where:

- k_i is the designation for the longitudinal layer nearest to the panel's centre of gravity.
- a_k is the distance from the neutral axis to the centre of gravity of the layer in question.
- t_k is the thickness of the layer in question.

If the panel's centre of gravity (cog) lies in the layer in question:

$$S_{x,net} = \sum_{i=1}^{k_L} \frac{E_{x,i}}{E_{ref}} \cdot b_x \cdot t_i \cdot a_i + b_x \cdot \left(\frac{t_k}{2} - a_k \right)^2 \quad (14)$$

$$S_{y,net} = \sum_{i=1}^{k_L} \frac{E_{y,i}}{E_{ref}} \cdot b_y \cdot t_i \cdot a_i + b_y \cdot \left(\frac{t_k}{2} - a_k \right)^2 \quad (15)$$

If the panel's cog does not lie in the layer in question:

$$S_{x,net} = \sum_{i=1}^{k_L} \frac{E_{x,i}}{E_{ref}} \cdot b_x \cdot t_i \cdot a_i \quad (16)$$

$$S_{y,net} = \sum_{i=1}^{k_L} \frac{E_{y,i}}{E_{ref}} \cdot b_y \cdot t_i \cdot a_i \quad (17)$$

2.2.1.3 Shear capacity in calculation of deformation

The assumption that in plane shear has no influence is actually not correct and the shear compliance should be considered. This is done by using the shear correction factor κ and then the shear capacity can be calculated as follows:

$$S_{x,CLT} = \kappa_x \cdot \sum G_{x,i} \cdot b_x \cdot t_i = \kappa_x \cdot b_x \cdot (G_0 \cdot t_1 + G_{90} \cdot t_2 + G_0 \cdot t_3 + \dots) \quad (18)$$

$$S_{y,CLT} = \kappa_y \cdot \sum G_{y,i} \cdot b_y \cdot t_i = \kappa_y \cdot b_y \cdot (G_{90} \cdot t_1 + G_0 \cdot t_2 + G_{90} \cdot t_3 + \dots) \quad (19)$$

The shear correction factor κ can be calculated based on the thickness of the layers if the ratio of G_0/G_{90} differs from zero or $E_{90} > 0$.

κ is calculated based on the following formula:

$$\kappa = \frac{(\sum(EI + EAa^2))^2}{\sum G_i \cdot b \cdot t_i \cdot \int \frac{S^2(z) \cdot E^2(z)}{G(z) \cdot b(z)} dz} \quad (20)$$

These factors for the materials used in this dissertation can be retrieved in Attachment 2.

2.2.2 Gamma method

In CLT panels, shear deformations account for a large portion of the overall deformation (Fröbel & Gustafsson, 2022).

The gamma method is a technique based on the Bernoulli-Euler theory, which takes shear force deformations into account in a more straightforward manner and is described in (NBN EN16351, 2021) Annex B. The bending stiffness for pure bending, as explained in §3.2.1, is calculated using the net cross-section I_{net} and recorded as $E I_{net}$. The effective moment of inertia or I_{eff} is introduced in the gamma method. The second longitudinal layer from the upper side is used as the base layer in both three- and five-layer CLT panels when using the gamma method.

This technique treats adjacent layers as having a flexible link to the base layer. The "Steiner" component of stiffness for each layer is multiplied with a Gamma (γ) value determined by the span length and transverse layer parameters.

$$I_{x,eff} = \sum \frac{E_{x,i}}{E_{ref}} \cdot \frac{b_x \cdot t_i^3}{12} + \gamma_i \cdot \frac{E_{x,i}}{E_{ref}} \cdot b_x \cdot t_i \cdot a_i^2 \quad (21)$$

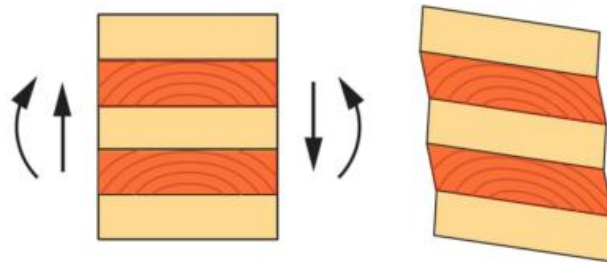


Figure 6: Shear deformations in Gamma method (Danielsson, 2025)

For cross-sections with two transverse layers, the sub-formulas produce non-symmetrical results. While the method is simple to use with three- and five-layer CLT components, it requires more sophisticated computations for parts with seven or more levels. Because cross-sectional values are span-dependent, a reference length l_{ref} is used depending on the beam's support configuration as shown in

Table 5:

$$l_{ref} = \mu \cdot L \quad (22)$$

Table 5: Reference length

For a simply supported beam a single span	$\mu = 1$
For a simply supported continuous beam with ≥ 2 spans	$\mu = 0.8$
For a cantilever beam	$\mu = 2$

Below the gamma-method is shown for a three- and five-layer CLT panel.

2.2.2.1 Three-layer CLT

Each layer is numbered from one to n starting from the bottom and going up. Only the longitudinal layers should be considered since the transverse layers are not considered. The formulas can be found in Table 6.

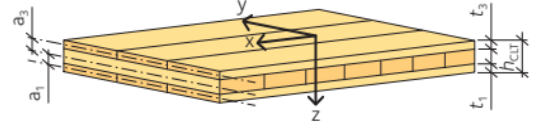


Figure 7: CLT structure 3-layer CLT (Fröbel & Gustafsson, 2022)

Table 6: Formulas 3-layer CLT

$\gamma_1 = 1$	(23)
$\gamma_3 = \frac{1}{1 + \frac{\pi^2 \cdot E_{x,3} \cdot t_3}{l_{ref}^2} \cdot \frac{t_2}{G_{9090,2}}}$	(24)
$a_1 = \frac{\gamma_3 \cdot \frac{E_{x,3}}{E_{ref}} \cdot b \cdot t_3 \left(\frac{t_1}{2} + t_2 + \frac{t_3}{2} \right)}{\gamma_1 \cdot \frac{E_{x,1}}{E_{ref}} \cdot b \cdot t_1 + \gamma_3 \cdot \frac{E_{x,3}}{E_{ref}} \cdot b \cdot t_3}$	(25)
For symmetrical cross-section from the same strength class:	
$a_1 = \frac{t_1}{2} + \frac{t_2}{2}$	(26)
$a_3 = \frac{t_2}{2} + \frac{t_3}{2}$	(27)
$I_{x,ef} = \sum \frac{E_{x,i}}{E_{ref}} \cdot \frac{b_x t_i^3}{12} + \gamma_i \cdot \frac{E_{x,i}}{E_{ref}} \cdot b_x \cdot t_i \cdot a_i^2$	
$= \frac{E_{x,1}}{E_{ref}} \cdot \frac{b_x t_1^3}{12} + \gamma_1 \cdot \frac{E_{x,1}}{E_{ref}} \cdot b_x \cdot t_1 \cdot a_1^2 + \frac{E_{x,3}}{E_{ref}} \cdot \frac{b_x t_3^3}{12} + \gamma_3 \cdot \frac{E_{x,3}}{E_{ref}} \cdot b_x \cdot t_3 \cdot a_3^2$	(28)
For symmetrical cross-section from the same strength class:	
$I_{x,ef} = b_x \cdot \left(\frac{2 \cdot t_1^3}{12} + (1 + \gamma_3) \cdot t_1 \cdot a_1^2 \right)$	(29)
$i_{x,ef} = \sqrt{\frac{I_{x,ef}}{A_{x,ef}}}$	(30)
$i_{y,ef} = \sqrt{\frac{I_{y,ef}}{A_{y,ef}}}$	(31)

2.2.2.2 Five-layer CLT

In case of a five-layer CLT panel, the calculation method is identical to a three-layer CLT panel, except of the fact that now the influence of the longitudinal layers, one, three and five, needs to be considered and the influence of transverse layers two and four is negligible. The formulas are mentioned in Table 7.

Table 7: Formulas five-layer CLT structure

$$\gamma_1 = \frac{1}{1 + \frac{\pi^2 \cdot E_{x,1} \cdot t_1}{l_{ref}^2} \cdot \frac{t_2}{G_{9090,2}}} \quad (32)$$

$$\gamma_3 = 1 \quad (33)$$

$$\gamma_5 = \frac{1}{1 + \frac{\pi^2 \cdot E_{x,5} \cdot t_5}{l_{ref}^2} \cdot \frac{t_4}{G_{9090,4}}} \quad (34)$$

For symmetrical cross-section ($t_1=t_3=t_5$) from the same strength class, $\gamma_1=\gamma_5$:

$$a_3 = \frac{\gamma_1 \cdot \frac{E_{x,1}}{E_{ref}} \cdot b \cdot t_1 \left(\frac{t_1}{2} + t_2 + \frac{t_3}{2} \right) - \gamma_5 \cdot \frac{E_{x,5}}{E_{ref}} \cdot b \cdot t_5 \left(\frac{t_3}{2} + t_4 + \frac{t_5}{2} \right)}{\gamma_1 \cdot \frac{E_{x,1}}{E_{ref}} \cdot b \cdot t_1 + \gamma_3 \cdot \frac{E_{x,3}}{E_{ref}} \cdot b \cdot t_3 + \gamma_5 \cdot \frac{E_{x,5}}{E_{ref}} \cdot b \cdot t_5} \quad (35)$$

For a symmetrical cross-section ($t_1=t_3=t_5$) and same strength grade, $a_3=0$:

$$a_1 = \frac{t_1}{2} + t_2 + \frac{t_3}{2} - a_3 \quad (36)$$

$$a_5 = \frac{t_3}{2} + t_4 + \frac{t_5}{2} - a_3 \quad (37)$$

$$I_{x,ef} = \sum \frac{E_{x,i}}{E_{ref}} \cdot \frac{b_x t_i^3}{12} + \gamma_i \cdot \frac{E_{x,i}}{E_{ref}} \cdot b_x \cdot t_i \cdot a_i^2$$

$$= \frac{E_{x,1}}{E_{ref}} \cdot \frac{b_x t_1^3}{12} + \gamma_1 \cdot \frac{E_{x,1}}{E_{ref}} \cdot b_x \cdot t_1 \cdot a_1^2 + \frac{E_{x,3}}{E_{ref}} \cdot \frac{b_x t_3^3}{12} + \gamma_3 \cdot \frac{E_{x,3}}{E_{ref}} \cdot b_x \cdot t_3 \cdot a_3^2 + \frac{E_{x,5}}{E_{ref}} \cdot \frac{b_x t_5^3}{12} + \gamma_5 \cdot \frac{E_{x,5}}{E_{ref}} \cdot b_x \cdot t_5 \cdot a_5^2 \quad (38)$$

For symmetrical cross-section from the same strength class:

$$I_{x,ef} = b_x \cdot \left(\frac{3 \cdot t_1^3}{12} + 2 \cdot \gamma_1 \cdot t_1 \cdot a_1^2 \right) \quad (39)$$

$$i_{x,ef} = \sqrt{\frac{I_{x,ef}}{A_{x,ef}}} \quad (30)$$

$$i_{y,ef} = \sqrt{\frac{I_{y,ef}}{A_{y,ef}}} \quad (31)$$

In both cases the bending- and shear stress can be calculated as depicted in Figure 8 for a five-layer CLT panel :

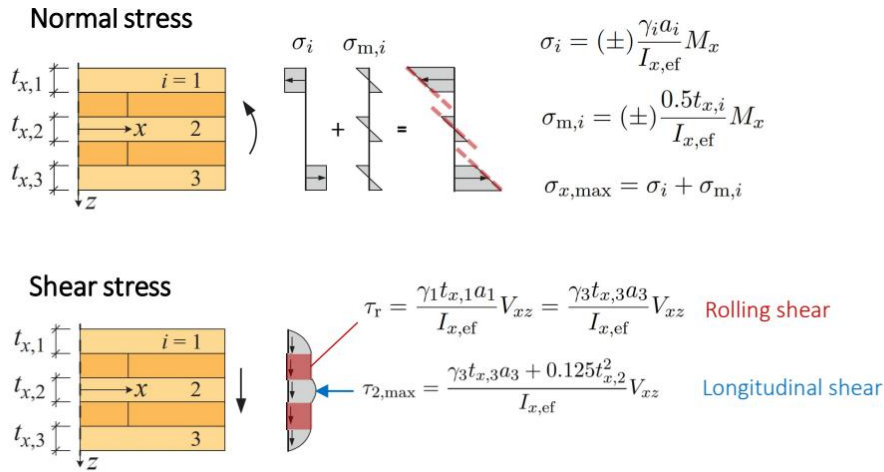


Figure 8: Stress distribution according to the gamma method for a five-layer CLT structure (Danielsson, 2025)

2.2.2.3 Comparison

The main difference between Timoshenko beam theory and gamma method lays in the calculations of the bending stress but the differences in typical CLT-applications are negligible (2-5% difference in the total capacity of an element).

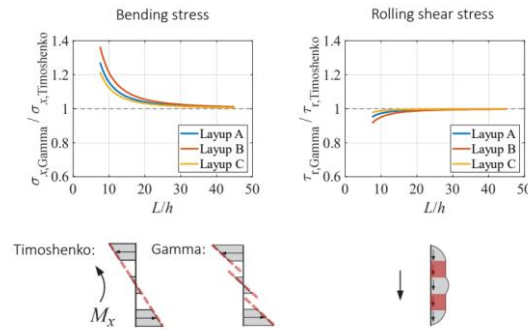


Figure 9: Differences Timoshenko's and gamma method (Danielsson, 2025)

The differences between Timoshenko's and the gamma method shown in Figure 9.

According to Timoshenko beam theory as described in §0 is sufficiently accurate in most cases and used in the majority of FEM software and handbooks (Danielsson, 2025), therefore for the rest of this thesis calculations will be carried out following this theory.

2.2.3 Designing in Ultimate Limit State (ULS)

Once all the material and cross-sectional properties are determined, the ULS capacity can be checked.

If the ratio of the occurring stresses divided by the maximum resistance exceeds 1, it is assumed that the structural element will fail. The direction of the stresses is visualised in Figure 10:

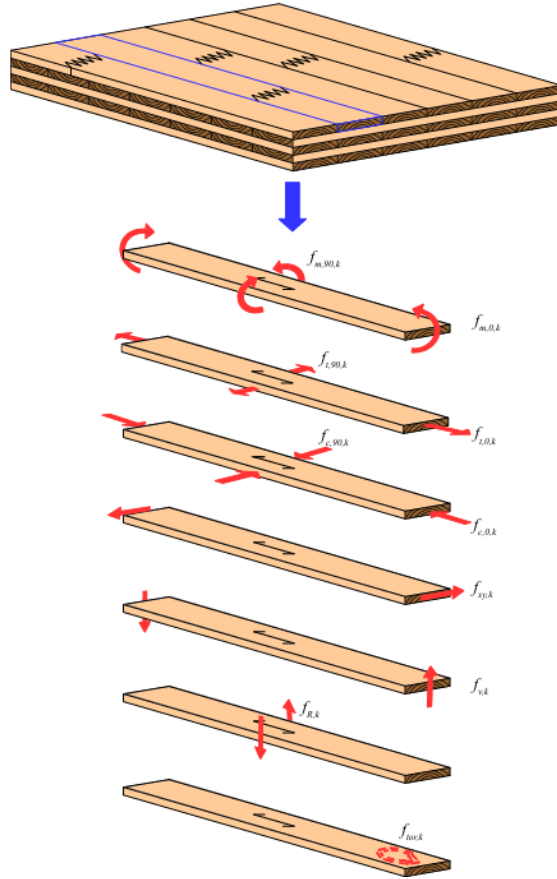


Figure 10: Directions and notation stresses CLT (Bocskai, 2019)

Stresses resulting from bending around the longitudinal layers, around the Y- and X-axis display a stress gradient as visualised in Figure 11. This course of these stresses can be calculated with the following formulas:

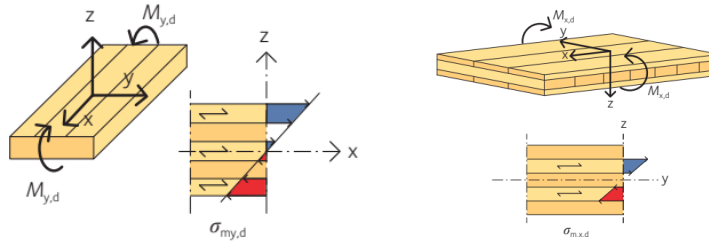


Figure 11: a) Bending in the longitudinal layers a) Y-axis and b) X-axis

$$\sigma_{m,y,d} = \frac{M_{y,d}}{W_{x,net}} \leq f_{m,xlay,d} = k_{sys} \cdot k_{mod} \cdot \frac{f_{m,xlay,k}}{\gamma_M} \quad (40)$$

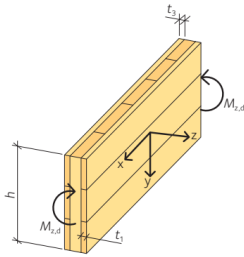
$$\sigma_{m,x,d} = \frac{M_{x,d}}{W_{y,net}} \leq f_{m,y lay,d} = k_{sys} \cdot k_{mod} \cdot \frac{f_{m,y lay,k}}{\gamma_M} \quad (41)$$

Where:

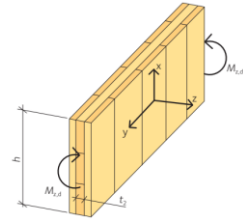
- $M_{y,d}$ is the moment design value about the Y-axis
- $W_{x,net}$ is the panel's net moment of resistance.
- $f_{m,xlay,d}$ is the bending strength design value.
- $f_{m,xlay,k}$ is the characteristic bending strength
- k_{sys} is a system factor see §2.1.1
- k_{mod} is a modification factor
- γ_m is the partial factor for the material
- $M_{x,d}$ is the moment design value about the X-axis
- $W_{x,net}$ is the panel's net moment of resistance.
- $f_{m,ylay,d}$ is the bending strength design value.
- $f_{m,ylay,k}$ is the characteristic bending strength

In case of bending around the Z-axis, two possibilities can occur. These possibilities are visualised in Table 8.

Table 8: Different options if bending in the transverse layers



$$\sigma_{m,z,d} = \frac{M_{z,d}}{W_{z,x,net}} \leq f_{m,xlay,d} = k_{sys} \cdot k_{mod} \cdot \frac{f_{m,xlay,k}}{\gamma_m} \quad (42)$$



$$\sigma_{m,z,d} = \frac{M_{z,d}}{W_{z,y,net}} \leq f_{m,ylay,d} = k_{sys} \cdot k_{mod} \cdot \frac{f_{m,ylay,k}}{\gamma_m} \quad (43)$$

$$W_{z,x,net} = \sum \frac{t_i \cdot h^2}{6} = \frac{(t_1 + t_3 + \dots) \cdot h^2}{6} \quad (44)$$

$$W_{z,y,net} = \sum \frac{t_i \cdot h^2}{6} = \frac{(t_2 + t_4 + \dots) \cdot h^2}{6} \quad (45)$$

2.2.3.1 Combined bending in two directions

For CLT components used in load-bearing roofs or similar structures where buckling does not form a risk, bending stresses might be occurring around the same axis and the stress should be verified with the following formula:

$$\frac{\sigma_{m,y,d}}{f_{m,xlay,d}} + \frac{\sigma_{m,z,d}}{f_{m,xlay,d}} \leq 1 \quad (46)$$

$\leftrightarrow$

$$\frac{M_{y,d}}{W_{x,net} \cdot f_{m,xlay,d}} + \frac{M_{z,d}}{W_{z,x,net} \cdot f_{m,xlay,d}} \leq 1 \quad (47)$$

Where:

- $\sigma_{m,y,d}$ and $\sigma_{m,z,d}$ are the bending stress design values about the main axes
- $f_{m,xlay,d}$ are the corresponding bending strengths
- $M_{y,d}$ and $M_{z,d}$ are the design values for the moment about the main axes.
- $W_{x,net}$ and $W_{z,x,net}$ are the corresponding moments of resistance.

2.2.3.2 Control of tension in the CLT plane

$$\sigma_{t,x,d} = \frac{F_{t,x,d}}{A_{x,et}} \leq f_{t,0,xlay,d} = k_{sys} \cdot k_{mod} \cdot \frac{f_{t,0,xlay,k}}{\gamma_M} \quad (48)$$

$$\sigma_{t,xy,d} = \frac{F_{t,y,d}}{A_{y,et}} \leq f_{t,0,y,lay,d} = k_{sys} \cdot k_{mod} \cdot \frac{f_{t,0,y,lay,k}}{\gamma_M} \quad (49)$$

Where:

- $F_{t,x,d}$ is the design value for tension along X-axis
- $A_{x,net}$ is the cross-section's effective net area along X-axis
- $f_{t,0,x,lay,d}$ is the tensile strength design value for boards along X-axis
- $f_{t,0,x,lay,k}$ is the characteristic strength design value for boards along X-axis
- k_{sys} is a system factor see 2.1.1
- k_{mod} is a modification factor
- γ_m is the partial factor for the material
- $F_{t,y,d}$ is the design value for tension along Y-axis
- $A_{y,net}$ is the cross-section's effective net area along Y-axis
- $f_{t,0,y,lay,d}$ is the tensile strength design value for boards along Y-axis
- $f_{t,0,y,lay,k}$ is the characteristic strength design value for boards along Y-axis

2.2.3.3 Control of compression in the CLT plane

$$\sigma_{c,x,d} = \frac{F_{c,x,d}}{A_{x,et}} \leq f_{c,0,x,lay,d} = k_{sys} \cdot k_{mod} \cdot \frac{f_{c,0,x,lay,k}}{\gamma_M} \quad (50)$$

$$\sigma_{c,y,d} = \frac{F_{c,y,d}}{A_{y,et}} \leq f_{c,0,y,lay,d} = k_{sys} \cdot k_{mod} \cdot \frac{f_{c,0,y,lay,k}}{\gamma_M} \quad (51)$$

$$\sigma_{c,z,d} = \frac{F_{c,z,d}}{A_{ef}} \leq f_{c,90,x,lay,d} = k_{c,90} \cdot k_{mod} \cdot \frac{f_{c,90,x,lay,k}}{\gamma_M} \quad (52)$$

Where:

- $F_{c,x,d}$ is the design value for tension along X-axis
- $A_{x,net}$ is the cross-section's effective net area along X-axis
- $f_{c,0,x,lay,d}$ is the tensile strength design value for boards along X-axis
- $f_{c,0,x,lay,k}$ is the characteristic strength design value for boards along X-axis
- k_{sys} is a system factor see 2.1.1
- k_{mod} is a modification factor
- γ_m is the partial factor for the material
- $F_{c,y,d}$ is the design value for tension along Y-axis
- $A_{y,net}$ is the cross-section's effective net area along Y-axis
- $f_{c,0,y,lay,d}$ is the tensile strength design value for boards along Y-axis
- $f_{c,0,y,lay,k}$ is the characteristic strength design value for boards along Y-axis
- $F_{c,z,d}$ is the design value for compression force perpendicular to grain.
- A_{ef} is the effective contact area with compression to the grain.
- $f_{c,90,x,lay,d}$ is the design value for compression strength perpendicular to grain
- $f_{c,90,x,lay,k}$ is the characteristic compression strength perpendicular to grain
- $k_{c,90}$ is a factor that takes account of how the load acts and the degree of compression

2.2.3.4 Control of shear stress perpendicular to the plain

The CLT panel includes longitudinal and transverse boards and this results in the fact that both directions should be controlled. The rolling shear strength $f_{v,r,k}$ across the grain is often clearly lower than along the grain $f_{v,k}$ ($f_{v,r,k}=20\%f_{v,k}$).

Verification shear along the grain in layer 3

$$\tau_{v,xz,d} = \frac{S_{x,net} \cdot V_{xz,d}}{I_{x,net} \cdot b_x} \leq f_{v,090,y,lay,d} = k_{mod} \cdot \frac{f_{v,090,y,lay,k}}{\gamma_M} \quad (53)$$

Verification shear across the grain in layer 2 and 4

$$\tau_{v,yz,d} = \frac{S_{y,net} \cdot V_{yz,d}}{I_{y,net} \cdot b_y} \leq f_{v,9090,x,lay,d} = k_{mod} \cdot \frac{f_{v,9090,x,lay,k}}{\gamma_M} \quad (54)$$

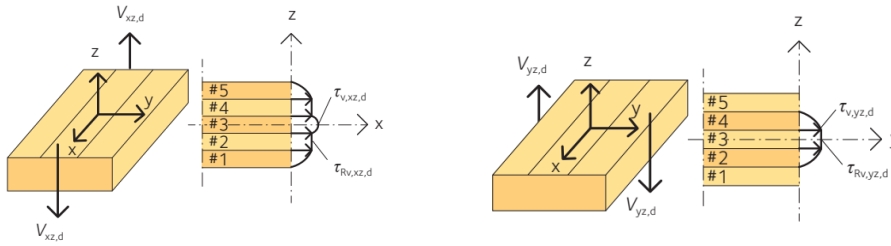


Figure 12: a) Shear stress distribution XZ-axis b) Shear stress distribution YZ-axis

Where:

$V_{xz,d}$ is the design shear force

$S_{x,net}$ is the panel's net static moment.

$f_{v,090,y,lay,d}$ is the design longitudinal shear strength of the boards

$f_{v,090,y,lay,k}$ is the characteristic longitudinal shear strength of the boards

k_{mod} is a modification factor

γ_m is the partial factor for the material

2.2.3.5 Control of shear strength in the CLT plane

CLT panels are often used as a stabilising structure. Their goal is then to absorb horizontal loads, such as wind loads, with the plane which gives birth to the shear forces V_{xy} and V_{yx} . These forces can occur in multiple directions thus the CLT panels should be capable to withstand these loads in multiple directions. This is why the strengths should be checked in for a whole panel (panel shear) and the constituent layers in the panel (layer shear) as shown in Figure 13.

Panel shear

$$\tau_{v,xy,d} = \frac{V_{xy,d}}{A_{x,net}} \leq f_{v,090,xlay,d} = k_{mod} \cdot \frac{f_{v,090,xlay,k}}{\gamma_M} \quad (55)$$

$$\tau_{v,yx,d} = \frac{V_{yx,d}}{A_{y,net}} \leq f_{v,090,ylay,d} = k_{mod} \cdot \frac{f_{v,090,ylay,k}}{\gamma_M} \quad (56)$$

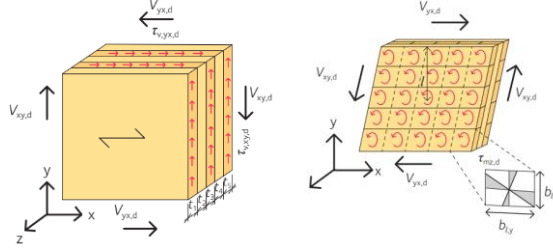


Figure 13: a) Panel shear b) Layer shear

Where:

- $V_{xy,d}$ is the design shear force.
- $A_{x,net}$ is the panel's net area.
- $f_{v,090,xlay,d}$ is the design value for longitudinal shear strength.
- $f_{v,090,xlay,k}$ is the characteristic longitudinal shear strength.
- k_{mod} is a modification factor
- γ_m is the partial factor for the material
- $V_{yx,d}$ is the design shear force.
- $A_{y,net}$ is the panel's net area.
- $f_{v,090,ylay,d}$ is the design value for longitudinal shear strength.
- $f_{v,090,ylay,k}$ is the characteristic longitudinal shear strength.

Layer shear

The properties and their calculation method are summarized in Table 9:

$$\tau_{mz,d} = \frac{M_{t,d}}{n_t \cdot W_p} \leq f_{mz,9090,d} = k_{mod} \cdot \frac{f_{mz,9090,k}}{\gamma_M} \quad (57)$$

Table 9: Properties layer shear

$M_{t,d}$ is the moment design value	$M_{t,d} = V_{x,d} \cdot l$	(58)
l is the distance between the roll centre and the force	$W_p = \frac{2 \cdot I_p}{\sqrt{b_{l,x} \cdot b_{l,y}}}$	(59)
W_p is the board's polar moment of inertia		
I_p is the polar moment of inertia	$I_p = \frac{b_{l,x} \cdot b_{l,y}^3}{12} + \frac{b_{l,x}^3 \cdot b_{l,y}}{12} = \frac{b_l^4}{6}$	(60)
n_t is the number of bonded surfaces in the panel	$n_t = \#bonded\ layers \cdot \#boards\ Xaxis \cdot \#boards\ Yaxis$	(61)
$f_{mz,9090,d}$ is the design shear strength.		
$f_{mz,9090,k}$ is the characteristic shear strength.		

2.2.3.6 Checking buckling in walls and posts

In an identical manner as described in Eurocode 5, (NBN EN 1995, 2005), the posts are designed according to the linear buckling theory. Non-linear effects are considered and taken into account in the reduction factor k_c . In order to check buckling in a CLT wall panel two different load cases should be considered, pure axial loads and transverse loads, and combined to check the panel's capacity as shown in Figure 14

$$\frac{\sigma_{c,x,d}}{k_{c,y} \cdot f_{c,0,xlay,d}} + \frac{\sigma_{m,y,d}}{f_{m,xlay,d}} \leq 1 \quad (62)$$

$$\leftrightarrow \frac{N_d}{k_{c,y} \cdot A_{x,net} \cdot f_{c,0,xlay,d}} + \frac{M_{y,d}}{W_{x,net} \cdot f_{m,xlay,d}} \leq 1 \quad (63)$$

Where:

$$M_{y,d} = \frac{q_d \cdot l_e^2}{8} \quad (64)$$

$$l_e = \mu \cdot l \quad (65)$$

μ check

Table 5

$$k_c = \frac{1}{k_y + \sqrt{k_y^2 - \lambda_{rel,y}^2}} \leq 1 \quad (66)$$

$$k_y = 0.5 \cdot (1 + 0.1 \cdot (\lambda_{rel,y} - 0.3) + \lambda_{rel,y}^2) \quad (67)$$

$$\lambda_{rel,y} = \frac{\lambda_y}{\pi} \cdot \sqrt{\frac{f_{c,0,xlay,k}}{E_{0,x,05}}} \quad (68)$$

$$\lambda_y = \frac{l_e}{i_{x,ef}} \quad (69)$$

$$i_{x,ef} = \sqrt{\frac{I_{x,ef}}{A_{x,e}}} \quad (70)$$

$$E_{0,x,05} = k \cdot E_{0,x,mean} \quad (71)$$

$$k = 1 - \frac{0.328}{\sqrt{\frac{2 \cdot b_x}{0.15} - 1}} \quad (72)$$

If $\lambda_{rel,y} < 0.3$, the risk of buckling is minimal and the influence of the axial compression force can be reduced:

$$\left(\frac{\sigma_{c,x,d}}{f_{c,0,xlay,d}} \right)^2 + \frac{\sigma_{m,y,d}}{f_{m,xlay,d}} \leq 1 \quad (73)$$

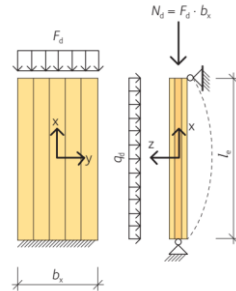


Figure 14; Buckling CLT panel

2.3 Shell theory

When multiple load directions are present, such as point support, angle support, openings or local area loads, the biaxial loading effect on the panel must be considered. A commonly used model to take to account these effects is the orthotropic shell model. In this scenario, cross-section values are specified for CLT as a shell component. A significant property of CLT components emerges when they function as shell elements. Rather than being limited to one-dimensional behaviour like beams or posts, CLT components can act in two dimensions. They may function as slabs, carrying loads in various directions, or as panels, simultaneously transferring shear and axial forces. Modelling based on stiffness values organized in a matrix facilitates the comprehensive utilization of CLT properties. Design should be based on force levels or load-bearing capacity, as these two-dimensional models do not represent internal stresses within individual layers.

It thus can be stated that there is a shift from verifying the capacity on a material point level in the beam theory to a verification on a cross-sectional level in the shell theory.

2.3.1 Orthotropic shell with direct determination of stiffness matrix

According to the Timoshenko beam theory, incorporating shear correction factors as described in §2.2.1.3, the stiffness values for shell components subject to bending under shear force can be determined independently of the static system. This approach utilizes cross-section values in both directions, as outlined by Reissner-Mindlin. The direction of the forces is shown in Figure 15.

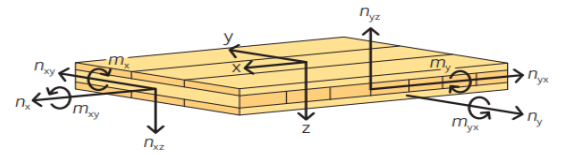


Figure 15: Normal forces and moments according to the shell theory (Fröbel & Gustafsson, 2022)

2.3.1.1 Material strength for CLT shell components

The following stiffness matrix can be composed for orthotropic shell components p where [D11-D33] represents the bending and torsion properties of the CLT slab, [D44-D55] describes the shear stiffness properties of the CLT slab and [D66-D88] expresses the shear stiffness properties of the CLT panel:

$$C_{CLT} = \begin{bmatrix} D_{11} & D_{12} & 0 & 0 & 0 & 0 & 0 & 0 \\ D_{21} & D_{22} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & D_{33} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & D_{44} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & D_{55} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & D_{66} & D_{67} & 0 \\ 0 & 0 & 0 & 0 & 0 & D_{76} & D_{77} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & D_{88} \end{bmatrix} \quad (74)$$

Where:

Bending and torsion properties
CLT slab

$$D_{11} = E_{0,mean} \cdot I_{x,net} \quad (75)$$

$$D_{12} = 0 \quad (76)$$

$$D_{21} = 0 \quad (77)$$

$$D_{22} = E_{0,mean} \cdot I_{x,net} \quad (78)$$

$$D_{33} = 0.65 \cdot G_{0,mean} \cdot \frac{h_{CLT}^3}{12} \quad (79)$$

Shear stiffness properties
CLT slab

$$D_{44} = \kappa_x \cdot G_{0,mean} \cdot h_x \quad (80)$$

$$D_{55} = \kappa_y \cdot G_{0,mean} \cdot h_y \quad (81)$$

Shear stiffness properties
CLT panel

$$D_{66} = E_{0,mean} \cdot h_x \quad (82)$$

$$D_{67} = D_{66} \cdot \nu \quad (83)$$

$$D_{76} = 0 \quad (84)$$

$$D_{77} = E_{0,mean} \cdot h_y \quad (85)$$

$$D_{88} = 0.75 \cdot G_{0,mean} \cdot h_{CLT} \quad (86)$$

$$C_{CLT} = \begin{bmatrix} E_{0,mean} \cdot I_{x,net} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & E_{0,mean} \cdot I_{x,net} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.65 \cdot G_{0,mean} \cdot \frac{h_{CLT}^3}{12} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \kappa_x \cdot G_{0,mean} \cdot h_x & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \kappa_y \cdot G_{0,mean} \cdot h_y & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & E_{0,mean} \cdot h_x & D_{66} \cdot \nu & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & E_{0,mean} \cdot h_y & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.75 \cdot G_{0,mean} \cdot h_{CLT} \end{bmatrix} \quad (87)$$

2.3.1.2 Verifying the material strength

The ratio between forces (n for normal forces and m for moments) and displacements (u for displacements and ϕ for rotations) of the cog for the component's surface according to Figure 15, is defined by the following matrix form and can effectively be used in FEM software:

$$\begin{Bmatrix} m_x \\ m_y \\ m_{xy} \\ n_{xz} \\ n_{yz} \\ n_x \\ n_y \\ n_{xy} \end{Bmatrix} = C_{clt} \cdot \begin{Bmatrix} K_x = \frac{\partial \Phi_y}{\partial x} \\ K_x = -\frac{\partial \Phi_x}{\partial y} \\ K_{xy} = \frac{\partial \Phi_y}{\partial y} - \frac{\partial \Phi_x}{\partial x} \\ \gamma_{xz} = \frac{\partial u_z}{\partial x} + \Phi_y \\ \gamma_{yz} = \frac{\partial u_z}{\partial y} - \Phi_x \\ \varepsilon_x = \frac{\partial u_x}{\partial x} \\ \varepsilon_y = \frac{\partial u_y}{\partial y} \\ \gamma_{yz} = \frac{\partial u_x}{\partial y} - \frac{\partial u_y}{\partial x} \end{Bmatrix} \quad (88)$$

2.3.2 Verifying the element's capacity

2.3.2.1 Bending moment about X-and Y-axis

$$\begin{aligned} m_{x,E,d} &\leq m_{x,R,d} & (89) \quad m_{y,E,d} &\leq m_{y,R,d} & (90) \\ m_{x,R,d} &= W_{x,net} \cdot f_{m,xlay,d} & (91) \quad m_{y,R,d} &= W_{y,net} \cdot f_{m,ylay,d} & (92) \end{aligned}$$

2.3.2.2 Axial force along the X-and Y-axis

$$\begin{aligned} n_{x,E,d} &\leq n_{x,R,d} & (93) \quad n_{y,E,d} &\leq n_{y,R,d} & (94) \\ \text{For tension:} & & & & \\ n_{x,R,d} &= A_{x,net} \cdot f_{t,xlay,d} & (95) \quad n_{y,R,d} &= A_{y,net} \cdot f_{t,ylay,d} & (96) \\ \text{For compression:} & & & & \\ n_{x,R,d} &= A_{x,net} \cdot f_{c,xlay,d} & (97) \quad n_{y,R,d} &= A_{y,net} \cdot f_{c,ylay,d} & (98) \end{aligned}$$

2.3.2.3 Shear force in the XY-or YX-plane:

$$n_{xy,E,d} \leq n_{x,yR,d} \quad (99)$$

$n_{xy,E,d}$ is the design shear force in the CLT panel's plane in kN/m.

$n_{x,yR,d}$ is the design shear capacity in kN/m

$$n_{xy} = n_{yx} \quad (100)$$

2.4 Design in Serviceability Limit State (SLS)

The utilisation factor of load-bearing capacity in floors is usually less than 50%, making the SLS requirements the determining factor (Fröbel & Gustafsson, 2022). In Belgium there was recently a case where the timber decay was so severe resulting in non-compliant deflections that the whole structure had to be demolished after only seven years. This resulted in a serious damage. The state of the deflection can be seen in Figure 16.

When designing CLT elements in SLS deformations, sagging and vibrations should be considered.

In wooden structures, where the variable load dominates, deflections vary during the lifetime of the structure (Fröbel & Gustafsson, 2022).

For a structural element subjected to sustained loading throughout its service life, the total deflection is governed by three contributions: the instantaneous deflection w_{inst} occurring upon load application, the time-dependent creep deflection w_{creep} , and the deformation factor k_{def} , the latter being a function of the ambient moisture content of the timber and the degree to which that moisture content fluctuates over time. (Fröbel & Gustafsson, 2022). The values for k_{def} are divided based on the service class in which the element is exposed similarly to the values for k_{mod} .

These values are summarised in Table 10 based on (Zoltán I. Bocskai, 2019):

Table 10: k_{def} based on Service Class from (Zoltán I. Bocskai, 2019):

Service Class	k_{def}
1	0.6
2	0.8
3	2

These different deflections are shown in Figure 17.

$$w_{creep} = k_{def} \cdot w_{inst} \quad (101)$$

$$w_{fin,G} = w_{inst,G} + w_{creep,G} = w_{inst,G} \cdot (1 + k_{def}) \quad (102)$$

$$w_{fin,G} = w_{inst,G} + w_{creep,G} = w_{inst,G} \cdot (1 + \psi_{2,i} \cdot k_{def}) \quad (103)$$

The deflection of a floor is treated as strips between two supports.



Figure 16: Decay damage in Belgium (<https://www.nieuwsblad.be/regio/limburg/sint-truiden/zien-eigenaars-ooit-iets-van-hun-centen-terug-proces-rond-rotte-appartementen-van-start/87714404.html>)

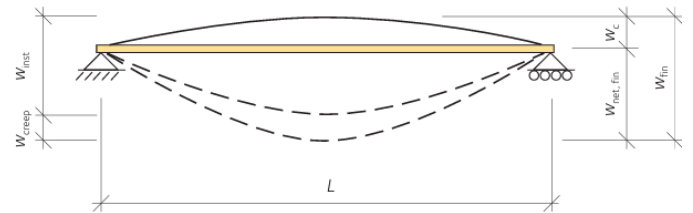


Figure 17: Definitions of deflection in SLS (Fröbel & Gustafsson, 2022)

For a floor structure that is simply supported on two supports, the deflection in the middle of the span due to bending moment w_m can be calculated as follows:

$$w_m = \frac{5 \cdot q \cdot L}{384 \cdot E \cdot I_{net}} \quad (104)$$

Where I_{net} can be calculated according to the (simplified) Timoshenko beam theory or the gamma method, both described in §2.2.

If the ratio between the span and the slab's h_{clt} thickness is bigger than 10, also shear deflection w_s should be taken in account. Also, the shear correction factor κ should be considered.

$$w_s = \frac{q \cdot L^2}{8 \cdot G \cdot \kappa \cdot A_s} \quad (105)$$

So, the total deflection can be calculated as:

$$w_{inst,G} = w_m (+ w_s) \quad (106)$$

2.5 Design of the connection in ULS

To calculate the capacity of a connection between several CLT elements, the embedment strength of the panel. This is done based on (Fröbel & Gustafsson, 2022) as follows:

$$f_{h,k} = \frac{0.082 \cdot \rho_k \cdot d^{-0.3}}{2.5 \cdot \cos^2 \varepsilon + \sin^2 \varepsilon} \quad (107)$$

Where:

d is the wood screw's outer thread diameter

ρ_k is h-the characteristic dry density of the wood

ε is the angle between the screw and the plane of the CLT plate.

Once the embedment strength is known, the theory of Johansen can be adopted according to Eurocode 5 for a timber-timber connection with once shear plane. The different failure mechanisms are expressed in the formulas below and visualised in Figure 18 .

β is the ratio between the embedment strengths of members. This variable will express the influence of the different orientations of the wall and floor and is calculated as follows:

$$\beta = \frac{f_{h2k}}{f_{h1k}} \quad (108)$$

$$F_{v,RK} = \min \left\{ \begin{array}{l} f_{h,1,k} \cdot t_1 \cdot d \quad (a) \\ f_{h,2,k} \cdot t_2 \cdot d \quad (b) \\ \frac{f_{h,1,k} \cdot t_1 \cdot d}{1 + \beta} \left[\sqrt{\beta + 2\beta^2 \left[1 + \frac{t_2}{t_1} + \left(\frac{t_2}{t_1} \right)^2 \right]} + \beta^3 \cdot \left(\frac{t_2}{t_1} \right)^2 - \beta \cdot \left(1 + \frac{t_2}{t_1} \right) \right] + \frac{F_{ax,Rk}}{4} \quad (c) \\ 1.05 \frac{f_{h,1,k} \cdot t_1 \cdot d}{2 + \beta} \left[\sqrt{2\beta(1 + \beta) + \frac{4\beta(2 + \beta) \cdot M_{y,Rk}}{f_{h,1,k} \cdot d \cdot t_1^2}} \right] - \beta + \frac{F_{ax,Rk}}{4} \quad (d) \\ 1.05 \frac{f_{h,1,k} \cdot t_2 \cdot d}{1 + 2\beta} \left[\sqrt{2\beta^2(1 + \beta) + \frac{4\beta \cdot (1 + 2\beta) \cdot M_{y,Rk}}{f_{h,1,k} \cdot d \cdot t_2^2}} \right] - \beta + \frac{F_{ax,Rk}}{4} \quad (e) \\ 1.15 \sqrt{\frac{2\beta}{1 + \beta}} \sqrt{2 M_{y,Rk} \cdot f_{h,1,k} \cdot d} + \frac{F_{ax,Rk}}{4} \quad (f) \end{array} \right. \quad (109)$$

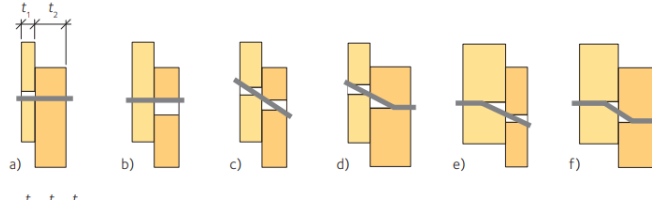


Figure 18: Failure mechanisms from Johansen for a timber-timber connection with one shear plane
a,b,c: Failure occurs as the wood crushes (embedment failure) without yielding of the fastener
d,e: Failure occurs with one plastic hinge forming in the fastener, coupled with wood embedding.
f: Failure with two or more plastic hinges, typical for thicker or more rigid fasteners. (Isaksson, 2022)

It should also be noted that the beneficial influence of the rope effect, expressed as $F_{ax,Rk}/4$, is not considered for the calculation of capacity of the connection in this master thesis since the research for the set up that will be examined is too scarce.

When designing a metal fastener connection, it is also desirable to ensure a ductile failure instead of a brittle failure. This can be done by designing the connection in such a way that mode e or f will be the governing equation. (Fröbel & Gustafsson, 2022)

It can also be noted that in Equation 107 the influence of element 2 is expressed in part b of the equation. (Fröbel & Gustafsson, 2022) also states that :

$$l_{ef,1} \geq 0.8 \cdot l_{ef,2} \quad (110)$$

The effective length of the metal fastener corresponds with the thickness of the members t_1 and t_2 .

This leads to the fact that only if the self-weight of second member is smaller than 0.8 the self-weight of the first member, it could dominate its influence in Equation b and a in Equation 107.

So, it can be checked according to (NBN EN 1995, 2005):

$$F_{v,Rd} = n_{ef} \cdot k_{mod} \cdot \frac{F_{v,Rk}}{\gamma_M} \quad (111)$$

This is the capacity for one screw. To calculate the resistance of the total connection in case of a group of screws, the group effect should be considered. This is done by multiplying the resistance of one screw with the effective amount of screw. A distinction needs to be made based on the layout of the connection:

The effective number of screws groups with screws with a diameter larger than 6mm, can be expressed with the following equation:

$$n_{ef} = 0.74 \cdot n^{0.9} \quad (112)$$

If the outer diameter is larger than 6mm and the spacing is at least $7d$ the effective number of screw groups with screws can be calculated as:

$$n_{ef} = n^{0.7} \quad (113)$$

Where: n_{ef} is the effective no. of wood screws
 n is the no. of wood screws in the joint

It can finally be controlled if the connection is able to resist the present forces:

$$\frac{F_{v,Ed}}{F_{v,Rd}} \leq 1 \quad (114)$$

2.6 Timber decay

Wood decay fungi have long presented significant challenges to the durability of timber structures since wood remains the most prevalent natural resource utilized in global construction. That is why developing methods to protect timber is very important within the built environment. While various factors such as insects, marine organisms and weathering

contribute to the deterioration of wood products, fungal decay remains responsible for more destruction worldwide than any of these other agents (Mankowski & Morrell, 2000).

In technical terms decay refers specifically to the degradation of wood through fungal action. This is a process that ultimately leads to a loss of structural strength of the timber element. It is important to distinguish decay fungi from staining and mould fungi, which are generally not considered decay organisms (Goodell et al., 2008). This is because these latter types can increase moisture uptake or cause minor strength losses in temperate climates but they usually don't result in a loss of mechanical properties. However, in certain tropical environments, staining fungi have been known to cause significant strength loss and can reduce the toughness of colonized timber. (Goodell et al., 2008)

The decay fungi were divided into three groups based on the appearance of the damaged wood, namely brown, white and soft rot fungi. This classification is arbitrary and today these decay types are recognised more as a continuum (Riley et al., 2014) but these categories are still helpful in classifying these fungal degradative agents and for discussions (Goodell et al., 2020).

Since soft rot fungi are often found in more extreme and wetter conditions that are less suitable for brown and white rot fungi and it only affects the outermost mm of the boards (Goodell et al., 2020), it was opted in this research to neglect its influence and focus on white and brown rot fungi.

2.6.1 Decay process

The decay process begins when fungi invade the wood ray cells. As the invasion progresses, the fungi extend to degrade the cell walls for nutrients. This first step can take 0.5-5 years to start (Käärik, 1974). A specific micro-environment is necessary to support fungal growth and the diffusion of these metabolites. This micro-environment is characterized by appropriate temperature, oxygen levels and moisture contents (MC) (Schmidt Olaf, 2006). Generally, wood degradation requires a moisture content at or above the fibre saturation point, with optimal ranges between 19% and 80% depending on the wood and fungal species (Zabel & Morrell, 2012).

Most fungi grow more aggressively as the wood reaches MC between 40-60% (Wang et al., 2018).

Temperature also plays a critical role; most decay fungi prefer a range of 5–30°C since fungi are dormant below 5°C and above approximately 65 °C the fungi are killed. (Brites et al., 2013) When conditions are unfavourable, fungi can form resting structures like spores or mycelial fragments that survive for years, germinating to re-colonize the wood as soon as it is rewetted (Goodell et al., 2008).

2.6.2 Brown rot

Following the initial stages of colonization, brown rot fungi primarily target the carbohydrate polymers within the wood cell wall, though they eventually affect all three major wood polymers. These fungi are of particular commercial significance due to their impact on structural integrity, especially since they frequently attack the softwoods that comprise the majority of construction timber in North America and Europe. While their preference for softwoods is notable, they are also capable of degrading hardwoods under specific environmental circumstances. The progression of this decay typically results in a fractured, brownish appearance. A defining and critical aspect of brown rot is that the degradation often occurs well in advance of the actual hyphal growth at the cellular level. Furthermore, the fungi depolymerize wood carbohydrates at a rate much faster than they can be utilized for nourishment. This biochemical process leads to severe reductions in mechanical properties, such as tension and bending strength, even when the wood shows very little visual change or minimal mass loss (Curling et al., n.d.; Willox Wayne, 1977).

2.6.3 White rot

In contrast to brown rot fungi, white rot fungi utilize a suite of secreted enzymes to break down all three major cell wall polymers. This process can lead eventually in a mass loss up to 97%.

While the majority of white rot species digest all the polymeric components as they break down, there are some varieties that preferentially target lignin and hemicellulose while leaving the crystalline cellulose largely intact (Goodell et al., 2020).

In contrast to the rapid failure seen in brown rot, structural decline in white rot occurs more gradually. This is because the depolymerization of the cell wall is more tightly coupled with the fungus's own metabolic utilization and the direct enzymatic erosion of the wall layers. That is the reason why the reductions in mechanical properties like bending and tension strength tend to occur in line with actual mass loss (Goodell et al., 2020).

Although these fungi primarily target hardwoods, they are also capable of infesting softwoods under certain conditions (Krah et al., 2018).

2.7 Modelling decay

2.7.1 Introduction

CLT is a fairly new construction material with a lack of technical guidance and based on (Viitanen et al., 2010) Belgium has been identified as one of the regions with the highest risk of wood decay. This makes it extremely relevant to find a correct manner to predict and model decay in function of time and loss of mechanical properties.

2.7.2 Dose response model

In the European research project Woodexter a performance-based design model was developed. (Thelandersson et al., 2011). The basic concept is to define a model based on separate variables representing the climatic exposure on one hand and the material resistance on the other hand as shown in Figure 19.

A limit state is defined which represents onset of decay. This approach has the advantage that the exposure can be expressed as a function of global and local climate, component design and surface treatment in a general way independent of the exposed material. The material resistance can in the same way be expressed in terms of response to quantified and standardized climate conditions independent of the design situation (Isaksson & Thelandersson, 2013).

The impact of a general time variation of moisture content MC and temperature T on the potential for decay can be described by a so-called dose-response relation (Brischke & Rapp, 2010). Dose stands for the normalized time of exposure of the material to temperature and moisture levels favourable for the development and growth of wood decay (Hradil & Fortino, 2023). This phenomenon is shown in Figure 20.

Models based on dose-response relationships have the benefit of enabling time-series analysis. On the one hand, the effect in terms of fungal decay (= reaction) can be directly linked to the dose in terms of meteorological factors and moisture loads. However, performance (materials, design details, etc.) may have an impact on the dosage. This allows both to estimate the service lives (i.e. the expected time to reach a defined level of decay) and evaluate relative performance between different design details, materials, geographic locations and climatic conditions.

The total daily dose D can be written in relation to component D_{mc} which depends on the daily average moisture content MC and D_t which corresponds with the daily average temperature T as shown in Figure 20 (Isaksson et al., 2013; NBN EN 1995, 2005).

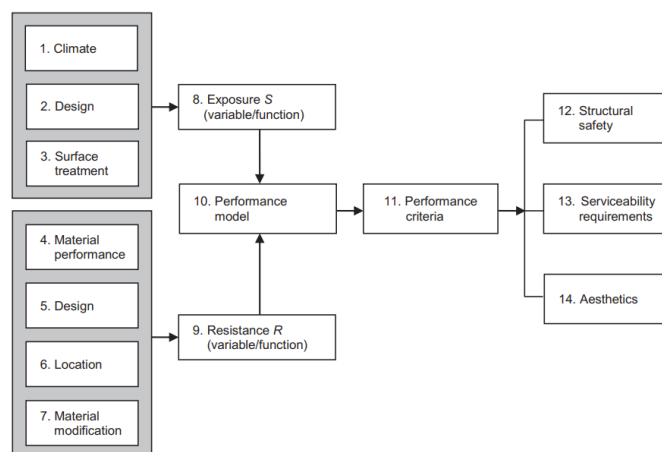


Figure 19: Flowchart of modelling decay (Isaksson & Thelandersson, 2013)

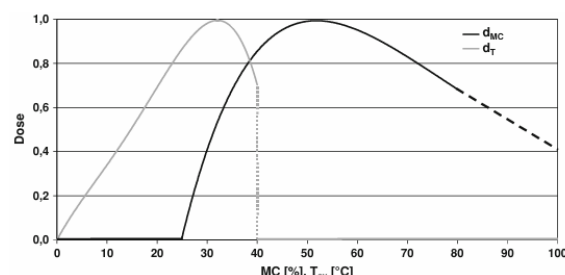


Fig. 4 Relationship between MC and daily moisture-induced dose d_{MC} , and between average wood temperature T_{av} and daily temperature-induced dose d_T , respectively. Dashed black line: MC > 80% did not occur; therefore, the curve progression is uncertain

Figure 20 : Dose-response functions (Brischke & Rapp, 2010)

$$D = f(D_T(T_i), D_{MC}(MC_i)) \quad (115)$$

For n days of exposure to a certain dose, the total dose can be written as:

$$D(n) = \sum_{i=1}^n D_i = \sum_{i=1}^n f(D_T(T_i), D_{MC}(MC_i)) \quad (116)$$

Decay starts when the sum of the doses surpasses a certain critical dose.

For white rot this is 451 doses and for brown rot it is 229 doses (Brischke & Meyer-Veltrup, 2016).

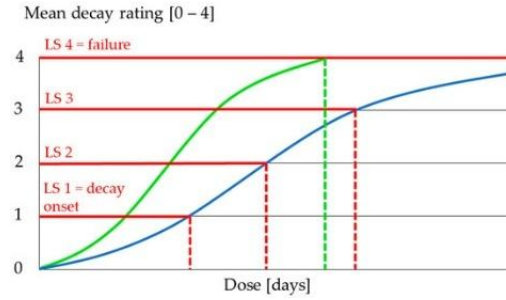


Figure 21: Decay model (Marais et al, 2021)

2.7.3 Logistic dose-response model for above ground applications

The physiological foundation characteristics of wood decay fungi were strictly taken into account in the first method of describing the relationship between the development of fungal decay on wood and corresponding exposure conditions. To determine a logistic link between temperature-based dose and responding timber deterioration and wood moisture content, a dose-response model was created. Therefore, it was thought that the total daily dose, which affects the wood, is a function of the temperature-induced component D_T and the moisture-induced component D_{MC} .

$$D_{MC}(MC) = \begin{cases} 0 & \text{if } MC < 25\% \\ e \cdot MC^5 - f \cdot MC^4 + g \cdot MC^3 - h \cdot MC^3 + i \cdot MC - j & \text{if } MC \geq 25\% \end{cases} \quad (117)$$

$$D_T(T) = \begin{cases} 0 & \text{if } T_{min} < 0^\circ\text{C or if } T_{max} > 40^\circ\text{C} \\ k \cdot T^4 + l \cdot T^3 - m \cdot T^2 + n \cdot T & \text{if } T_{min} \geq 0^\circ\text{C or if } T_{max} < 40^\circ\text{C} \end{cases} \quad (118)$$

$$D = (a \cdot D_T(T) + D_{MC}(MC)) \cdot (a + 1)^{-1} \text{ if } D_{MC} > 0 \text{ and } D_T > 0 \quad (119)$$

The best fit for this model based on several datasets can be written with the following parameters shown in Table 11:

Table 11: variables dose-response function above ground applications (Isaksson et al, 2013)

$a = 3.2$	$j = 4.98$
$e = 6.75 \cdot 10^{-10}$	$k = 1.80 \cdot 10^{-7}$
$f = 3.50 \cdot 10^{-7}$	$l = 9.57 \cdot 10^{-5}$
$g = 7.18 \cdot 10^{-5}$	$m = 1.55 \cdot 10^{-3}$
$h = 7.22 \cdot 10^{-3}$	$n = 4.17$
$i = 0.34$	

The total dose D for n days can then be written as the sum of each dose, as shown above:

$$D(n) = \sum_{i=1}^n Di \quad (120)$$

The decay rating is done by using (EN 252, 2014) . Here the level of decay is classified in five levels as shown in Figure 21 and Table 12:

Table 12: Rating decay according to (EN 252, 2014)

0: Sound – no decay
1: Slight decay
2: Moderate decay
3 : Severe decay
4: Failure

The decay rating can be calculated based on (EN 252, 2014) by the following formula in case of the logistic model:

$$DR(D(n)) = 4 \cdot EXP \left(EXP \left(a_{DR} - (b_{DR} \cdot D(n)) \right) \right) \quad (121)$$

Figure 22 also shows clearly that the temperature is the defining factor over the moisture content.

In this thesis the logistic model is adapted to conduct research but is it also worth mentioning that there is a second logistic model that can be retrieved from literature , namely the simplified logistic model . For more information about this model, (Isaksson et al, 2013) can be contacted.

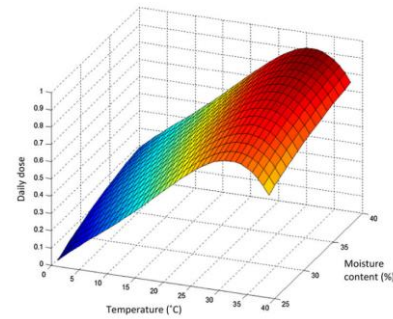


Figure 22: Temperature and moisture influence Daily dose (Isaksson et al, 2013)

2.8 Modelling moisture

Timber buildings can suffer from moisture-induced problems. Heat-Air and Moisture (HAM) simulations have been developed to study, avoid and restore moisture related problems in a systematic and comprehensible way.

These hygrothermal simulations have emphasized their importance to help understanding and predicting various hygrothermal processes and risks on a material, component and building scale.

These simulations have advanced so much in the recent years in to such that they can predict the service life of components (Vanderschelden et al., 2022). The reliability of HAM simulations and, by extension, the accuracy of decay dose predictions, depends critically on the quality of the input and model parameters used. To address the complexity and inconsistency with which these parameters are selected in practice, (Vanderschelden et al, 2024) developed SAMiRA (Superior, Advanced and Minimum Requirement Approach): a 12-step decision framework for the systematic definition of input and model parameters in hygrothermal simulations, illustrated in Figure 23. The feedback loop is only relevant for existing structures.

The framework surpasses the scope of existing standards such as (Vanderschelden et al, 2024) by providing structured guidance across three strategic levels of complexity and granularity: Superior, Advanced, and

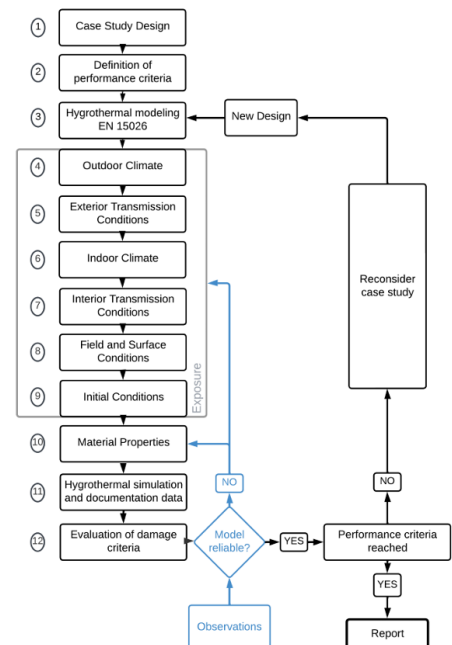


Figure 23: Flowchart summarizing SAMiRA: 12 comprehensive steps for hygrothermal simulations (Vandemeulebroucke et al, 2022)

Minimum. Each level reflects the degree to which case-specific information can be gathered, measured, or determined. As the strategic level increases from Minimum to Superior, model accuracy and reliability improve, but at higher computational and financial cost. At the Minimum level, sensitivity analyses using optimistic and pessimistic parameter scenarios are recommended to quantify the uncertainty introduced by the simplifications.

The 12 steps cover the full scope of a HAM simulation: from defining the case study and performance criteria, over boundary conditions (outdoor climate, wind-driven rain, interior climate), to material properties, initial conditions, and post-processing of results. The post-processing step is particularly relevant in the context of this thesis: HAMalyser, the publicly available web tool in which SAMiRA is implemented, includes a post-processing module that computes decay prediction models including dose-response models such as the one by (Brischke & Rapp, 2008), based on simulation output (Vanderschelden et al., 2024).

CLT panels are fabricated and transported with an initial MC of 16% (Fröbel & Gustafsson, 2022). This is called the delivery moisture content. This value, as it should vary between 12-20% according to (Fröbel & Gustafsson, 2022) has a negligible influence on the result if the HAM simulation is run for a longer period. (Blommaert et al., 2025)

The potential moisture sources are moisture accumulation during the service life of the building and during the construction phase, these sources are related to the outdoor environment. Then there are leaks due to imperfections in water resistive barriers and ducts.

2.8.1 Outdoor environment

A long-term 30-year climate file for HAM tools is the first set of climate data. A "full response-based simulation" can be carried out using this climate file. This indicates that the entire 30-year (or 31-year) climate is replicated. A full 30-year response of the building envelope (such as a temperature and relative humidity profile for 30 years of hourly simulation results) is the outcome of the simulation. This method yields the most dependable results, but it demands a lot of processing power. (Vanderschelden et al., 2022) The second set of climate data is defined based on a Moisture Reference Year (MRY) based on (Vandemeulebroucke et al., 2022)

In the context of this research, an MRY is used as the outdoor climate input, corresponding to the Minimum to Advanced level in the SAMiRA framework. This choice is consistent with the approach recommended by (Vandemeulebroucke et al., 2022) and is justified by the focus on relative comparisons between decay scenarios rather than absolute service-life predictions.

A MRY is one year of climate data with a return period in terms of moisture stress on building envelopes on a specific location (Cornick et al., 2003; Vandemeulebroucke et al., n.d.; Zhou et al., 2016). A climate index is used to select the MRY. This climate index is a Moisture Index. This is an index which is solely based on climate parameters (Cornick et al., 2003). The hygrothermal performance of building envelopes at the designated site is known to be correlated with the selected climate index. In this dissertation the chosen climate index corresponds to Brussels, in Belgium.

The used data sets in the HAM simulations were Temperature, Shortwave radiation, Relative humidity, Longwave radiation and Rain flow density.

2.8.2 Rain

Rain is determined by the MRY. A western orientation for the vertical elements is chosen as the baseline scenario since this is the most common wind direction in Belgium.

The rain exposure (RE) can be calculated as follows:

$$RE = \frac{C_R \cdot C_T \cdot O \cdot W}{C_{R, fixed} \cdot C_{T, fixed} \cdot O_{fixed} \cdot W_{fixed}} \quad (122)$$

Where: C_R = Factor for terrain variations
 C_T = Factor for topography
 O = Obstacle factor
 W = Wall factor

The coefficient for rain exposure is set at 0.5 based on (Blommaert et al., 2025). Since a brick façade cladding is assumed, it is assumed that 7% of the rain flux will penetrate the building envelope. This seeped in water is allocated to the insulating board's outside to account for rain leakage through the façade cladding for walls (Van Linden & Van Den Bossche, 2022.). Five air changes per hour is the air change rate in the air cavity in walls (Langmans et al., 2015). The roofs are expected to be waterproof so no rain penetration is modelled.

2.8.3 Moisture accumulation during the construction phase

As for rain also here some influence factors can be determined based on (Blommaert et al., 2025):

The orientation and rain exposure coefficient are determined identical as in §2.8.2.

Additional influence factors are the wood type and type of insulation material, followed from the research from (Blommaert et al., 2025). It thus can be stated that the biggest influence factor is the RE, then the orientation, then the wood type and eventually the insulation material.

The glue type and delivery moisture content had a minimal influence in a longer period (Blommaert et al., 2025).

2.8.4 Leakage

Leaks from improper plumbing and poorly built or deteriorating window sealing are two examples of water sources that, in theory, never exist but, in practice, frequently do. These imperfections have the potential to cause significant damage, which might be especially difficult in the case of mass lumber. Many of these locations are hidden behind plasterboard or other facades that hinder drying and make it challenging to identify fungal rot and excessive moisture. (Wang et al., 2018). These water leakages form a serious threat for the structural integrity of the building. To date, little research has been conducted into the consequences of water leakage in a structure. (Khartode et al., 2024)

According to research performed by (Zese et al., 2021), water leaks in residential buildings can be divided into three categories based on the extent of the leak, shown in Table 13:

Table 13: leak categories

Small leak	0.5 l/h
Medium-sized leak	5 l/h
Big leak	20 l/h

Minor leaks are usually caused by dripping joints, medium-sized leaks by faulty sanitary appliances and major leaks by damaged pipes. (Zese et al., 2021)

(Britton et al., 2008) found that it takes 156 days on average to discover a water leak.

(De Smet, 2025) discovered that there is no clear difference in terms of modelling a small, medium or big leak since the material will be saturated already in case of a small leak. The author also makes a differentiation in terms of the duration of the leak, namely a short (1 day), medium (30 days) and long (150 days) leak. (De Smet, 2025) also proved that the leaks in case of the most realistic situation, namely a leak in the cavity, will not cause any damage.

(De Smet, 2025) also found out that the influence of the scale of the leakage do not have a significant effect on the decay process since the cells will be saturated in the three scenarios but it is the duration of the leakage that determines the effect on the decay process.

It was found during the simulation of the different moisture sources that the influence of a leak on the load-bearing capacity of a lamellae in a CLT panel was negligible.

That is why this moisture source is not worked out in greater detail.

2.8.5 Influence of insulation material on modelling moisture

In this research three different types of insulation materials are evaluated, namely Mineral Wool (MW), Polyurethane (PUR) and Cellulose (CEL).

These insulation materials can be subdivided into two categories: capillary materials and non-capillary materials.

Capillary materials such as CEL are prone to brown rot, dry out slowly and stay wet often longer than a year.(De Smet, 2025)

Non-capillary materials such as MW and PUR are insulations materials that are largely vapour-tight or hydrophobic and designed to prevent the movement of moisture.(Freimanis et al, 2023)

PUR retains its thermic properties and absorbs hardly any moisture. MW will show some thermic degradation in case of long-term moisture source due to its vapour open character. (De Smet, 2025)

Nevertheless, it is very important to mention the difference between simulations and real-life situations. For non capillary materials this means that it is assumed that the majority of the water drains mainly via run-off along the contact surfaces with the CLT. That is why a leak in case of MW or PUR is modelled in air layer between the CLT and the insulation layer since this is the most realistic simulation.(De Smet, 2025) In reality some of the water is absorbed by the CLT and insulation.

For capillary materials such as CEL, it was assumed that the moisture is firstly absorbed by the insulation and then spread out over the total insulation layer. That is why a leak is modelled in the total insulation layer in case of CEL. But in reality, it is possible that some of the water is also absorbed by other materials than the insulation layer. (De Smet, 2025)

Another note that is worth mentioning is the way how moisture is simulated in the hydrothermal simulation in Delphin: Once the layer where the moisture source is modelled in, is fully saturated, the water intake is automatically limited.(De Smet, 2025)

2.9 Modelling the loss of mechanical properties

Decay degrades the durability and integrity of timber products because fungi breaking down cellulose, hemicellulose and lignin as discussed in 0. This causes the wood to soften, weaken its mechanical properties and eventually collapse. The most effective way to prevent decay is by controlling the moisture levels in the environments surrounding (Hradil & Fortino, 2023).

Decay ratings, which may be measured on-site, are commonly used to describe the degree of deterioration brought on by the rot (EN 252, 2014). It is possible to confirm experimentally that the degradation causes a loss of wood mass and mechanical qualities (CEN/EN 350, 2016).

It was found that both the decay rating and mass loss are linked to the accumulated duration of a moisture state above the fibre saturation point at an appropriate temperature(Brischke & Rapp, 2008).

2.9.1 Predictive models

The numerical prediction of the moisture and temperature dose from the external variables is the most computationally demanding aspect of the calculation of moisture-induced effects. Usually, Heat, Air and Moisture (HAM) simulations are used in finite element or finite difference models with boundary conditions that reflect the external climate(Hradil & Fortino, 2023).

2.9.1.1 Mass loss above ground

, there is an incubation period before the fungi becomes active. The worst-case scenario is considered, namely the shortest incubation period of 150 days. But since it is not always known how long the CLT panels have been subjected to moisture and temperature and thus how many daily doses have been produced before construction, it is here assumed that all elements have surpassed the incubation period of 150 days. Based on (Hradil & Fortino, 2023)ML and the reduced mass (m_{red}) can be expressed according to the type of rot as:

$$ML = k_{sh} \cdot A_{ML} \cdot (1 - EXP(-k_{ML} \cdot (D - D_0)^{n_{ML}})) \text{ in } [\%] \quad (123)$$

$$m_{red} = m * (1 - ML) \text{ in } \left[\frac{kg}{m^3} \right] \quad (124)$$

$$k_{sh} = 7.9 \cdot \frac{b + h}{b \cdot h} \quad (125)$$

K_{sh} is a shape factor to incorporate the influence of different cross-sections compared to the tested specimens from (Hradil & Fortino, 2023).

The variables for brown and white rot can be extracted from Table 14:

Table 14: Modelling mass loss for above ground applications

Decay Type	A_{ML}	k_{ML}	n_{ML}
Brown rot	52.15172	0.00092	1.172185
White rot	21.557946	0.000732	1.66255

2.9.1.2 Decay rating

The decay rating is modelled based on the earlier mentioned dose-response method. The parameters were based on (Brischke & Meyer-Veltrup, 2016) and shown in Table 15:

$$DR(D(n)) = 4 \cdot EXP \left(EXP \left(a_{DR} - (b_{DR} \cdot D(n)) \right) \right) \quad (126)$$

Where:

Table 15: parameters by (Brischke & Meyer-Veltrup, 2016)

Decay Type	a_{DR}	b_{DR}
Brown rot (shade)	2.026	0.0037
Brown rot (no shade)	1.564	0.0054
White and soft rot	1.7716	0.0032

2.9.1.3 Structural integrity

Decay not only causes a ML but also significantly reduces the material's behaviour, especially its strength due to the fact the hemicellulose and lignin vanish.

To evaluate the element's resistance to external loads, the engineer usually needs to know the cross-section of the wooden element and the timber's characteristic strength. The designers may keep utilising the nominal value of the second parameter (nominal cross-section with lower equivalent strength or vice versa), but only one of those parameters can be changed for practical reasons.

As a result, two techniques namely the reduction of material strength and decrease of element's cross section, were devised to compute bending and compression resistance. The bending and compression tests serve as their foundation (Bollmus S. et al., 2020) .

In this dissertation it was opted to work with the nominal cross-section with lower equivalent strength.

2.9.1.4 Reduction of material strength

The approximation model of tested bending or compression resistance at various mass loss levels is directly used to calculate the reduced material strength (Bollmus S. et al., 2020).

It denotes the homogenous material's equivalent strength with the nominal cross-section.

The reduced strength f_{red} can be calculated based on the loss of material strength FL. FL is calculated based on ML by applying a sigmoid function.

The used parameters for bending strength, parallel compression and perpendicular compression can be retrieved from Table 16 for each case:

$$FL = A_{FL} \cdot (1 - EXP(-k_{FL} \cdot (ML)^{n_{FL}})) \quad (127)$$

$$f_{red} = f \cdot (1 - FL) \quad (128)$$

Table 16: Strength loss properties decay (Bollmus S. et al, 2020)

Bending strength $f_{m,k}$			
Decay Type	A_{ML}	k_{ML}	η_{ML}
Brown rot	0.8833	9.6601	0.6155
White rot	2.7368	1.9995	0.7488
Compressive strength parallel to the grain $f_{c0,k}$			
Decay Type	A_{ML}	k_{ML}	η_{ML}
Brown rot	0.901353	13.06994	1.155478
White rot	1.085979	7.631163	1.248356
Compressive strength perpendicular to the grain $f_{c90,k}$			
Decay Type	A_{ML}	k_{ML}	η_{ML}
Brown rot	0.989291	5.823211	1.103143
White rot	1.049224	3.977650	0.775042

The strength-loss model of (Bollmus S. et al, 2020) is calibrated on small clear specimens decayed under controlled laboratory conditions by monocultures of decay fungi. This is the targeted growing of one specie of decay on a certain number of elements. Laboratory conditions are generally more aggressive than field exposure (Brischke & Rapp, 2008; Meyer-Veltrup et al, 2017) and results are not directly transferable to above-ground service conditions. This means the predicted capacity losses in this thesis are likely conservative

2.10 One-At-a-Time Sensitivity Analysis

The methodology of the preceding sections runs as a chain. A hygrothermal simulation produces moisture contents and temperature profiles for each lamella of a CLT element. From these profiles a cumulative dose of decay follows. This dose sets the reduction of the mechanical properties of the timber and the reduced properties enter a structural verification according to (NBN EN 1995, 2005). Each step carries several design choices: the type of insulation of the wall and the roof, the type of rot, the duration of exposure and the number of CLT layers. The question is which of those choices govern the final result and which can be fixed without affecting the conclusions.

Sensitivity analysis answers that question. (Saltelli A. et al, 2008) define it as the study of how variations in the inputs of a model affect its output. The European Commission Joint Research Centre treats it as a required component of any policy- or design-relevant numerical analysis (European Commission JRC, 2021). In the present work it ranks the five design factors of the connection study, namely rot type, exposure duration, layer count and insulation type of the roof and wall, by their influence on the load-bearing capacity.

Methods differ in how widely they sample the input space and in how they report the influence. The One-At-a-Time (OAT) method varies each input independently from a baseline configuration and records the resulting change in the output. The result has the same physical units as the engineering response.

$$\Delta_i = |y_i - 1.00| \quad (129)$$

This study uses OAT. For a factor X with discrete levels ℓ , for instance $\ell \in \{\text{brown, white}\}$ for the rot type, the average response over the configurations sharing level ℓ is

$$\bar{\Delta}_{X=\ell} = \frac{1}{N_\ell} \sum_{i \in \{X=\ell\}}^n \Delta_i \quad (130)$$

with N_ℓ the number of configurations at level ℓ and y_i the output of configuration i . The OAT sensitivity index of factor X is the gap between the highest and lowest of those averages:

$$S_X = \bar{\Delta}_{Worst} - \bar{\Delta}_{Best} \quad (131)$$

A factor with a large S_x is one whose change of level moves the average output. S_x carries the units of the output, so a value of 0.074 on a fractional utilisation ratio shows that a switch of the factor from its worst to its best level shifts the average utilisation of the connection by 7.4 % of the design capacity.

The choice to use an OAT analysis can be defend due to the following reasons:

The simulation chain from Delphin through the strength-loss model to the (NBN EN 1995, 2005) verification is deterministic and repeating a configuration produces the same number.

A reader can also reproduce an OAT result from the raw data by simple averaging, without rerunning the model chain. (NBN EN 1995, 2005) itself treats k_{mod} , k_{def} , k_{sys} and γ_M as independent multiplicative modifiers of the design strength (NBN EN 1995, 2005): the OAT decomposition shares that structure and keeps the conclusions consistent with daily design practice.

3 METHODOLOGY

3.1 Workflow

The research consists of two verification streams: serviceability of the CLT panel and ultimate capacity of the panel and the screwed connection. The SLS depends on fewer material properties than the ULS, so a sensitivity analysis on the roof panel was used to identify the dominant property. The cross-section was reduced by reducing the thickness of the top layer which is mostly affected by decay. Also, the modulus of elasticity of the outer and centre layer were reduced. This was done to find the most influential parameter.

For ULS the mechanical properties and limit stresses were adapted to find the influence of multiple influence factors.

The working method as shown in Figure 24 will now be discussed in greater detail:

A specific element and situation are modelled in an HAM software for a hygrothermal simulation, namely Delphin.

For a specific configuration subjected to a specific climate and moisture source, the output is a list of moisture contents and temperatures in the CLT layers.

Both encapsulated building moisture (introduced during the construction period) and leaks (occurring during the usage period) were considered. The encapsulated building moisture was implemented as defining it as the initial MC of the lamellae. For the part about leaks, it was assumed that these occur after the CLT elements have been fully finished with insulation and cladding and have had the time to completely acclimatise to the in-service conditions. This situation is obtained in simulations by executing a 4-year conditioning period. Only after this conditioning period, the leaks were introduced in the model. The leaks were introduced according to the classification of (De Smet, 2025): short leak 1 day, medium leak 30 days and a long leak of 150 days.

The initial moisture conditions for the hygrothermal simulations are based on on-site measurements carried out by Anke Blommaert on a CLT structure that has been exposed to the Belgian outdoor climate for more than three years. The measurement data are grouped in Figure 25 into clusters, each of which corresponds to a specific location and exposure situation within the structure. Three of these clusters are used as input in the present work. Cluster 2 represents the encapsulated building-moisture content in the middle of a wall panel and is used whenever the load-bearing capacity of the panel itself is verified, both for walls and for roofs. Cluster 3 corresponds to short-term exposure at a node, lasting less than a month, and Cluster 4 to long-term, extreme water exposure at a node, lasting more than a year. Both are used to verify the wall–roof connection by using the modified self-weight of the wall element, with Cluster 3 capturing the short-term scenario and Cluster 4 the long-term one.

Because the clusters were measured on vertical five-layer CLT panels, the moisture contents need to be mapped onto the other panel configurations considered in the dissertation. For a three-layer wall panel, layer A keeps the moisture content of layer A from the five-layer reference, and layer C keeps the moisture content of layer E; the moisture content of the central layer B is taken as the average of layers B and D from the five-layer panel.

For a horizontal five-layer panel (the roof), two cases are distinguished: Cluster 2 is used when the capacity of the roof element itself is checked, while Cluster 3 is used when the moisture contents at a node need to be assessed, both visualised in Figure 26. These moisture-content profiles, together with the corresponding temperature profiles, then serve as the initial conditions for the HAM simulations of each CLT panel.

The HAM-simulations provide daily data regarding the MC and temperature in the different lamella of the CLT panel. Subsequently this data is used to calculate the daily doses based on the theory of (Brischke & Rapp, 2008). Once the daily doses are calculated and thus the cumulative dose, the decay rating can be carried out. Once these daily and cumulative doses are known, the reduction of mass and limit stresses can be calculated according to (Hradil & Fortino, 2023) based on the daily doses. The loss of strength is not directly related to the loss of limit stresses since the loss of limit stresses happens before the loss of mass because of the decay mechanism as explained in §2.6.

If these calculations are carried out, the stiffness matrix of the CLT element can be adjusted and the new capacity can be checked. Likewise, the capacity of both situations for the connection can be adapted based on the new self-weight of the wall and roof.

The new capacities can be compared to the original to find the most influential factors for the influence of decay on the load-bearing structure of CLT elements and connections. This is done by performing a One At the Time sensitivity analysis (OAT) to find the influence of each parameter separately. An OAT was selected for this study. The parameter space is small, full-factorial, and deterministic and the objective is to identify the dominant design factors rather than to perform a probabilistic uncertainty quantification. OAT was preferred over a variance-based decomposition for three reasons: sensitivity is expressed in the same engineering units as the response, results can be reproduced independently by the reader and the method is consistent with the partial-factor logic of (EN1995, 2005).

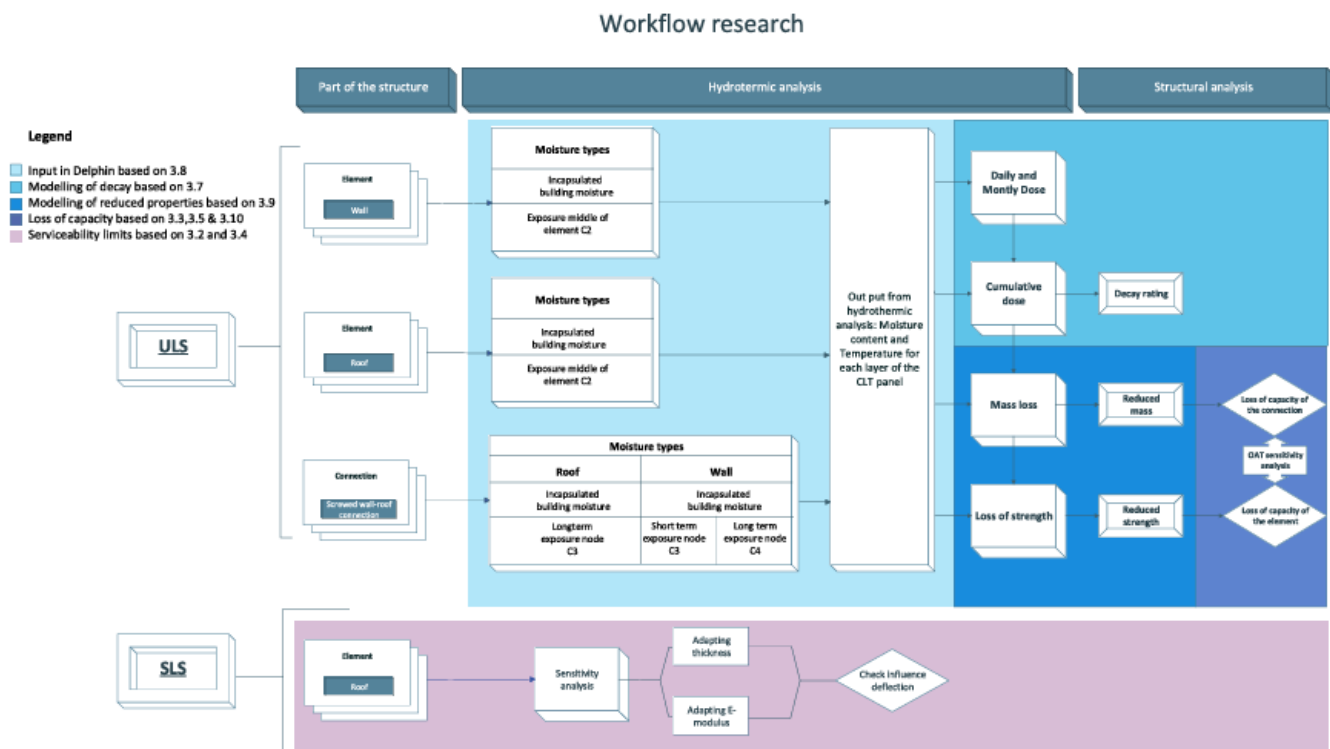


Figure 24: Workflow to model ULS

Average Moisture per Cluster and Layer

Cluster	MC_A	MC_B	MC_C	MC_D	MC_E
4	120.2	66.6	142.1	50.2	159.5
3	32.9	33.1	122.1	30.2	31.7
2	22.7	25.8	31.1	30.1	22.8
1	20.1	18.7	17	17	17.7

Layer

Figure 25 Moisture content in the different layers of a vertical five-layer CLT panel based on tests by Anke Blommaert

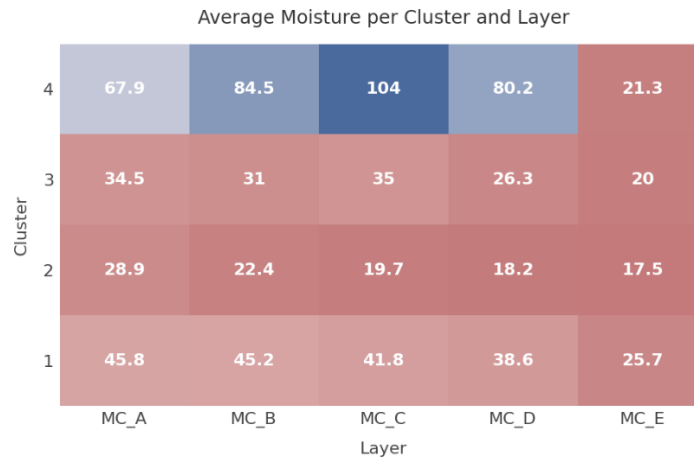


Figure 26: Moisture content in the different layers of a horizontal 5 layered CLT wall panel based on tests by Anke Blommaert

Since there was plenty of data and only simulations had to be carried out, a lot of different configurations could be compared to find the most influential influence factors and to be avoided situations.

Different types of moisture sources will be compared (encapsulated building moisture and leakage both in accordance with wind driven rain penetration), the amount of layers (three layered versus five layer panels), the type of element and thus the direction of the loads compared to the direction of the fibres (wall vs roof), the type of insulation material (MW, PUR and CEL) , the type of rot (brown versus white rot) and lastly the influence of the exposure time (Short Term (ST) (cluster 3) versus Long Term (LT) (cluster 4) for walls and short-term equals long-term (cluster 3) for roof elements).

The different options were illustrated in Figure 27.

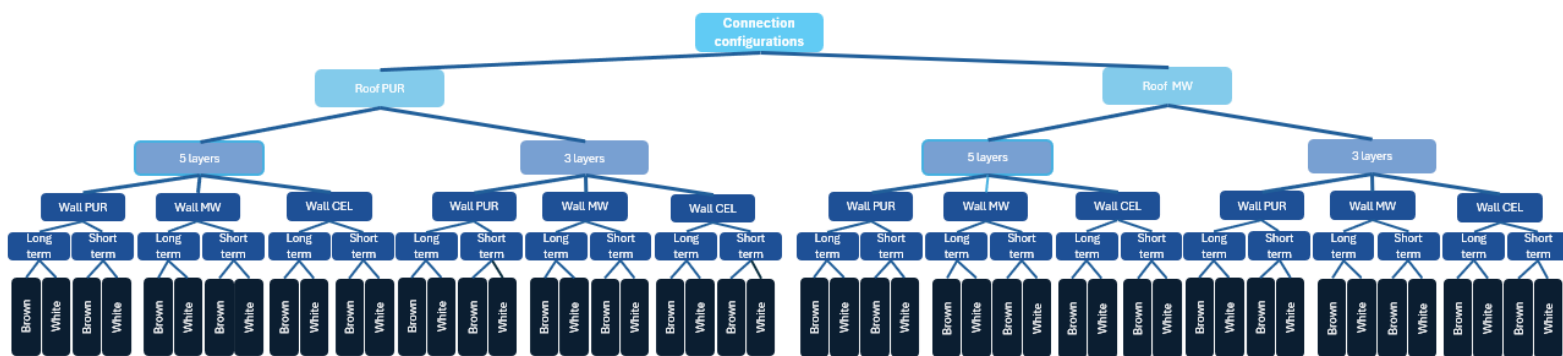


Figure 27: Different configurations of the roof to check the connection's capacity

3.2 Reference building

3.2.1 General information

The elements assessed are based on a CLT building designed by HOUTVAST engineers from Belgium. The building is a house build in Boortmeerbeek, Belgium. The load-bearing structure of the building is a fully CLT structure. The floors transfer the loads to the walls who lead it to the foundation. The structure is shown in Figure 28.

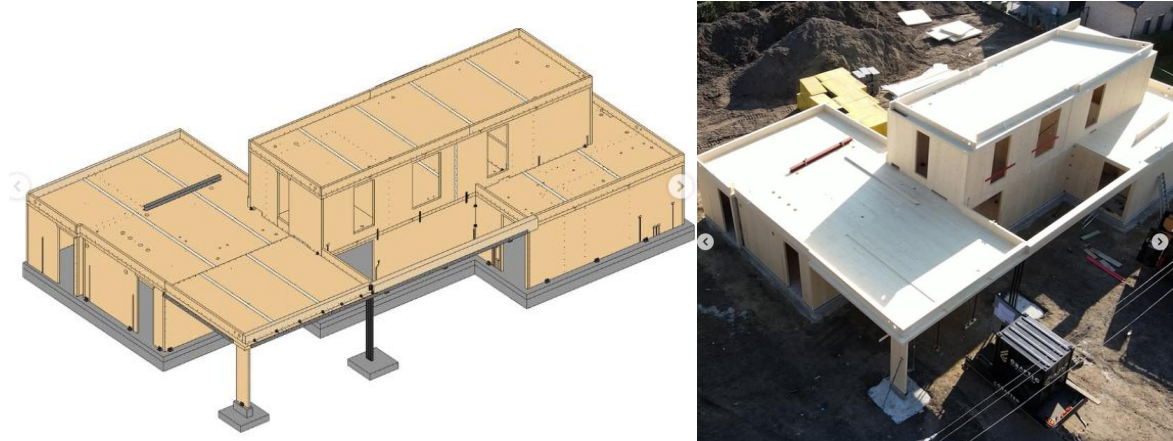


Figure 28: Reference building by Houtvast

The configuration of the walls is based on the wall's layout provided by (Blommaert et al., 2025). The properties of the configurations can be found in Table 17 for the wall and in Table 18 for the roof. It was also assumed that the adhesive used in the CLT panels was waterproof and did not dissolve if it is in contact with moisture.

Table 17: Properties of the wall in the simulations

Material	ID delphin	d [mm]	Cp [J/kgm ³]	μ [-]	Λ [W/mK]	θ80 [kg/m ³]	θsat [kg/m ³]	Aw [kg/m ² Vs]
CLT								
Spruce tangential	713	40/20/20/20/40	1843	487.72	0.106	59.8	728.1	0.01
MUF	-	3x0.25	1245	416	0.079	72.6	590.2	0
Insulation- PUR								
Polyurethane board	194	140	1500	65	0.031	1.1	945	0
Insulation-CEL								
Wood fibre insulation board	693	22	1662	3.45	0.039	17.9	550	1.6e-08
Blown-in Cellulose	580	186	2544	2.05	0.048	6.3	780	3.5e-06
Insulation-MW								
Mineral Wool 035	731	160	840	1	0.035	0.1	900	0
Façade cladding								
Air gap 40 mm vertical	17	40	1050	0.25	0.222	0	1000	0
Normal brick	512	100	889	18.01	0.548	13.4	319.4	0.20

Table 18: Properties of the roof in the simulations

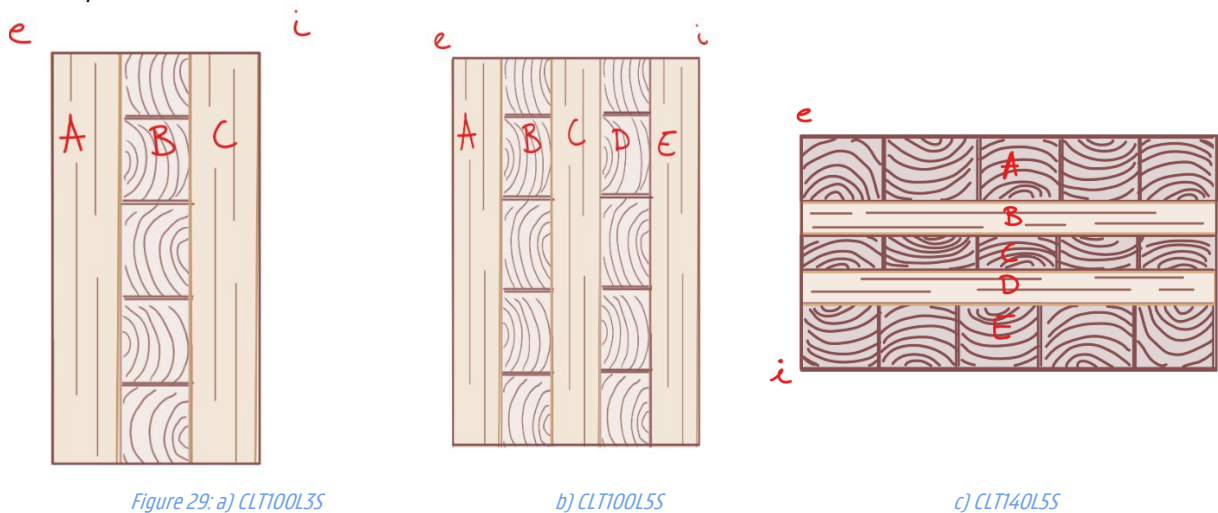
Material	ID delphin	d [mm]	Cp [J/kgm³]	μ [-]	Λ [W/mK]	Ø80 [kg/m³]	Øsat [kg/m³]	Aw [kg/m²Vs]
CLT								
Spruce tangential	713	140	1843	487.72	0.106	59.8	728.1	0.01
MUF	-	1	1245	416	0.079	72.6	590.2	0
Insulation- PUR								
Polyurethane board	194	349	1500	65	0.031	1.1	945	0
Insulation-MW								
Mineral Wool 032	730	361	840	1	0.032	0.1	900	0
Roof finishing								
Bitumen	28	1	2000	15000	0.145	0	2.5	0

3.2.2 Wall element

The wall element that is used in the reference building is a CLT panel of 4.8m wide and 3m high. It is a panel of 100mm thick. Two configurations are considered, namely a three-layer panel with lamella thicknesses 30/40/30 mm (CLT100-L3s) and a five-layer panel with lamella thicknesses of 20 mm each (CLT100-L5s). These elements are drawn with the legend of the lamellae in Figure 29a) and b).

3.2.3 Roof element

The roof element that will be checked is a CLT140-L5s as shown in Figure 29c). Since it is an element of 140mm thick, only a five-layered option is available and thus the influence of the number of layers cannot be compared since there are no three-layered alternatives.



3.2.4 Connection

It was chosen to work with a connection between the wall and the roof with inclined screws as visualised in Figure 31. This was done to maximise the influence of decay on the connection and find the influence factors better.

The impact of decay is bigger in such a connection since it is a timber-to-timber connection. Often also brackets as shown in Figure 30, are used but since these are calculated by controlling the withdrawal strength of the screws from the roof and metal-to-timber connection between the steel plate and wall, the influence of the deteriorated timber elements is less.

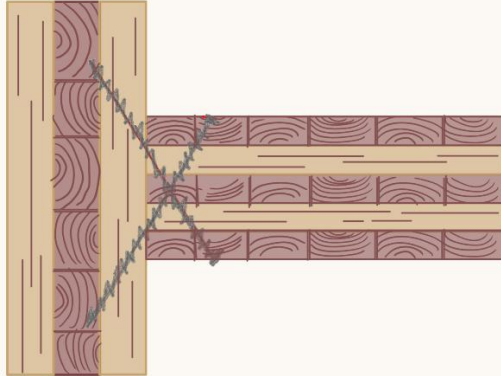


Figure 31: Connection with skew screws between roof and wall

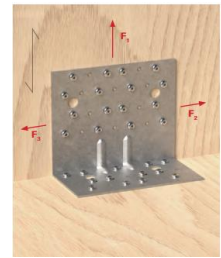


Figure 30: Steel-to-timber bracket connection (Simpson Strong Tie, n.d.)

3.3 Load-bearing system

The reference building is a mass timber construction. This means that the elements such as the walls and floors are the principal load-bearing elements. The floors transfer the loads to walls through screwed connections. These floors transfer the received loads either to lower situated wall or to the foundation.

Since the walls and floors are the principal load carrying elements since it is a mass timber building and not a timber frame building, it was chosen to use these to check the load carrying capacity of the building.

3.4 Loads

The loads considered on the building can be subdivided into the loads acting on the wall and acting on the roof element.

3.4.1 Roof elements

To derive the forces acting on the wall, it is crucial to consider the loads acting on the roof. The forces acting on the roof are summarized in Table 19. This results in a reaction force at the connection of 8.75 kN/m as shown in Figure 32.

Table 19: Loads acting on the roof

Permanent loads		
Solar panels and ballast	0.4	[kN/m ²]
7cm sloped concrete	1.4	[kN/m ²]
Insulation + roof sealing	0.2	[kN/m ²]
Self weight	0.7	[kN/m ²]
Total permanent loads	2.7	[kN/m²]
Variable loads		
Repair	0.8	[kN/m ²]
Snow	0.5	[kN/m ²]
Wind pressure	0.2	[kN/m ²]

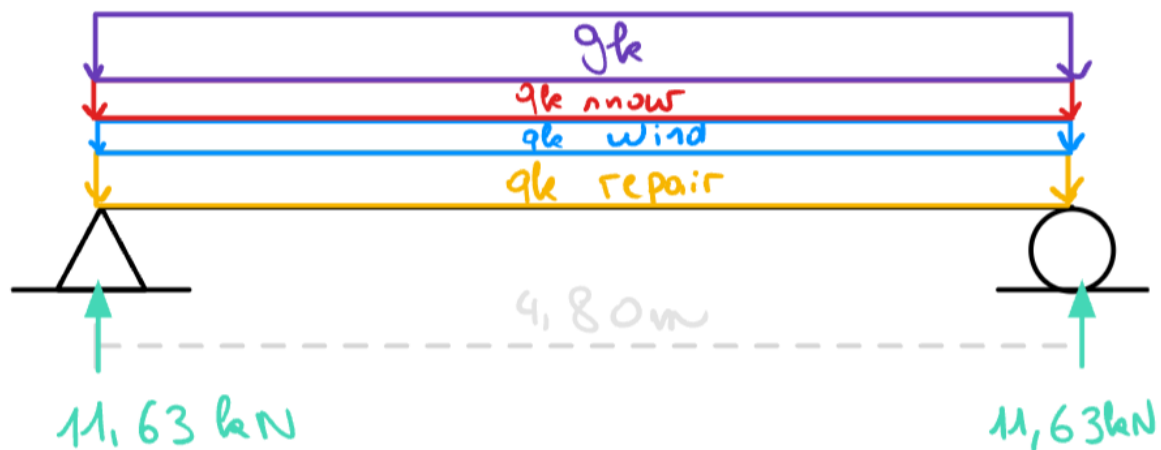


Figure 32: Reactions on the wall

It now can be found that the reaction force which should be carried by the connection, is 11.63kN/m.

3.4.2 Wall elements

The designers of Houtvast made some conservative simplifications to find the line load acting on the underlying wall:

$$r_g = \frac{g_k \cdot l}{2} = 6.48 \frac{kN}{m} \approx \frac{7kN}{m}$$

$$q_k = q_{k,repair} + q_{k,snow} + q_{k,wind} = 0.8 + 0.5 + 0.2 = 1.50 \frac{kN}{m^2} \quad (132)$$

$$r_q = \frac{q_k \cdot l}{2} = 3.48 \frac{kN}{m} \approx 3.60 \frac{kN}{m} \quad (133)$$

To calculate forces acting on the wall, the self-weight of the CLT wall must be considered and the concentration effects due to supports (add 30% to the acting line loads) . The self weight for a CLT panel according to the calculation sheet of Houtvast is 4.5 kN/m for a 3m high wall. This results in the following calculations:

$$p = \frac{7kN}{m} + 0.3 \cdot \frac{7kN}{m} + \frac{4.5kN}{m} = \frac{13.6kN}{m} \quad (134)$$

$$q = \frac{3.8kN}{m} + 0.3 \cdot 3.8 \frac{kN}{m} = 5.0 \frac{kN}{m} \quad (135)$$

3.4.3 Design of the connection

The properties of the connection, drawn in Figure 33, are grouped in Table 20.

Once these are known, the formulas described in §2.5 can be used. As mentioned in §3.4.1, the force to bear is 10.61 kN/m.

Table 20: Properties of the connection

Data		
$\rho_{k, wall}$	350	kg/m ³
$\rho_{k, roof}$	350	kg/m ³
l	240	mm
l_{ef}	139	mm
ε_1	60°	1.05rad
ε_2	30°	0.52rad
d	12	mm
f_u	800	Mpa
t_1	139	mm
t_2	101	mm
M_{yrk}	48000	Nmm
k_{mod}	0.8	-
γ_m	1.3	-
f_{h1k}	9.91	Mpa
f_{h2k}	6.41	Mpa
β	0.65	-

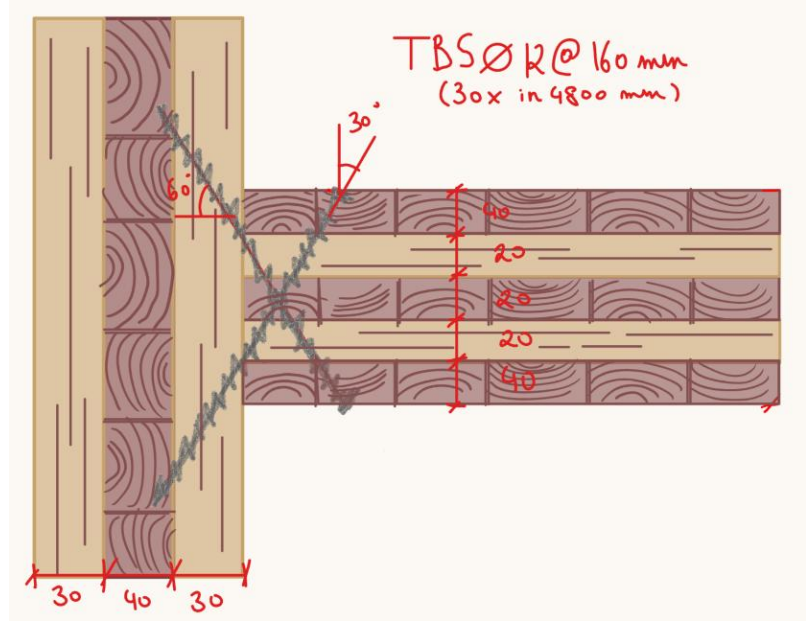


Figure 33: Connection wall and roof

$$f_{h,k1} = \frac{0.082 \cdot \rho_{k,wall} \cdot d^{-0.3}}{2.5 \cdot \cos^2 \varepsilon + \sin^2 \varepsilon} = 8.06 \text{ MPa} \quad (136)$$

$$f_{h,k2} = \frac{0.082 \cdot \rho_{k,floor} \cdot d^{-0.3}}{2.5 \cdot \cos^2 \varepsilon + \sin^2 \varepsilon} = 5.22 \text{ MPa} \quad (137)$$

$$\beta = \frac{f_{h2k}}{f_{h1k}} = 0.65 \quad (138)$$

$$F_{v,Rk} = \min \left\{ \begin{array}{l} \frac{f_{h,1,k} \cdot t_1 \cdot d}{1 + \beta} \left[\sqrt{\beta + 2\beta^2 \left[1 + \frac{t_2}{t_1} + \left(\frac{t_2}{t_1} \right)^2 \right]} + \beta^3 \cdot \left(\frac{t_2}{t_1} \right)^2 - \beta \cdot \left(1 + \frac{t_2}{t_1} \right) \right] = 5.21 \text{ kN} \\ 1.05 \frac{f_{h,1,k} t_1 d}{2 + \beta} \left[\sqrt{2\beta(1 + \beta) + \frac{4\beta(2 + \beta) \cdot M_{y,Rk}}{f_{h,1,k} \cdot d \cdot t_1^2}} \right] - \beta = 5.64 \text{ kN} \\ 1.05 \frac{f_{h,1,k} \cdot t_2 \cdot d}{1 + 2\beta} \left[\sqrt{2\beta^2(1 + \beta) + \frac{4\beta \cdot (1 + 2\beta) \cdot M_{y,Rk}}{f_{h,1,k} \cdot d \cdot t_2^2}} \right] - \beta = 3.43 \text{ kN} \\ 1.15 \sqrt{\frac{2\beta}{1 + \beta}} \sqrt{2 M_{y,Rk} \cdot f_{h,1,k} \cdot d} = 3.44 \text{ kN} \end{array} \right. \quad (139)$$

$$F_{v,Rk} = 3.43 \text{ kN} \quad (140)$$

$$F_{v,Rd} = \frac{k_{mod} \cdot F_{v,Rk}}{\gamma_M} = 2.11 \frac{kN}{screw} \quad (141)$$

$$n_{ef} = n^{0.7} = 12^{0.7} = 5.69 \frac{screws}{m} \quad (142)$$

$$F_{v,Rdtot} = n_{ef} \cdot F_{v,Rd} = 12.01 \frac{kN}{m} \quad (143)$$

$$\frac{F_{v,Ed}}{F_{v,Rd}} = \frac{11.63}{12.01} = 0.97 \leq 1 \rightarrow OK \quad (144)$$

It can be stated that for the connection between the wall and the roof, a connection consisting of crossed TBS Ø 12 × 240 mm screws at 160 mm spacing is sufficient.

3.5 Environmental conditions

The environmental conditions are chosen according to the literature discussed in §2.8 in this master dissertation. An MRY is used so that the worst days of the last years is cut and pasted together to form the worst possible realistic scenario. This MRY is repeated several times to model a period of several years.

As mentioned in §2.8.2 the least favourable direction of an element is Southwest in terms of being exposed to WDR.

The RE is calculated for this situation to be equal to 0.5.

Since a brick façade cladding is assumed, a water source equal to 7% of the rain flux is allocated to the insulating board's outside to account for rain leakage through the façade cladding (Van Linden & Van Den Bossche, 2022.). Five air changes per hour is the air change rate in the air cavity (Langmans et al., 2015).

3.6 Processing of data

The cell size used for the CLT-lamellae are 1mm thick.

The cell size for the adhesive layers, MUF, are 0.25mm thick, resulting in 3 cell-layers for each adhesive layer of 0.75mm. This is done as well for the bitumen layer to better model the waterproof character of the material.

The data from the Delphin simulations, namely the MC and the T, are thus also calculated per mm in the CLT.

The temperature can be used directly from temperature output from Delphin for each cell of 1mm.

The moisture content needs an additional step: The moisture mass density still needs to be divided by the self-weight of the element, 393.7 kg/m³ based on the characteristics of spruce with the ID of 731 in Delphin.

Once the values for the T and MC are known for each cell of the CLT element, the average is taken over the total size of 1 lamella.

$$\bar{T}_l = \sum_j^n \frac{T_{ij}}{n} \quad (145)$$

$$\overline{MC}_l = \sum_j^n \frac{MMD_{ij}}{\rho_{Spruce} \cdot n} \quad (146)$$

3.7 Assumptions

Before the first results are going to be discussed, it is very important to address the fact that this research is based on specific sources who all made choices and simplifications.

The first major decisive decision was to rate decay based on the dose-response model from (Brischke & Rapp, 2008). Here it was chosen also to work with the logistic model which is more correct than the simplified logistic model but thus also more prone to the influence of certain simplifications.

Another important factor is that it was also chosen to translate the influence of decay on the mechanical properties as the degradation of mechanical properties rather than the loss of cross-section. This was done because the wall – and roof structure included multiple different materials so adapting the thickness of the panel would lead to gaps and irregularities between different materials.

3.8 Limitations

There are a lot of sources suggesting that the loss of mechanical properties could be translated in the degradation of different properties, for example the loss of E-modulus, the loss of self-weight etc. In this thesis it was chosen to work with the loss of stresses according to the research of (Hradil & Fortino, 2023) in this way, namely the biological aspect that if the lignin and hemicellulose in a timber element will degrade in case of decay, the element will first lose its mechanical properties like load-bearing capacity before it loses its self-weight.

Another reason is that for this research, the load-bearing capacity of an element is examined and this is directly dependent on the stress bearing capacity of the element.

But since the data and formulas from (Hradil & Fortino, 2023) is the only source that relates daily doses to mass- and stress-loss and no elements were tested for this research, it is necessary to address this simplification and potential mistakes.

The data of (Bollmus S. et al., 2020) is also based on laboratory exposed elements and is thus not necessarily valid for natural exposed elements.

Further research could dive deeper into this.

It is also important to state that the data that is used to visualise Figure 25 are based on a long-term exposure time and calculated back to a certain period based on the location of a sample. These samples are thus not in situ measured moisture levels at certain time periods for the same element so also here extra attention is required.

4 SLS SENSITIVITY ANALYSIS

As mentioned, §2.4, often the SLS is the governing limit state.

Also, in Belgium there were examples of buildings which caused damage due to failing the serviceability. An example of this is illustrated in Figure 34, where decay resulted in a premature demolition of the building. This failure was found in the balcony where the deflections were too big to guarantee the function and appearance of the balcony.

In this research the deflection of the roof panel was investigated to find the influence of decay on the SLS.

Since the only mechanical property of the CLT influencing the deflection is the E modulus, a sensitivity analysis was performed by reducing the thickness of the outermost lamella and the modulus of elasticity of the most decay influenced layers, layer A and layer C to find how the deflection changes when the timber deteriorates.

To find the net moment of inertia, the two methods described in §2.2 were used. The difference between the calculation methods on the deflection are minimal as proofed in Table 21.

In instantaneous deflection w_{inst} and long term deflection w_{fin} are both displayed and calculated. It should be noted that only in the long term deflection the influence of the Service Classes (SC) have an influence since from there on factor k_{def} is taken in to account.

The instant deflection, the final deflection for SC1, SC2 and SC3 are summarised in Table 21.

Combinations that still fulfil the limit of $L/300$, in this case 16mm, were indicated in white while the other non fulfilling combinations were shown in grey.

Table 21: comparison in deflection using the Timoshenko beam theory and the gamma method for the CLT140L55 roof

Simplified Timoshenko beam theory						Gamma method						
Modulus of elasticity for outer and centre layer E_s and E_c [MPa]	W_{inst} [mm]	thickness outer floor layer t_s [mm]					W_{inst} [mm]	thickness outer floor layer t_s [mm]				
		40	30	20	10	0		40	30	20	10	0
	11000	12.4	15.7	21.2	31.8	63.2	11000	12.3	15.7	21.1	31.7	63.1
	10000	12.9	16.5	22.3	33.6	66.7	10000	12.9	16.5	22.2	33.4	66.7
	9000	13.6	17.4	23.6	35.7	71.0	9000	13.6	17.4	23.6	35.5	70.9
	8000	14.4	18.6	25.3	38.3	76.2	8000	14.4	18.5	25.2	38.2	76.1
	7000	15.5	20.0	27.3	41.6	82.7	7000	15.5	19.9	27.2	41.4	82.5
	6000	16.9	21.8	30.0	45.9	91.0	6000	16.8	21.8	29.9	45.7	90.8
	5000	18.8	24.4	33.7	51.8	102.0	5000	18.7	24.4	33.6	51.6	101.7



Figure 34: Decay-deteriorated balcony

<https://www.vrt.be/vrtnws/nl/2022/05/10/appartementen-met-houtrot-in-sint-truiden-worden-best-afgebroken/>

	wfin	thickness outer floor layer t_5 [mm]					
		SC1	40	30	20	10	0
Modulus of elasticity for outer and centre layer E_s and E_3 [MPa]	11000		15.5	19.8	26.6	39.9	79.4
	10000		16.2	20.7	28.0	42.2	83.8
	9000		17.1	21.9	29.7	44.8	89.2
	8000		18.1	23.3	31.7	48.1	95.7
	7000		19.5	25.1	34.3	52.3	103.9
	6000		21.2	27.4	37.7	57.7	114.3
	5000		23.5	30.6	42.3	65.0	128.1

	wfin	thickness outer floor layer t_5 [mm]					
		SC2	40	30	20	10	0
Modulus of elasticity for outer and centre layer E_s and E_3 [MPa]	11000		17.2	22.0	29.6	44.4	88.2
	10000		18.0	23.0	31.1	46.8	93.1
	9000		19.0	24.3	33.0	49.8	99.1
	8000		20.2	25.9	35.2	53.5	106.3
	7000		21.6	27.9	38.1	58.1	115.4
	6000		23.5	30.5	41.9	64.1	127.0
	5000		26.2	34.1	47.0	72.3	142.4

	wfin	thickness outer floor layer t_5 [mm]					
		SC3	40	30	20	10	0
Modulus of elasticity for outer and centre layer E_s and E_3 [MPa]	11000		25.9	33.0	44.4	66.6	132.3
	10000		27.1	34.6	46.7	70.3	139.7
	9000		28.5	36.5	49.5	74.7	148.6
	8000		30.2	38.8	52.9	80.2	159.5
	7000		32.4	41.8	57.2	87.1	173.1
	6000		35.3	45.7	62.8	96.1	190.5
	5000		39.2	51.1	70.5	108.4	213.6

	wfin	thickness outer floor layer t_5 [mm]					
		SC1	40	30	20	10	0
Modulus of elasticity for outer and centre layer E_s and E_3 [MPa]	11000		15.5	19.7	26.6	39.8	79.3
	10000		16.2	20.7	27.9	42.0	83.7
	9000		17.1	21.8	29.6	44.6	89.1
	8000		18.1	23.3	31.6	47.9	95.6
	7000		19.4	25.0	34.2	52.0	103.6
	6000		21.1	27.4	37.6	57.4	114.0
	5000		23.5	30.6	42.2	64.8	127.8

	wfin	thickness outer floor layer t_5 [mm]					
		SC2	40	30	20	10	0
Modulus of elasticity for outer and centre layer E_s and E_3 [MPa]	11000		17.2	21.9	29.5	44.2	88.1
	10000		18.0	23.0	31.0	46.6	93.0
	9000		18.9	24.3	32.9	49.6	99.0
	8000		20.1	25.8	35.1	53.2	106.2
	7000		21.6	27.8	38.0	57.8	115.2
	6000		23.5	30.4	41.8	63.8	126.7
	5000		26.1	34.0	46.9	72.0	142.0

	wfin	thickness outer floor layer t_5 [mm]					
		SC3	40	30	20	10	0
Modulus of elasticity for outer and centre layer E_s and E_3 [MPa]	11000		25.8	32.9	44.3	66.3	132.1
	10000		27.0	34.5	27.9	70.0	139.6
	9000		28.4	36.4	29.6	74.4	148.4
	8000		30.2	38.8	31.6	79.9	159.3
	7000		32.4	41.7	34.2	86.7	172.7
	6000		35.2	45.6	37.6	95.7	190.0
	5000		39.2	51.0	42.2	107.9	213.0

Based on Table 20, it is clear that decay in the outer (and centre) layer plays a very crucial role in meeting the limits of SLS. It can be found that a reduction 10 mm of the outer layer is already sufficient to fail the SLS.

A reduction of 36% of the E-modulus also results in not meeting the requirements in the best-case scenario, in cases where the service class is 1. In case of SC2 or SC3 the baseline scenario is already exceeded due to a higher value of k_{def} . So implanting decay with increasing the SC is also already enough to fail the SLS factor. This shows that the thickness of the layers is the most important influence factor in meeting the requirements for the SLS. This can also be explained since the thickness is powered to the third in the calculation of the net moment of inertia while the modulus of elasticity is not.

5 LOSS OF CAPACITY IN A PANEL

To verify the loss of capacity in a panel and thus of the wall and roof elements, a hygrothermal simulation is ran to obtain the average MC and T over the CLT lamellae. This data is then used to calculate the daily doses as described in (Brischke & Rapp, 2008). These daily doses were then used to calculate the declined properties of the timber lamellae, based on the theory of (Hradil & Fortino, 2023). Once these properties are known, visualised in Figure 35, Figure 36, Figure 37 and Figure 38, the capacity of the roof in ULS is checked.

Two different moisture sources were examined, namely the case of encapsulated building moisture but also leakages of different flow rates and periods.

After several simulations, it was concluded that the leakages, did not influence the load-carrying behaviour of the structure, independent of the type of insulation. That is the reason why only encapsulated building moisture is discussed in the following chapters.

5.1 Wall element

5.1.1 Three-layer CLT wall panel

Based on the figures in Table 23, it is clear that the temperature in the three different insulation scenarios is approximately constant, i. e. between 20 and 25°C. The biggest difference in behaviour, can be found in the MC of the centre lamellae.

It can be seen that a critical moisture content in case of PUR insulation remains trapped in the centre lamellae for the longest period. That is also the reason why the properties of the middle layer are the most subjected to decay as illustrated in Figure 35, Figure 36, Figure 37 and Figure 38.

In Attachment 5 a worked out example can be retrieved where for each layer the properties and differences as a function of time can be found in case of a three layer PUR insulated wall element.

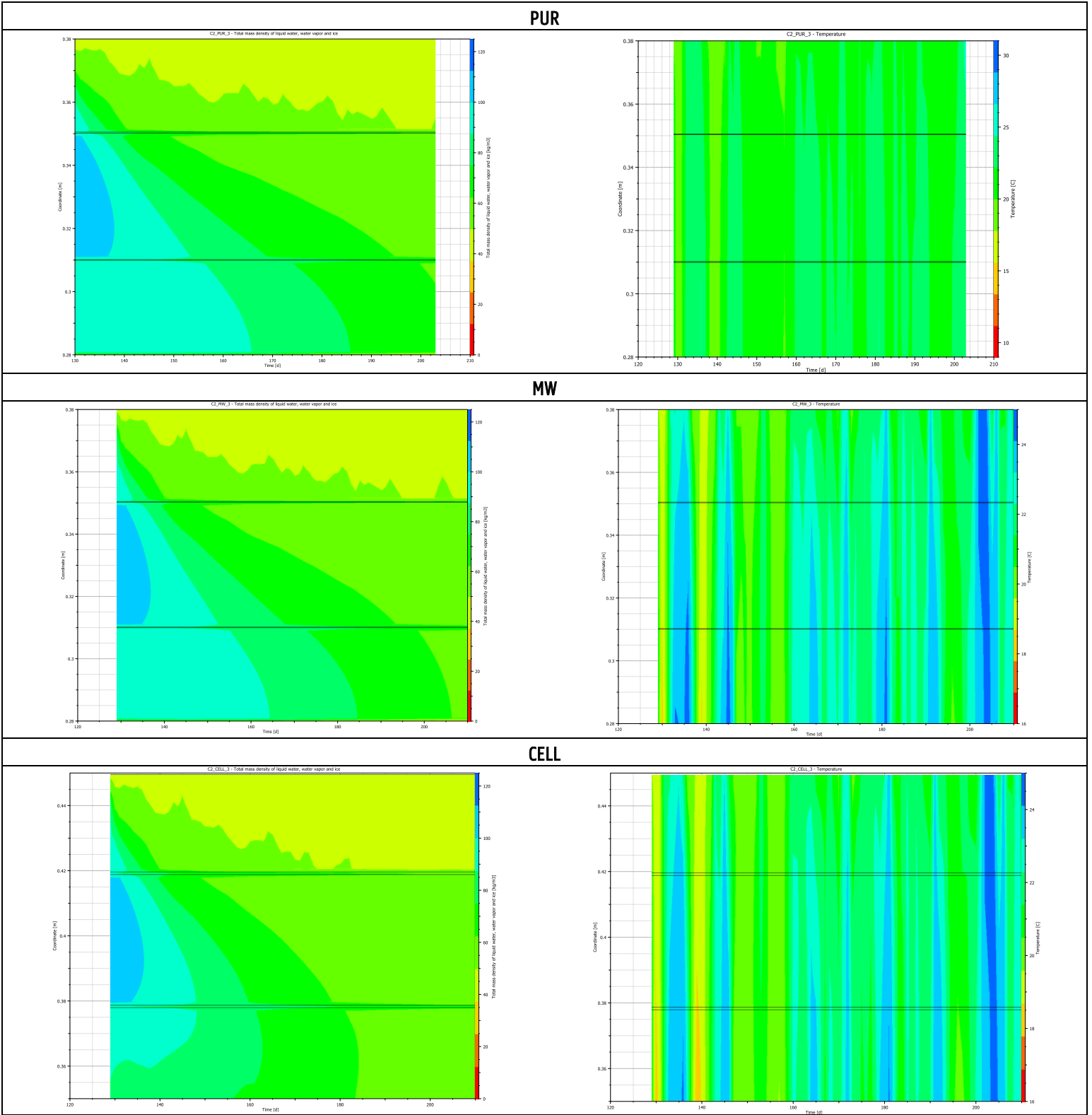
The results are summarised in Table 22. They all come from the same limit state namely in layer A even though PUR has a clearly higher MC. This can be explained by looking to the location of the governing location: This is layer A where the MC and T are relatively constant in the three scenarios. This results in a equal bending strength f_{mk} in the three scenarios, making an equal capacity ratio logic.

$$\frac{|\sigma_{c,0,d}|}{f_{m,0,d}} = \frac{|-7.14|}{10.08} = 0.71 \leq 1 \rightarrow OK \quad (147)$$

Table 22: Capacity check wall 3-layered element in case of exposure

Insulation	Type Rot	Max capacity	Location max
PUR	Brown rot	0.71	A
PUR	White rot	0.71	A
MW	Brown rot	0.71	A
MW	White rot	0.71	A
CEL	Brown rot	0.71	A
CEL	White rot	0.71	A

Table 23: Moisture mass density MMD (left) and temperatures T (right) of the CLT-lamellae of a three-layered wall element to verify the capacity of a wall panel with PUR, MW and CEL insulation



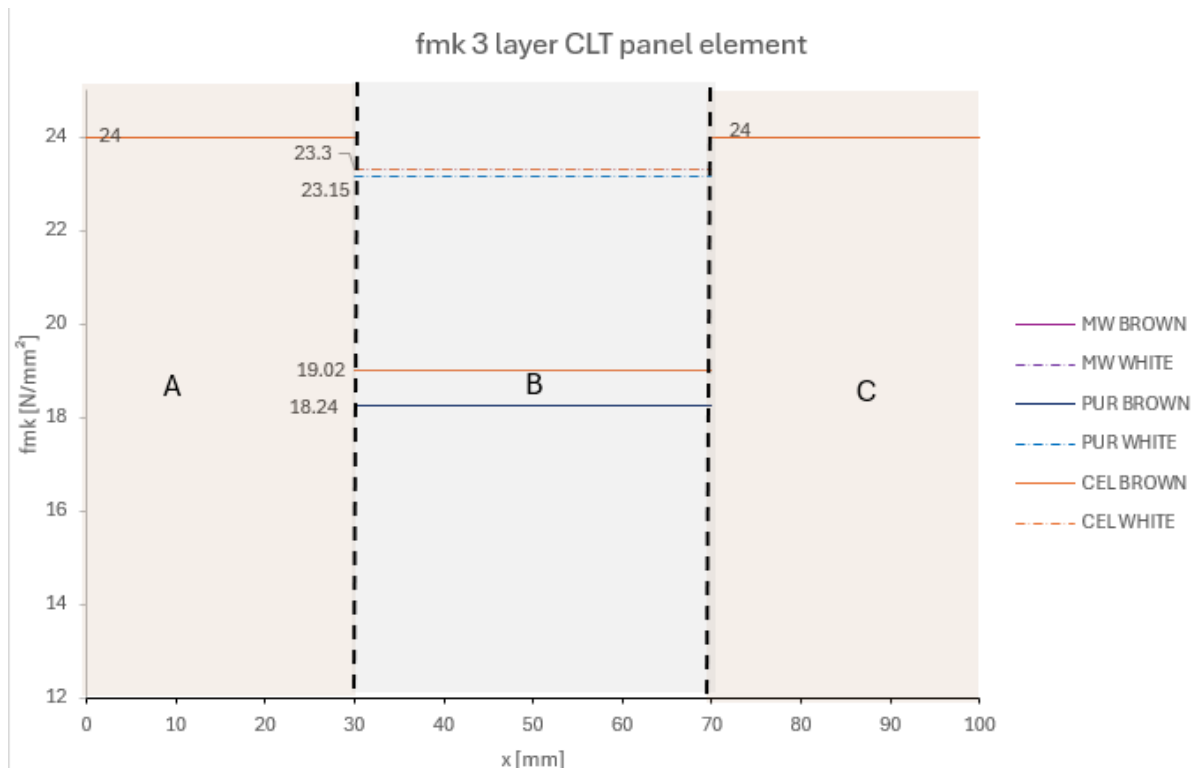


Figure 35: bending strength for each layer for a three-layer CLT wall in case of encapsulated building moisture

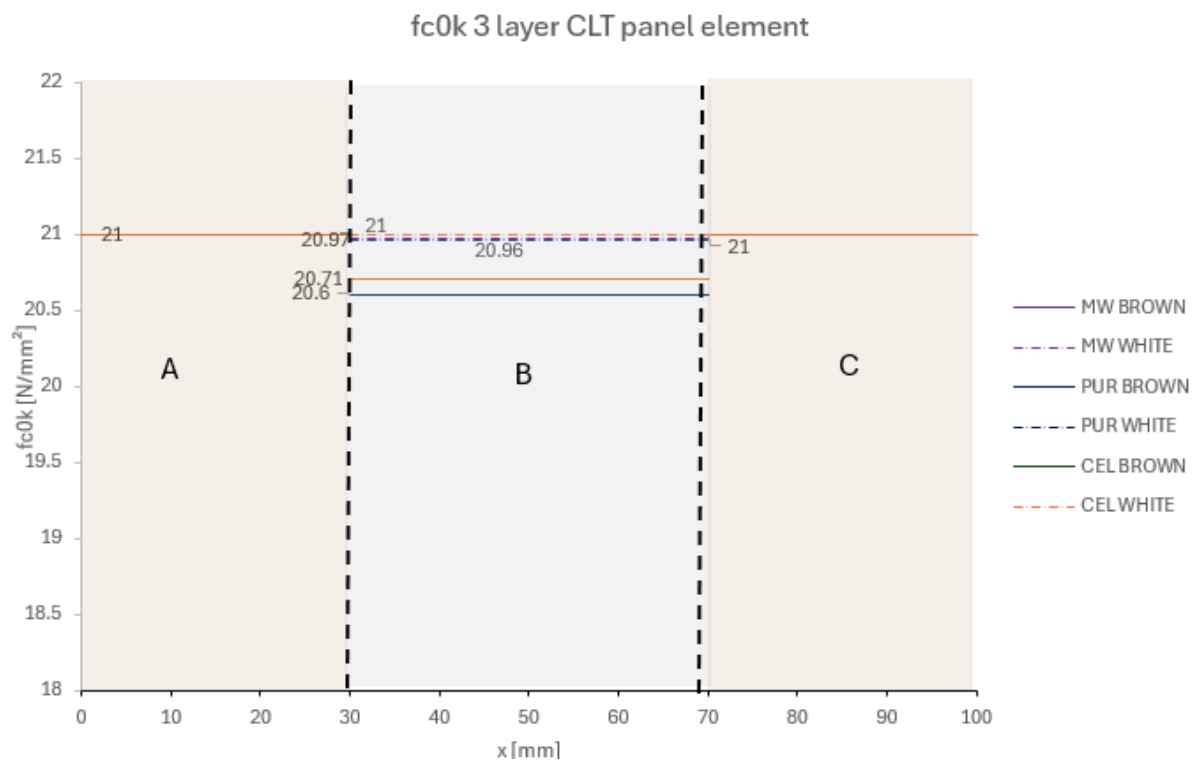


Figure 36: parallel compressive strength for each layer for a three layered CLT wall in case of encapsulated building moisture

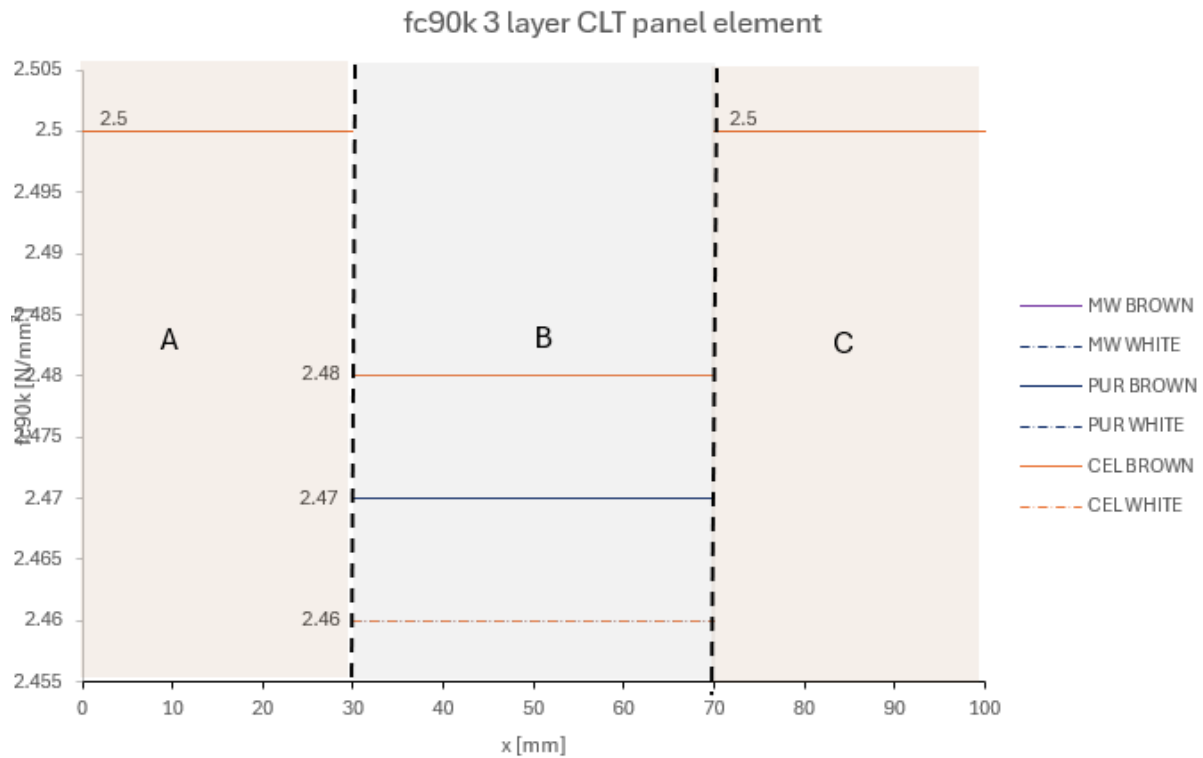


Figure 37: perpendicular compressive strength for each layer for a three-layer CLT wall in case of encapsulated building moisture

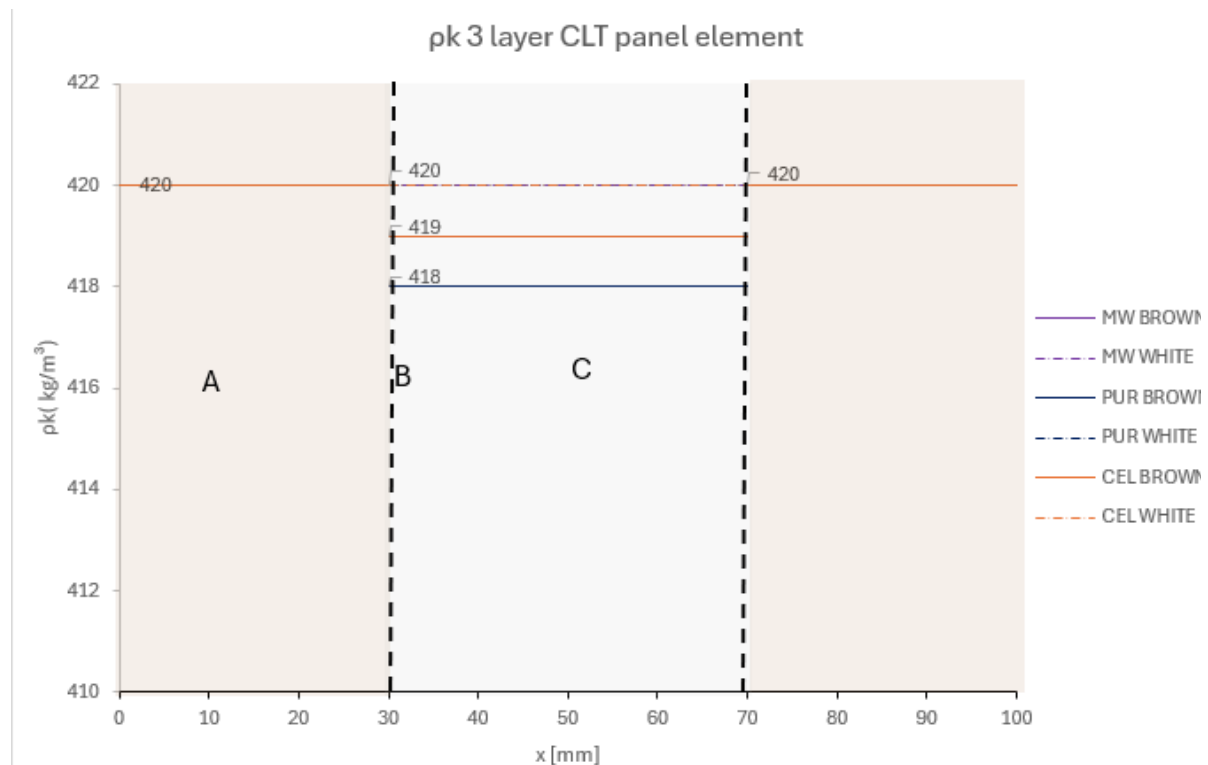


Figure 38: self-weight for each layer for a three-layer CLT wall in case of encapsulated building moisture

5.1.2 Five-layer CLT wall panel

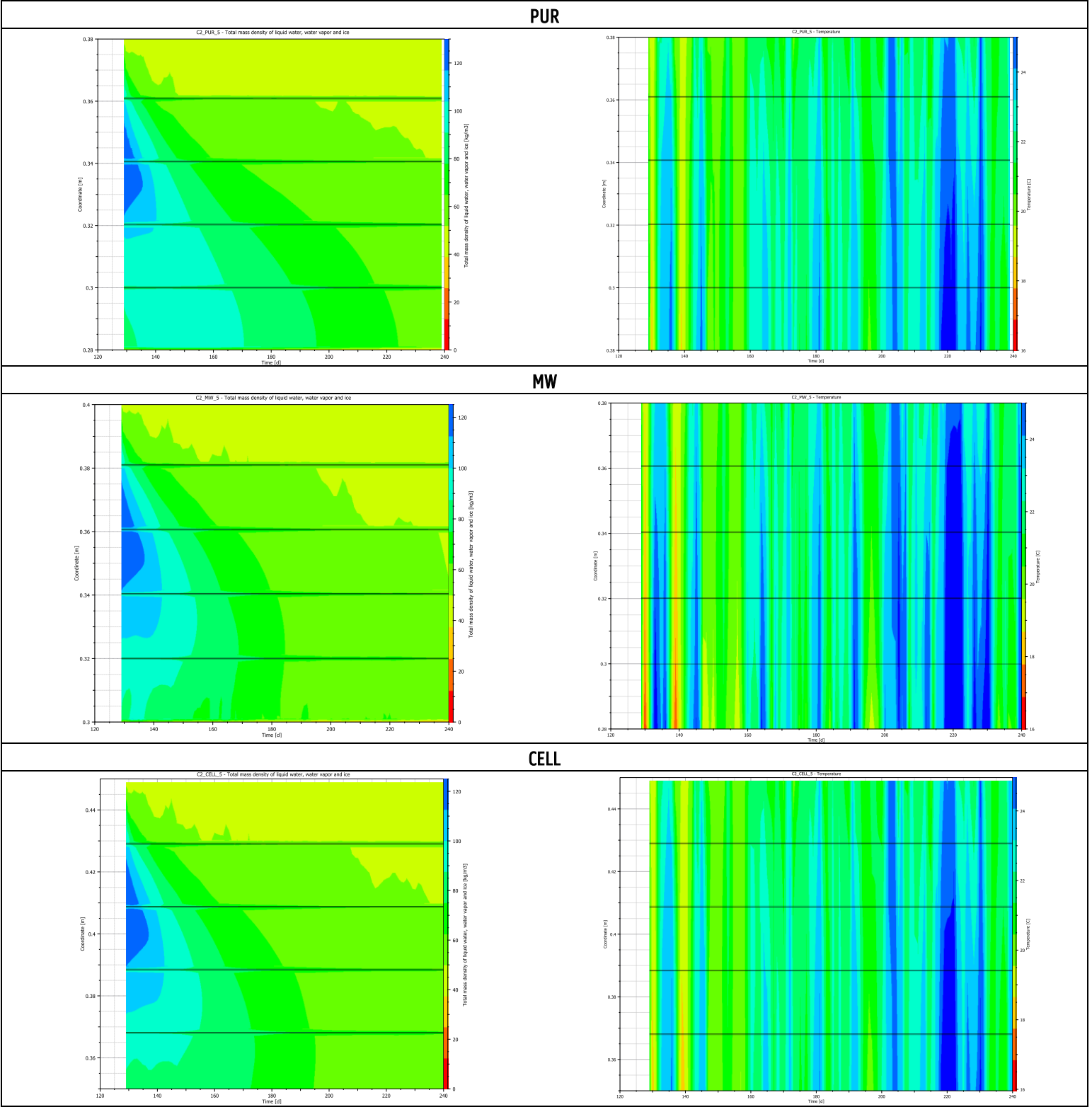
As with the three-layer CLT wall panel, the temperature in the five-layer wall panel remains approximately constant, namely between 17 and 27 °C. The moisture contents in the central lamellae are higher than in the three-layer configuration, which can be attributed to the low vapour permeability of the adhesive that retains moisture in the central layers.

In contrast with a three layered configuration, now the limit stresses take place in the central layers where a clear difference in MC is visible as summarised in Table 25. Since PUR is a vapour tight material which is non-capillary, it is difficult for the panel to dry out towards the outside. This results in higher and longer critical MC of more than 25% and thus more decay. This leads to the results in Table 24 where a PUR insulated wall is the most affected material. The new limit stresses are visualised in Figure 39, Figure 40, Figure 41 and Figure 42.

Table 24: Capacity check wall 5-layered element in case of exposure

Insulation	Type Rot	Max capacity	Location max
PUR	Brown rot	0.77	C
PUR	White rot	0.71	C
MW	Brown rot	0.76	C
MW	White rot	0.71	C
CEL	Brown rot	0.76	C
CEL	White rot	0.71	C

Table 25: Moisture mass density MMD (left) and temperatures T (right) of the CLT-lamellae of a five-layered wall element to verify the capacity of a wall panel with PUR, MW and CEL insulation



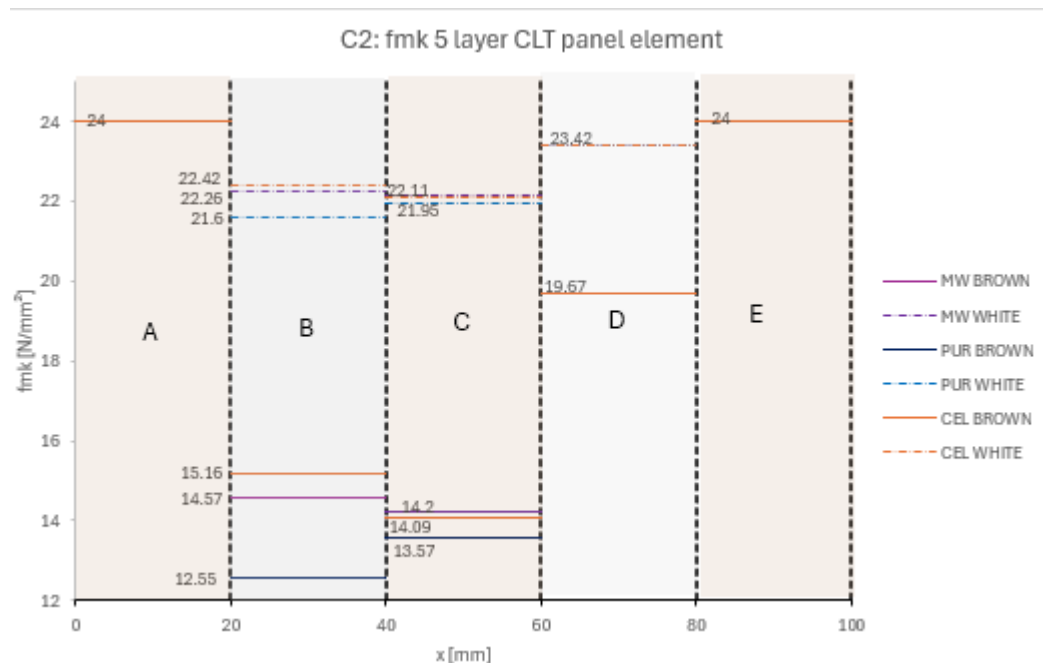


Figure 39: bending strength for each layer for a five layered CLT wall in case of encapsulated building moisture

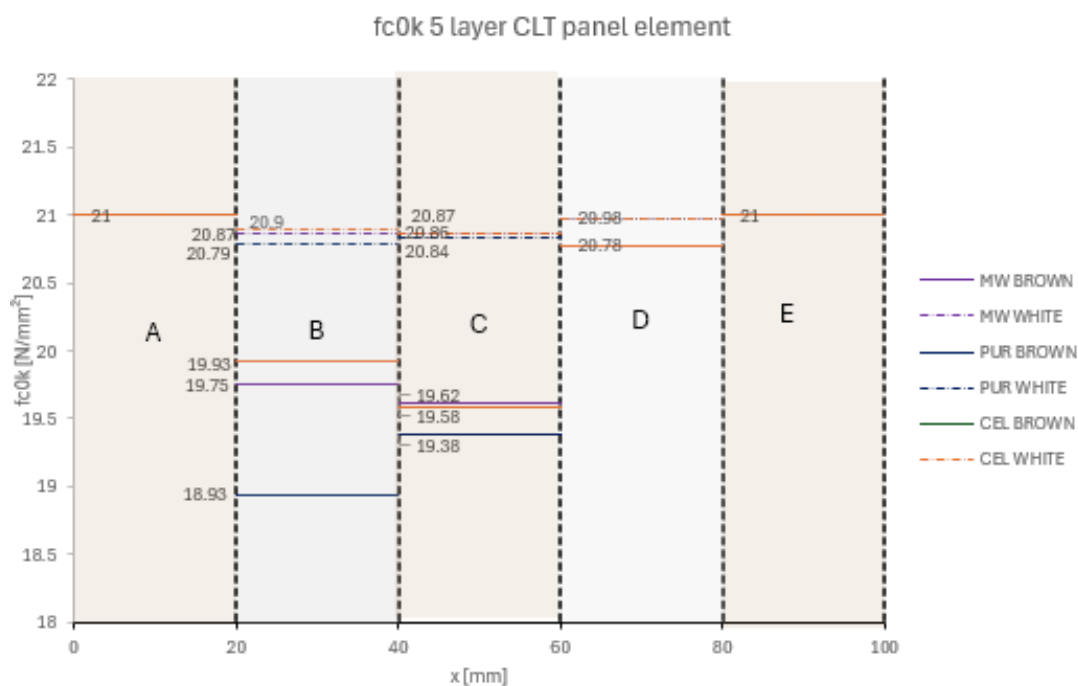


Figure 40: parallel compressive strength for each layer for a five layered CLT wall in case of encapsulated building moisture

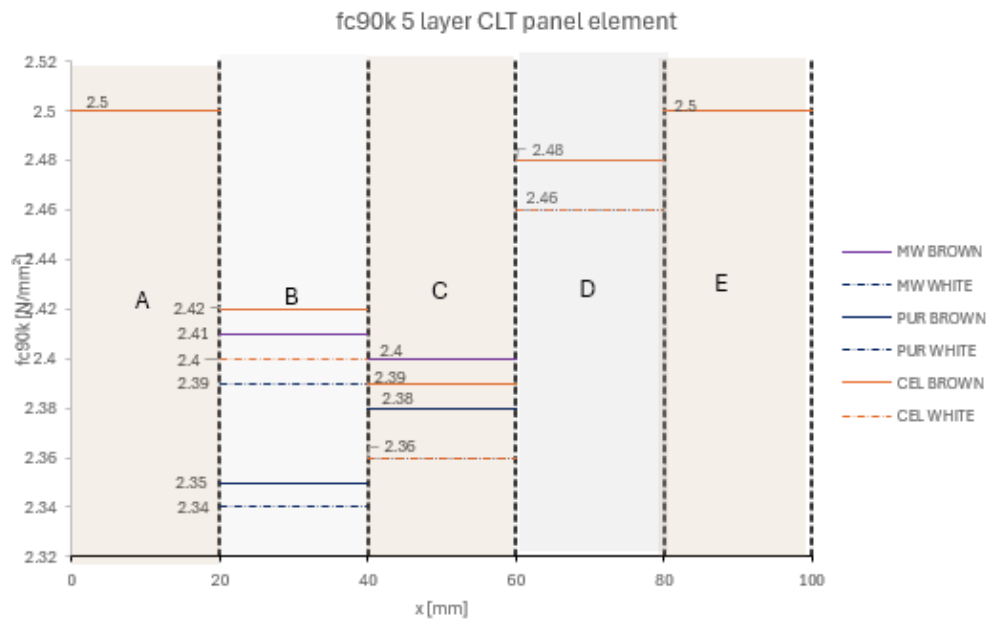


Figure 41: perpendicular compressive strength for each layer for a five layered CLT wall in case of encapsulated building moisture

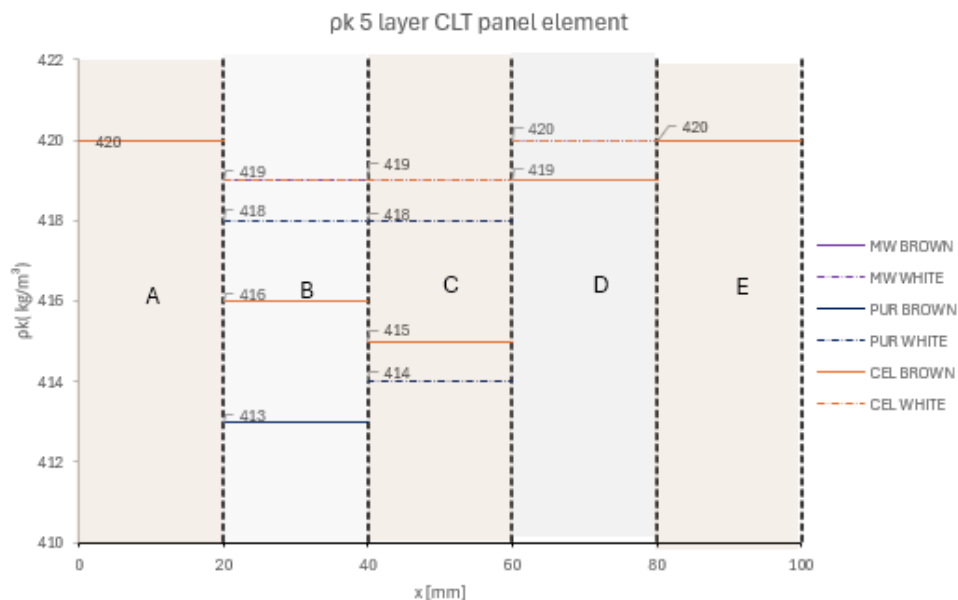


Figure 42: self-weight for each layer for a five layered CLT wall in case of encapsulated building moisture

5.1.3 Results

Based on §5.1.1 and §5.1.2, it can be stated that brown rot and white rot does not lead to the failure of a wall panel. This can also be explained due to the location of measurements: often moisture is accumulated in corners, connection interfaces and on places where drying out is not possible. These locations are controlled in §6.

The performance of the insulation results in differences in limit stresses and self-weight, with PUR being the worst performer. CEL and MW behave similarly.

This can also be explained by the fact that PUR is the only vapour-tight insulation material preventing drying out.

The type of rot influences the properties significantly in case of a three- and five-layered panel but the influence on the capacity is only remarkable in a five-layered panel.

5.2 Roof element

The roof element is investigated in an identical manner as the wall except of the fact that now no cellulose insulation is considered since it is rarely used as roof insulation in Belgium.

5.2.1 Five-layer CLT roof panel

The MC and T for the lamellae in a roof configuration are displayed in Table 27. It can be found that in case of a roof, layer A experiences the high MC. Analogous to the wall element, the vapour-tight PUR layer prevents drying of the adjacent CLT so moisture is consequently trapped in lamella A. The temperature is again approximately constant in both cases over time, namely between 20 and 30°C.

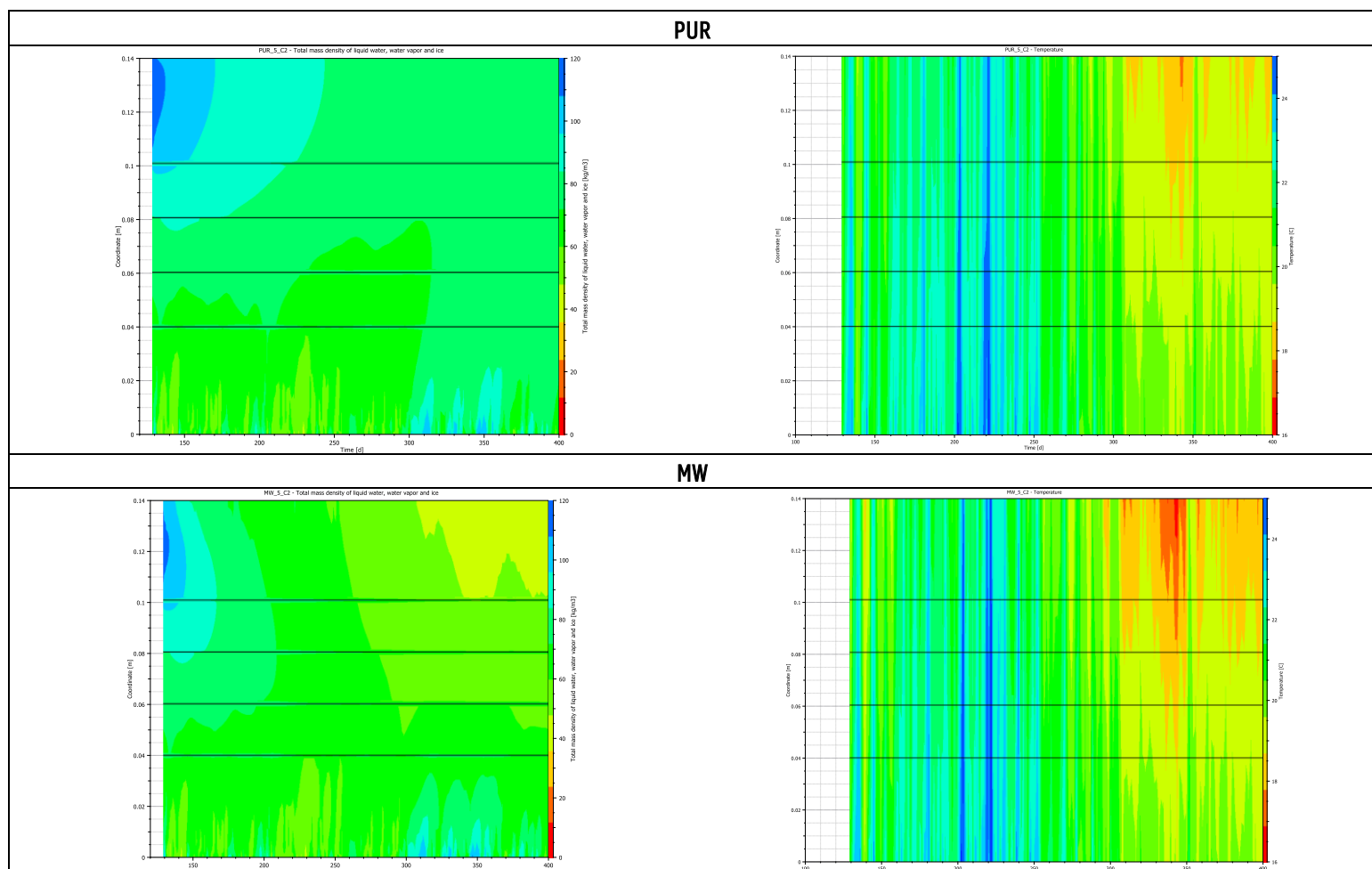
As mentioned in §2.4, the capacity of a roof panel in ULS rarely exceeds 50% so the results in Table 26 show an expected result.

Table 26: Capacity check roof element

Insulation	Type Rot	Max capacity	Location max
PUR	Brown rot	0.48	E
PUR	White rot	0.46	E
MW	Brown rot	0.46	E
MW	White rot	0.46	E

SSSSSSKKKKKKKKKKKKKKKK

Table 27: Moisture mass density MMD (left) and temperatures T (right) of the CLT-lamellae of a five-layered roof element to verify the capacity of a roof panel with PUR and MW



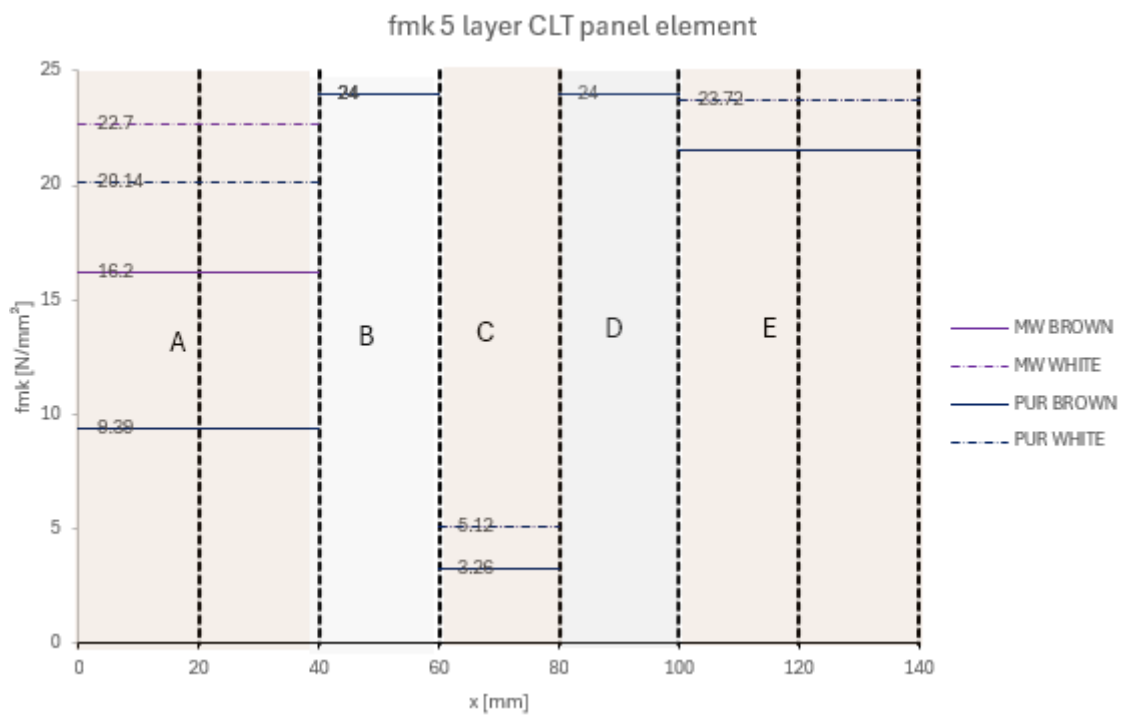


Figure 43: bending strength for each layer for a five layered CLT roof in case of encapsulated building moisture

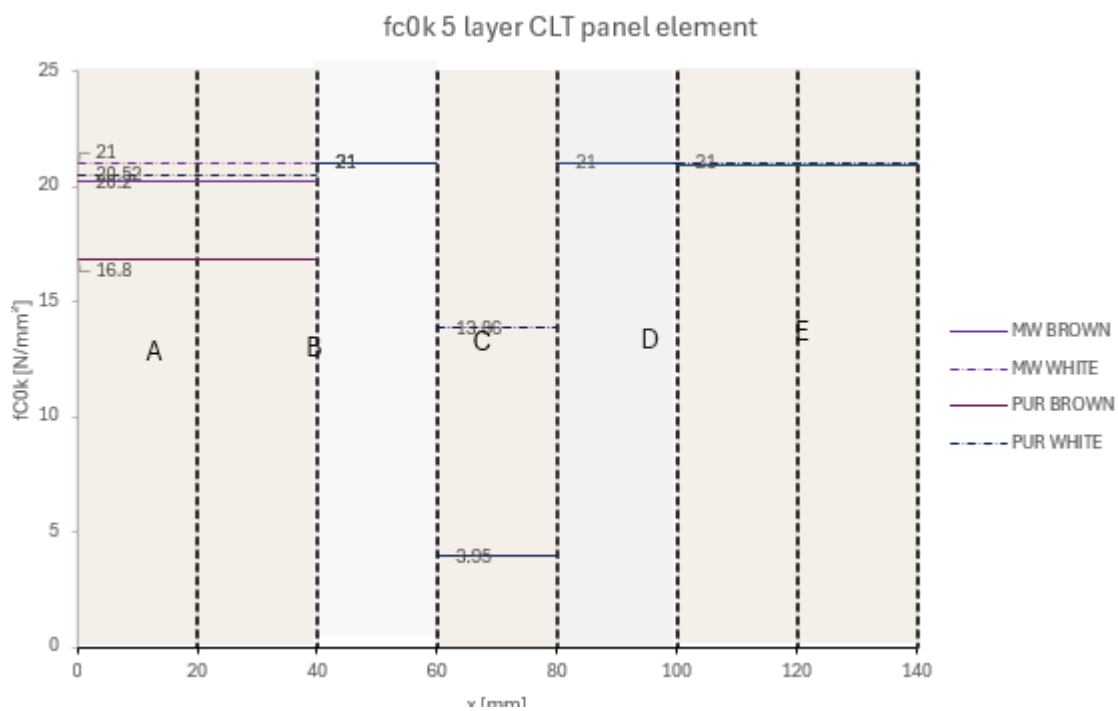


Figure 44: parallel compressive strength for each layer for a five layered CLT roof in case of encapsulated building moisture

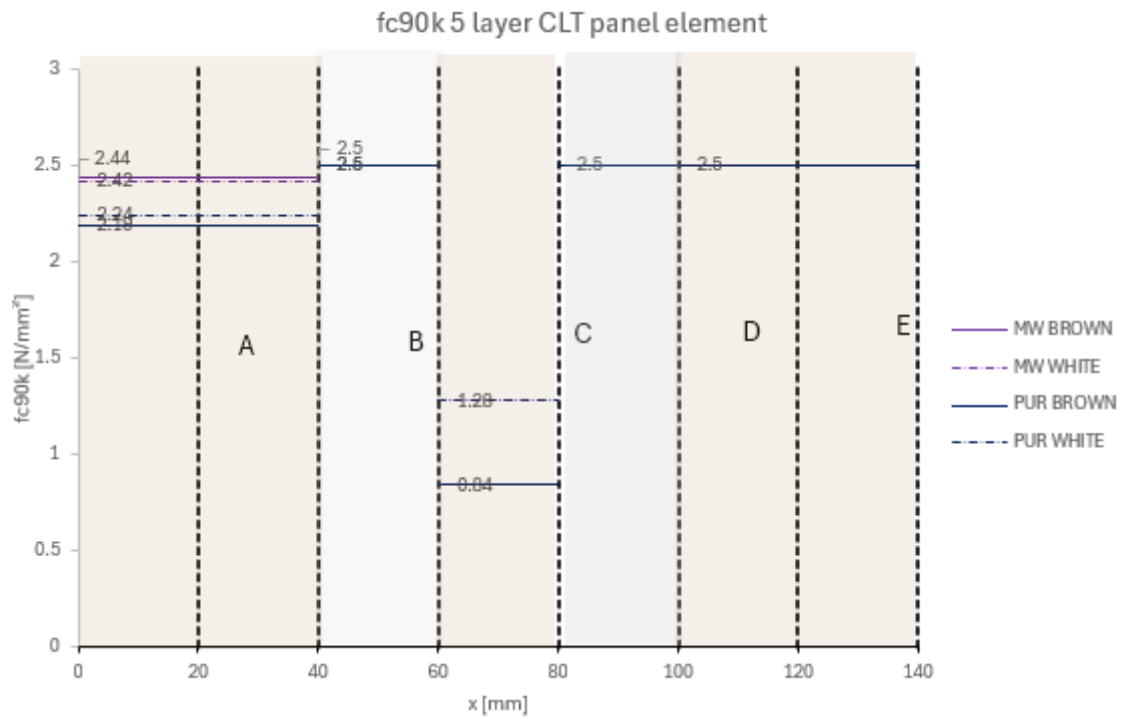


Figure 45: perpendicular compressive strength for each layer for a five layered CLT roof in case of encapsulated building moisture

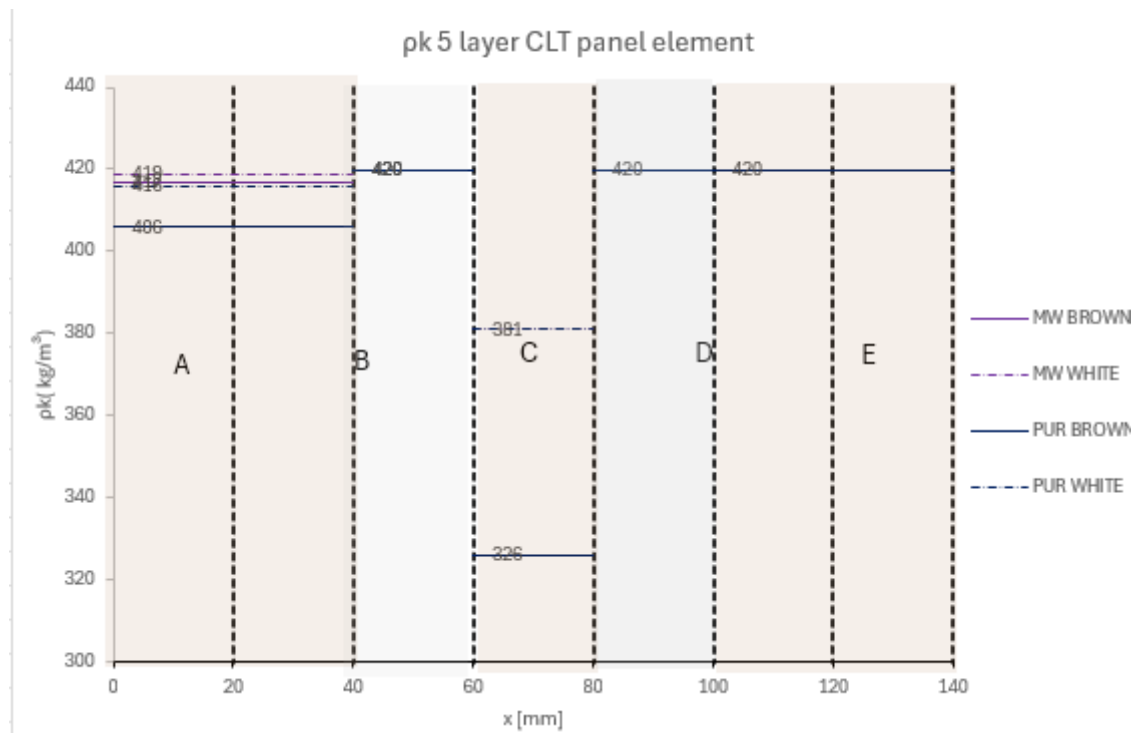


Figure 46: self-weight for each layer for a five layered CLT roof in case of encapsulated building moisture

5.2.2 Results

Since the moisture is trapped in layer E in case of PUR insulation, this leads to a higher reduction of limit stresses due to a higher level of decay.

Yet the results in capacity are similar for the kind of rot and type of insulation making the influence of rot minimal on the final result since layer E is the governing layer and it was not influenced by the decay in both compositions.

A rise in MC in layer E between days 300–360 can be observed in both cases. This corresponds to March–April, given that day 1 is taken as 9 May. The start of spring is typically associated with a reduction in indoor heating and a rise in outdoor temperature, leading to an increase in both outdoor absolute humidity and indoor relative humidity. The resulting shift in the vapour-pressure gradient across the assembly causes the panel to briefly absorb moisture, which explains the short increase in MC in layer E.

6 LOSS OF CAPACITY IN THE CONNECTION

6.1 General information

To find the influence of decay on the connection, a new connection was designed since the original connection could not incorporate the influences of decay.

Since the self-weight of CLT panel plays a crucial role as showed in 2.5 and decay is not constant over the panel, a method is needed to find the corresponding self-weight of the panel that can be used in the calculation of the connection. (Srivaro et al., n.d.) found out that the corresponding self-weight of a CLT panel with different densities can be written as:

$$\rho_{CLT} = f_{outer} \cdot \rho_{outer} + \rho_{center} \cdot (1 - f_{outer}) \quad (147)$$

with f_{outer} the volume fraction of the panel

Once the corresponding self-weight of the panels are known, it is now possible to start calculating the capacity of the connection.

The following 48 different scenarios are investigated:

- 3 types of wall insulation: PUR, MW and CEL
- 2 types of roof insulation: PUR and MW
- 2 types of rot: Brown rot and White rot
- 2 amounts of layers: 3 and 5 layered configurations
- 2 periods of exposure :Short term and long term

Based on all these scenarios, the most influential factors are investigated and the most detrimental combinations are mentioned.

Also, here leakages were modelled but did not show a significant influence on the load-bearing capacity of the connection.

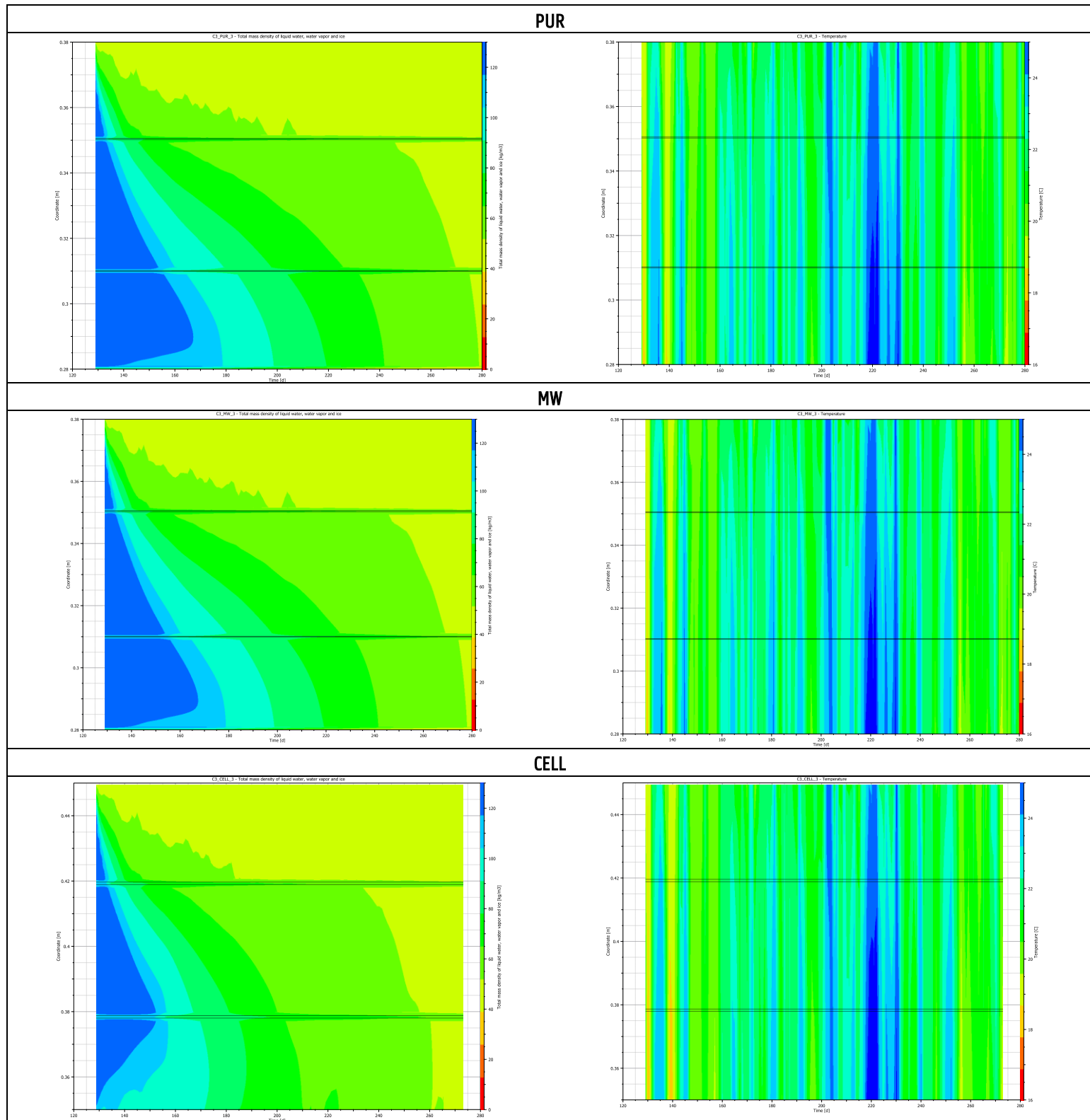
6.2 Three layered CLT connection

A connection between a three-layered wall element and a five layered roof element is considered in this chapter. Two levels of exposure of the wall element are considered, namely short-term exposure and long-term exposure.

Table 29 exhibits the MC and T for each lamella of a three layered CLT panel in case of short-term exposure of the wall. The three different insulation types display a similar behaviour in case of MC and T. The self-weight is visualised in Figure 46.

6.2.1 Short term exposure of wall panel

Table 28: Moisture mass density MMD (left) and temperatures T (right) of the CLT-lamellae of a three-layered wall element to verify the capacity of a connection in case of short term exposure with PUR, MW and CEL insulation



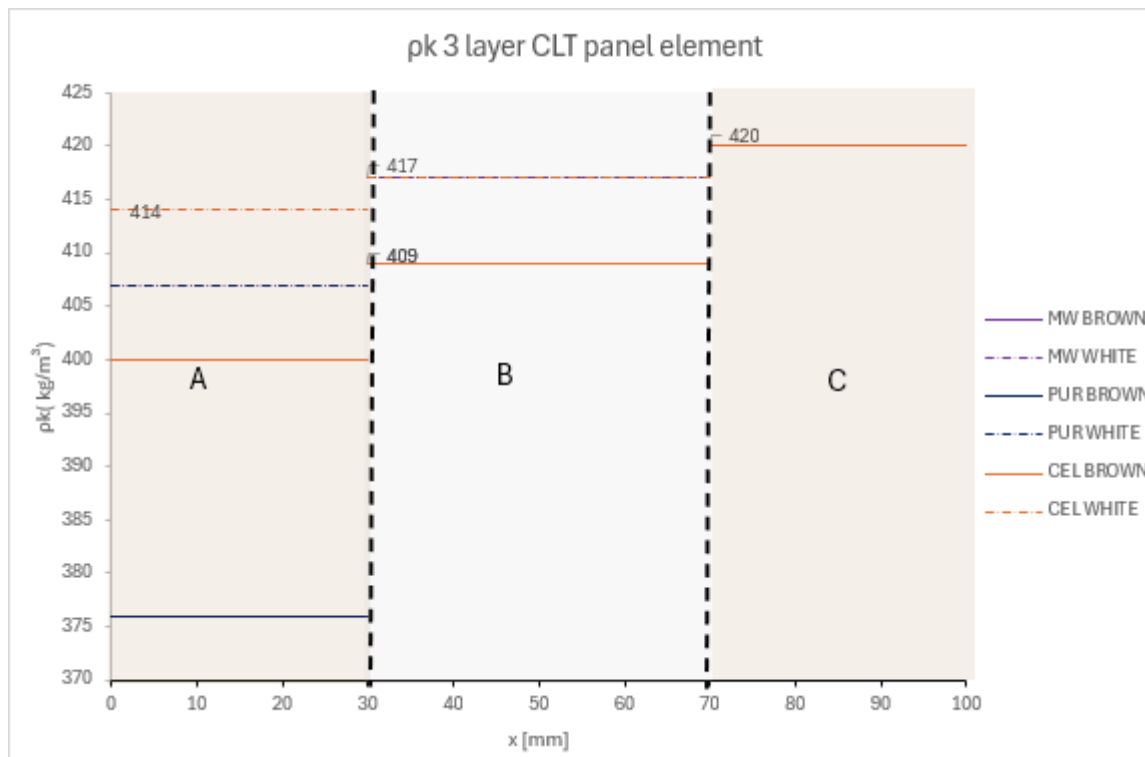


Figure 47: Self-weight per layer for a three layered CLT wall panel in case of short-term exposure

6.2.1 Results

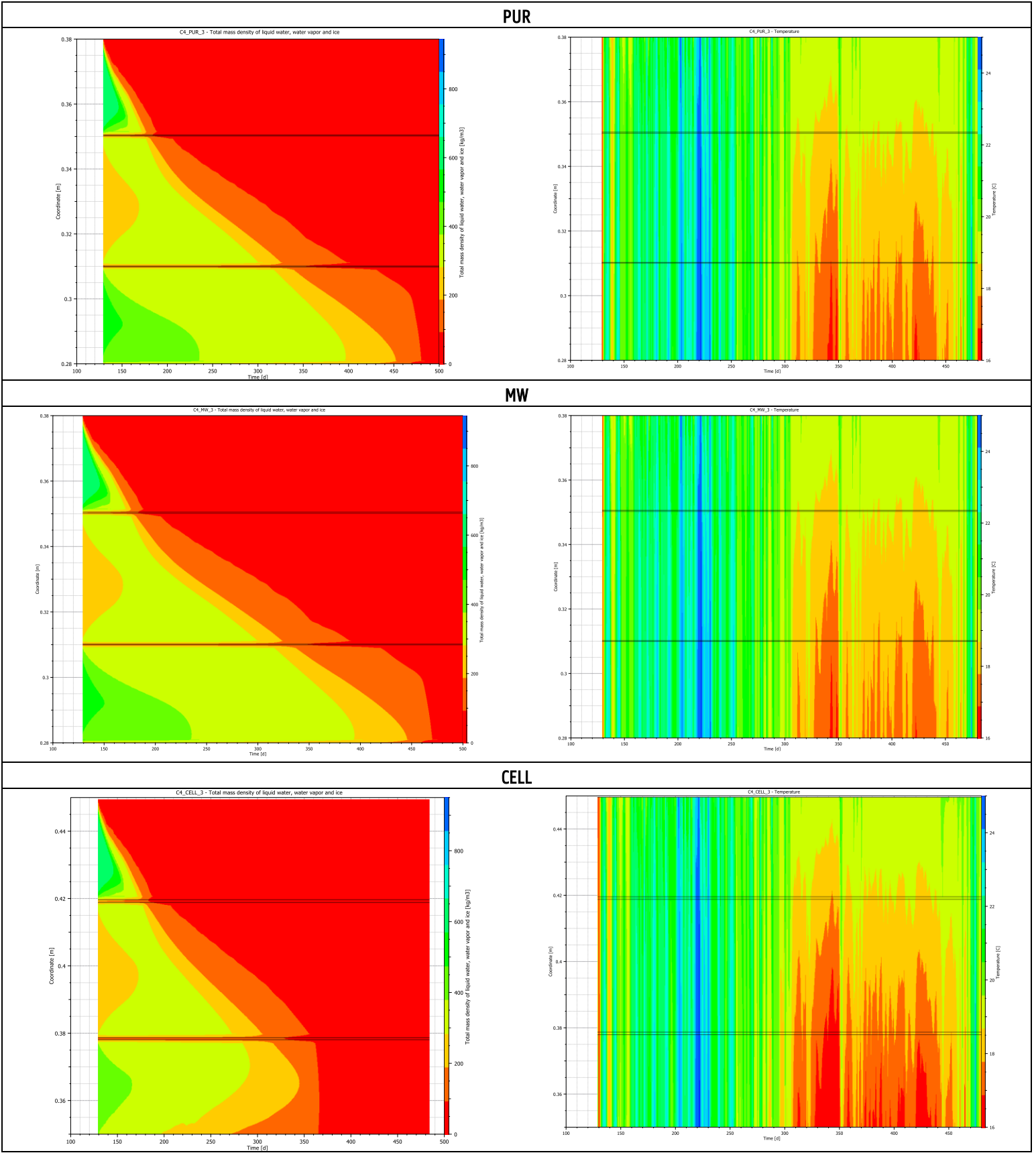
It can be found in Table 28 that the three different types of insulation have a relatively similar influence on the temperature of the CLT panel, as expected since they have the same thermal transmittance. The biggest differences can be found in the MMD of the panels. The drying behaviour of the outer CLT lamella explains the differences observed between the three insulation configurations. With PUR ($\mu = 65$), outward drying is almost entirely blocked and the built-in moisture remains trapped against the insulation interface, resulting in a persistently high MC in lamella A (De Smet, 2025; Freimanis et al., 2023). With MW ($\mu = 1$), vapour diffusion outward is possible but is the only available drying mechanism, leading to intermediate behaviour (De Smet, 2025). CEL is both vapour-open and capillary-active: it wicks liquid water directly out of the adjacent CLT lamella, producing the fastest MC drop and bringing lamella A below the critical moisture content for rot to develop.

This explains why MW and PUR have similar properties in Figure 47 and why CEL has better properties.

6.2.2 Long term exposure of wall panel

In case of a long-term exposure, differences in MC behaviour between the insulation materials can be witnessed while the temperature profiles stay relatively constant, between 16 and 25°C, as shown in Table 29.

Table 29: Moisture mass density MMD (left) and temperatures T(right) of the CLT-lamellae of a three-layered wall element to verify the capacity of a connection in case of long term exposure with PUR, MW and CEL insulation



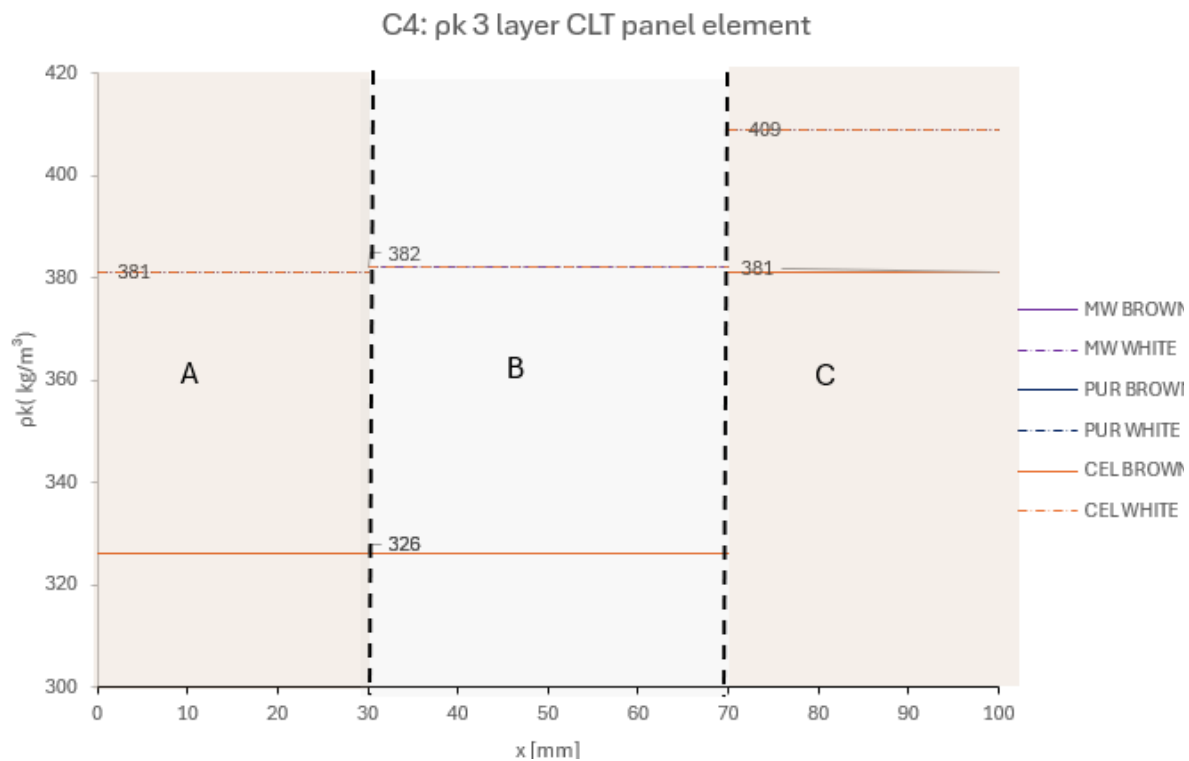


Figure 48: Self-weight per layer for a three layered CLT wall panel in case of long-term exposure

6.2.2.1 Results

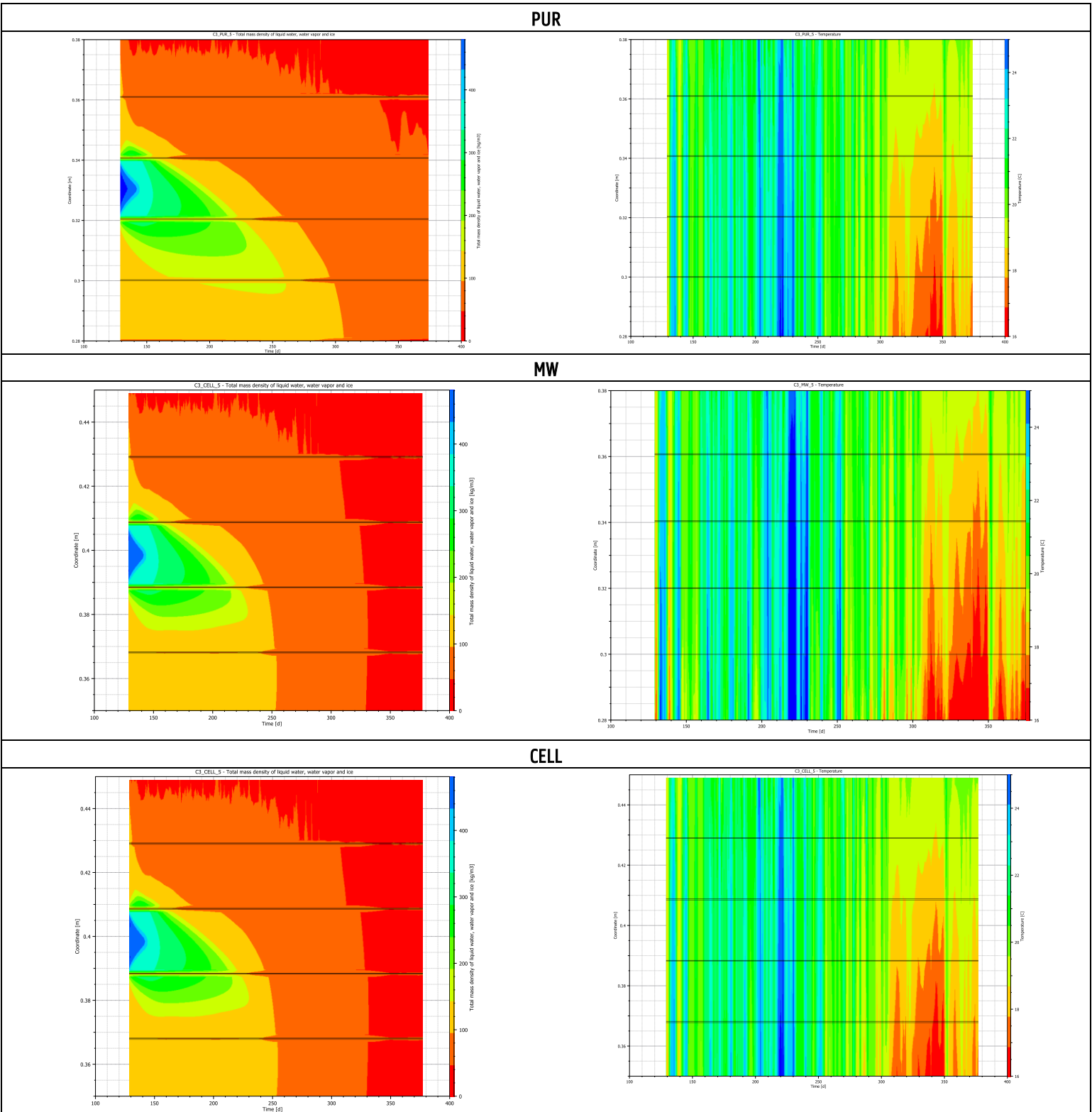
Based on Figure 48 and Table 29 it can be found that there are some differences in behaviour and performance compared to a short term exposure. The first observation is that behaviour and values for the MDD in layer A and B are approximately equal in the three compositions. As discussed in §6.2.1.1, the drying out is better in CEL. The MMD lowers faster but still remains high enough to surpass the critical MC and contribute to a daily dose and degrade equally. It can then be concluded that CEL is the best option three layered CLT wall elements in short and long term exposure.

6.3 Five layered CLT connection

Like the capacity calculation of a panel and based on the figures in Table 30 and Table 31, the moisture remains trapped in the area around the adhesive layers which results in a higher decline of the properties due to decay as shown in Figure 49 and Figure 50.

6.3.1 Short term exposure of wall panel

Table 30: Moisture mass density MMD (left) and temperatures T (right) of the CLT-lamellae of a five-layered wall element to verify the capacity of a connection in case of short term exposure with PUR, MW and CEL insulation



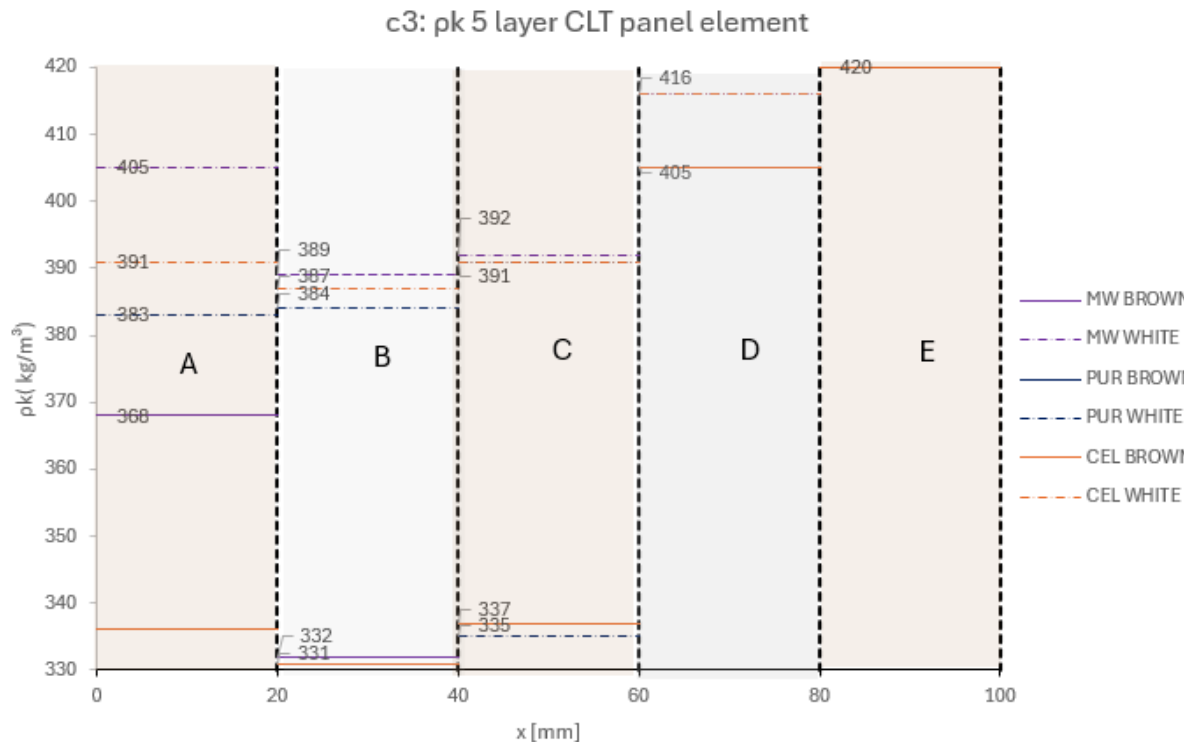


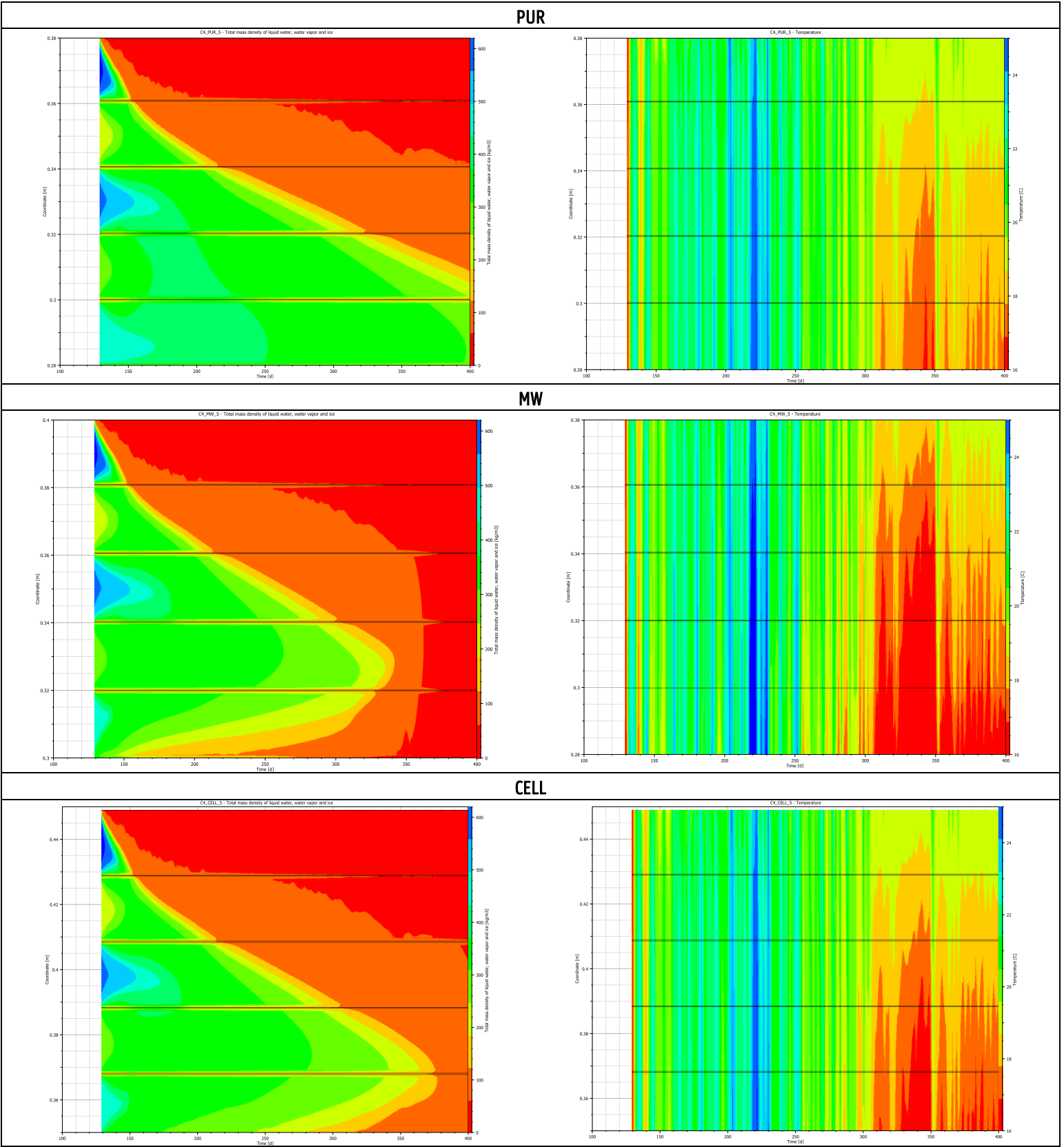
Figure 49: Self-weight per layer for a five layered CLT wall panel in case of short-term exposure

6.3.1.1 Results

For long-term exposure the drying-speed ranking observed in the short term scenario is reversed: MW now yields higher characteristic densities than CEL across the outer lamellae A and B. The difference is most pronounced in layer A for brown rot. This reversal reflects the fact that CEL's capillary activity is only beneficial as long as the total moisture supply is finite. Under sustained exposure, the CEL layer itself becomes and remains saturated for over a year (De Smet, 2025) and therefore acts as a continuous moisture reservoir in capillary contact with the outer CLT lamella. This keeps the MC above the critical MC and produces high cumulative daily doses (Brischke & Rapp, 2008). MW, being non-capillary and vapour-open, has no such moisture-storage capacity. Here liquid water drains off along the CLT and MW interface and the outer lamella can dry by vapour diffusion outward. The effect is amplified in the 5-layer configuration because the additional glue planes traps the moisture, so the outer lamellae depend almost entirely on the insulation interface for drying and that is exactly the path that CEL keeps wet and MW leaves open. This makes MW the best option in case of short term exposure of a five layered wall element.

6.3.2 Long term exposure of wall panel

Table 31: Moisture mass density MMD (left) and temperatures T (right) of the CLT-lamellae of a five-layered wall element to verify the capacity of a connection in case of long term exposure with PUR, MW and CEL insulation



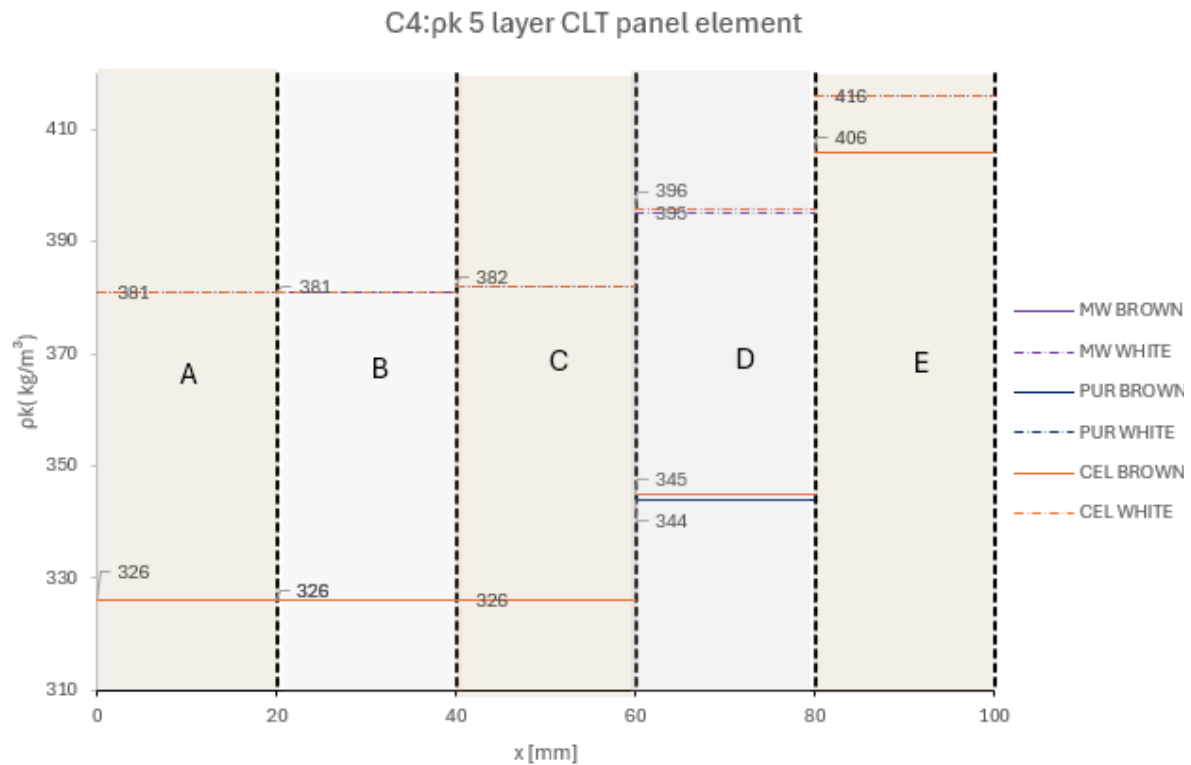


Figure 50: Self-weight per layer for a five layered CLT wall panel in case of long-term exposure

6.3.2.1 Results

In Table 31 and Figure 50 it can be found that identical to §6.3.1.1, MW remains the best option for a five layered CLT wall since the drying out works the best here. The temperature remains also approximately constant for the three configurations.

6.4 Exposure of Roof panel

For the roof configuration, only two types of insulation were considered. Additionally, no differentiation was made between the duration of exposure.

Table 32: Moisture mass density MMD (left) and temperatures T(right) of the CLT-lamellae of a five-layered roof element to verify the capacity of a connection in case of exposure with PUR and MW insulation

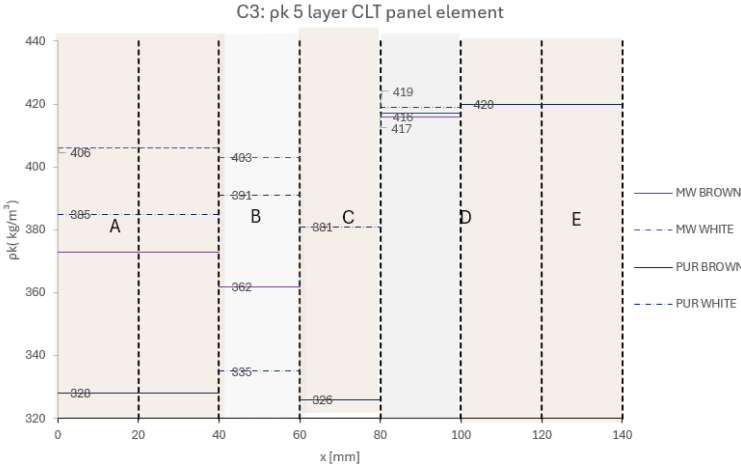
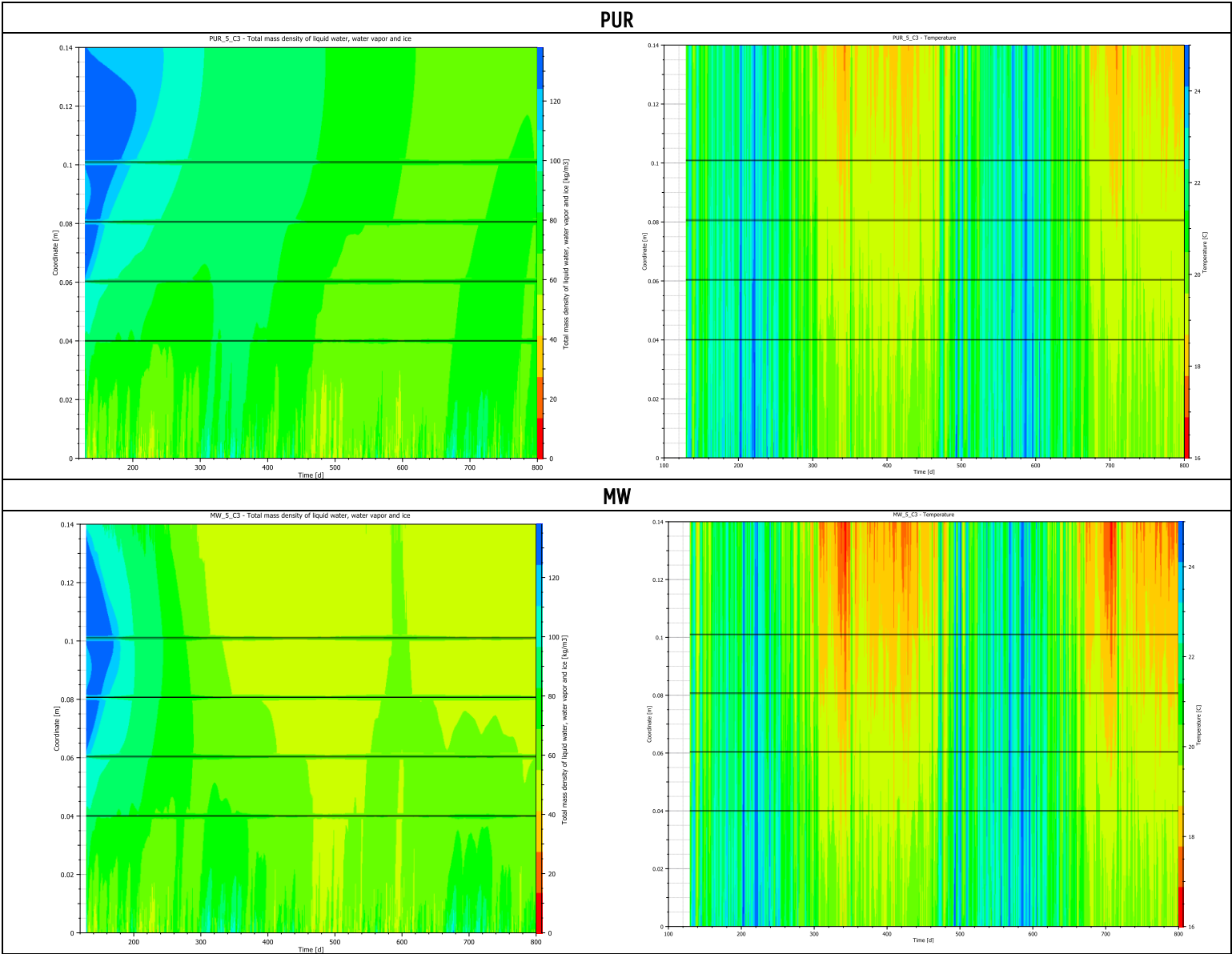


Figure 51: Self-weight per layer for a five layered CLT roof panel in case of exposure

6.4.1 Results

As the MC and T were presented in Table 32, there is a distinct difference in behaviour due to the nature of the insulation. A build up with PUR takes noticeable longer to dry out in the outer layers as MW. This also explains the difference between the self-weight in Figure 51. So it can be stated that MW is the better option for insulating a roof that has been exposed to rain and other natural influences.

6.5 Loss of design capacity

To express the influence of all the different parameters on the load-bearing capacity, all the different configurations were compared to the original situation to find the loss in capacity in the connection. A legend, visualised in Table 34, helps with visualising Figure 52 and Figure 53.

Since the load that needs to be transferred from the roof to the wall in the connection, as determined in §3.4.1 is 11.63 kN/m, a connection was made in §3.4.3 with a reference capacity of 12kN/m. This original capacity is used in the thesis as reference value to calculate the loss in capacity in *kN* and in %.

Table 33: Legend for Table 34

Legend Table 34	
PUR	Polyurethane insulation
MW	Mineral Wool
CEL	Cellulose
ST	Short term exposure of the Wall
LT	Long term exposure of the wall
3L	Three layered CLT wall panel
5L	Five layered CLT wall panel

Table 34: Legend to Figure 52 and Figure 53

Roof PUR insulation				Roof MW insulation			
1	Wall PUR ST Brown 3L	13	Wall PUR ST Brown 5L	25	Wall PUR ST Brown 3L	37	Wall PUR ST Brown 5L
2	Wall PUR LT Brown 3L	14	Wall PUR LT Brown 5L	26	Wall PUR LT Brown 3L	38	Wall PUR LT Brown 5L
3	Wall PUR ST White 3L	15	Wall PUR ST White 5L	27	Wall PUR ST White 3L	39	Wall PUR ST White 5L
4	Wall PUR LT White 3L	16	Wall PUR LT White 5L	28	Wall PUR LT White 3L	40	Wall PUR LT White 5L
5	Wall MW ST Brown 3L	17	Wall MW ST Brown 5L	29	Wall MW ST Brown 3L	41	Wall MW ST Brown 5L
6	Wall MW LT Brown 3L	18	Wall MW LT Brown 5L	30	Wall MW LT Brown 3L	42	Wall MW LT Brown 5L
7	Wall MW ST White 3L	19	Wall MW ST White 5L	31	Wall MW ST White 3L	43	Wall MW ST White 5L
8	Wall MW LT White 3L	20	Wall MW LT White 5L	32	Wall MW LT White 3L	44	Wall MW LT White 5L
9	Wall CELL ST Brown 3L	21	Wall CELL ST Brown 5L	33	Wall CELL ST Brown 3L	45	Wall CELL ST Brown 5L
10	Wall CELL LT Brown 3L	22	Wall CELL LT Brown 5L	34	Wall CELL LT Brown 3L	46	Wall CELL LT Brown 5L
11	Wall CELL ST White 3L	23	Wall CELL ST White 5L	35	Wall CELL ST White 3L	47	Wall CELL ST White 5L
12	Wall CELL LT White 3L	24	Wall CELL LT White 5L	36	Wall CELL LT White 3L	48	Wall CELL LT White 5L

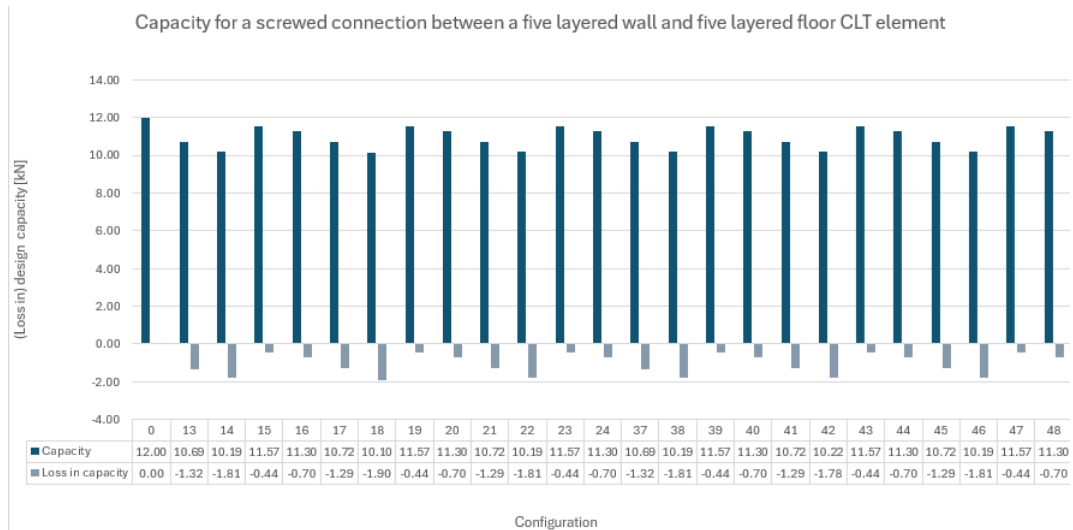


Figure 52: Capacity for a screwed connection between a five layered wall and five layered roof CLT element

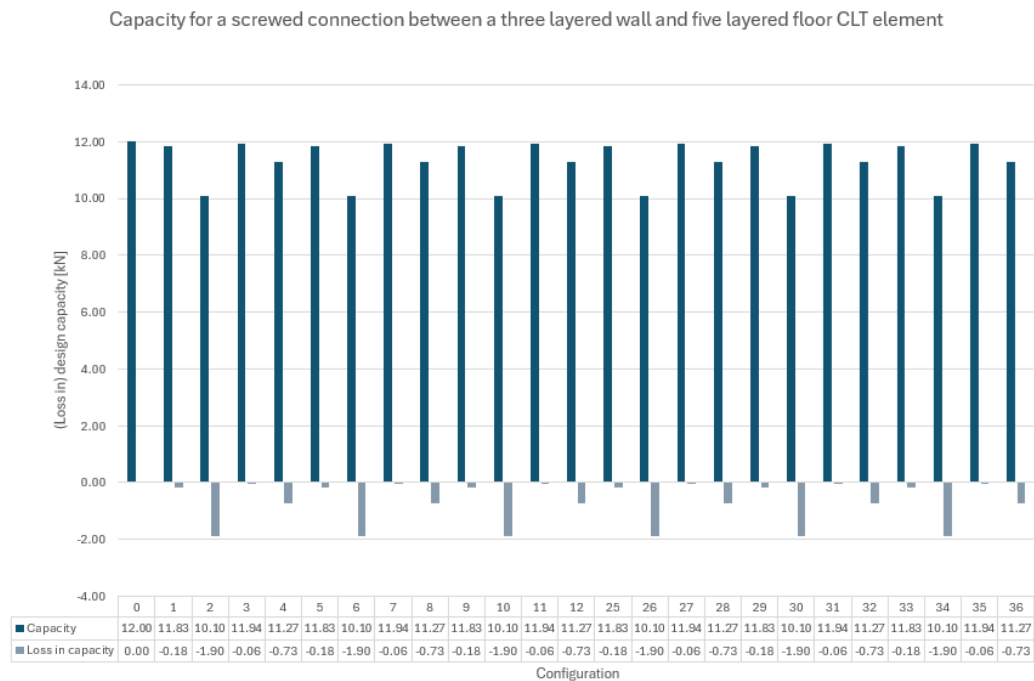


Figure 53: Capacity for a screwed connection between a three-layered wall and five layered roof CLT element

6.5.1 Results

Based on Figure 52 and Figure 53, it can be found that in some cases the capacity of the connection is exceeded.

The most significant examples are the cases where brown rot is considered in combination with long term exposure in Figure 52. In these cases the type of insulation has no influence on the capacity.

If Figure 52 is considered, the case with a three layered CLT wall panel, it is clear that PUR performs worse than MW and CEL.

A second important conclusion is that in case of a inclined screwed wall to roof connection the kind of insulation of the roof is irrelevant unless failure mode B from Figure 18 occurs. This is the failure modus where the wood in element 2, and thus the roof element, crushes without the yielding of the screw. This is because only in that expression the self-weight of the roof is considered.

This results in identical values for the configurations , independently from the kind of insulation used in the roof.

6.5.2 Solutions

As seen in Figure 52 and Figure 53, in some cases the capacity of the connection is exceeded.

To solve this, some actions could be done. It could be opted to install more screws, longer and/or screws if the material is not yet ordered.

6.6 OAT- sensitivity analysis

An OAT sensitivity analysis is performed to rank the influence parameters and quantify the influence according to (Saltelli A. et al., 2008) based on the capacity of the connection, calculated as:

$$\frac{F_{v,Rd}}{F_{v,ORd}} \quad (148)$$

An OAT analysis was adopted because it is well suited to screening a small set of categorical factors for their dominant effects. (Saltelli A. et al., 2008) stated that in that scenario, an OAT sensitivity analysis is preferable as mentioned in §2.10.

The following properties were used as a factor:

Table 35: factors in the OAT analysis

Factor X	Levels
Type of rot	Brown, White
Duration of exposure	Short term, long term
Number of layers	3-Layered, 5-layered
Insulation wall	PUR,MW,CELL
Insulation roof	PUR, MW

The influence of brown rot is shown in the following equation:

$$\bar{\Delta}_{Brown} = \frac{1}{12} \sum_{i \in Brown}^{12} |y_i - 1| = \frac{0.02 + 0.15 + 0.02 + \dots + 0.14}{12} = 0.099 \quad (149)$$

The results for each case are presented in Table 36

Table 36: Results OAT sensitivity analysis

Factor	Best level	$\bar{\Delta}_{Best}$	Worst level	$\bar{\Delta}_{Worst}$
Type of rot	White	0.03999	Brown	0.1076
Duration of exposure	Short Term	0.0407	Long Term	0.1067
Number of layers	3	0.0594	5	0.088
Insulation wall	MW	0.0734	PUR	0.0740
Insulation roof	MW=PUR	-	MW=PUR	-

Once these factors are determined, the sensitivity index can be calculated and the factors can be ranked:

$$S_X = \bar{\Delta}_{Worst} - \bar{\Delta}_{Best} \quad (150)$$

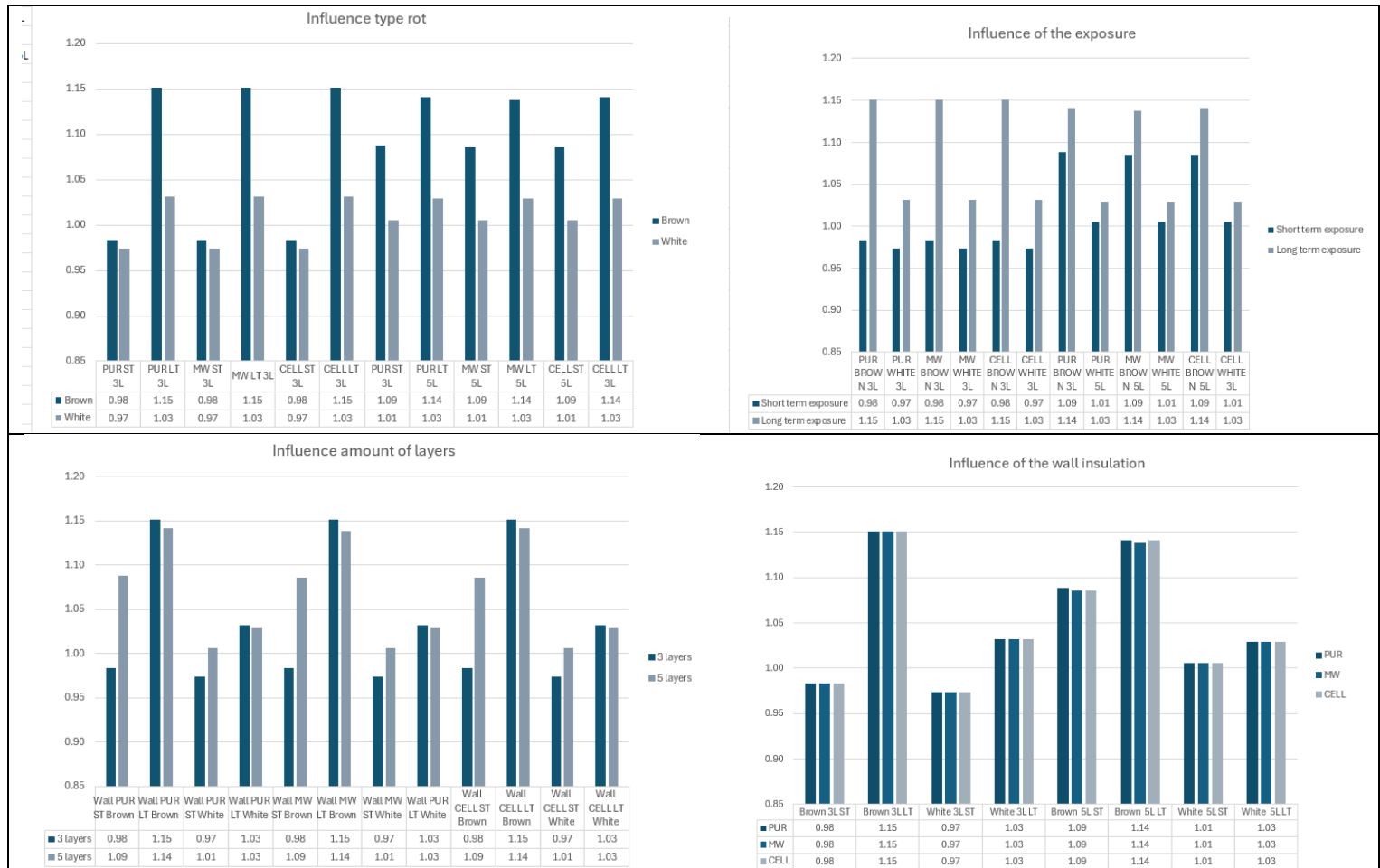
Now the influence can be ranked as displayed in Table 37:

Table 37: Ranking of influence factors

Factor	S_x	Rank
Type of rot	0.0677	1
Duration of exposure	0.0660	2
Number of layers	0.0286	3
Insulation wall	0.006	4
Insulation roof	0.000	5

The influence of the different parameters is visualised in Table 38. These also clearly show that as stated in Table 37, the biggest influence is the type of rot, then the period of exposure, next the amount of layers and eventually the type of insulation has a very little influence.

Table 38: Visualisation of the influences



7 CONCLUSIONS AND RECOMMENDATIONS

7.1 General synthesis

This dissertation investigated the influence of fungal decay on the load-bearing capacity of CLT structures designed in accordance with (NBN EN 1995, 2005) in a Belgian climatic context. The workflow combined four established models: the hygrothermal simulation of a building envelope in Delphin to obtain the layer-wise moisture content and temperature; the daily-dose model of (Brischke & Rapp, 2008) with the logistic parameters of (Isaksson et al., 2013) to quantify the cumulative exposure; the mass-loss and strength-loss models of (Hradil & Fortino, 2023) and (Bollmus S. et al., 2020) to translate the cumulative dose into a reduction of the bending and compressive characteristic strength. These properties were then implemented in Finite Element software to investigate the influence on the capacity of a wall and roof element and also integrated in a screwed wall-roof calculation according to (NBN EN 1995, 2005). The methodology was applied to the reference building of HOUTVAST located in Boortmeerbeek (Belgium).

A sensitivity analysis was also performed to find out the influence of deteriorated properties on the SLS of a roof panel.

The investigation distinguished two limit states (SLS and ULS) and two structural systems (panel and connection) and considered 48 configurations for the connection combining four design variables (rot type, exposure duration, layout, insulation wall and insulation roof). An OAT sensitivity analysis, in the sense of (Saltelli A. et al., 2008) was carried out to rank these variables by their effect on the connection capacity. The conclusions of each component of the work are presented below.

7.2 Serviceability Limit State

For wood-based roofs the Serviceability Limit State is, on average, the governing limit state (Fröbel & Gustafsson, 2022). A sensitivity analysis was therefore carried out on the CLT140-L5s roof of the reference building by varying independently the thickness of the most-exposed outer lamella and the modulus of elasticity of the layers A and C, which are the layer's most exposed to elevated moisture content.

The deflection was computed with both the Timoshenko beam theory and the gamma-method described in §3.2. The two methods yielded essentially identical results for the geometry studied. This calculation confirms the recommendation of (Danielsson, 2025) that for normal CLT applications the Timoshenko formulation is sufficient. The choice between the two methods is therefore not a source of significant uncertainty in this work.

Three findings emerge from the SLS sensitivity analysis:

1- Decay can rapidly cause the roof to fail SLS deflection limit of $l/300$.

A loss of approximately 10 mm of the outer lamella is already sufficient to drive the final deflection w_{fin} beyond the limit. This corresponds to a moderate decay rating per (EN 252, 2014), well before the failure stage.

2-Layer thickness is more influential than the modulus of elasticity.

A reduction of 36 % of the E-modulus is needed before the SLS limit is breached, whereas the equivalent 10 mm reduction of the outer-layer thickness is much smaller in relative terms. The reason can be explained by looking to the calculation method to calculate the nett moment on inertia: the thickness enters at the third power, while the modulus of elasticity enters linearly. Decay that physically removes timber material (the cross-section reduction approach) is therefore far more detrimental for the SLS than decay that softens the timber without removing it. This is an important point because the two modelling approaches are presented as equivalent in (Bollmus S. et al., 2020). They are equivalent for the ULS but not for the SLS.

3-The Belgian context confirms the importance of SLS for decay-affected CLT.

The Sint-Truiden case study referenced in §4 (the residential balcony demolished due to excessive deflection caused by decay, as reported by VRT NWS, 2022) is a documented example of an SLS-driven decay failure in Belgium and corroborates the conclusion that the SLS and not the ULS is the limit state that practitioners should monitor most closely for moisture-exposed CLT.

The practical consequence is that any reasoned durability assessment of a CLT structure should include an SLS check based on the cross-section-reduction approach in addition to the ULS check based on the strength-reduction approach. A check based on strength reduction alone, as is implicitly done when the modulus of elasticity is treated as the only decay-affected mechanical property — is non-conservative for the SLS and can become dangerous.

7.3 Conclusions on the Ultimate Limit State of CLT panels

7.3.1 Walls

The wall panels were verified for the encapsulated building-moisture scenario in three insulation configurations (PUR, MW, CEL) and the two rot types (brown, white). Two layups were considered: the three-layer panel CLT100-L3s (30/40/30 mm) and the five-layer panel CLT100-L5s (5 × 20 mm). The utilisation ratio of the ULS check, reported in Table 22 and Table 24, can be summarised as done in Table 39:

Table 39: Summarising table for capacity check

Insulation	Rot type	CLT100-L3s	Governing layer (3L)	CLT100-L5s	Governing layer (5L)
PUR	Brown	0.71	A	0.77	C
PUR	White	0.71	A	0.71	C
MW	Brown	0.71	A	0.76	C
MW	White	0.71	A	0.71	C
CEL	Brown	0.71	A	0.76	C
CEL	White	0.71	A	0.71	C

Four conclusions follow from this synthesis:

1-Decay does not jeopardise the ULS of CLT walls under the moisture loads investigated.

The utilisation ratio remains comfortably below unity in every scenario and the increase in utilisation due to decay is relatively small.

2-The location of the governing layer shifts with the layup.

In the 3-layer panel the outer lamella A governs the verification, whereas in the five-layer panel the central lamella C governs. The mechanism is the moisture-trapping behaviour explained in §5.1.2: in a five-layer panel the inner longitudinal lamella is enclosed by two essentially vapour-tight MUF adhesive layers ($\mu = 416$, see Table 17), so moisture that has penetrated the outer lamella cannot redistribute and remains concentrated around the central layer. The fact that the governing layer is the central one in the five-layer case is a direct, mechanically traceable consequence of the moisture-content profile measured by (Blommaert et al, 2025) on vertical CLT walls and used as input here.

3-The insulation material has a measurable but small effect on the panel utilisation.

PUR is the worst-performing insulation, with utilisation reaching 0.77 in the five-layer brown-rot scenario, while MW and CEL perform identically at 0.76. The reason is that PUR is the only vapour-tight insulation considered ($\mu = 65$, $A_w = 0$), which prevents the inward drying of the CLT and sustains the elevated moisture content in the inner lamella for longer. MW ($\mu = 7$) and CEL ($\mu = 2.65$) both allow outward drying on top of inward drying as for the three cases. This conclusion is consistent with the findings of (Freimanis et al, 2023) on the hygrothermal behaviour of vapour-permeable versus vapour-tight insulation systems.

4-Rot type matters for the constitutive properties of the timber but not for the panel verification.

Brown rot causes a substantially larger reduction of the bending and compressive strengths of the central lamella than white rot (a factor of approximately three in the relevant dose range, per (Bollmus S. et al., 2020)), and this is clearly visible in the per-layer strength figures, namely Figure 39, Figure 40 and Figure 41. At the panel-verification level, however, this difference materialises only as a small change in the global utilisation ratio (0.77 vs. 0.71) because the central lamella is a contributing but not the dominant layer in the bending capacity of a five-layer CLT panel. The cross-laminated geometry therefore acts as a partial mechanical safeguard against decay of the inner layer.

7.3.2 Roof

The CLT140-L5s roof panel was verified for the same encapsulated building-moisture scenario, with PUR and MW insulation (CEL was excluded as it is not commonly used for roof insulation in Belgian residential construction). All four configurations yield an identical utilisation ratio of 0.46, as shown in Table 26, with the most-exposed outer lamella E governing the verification.

The conclusion for the roof panel is that decay has no measurable effect on the ULS, for two reasons. First, as anticipated by (Fröbel & Gustafsson, 2022) the ULS utilisation of CLT roofs and roofs in residential construction is typically below 50% because the SLS governs the design; the result of 0.46 in the undamaged reference is consistent with this expectation. Second, the moisture content of the inner lamellae of a roof element under encapsulated building-moisture conditions never reaches the threshold for which the strength-loss model of (Hradil & Fortino, 2023) predicts a significant reduction. The governing lamella E is fully protected by the roof finishing (bitumen, $\mu = 15\,000$, see Table 18) and is therefore not exposed to elevated moisture in any of the scenarios considered.

It must be emphasised, however, that this ULS conclusion does not extend to the SLS, where, as established in §7.2, decay can drive the deflection beyond the $L/300$ limit. For CLT floors and roofs, the SLS is the limit state to which design attention should be directed.

7.4 Conclusions on the Ultimate Limit State of the wall–roof connection

48 configurations were investigated for the screwed wall–roof connection, in accordance with the X-configuration of inclined TBS Ø12 × 240 screws described in §6. The response variable $\gamma = \frac{F_{v,Rd,decay}}{F_{v,Rd,0}}$ expresses the ratio between the design shear capacity of the decay-affected connection and the undamaged reference. The absolute departure from the undamaged state, $|\Delta| = |\gamma - 1|$, is the scalar response used by the OAT analysis in §6.6.

The qualitative picture across the 48 configurations is well captured by four observations:

1-The connection is markedly more sensitive to decay than the panel

The most adverse configuration (brown rot, long-term exposure, 3-layer wall, any wall insulation, any roof insulation) shows $|\Delta|$ reaching 0.16, i.e. a 16 % loss of the design capacity. This is to be contrasted with the maximum of 0.06 observed for the wall panel and the absence of any measurable effect on the roof panel. The connection and thus not the panel field, is therefore the governing element for the durability assessment of CLT structures under decay loads.

2-Brown rot is roughly four times more damaging than white rot.

Across all twelve brown-rot configurations the mean $|\Delta|$ is 0.1076, while across the twelve white-rot configurations the mean is 0.0399. This is a factor of four in the average and up to a factor of five in the most adverse cases. The underlying cause is the higher strength-loss coefficient k_{FL} of brown rot in the model of (Bollmus S. et al., 2020) ($k_{FL} = 13.07$ for parallel compression in brown rot, against $k_{FL} = 7.63$ for white rot), combined with the lower critical dose for the onset of brown rot decay (229 doses, against 451 doses for white rot, per (Brischke & Meyer-Veltrup, 2016) but in this research it was conservatively assumed that the CLT elements already had reached that critical dose due to the prior exposure. The biological reason, as discussed in §2.6, is that brown-rot fungi depolymerise wood carbohydrates well in advance of the actual hyphal growth, so the mechanical degradation runs ahead of the mass loss.

3-The effect of exposure duration is strongly conditional on the rot type.

For brown rot the move from short-term to long-term exposure raises the average $|\Delta|$ from 0.0407 to 0.1067 — almost a tripling. For white rot the same move only raises $|\Delta|$ from 0.020 to 0.030. This is the Rot $\times$ Exposure interaction that drives the design conclusion: the dominant design scenario is unambiguously brown rot under long-term exposure, while white-rot long-term exposure remains structurally tolerable.

4-The number of layers in the wall element matters in early life but not in the long term.

The difference in loss of capacity during short term exposure is smaller in case of a three layered wall panel than a five layered wall panel but this difference slackens in long term exposure.

The original screwed connection designed in §0 (TBS $\emptyset 12 \times 240$, 160 mm spacing) attained a utilisation ratio of 0.97 in the undamaged state. The 15 % loss observed in the most adverse decay scenario therefore exceeds the available design margin by a factor of four. The standard wall-roof screwed connection per (NBN EN 1995, 2005) §8.7 would not maintain ULS compliance throughout the service life of the building under sustained brown-rot decay.

7.5 Conclusions from the OAT sensitivity analysis

Three operational conclusions follow.

1-Rot type and exposure duration jointly govern the design.

The two leading factors together explain the bulk of the observed variability. Together with the qualitative observation that they interact strongly this means that the design conversation should always be framed in terms of 'the brown-rot long-term scenario', never in terms of a single factor.

2-Number of layers has an influence based on duration

Based on the OAT sensitivity analysis it could be found that there is a important influence of the number of layers on the load-bearing capacity the influence decreases as a function of time.

3-Insulation type has no influence on the connection capacity.

$S_{Ins,wall} = 0.006$ and $S_{Ins,roof} = 0$ are within the resolution of the FEM-Design output. Designers may therefore select the insulation material for thermal, acoustic, fire-performance or environmental reasons without compromising the durability of the wall-roof connection. But PUR performs the worst in all case in terms of effect on the limit stresses, but this did not had important effect on the capacity calculations.

7.6 Answer to the research question

This dissertation set out to quantify the influence of fungal decay on the load-bearing capacity of CLT elements and connections in Belgium. This question is answered as follows:

Under the encapsulated building-moisture scenario representative of the Belgian climate with data from A. Blommaert and with the work of (Brischke & Rapp, 2008) extended with the strength-loss model of (Bollmus S. et al., 2020) :

-The Serviceability Limit State of CLT floors is significantly affected by decay; a moderate-decay reduction of approximately 10 mm of the outer lamella or a 36 % reduction of the modulus of elasticity, is sufficient to violate the L/300 deflection limit. The SLS is the limit state that should be monitored most closely by Belgian practitioners for moisture-exposed CLT and the cross-section-reduction modelling approach is required to capture this effect.

-The Ultimate Limit State of CLT wall panels is mildly affected by decay; the utilisation ratio increases by up to 0.06 (from 0.71 to 0.77) in the worst case (PUR insulation, brown rot, 5-layer panel), and the governing layer shifts from the outer (3-layer) to the central (5-layer) lamella owing to moisture trapping by the impermeable adhesive layers. ULS compliance is not threatened.

-The Ultimate Limit State of CLT roof panels is not measurably affected by decay; the utilisation ratio remains at 0.46 in all configurations, because the governing outer lamella is protected by the impermeable bitumen finishing.

- The Ultimate Limit State of the screwed wall–roof is significantly affected by decay; the design capacity is reduced by up to 15 % in the most adverse scenario (brown rot, long-term exposure), which exceeds the design margin of the original connection. A connection redesign is required in such cases.
- The dominant design parameters are, in order: rot type ($S_x = 0.0677$), exposure duration ($S_x = 0.066$), number of layers in the wall ($S_x = 0.0286$, but conditional). The insulation type of the wall and the roof is essentially irrelevant for the connection capacity ($S_x \approx 0$).
- The single most actionable engineering implication is that durability assessment of CLT structures in Belgium should focus on (i) the SLS of the floors and (ii) the ULS of the wall–roof connection. The wall and roof panel ULS, which receives most attention in current design practice, is not the governing concern.

7.7 Recommendations for design practice in Belgium

Based on the results of this research, certain design practices can be considered and/or used to safely design elements.

- Adopt the cross-section-reduction approach for the SLS check of decay-exposed CLT floors. Modelling decay only through a reduction of the modulus of elasticity is non-conservative for the SLS, because layer thickness enters the moment of inertia at the third power while E enters linearly.
- Treat the wall–roof screwed connection as the governing element for the ULS durability check. The panel field is geometrically self-protecting due to its cross-laminated redundancy). The connection has no such redundancy and should therefore receive the higher design margin.
- Apply a baseline reduction of approximately 15 % to the design shear capacity $F_{v,Rd}$ of CLT wall–roof screwed connections whenever the cumulative dose at the joint cannot be guaranteed to remain below the brown-rot threshold of 229 days (Brischke & Meyer-Veltrup, 2016) over the design service life. This value matches the most adverse scenario observed in the present work. This reduction can be incorporated through a dedicated decay-related modification factor $k_{dec} = 0.84$ applied to $F_{v,Rd}$, in line with the partial-factor logic of NBN EN 1995-1-1.
- It is important to prioritise joint detailing, such as vapour control at the wall–roof interface, drying paths, screw spacing, over the choice of insulation material when designing for durability. The OAT analysis demonstrates that the insulation type has no measurable effect on the connection capacity.
- Avoid five-layer CLT panels at joints subjected to short-term moisture peaks (p.e, construction-phase wetting in the absence of a finished waterproof envelope). The inner adhesive layers trap moisture in the second longitudinal lamella, which is the lamella the screw passes through and accelerate decay around the embedment zone in early life due to the elevated MC.
- Avoid fully vapour-tight insulation systems (PUR) on the outside of vertical CLT elements exposed to elevated moisture. MW and CEL allow outward drying and yield a lower peak moisture content in the outer lamellae. The penalty in panel utilisation is small (0.06) but is removed at no thermal cost when MW or CEL is chosen.
- Use $k_{mod} = 0.5$ (service class 3) for CLT connection design whenever decay risk is a credible service-life concern, in line with the recommendations of (Fröbel & Gustafsson, 2022) for above-ground moisture-exposed applications.
- Include a documented SLS check of the long-term deflection of CLT floors in the durability assessment, using a cumulative-dose calculation based on the building-specific MRY rather than on generic climate data. The framework presented in this dissertation provides a workflow for such a check.
- Based on the reference building and calculation note and as mentioned in §0, a platform framing preforms better since there the major load-bearing elements are the walls which are not that susceptible to decay as the connection in a balloon frame.
- It can also be found based on the formulas from (Isaksson, 2022), that the load-bearing capacity significantly increases when a steel-to-wood connection is used rather than a wood to wood connection. This means that is beneficial to work with a bracket connection rather than a screwed connection as explained in §0 since the influence of decay on the timber is not negligible.

7.8 Future research

As mentioned in §3.7 and §3.8 there were still a lot of assumptions and limitations in this thesis.

A first interesting research topic could be to find an expression to find the influence of decay on the SLS behaviour of a CLT panel.

The influence of decay was now expressed based on laboratory test on small scale timber elements. To model decay more realistic, large scale timber elements should be tested in a natural environment.

The influence of decay on the horizontal load-bearing capacity of timber elements and other methods of connecting should also be worth investigating.

Another interesting research option is to perform 2D HAM simulations for the connections to find the daily doses specifically located at the zones where the connection is made since in this research 1D simulations were used.

8 SOCIAL REFLECTION

The goal of my thesis was to address the influence of decay on the load-bearing capacity of CLT elements and connections.

I truly believe that this was a very relevant topic to investigate since it is crucial to make the construction industry more sustainable. To do so, new materials and methods should be considered but it should not put habitants at risk.

Timber and thus CLT is a natural material which makes it extra prone to natural influences and decay. To ensure a safe and responsible building environment, I believe that it was necessary to find out how this decay influenced the material and structural properties of CLT.

I hope this master dissertation will also work as a guideline for municipalities, contractors and engineers to considered possibilities to find a solution for a CLT building which was exposed for a period to natural influences, rather than to be demolished.

9 USE OF ARTIFICIAL INTELLIGENCE IN THIS RESEARCH

From the academic year 2024-2025 onwards the responsible use of generative AI-tools is permitted within a master thesis at Ghent University.

The "Note on the responsible usage of generative AI-tools for the master's thesis", as found on the webpage of the Faculty of Engineering and Architecture of Ghent University concerning the modalities of its master's theses, defines responsible usage as: "The responsible use of generative AI tools implies that students are aware of the limitations, risks, and pitfalls associated with their use, such as reliability and bias, copyright, data security, privacy, social inequality, as well as ethical and sustainability impacts. The master's thesis remains the student's own work, reflecting the student's general critical-reflective attitude and research-oriented mindset."

This same note also mentions the "obligation of documentation" for theses written at this faculty. As no specific demands regarding this matter were posed by the advisory committee the note prescribes the obligation of the student to clearly and qualitatively describe which aspects were aided by generative AI-tools and how these tools were used. Inspired on the non-exhaustive list provided by this note this description will be made hereunder.

The AI tools used in this research were:

Copilot, Gemini, DeepL, NotebooksLM, Connected Papers and Claude

These AI-agents were used for:

- To aid the search for relevant academic sources: providing sources as well as summarising options to facilitate their filtering (note: all sources included were done so manually, and only after their thorough manual consultation) (NotebookLM & Connected papers)
- To brainstorm about data visualisation (Gemini, Copilot)
- To debug, enhance calculation sheets Excel and Visual Code (Copilot, Gemini, Claude)
- To help understand certain software packages such as Fem-design, Delphin, Postproc, Excel (Claude, Gemini, Copilot)
- To aid the writing process: helping with translations, acting as a thesaurus, correcting spelling or grammar and helping to write more academically (DeepL, Claude, Gemini)
- To help analyse large sets of data and find trends and/or patterns (Claude, Gemini)

I would like to address the fact that everything that every source used in this thesis was verified and nothing was written by AI without controlling the background and sources of the information.

REFERENCES

- Bayat, M. (2023). *Types of Engineered Wood and Their Uses*. www.intechopen.com
- Blommaert, A., Steeman, M., & Van Den Bossche, N. (2025a). Modeling Moisture Accumulation and Decay Potential in Cross-Laminated Timber Wall Assemblies Exposed During the Construction Phase. *Buildings*, 15(7). <https://doi.org/10.3390/buildings15071075>
- Bollmus S., Bester van Niekerk P., & Brischke C. (2020). Impact of fungal decay on the bending properties of wood. *Proceedings IRG Annual Meeting 2020 The International Research Group on Wood Protection*.
- Brandner, R., Flatscher, G., Ringhofer, A., Schickhofer, G., & Thiel, A. (2016). Cross laminated timber (CLT): overview and development. *European Journal of Wood and Wood Products*, 74(3), 331–351. <https://doi.org/10.1007/s00107-015-0999-5>
- Brischke, C., & Meyer-Veltrup, L. (2016). Modelling timber decay caused by brown rot fungi. *Materials and Structures*, 49(8), 3281–3291. <https://doi.org/10.1617/s11527-015-0719-y>
- Brischke, C., & Rapp, A. O. (2008). Dose-response relationships between wood moisture content, wood temperature and fungal decay determined for 23 European field test sites. *Wood Science and Technology*, 42(6), 507–518. <https://doi.org/10.1007/s00226-008-0191-8>
- Brischke, C., & Rapp, A. O. (2010). *THE INTERNATIONAL RESEARCH GROUP ON WOOD PROTECTION Section 2 Test methodology and assessment Service life prediction of wooden components-Part 1: Determination of dose-response functions for above ground decay Service life prediction of wooden components-Part 1: Determination of dose-response functions for above ground decay*. www.irg-wp.com
- Brites, R. D., Neves, L. C., Saporiti Machado, J., Lourenço, P. B., & Sousa, H. S. (2013). Reliability analysis of a timber truss system subjected to decay. *Engineering Structures*, 46, 184–192. <https://doi.org/10.1016/j.engstruct.2012.07.022>
- Britton, T., Cole, G., Stewart, R., & Wiskar, D. (2008). *Remote diagnosis of leakage in residential households Author Journal Title Water Copyright Statement Link to published version*. <http://hdl.handle.net/10072/22554http://www.awa.asn.au/>
- CEN/EN 350. (2016). *Durability of wood and wood-based products - Testing and classification of the durability to biological agents of wood and wood-based materials*. *CLT by Stora Enso Technical brochure*. (n.d.).
- Cornick, S., Djebbar, R., & Alan Dalgliesh, W. (2003). Selecting moisture reference years using a Moisture Index approach. *Building and Environment*, 38(12), 1367–1379. [https://doi.org/10.1016/S0360-1323\(03\)00139-2](https://doi.org/10.1016/S0360-1323(03)00139-2)
- Curling, S., Clausen, C. A., Winandy, J. E., & Curling, S. F. (n.d.). *The effect of hemicellulose degradation on the mechanical properties of wood during brown rot decay IRG SECRETARIAT SE-100 44 Stockholm Sweden The effect of hemicellulose degradation on the mechanical properties of wood during brown rot decay*.
- Danielsson, H. (2025). *Design of Cross Laminated Timber*.
- De Smet, S. (n.d.). *Hygrothermische analyse van een waterlek in een CLT-buitenwand: evaluatie via HAM-simulaties*.
- De Smet, S. (2025). *Hygrothermische analyse van een waterlek in een CLT-buitenwand: evaluatie via HAM-simulaties*.
- EN 252. (2014). *Field test method for determining the relative protective effectiveness of a wood preservative in ground contact*.
- EN1995. (2005). *Eurocode 5 Design of timber structures Part 1-1: General-Common rules and rules for buildings For publication Contents Page*.
- European Comission JRC. (2021). *BR toolbox - December 2025*.
- Freimanis, R., Vanaga, R., Balodis, V., Zundans, Z., & Blumberga, A. (2023). Hygrothermal Assessment of Insulation Systems for Internal Insulation of Solid Masonry Walls under Various Conditions. *Buildings*, 13(10). <https://doi.org/10.3390/buildings13102511>
- Fröbel, & Gustafsson. (2022). *Guide för fuktsäkert KL-träbyggande 1 The CLT Handbook CLT structures-design and detailing Confederation of Timber Industries*. www.traguiden.se,
- Goodell, B., Qian, Y., & Jellison, J. (2008). *Fungal Decay of Wood: Soft Rot-Brown Rot-White Rot*.

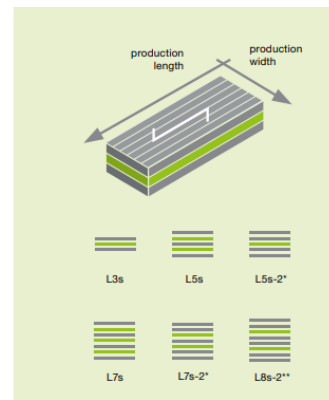
- Goodell, B., Winandy, J. E., & Morrell, J. J. (2020). Fungal degradation of wood: Emerging data, new insights and changing perceptions. In *Coatings* (Vol. 10, Number 12, pp. 1–19). MDPI AG. <https://doi.org/10.3390/coatings10121210>
- Gustafsson Anders, Borgstöm Eric, & Fröbel Johan. (2022). *The CLT Handbook CLT structures-facts and planning*. www.traguiden.se,
- Houtinfo Bois. (n.d.). *Enquete_NL_HIB_2011-2022_27-02-23-P03-BR-14_03_23*.
- Hradil, P., & Fortino, S. (2023). INTEGRATED APPROACH TO PREDICT DETERIORATION OF MECHANICAL PROPERTIES OF DECAYING WOOD. *13th World Conference on Timber Engineering, WCTE 2023*, 1, 536–541. <https://doi.org/10.52202/069179-0073>
- Huang, Z., Huang, D., Chui, Y. H., Shen, Y., Daneshvar, H., Sheng, B., & Chen, Z. (2022). Modeling of Cross-Laminated Timber (CLT) panels loaded with combined out-of-plane bending and compression. *Engineering Structures*, 250. <https://doi.org/10.1016/j.engstruct.2021.113335>
- Hyams, A., Watts, S., & Sweet, J. (n.d.). *Cost model: CLT frame buildings. Building*. <https://www.Building.Co.Uk/Cost-Model-CLT-Frame-Buildings/5107248.Article>.
- Isaksson, T. (2022). *Volume 2 Design of timber structures*. www.swedishwood.com.
- Isaksson, T., Brischke, C., & Thelandersson, S. (2013a). Development of decay performance models for outdoor timber structures. *Materials and Structures/Materiaux et Constructions*, 46(7), 1209–1225. <https://doi.org/10.1617/s11527-012-9965-4>
- Isaksson, T., & Thelandersson, S. (2013). Experimental investigation on the effect of detail design on wood moisture content in outdoor above ground applications. *Building and Environment*, 59, 239–249. <https://doi.org/10.1016/j.buildenv.2012.08.023>
- Käärik, A. (1974). *decomposition_of_wood*. <https://doi.org/10.1016/B978-0-12-215001-2.50011-8>
- Karacabeyli, E., & Douglas, B. (2019). *CLT Handbook: Cross-Laminated Timber*.
- Khartode, B., Sulaiman, S., Shewale, M., & Bhirud, Y. L. (2024). Need and Awareness of Leakages and waterproofing in High rise Building. *E3S Web of Conferences*, 559. <https://doi.org/10.1051/e3sconf/202455904016>
- Krah, F. S., Bässler, C., Heibl, C., Soghigian, J., Schaefer, H., & Hibbett, D. S. (2018). Evolutionary dynamics of host specialization in wood-decay fungi. *BMC Evolutionary Biology*, 18(1). <https://doi.org/10.1186/s12862-018-1229-7>
- Langmans, J., Desta, T. Z., Alderweireldt, L., & Roels, S. (2015). Experimental analysis of cavity ventilation behind residential rainscreen cladding systems. *Energy Procedia*, 78, 1750–1755. <https://doi.org/10.1016/j.egypro.2015.11.290>
- Mankowski, M., & Morrell, J. (2000). *PATTERNS OF FUNGAL ATTACK IN WOOD-PLASTIC COMPOSITES FOLLOWING EXPOSURE IN A SOIL BLOCK TEST*.
- Marais, B. N., van Niekerk, P. B., & Brischke, C. (2021). Studies into fungal decay of wood in ground contact—part 2: Development of a dose–response model to predict decay rate. *Forests*, 12(6). <https://doi.org/10.3390/f12060698>
- Meyer-Veltrup, L., Brischke, C., Alfredsen, G., Humar, M., Flæte, P. O., Isaksson, T., Brelid, P. L., Westin, M., & Jermer, J. (2017). The combined effect of wetting ability and durability on outdoor performance of wood: development and verification of a new prediction approach. *Wood Science and Technology*, 51(3), 615–637. <https://doi.org/10.1007/s00226-017-0893-x>
- NBN EN 1995. (2005). NBN EN 1995. *NBN EN 1995*.
- NBN EN16351. (2021). Timber structures - Cross laminated timber - Requirements. *NBN EN16351:2021*
- Riley, R., Salamov, A. A., Brown, D. W., Nagy, L. G., Floudas, D., Held, B. W., Levasseur, A., Lombard, V., Morin, E., Otiilar, R., Lindquist, E. A., Sun, H., LaButti, K. M., Schmutz, J., Jabbour, D., Luo, H., Baker, S. E., Pisabarro, A. G., Walton, J. D., ... Grigoriev, I. V. (2014). Extensive sampling of basidiomycete genomes demonstrates inadequacy of the white-rot/brown-rot paradigm for wood decay fungi. *Proceedings of the National Academy of Sciences*, 111(27), 9923–9928. <https://doi.org/10.1073/pnas.1400592111>
- Saltelli, A., Annoni, P., & D'Hombres, B. (2010). How to avoid a perfunctory sensitivity analysis. *Procedia - Social and Behavioral Sciences*, 2(6), 7592–7594. <https://doi.org/10.1016/j.sbspro.2010.05.133>
- Saltelli A, Ratto M, Andres T, Campolongo F, Cariboni J, Gatelli D, Saisana M, & Tarantola S. (2008). *Global Sensitivity Analysis. The Primer*.

- Schmidt Olaf. (2006). *Wood and Tree Fungi Biology, Damage, Protection, and Use*.
- SimpsonStrongTie. (n.d.). *Connectors and Fasteners for Cross-Laminated Timber Structures*.
- Srivaro, S., Lim, H., Li, M., & Pasztory, Z. (n.d.). *Properties of Mixed Species/Densities Cross Laminated Timber made of Rubberwood and Coconut Wood*.
- Thelandersson, S., Isaksson, T., ; Frühwald, E., & Suttie, E. (2011). *Service life of wood in outdoor above ground applications Engineering design guideline*.
- Thelandersson S, Isaksson T, Suttie E, Frühwald E, Toratti T, & Grüll G. (2011). *Service life of wood in outdoor above ground applications*.
- Van Linden, S., & Van Den Bossche, N. (n.d.). *Review of rainwater infiltration rates in wall assemblies*.
- Vandemeulebroucke, I., Caluwaerts, S., & Van Den Bossche, N. (2022). Decision framework to select moisture reference years for hygrothermal simulations. *Building and Environment*, 218. <https://doi.org/10.1016/j.buildenv.2022.109080>
- Vandemeulebroucke, I., Caluwaerts, S., Van, N., & Bossche, D. (n.d.). *Freeze-thaw risk in solid masonry: are moisture reference years able to represent real climate conditions?* <https://doi.org/10.1051/mateconf/201928>
- Vanderschelden, B., Be, B. V., Janssens, K., & Van Den Bossche, N. (2024). *SAMIRA: A decision framework for hygrothermal modelling implementation in HAMalysr*.
- Vanderschelden, B., Lacasse, M. A., Moore, T., Van, N., & Bossche, D. (2022). *Methodological framework for HAM-simulations: the litigation case of a CLT-balcony subjected to rain loads during construction*.
- Viitanen, H., Toratti, T., Makkonen, L., Peuhkuri, R., Ojanen, T., Ruokolainen, L., & Räisänen, J. (2010a). Towards modelling of decay risk of wooden materials. *European Journal of Wood and Wood Products*, 68(3), 303–313. <https://doi.org/10.1007/s00107-010-0450-x>
- Wang, J. Y., Stirling, R., Morris, P. I., Taylor, A., Lloyd, J., Kirker, G., Lebow, S., Mankowski, M. E., Barnes, H. M., & Morrell, J. (2018a). Durability of mass timber structures: A review of the biological risks. *Wood and Fiber Science*, 50, 110–127. <https://doi.org/10.22382/wfs-2018-045>
- Wang, J. Y., Stirling, R., Morris, P. I., Taylor, A., Lloyd, J., Kirker, G., Lebow, S., Mankowski, M. E., Barnes, H. M., & Morrell, J. (2018b). Durability of mass timber structures: A review of the biological risks. *Wood and Fiber Science*, 50, 110–127. <https://doi.org/10.22382/wfs-2018-045>
- Willox Wayne. (1977). *REVIEW OF LITERATURE ON THE EFFECTS OF EARLY STAGES OF DECAY ON WOOD STRENGTH*.
- Zabel, R., & Morrell, J. (2012). *Wood Microbiology: Decay and Its Prevention*.
- Zese, R., Bellodi, E., Luciani, C., & Alvisi, S. (2021). Neural Network Techniques for Detecting Intra-Domestic Water Leaks of Different Magnitude. *IEEE Access*, 9, 126135–126147. <https://doi.org/10.1109/ACCESS.2021.3111113>
- Zhou, X., Derome, D., & Carmeliet, J. (2016). Robust moisture reference year methodology for hygrothermal simulations. *Building and Environment*, 110, 23–35. <https://doi.org/10.1016/j.buildenv.2016.09.021>
- Zoltán I. Bocskai. (2019). *FEM-Design Theory of Laminated Composite Shells Cross Laminated Timber Application*. www.strusoft.com

ATTACHMENTS

1. Stora enso CLT catalogue

L panels									
The grain direction of the cover layers is always at right angles to the production widths.									
Thickness [mm]	Panel type [–]	Layers [–]	Panel design [mm]						
			L	C	L	C	L	C	L
60	L3s	3	20	20	20				
80	L3s	3	20	40	20				
90	L3s	3	30	30	30				
100	L3s	3	30	40	30				
120	L3s	3	40	40	40				
100	L5s	5	20	20	20	20	20		
120	L5s	5	30	20	20	20	30		
140	L5s	5	40	20	20	20	40		
160	L5s	5	40	20	40	20	40		
180	L5s	5	40	30	40	30	40		
200	L5s	5	40	40	40	40	40		
160	L5s-2*	5	60	40	60				
180	L7s	7	30	20	30	20	30	20	30
200	L7s	7	20	40	20	40	20	40	20
240	L7s	7	30	40	30	40	30	40	30
220	L7s-2*	7	60	30	40	30	60		
240	L7s-2*	7	80	20	40	20	80		
260	L7s-2*	7	80	30	40	30	80		
280	L7s-2*	7	80	40	40	40	80		
300	L8s-2**	8	80	30	80	30	80		
320	L8s-2**	8	80	40	80	40	80		



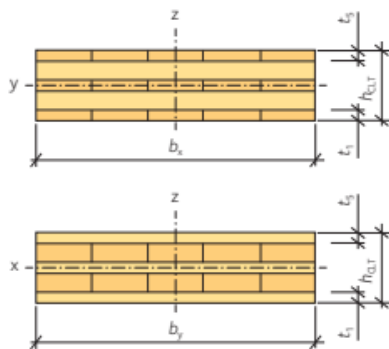
CLT by Stora Enso

2. Shear correction factor κ (Gustafsson et al, 2022)

Dimension h_{tot} (mm)	Thickness per layer					Strength class per layer					Shear correction factor	
	t_1 (mm)	t_2 (mm)	t_3 (mm)	t_4 (mm)	t_5 (mm)	s_1	s_2	s_3	s_4	s_5	κ_x	κ_y
(SS-EN 338)												
60	20	20	20			C24	C24	C24			0.163	0.722
70	20	30	20			C24	C24	C24			0.161	0.756
80	20	40	20			C24	C24	C24			0.168	0.774
80	30	20	30			C24	C24	C24			0.178	0.677
90	30	30	30			C24	C24	C24			0.163	0.722
100	30	40	30			C24	C24	C24			0.161	0.747
100	40	20	40			C24	C24	C24			0.196	0.637
110	40	30	40			C24	C24	C24			0.172	0.691
120	40	40	40			C24	C24	C24			0.163	0.722
100	20	20	20	20	20	C24	C24	C24	C24	C24	0.194	0.152
120	20	30	20	30	20	C24	C24	C24	C24	C24	0.197	0.169
140	20	40	20	40	20	C24	C24	C24	C24	C24	0.208	0.189
110	20	20	30	20	20	C24	C24	C24	C24	C24	0.212	0.150
130	20	30	30	30	20	C24	C24	C24	C24	C24	0.207	0.156
150	20	40	30	40	20	C24	C24	C24	C24	C24	0.213	0.166
120	20	20	40	20	20	C24	C24	C24	C24	C24	0.234	0.157
140	20	30	40	30	20	C24	C24	C24	C24	C24	0.221	0.153
160	20	40	40	40	20	C24	C24	C24	C24	C24	0.221	0.157
120	30	20	20	20	30	C24	C24	C24	C24	C24	0.188	0.147
140	30	30	20	30	30	C24	C24	C24	C24	C24	0.184	0.165
160	30	40	20	40	30	C24	C24	C24	C24	C24	0.189	0.186
130	30	20	30	20	30	C24	C24	C24	C24	C24	0.204	0.146
150	30	30	30	30	30	C24	C24	C24	C24	C24	0.194	0.152
170	30	40	30	40	30	C24	C24	C24	C24	C24	0.195	0.163
140	30	20	40	20	30	C24	C24	C24	C24	C24	0.221	0.152
160	30	30	40	30	30	C24	C24	C24	C24	C24	0.206	0.150
180	30	40	40	40	30	C24	C24	C24	C24	C24	0.203	0.155
140	40	20	20	20	40	C24	C24	C24	C24	C24	0.189	0.142
160	40	30	20	30	40	C24	C24	C24	C24	C24	0.179	0.162
180	40	40	20	40	40	C24	C24	C24	C24	C24	0.179	0.182
150	40	20	30	20	40	C24	C24	C24	C24	C24	0.203	0.141
170	40	30	30	30	40	C24	C24	C24	C24	C24	0.189	0.149
190	40	40	30	40	40	C24	C24	C24	C24	C24	0.186	0.160
160	40	20	40	20	40	C24	C24	C24	C24	C24	0.219	0.147
180	40	30	40	30	40	C24	C24	C24	C24	C24	0.199	0.146
200	40	40	40	40	40	C24	C24	C24	C24	C24	0.194	0.152

3. (Fröbel & Gustafsson, 2022)r CLT (Fröbel & Gustafsson, 2022)

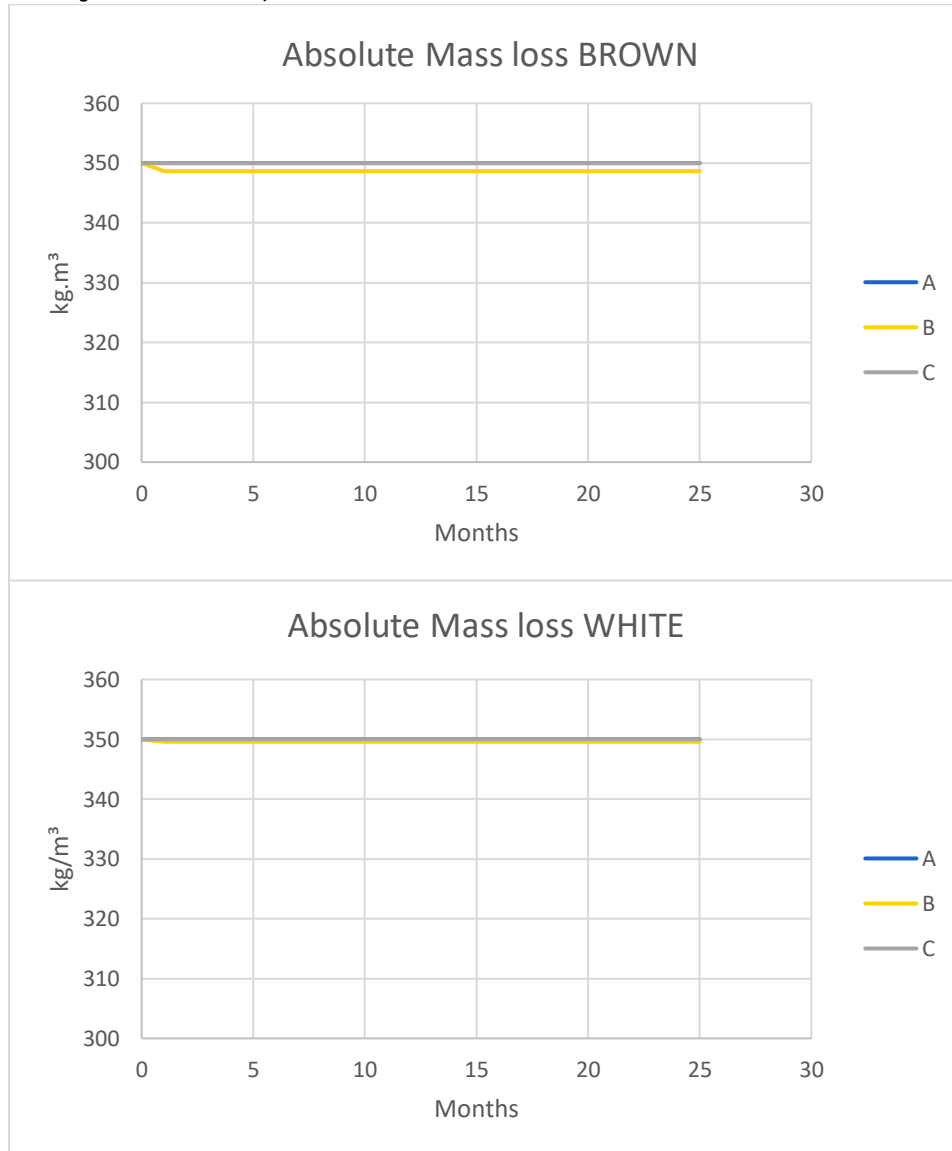
No.	Dimension (mm)	Thickness per layer (mm)					Cross-section (mm)			Weight and area (kg/m ² , cm ²)				
	h_{CLT}	t_1	t_2	t_3	t_4	t_5	h_x	h_y	z_s	g_{mean}	g_k	$A_{x,net}$	$A_{y,net}$	A_{CLT}
1	100	20	20	20	20	20	60	40	50	42	39	600	400	1,000
2	120	20	30	20	30	20	60	60	60	50	46	600	600	1,200
3	140	20	40	20	40	20	60	80	70	59	54	600	800	1,400
4	110	20	20	30	20	20	70	40	55	46	42	700	400	1,100
5	130	20	30	30	30	20	70	60	65	55	50	700	600	1,300
6	150	20	40	30	40	20	70	80	75	63	58	700	800	1,500
7	120	20	20	40	20	20	80	40	60	50	46	800	400	1,200
8	140	20	30	40	30	20	80	60	70	59	54	800	600	1,400
9	160	20	40	40	40	20	80	80	80	67	62	800	800	1,600
10	120	30	20	20	20	30	80	40	60	50	46	800	400	1,200
11	140	30	30	20	30	30	80	60	70	59	54	800	600	1,400
12	160	30	40	20	40	30	80	80	80	67	62	800	800	1,600
13	130	30	20	30	20	30	90	40	65	55	50	900	400	1,300
14	150	30	30	30	30	30	90	60	75	63	58	900	600	1,500
15	170	30	40	30	40	30	90	80	85	71	66	900	800	1,700
16	140	30	20	40	20	30	100	40	70	59	54	1,000	400	1,400
17	160	30	30	40	30	30	100	60	80	67	62	1,000	600	1,600
18	180	30	40	40	40	30	100	80	90	76	70	1,000	800	1,800
19	140	40	20	20	20	40	100	40	70	59	54	1,000	400	1,400
20	160	40	30	20	30	40	100	60	80	67	62	1,000	600	1,600
21	180	40	40	20	40	40	100	80	90	76	70	1,000	800	1,800
22	150	40	20	30	20	40	110	40	75	63	58	1,100	400	1,500
23	170	40	30	30	30	40	110	60	85	71	66	1,100	600	1,700
24	190	40	40	30	40	40	110	80	95	80	73	1,100	800	1,900
25	160	40	20	40	20	40	120	40	80	67	62	1,200	400	1,600
26	180	40	30	40	30	40	120	60	90	76	70	1,200	600	1,800
27	200	40	40	40	40	40	120	80	100	84	77	1,200	800	2,000

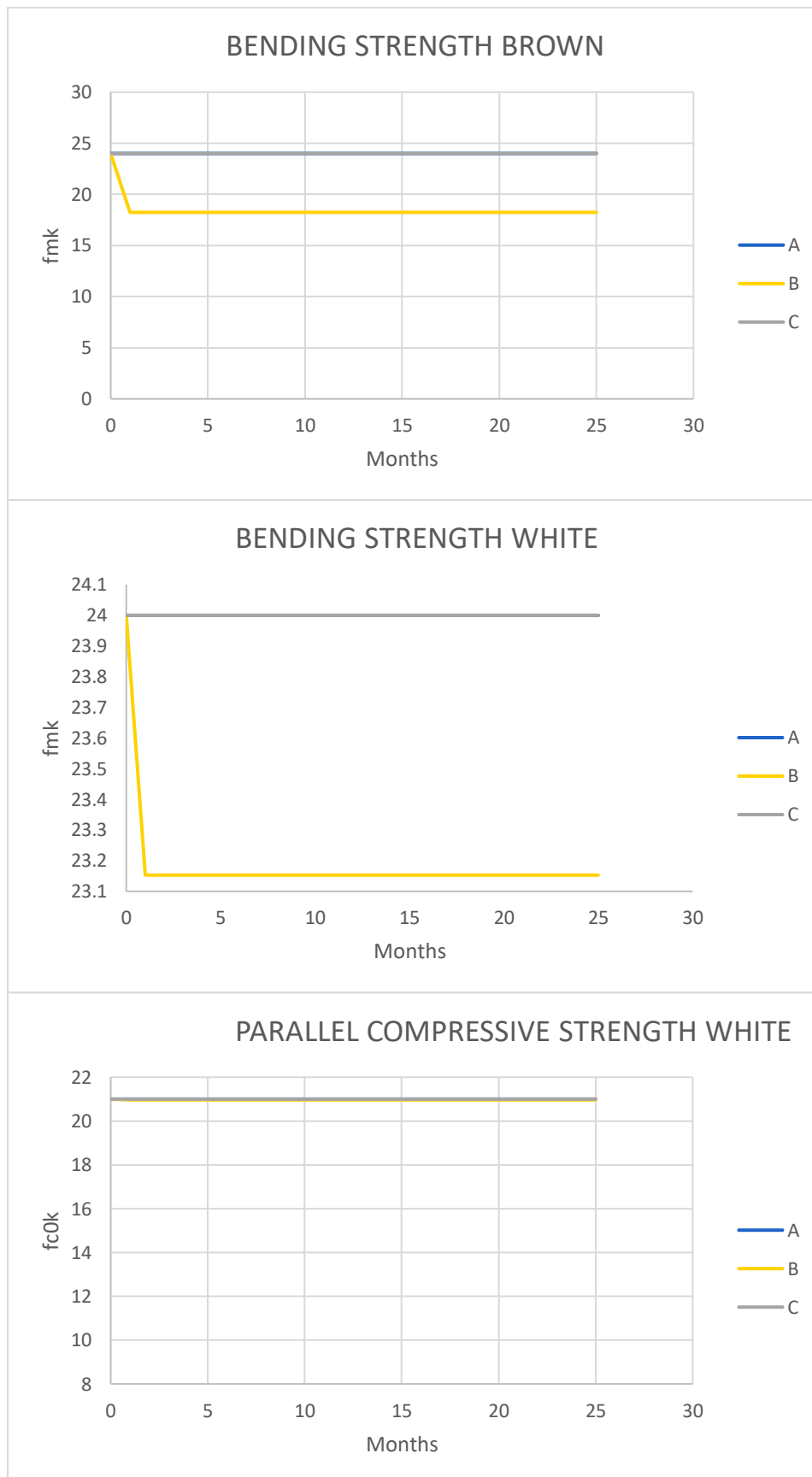


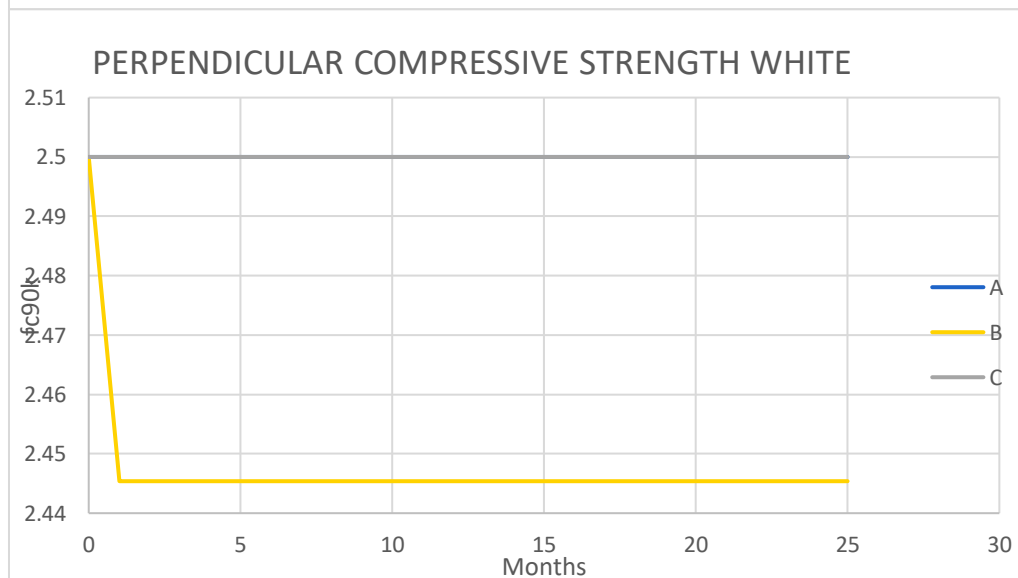
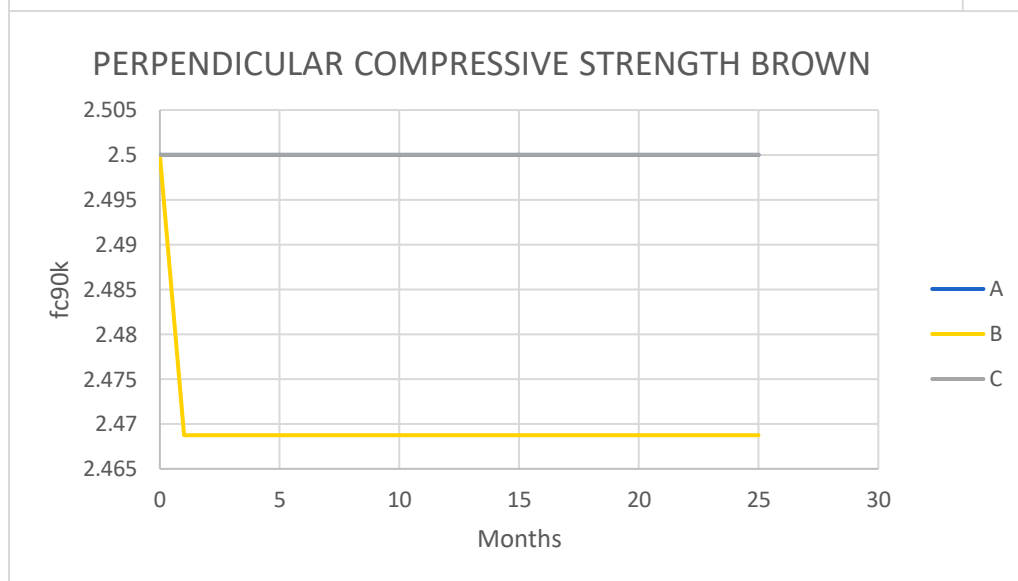
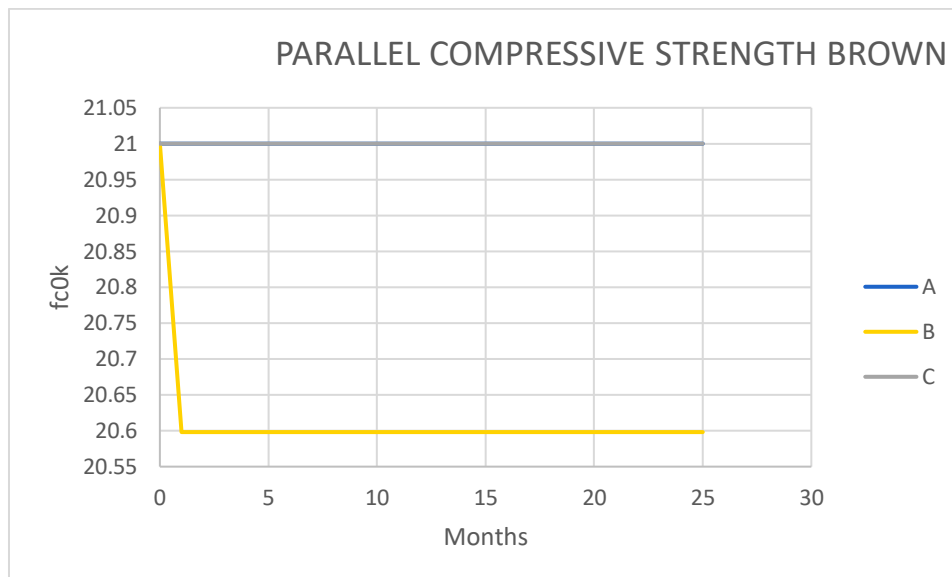
4. Properties 5-layer CLT (Fröbel & Gustafsson, 2022)

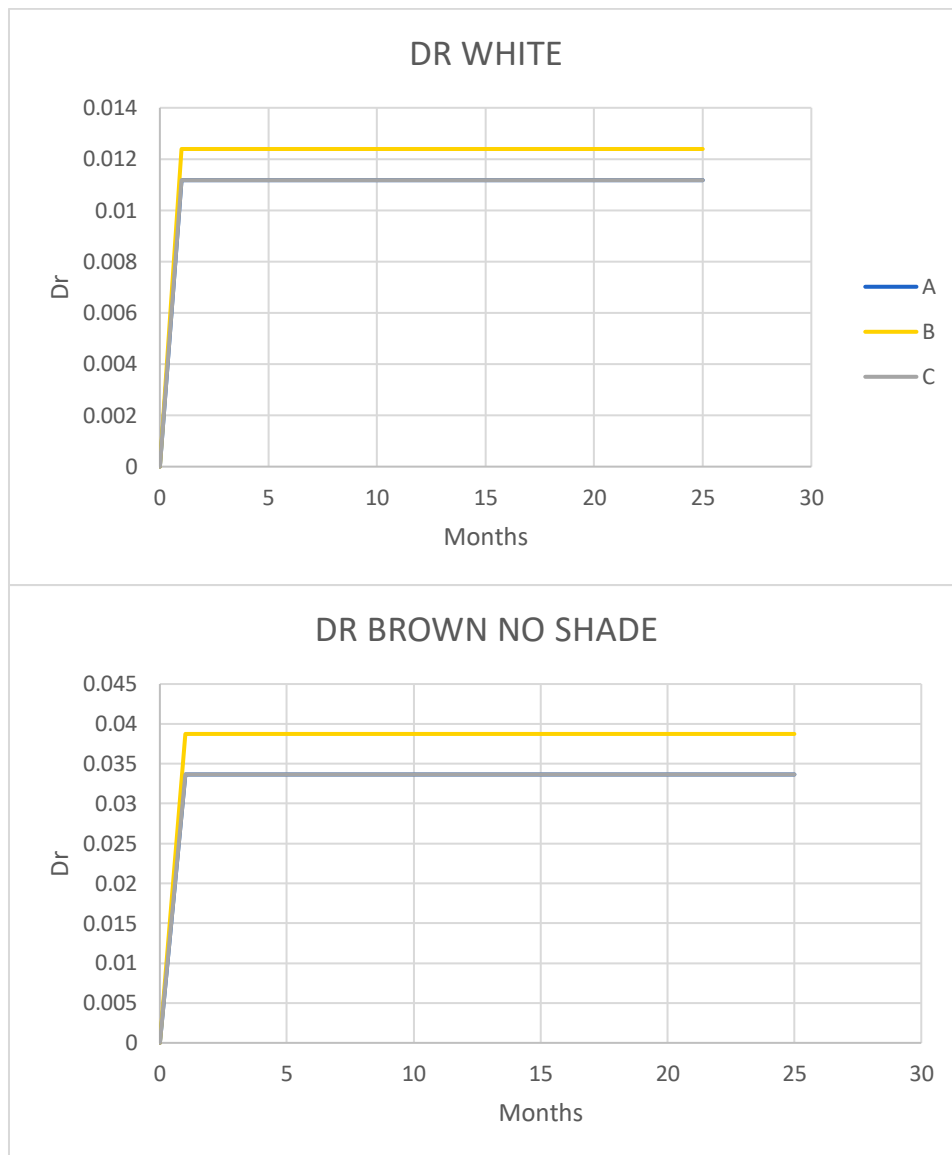
Dimension (mm)	Thickness per layer (mm)			Cross-section (mm)			Surfaces (cm ²)			Bending along y-axis (cm ⁴ , cm ³)			Bending along x-axis (cm ⁴ , cm ³)		
h_{CLT}	t_1	t_2	t_3	h_x	h_y	z_s	$A_{x,net}$	$A_{y,net}$	A_{CLT}	$I_{x,net}$	$W_{x,net}$	$S_{x,x,net}$	$I_{y,net}$	$W_{y,net}$	$S_{y,y,net}$
60	20	20	20	40	20	30	400	200	600	1,733	578	400	67	22	0
70	20	30	20	40	30	35	400	300	700	2,633	752	500	225	64	0
80	20	40	20	40	40	40	400	400	800	3,733	933	600	533	133	0
80	30	20	30	60	20	40	600	200	800	4,200	1,050	750	67	17	0
90	30	30	30	60	30	45	600	300	900	5,850	1,300	900	225	50	0
100	30	40	30	60	40	50	600	400	1,000	7,800	1,560	1,050	533	107	0
100	40	20	40	80	20	50	800	200	1,000	8,267	1,653	1,200	67	13	0
110	40	30	40	80	30	55	800	300	1,100	10,867	1,976	1,400	225	41	0
120	40	40	40	80	40	60	800	400	1,200	13,867	2,311	1,600	533	89	0

5. Working out of a three-layered wall element with PUR insulation









MAXIMUM OF LOAD COMBINATIONS

Panel properties (C2_PUR_B)

Service class: 1, $\gamma_{M,ult.} = 1.25$, $\gamma_{M,acc./seis.} = 1.00$, $k_{sys} = 1.00$

No	Material	Thickness [mm]	Θ [°]	ρ [kg/m ³]
1	C24	30	0	420
2	C24	40	90	418
3	C24	30	0	420

Mechanical properties

No	$E_{0,mean}$ [N/mm ²]	$E_{90,mean}$ [N/mm ²]	ν_{xy} [-]	$G_{xy,mean}$ [N/mm ²]	$G_{xz,mean}$ [N/mm ²]
1	12500	0	0.00	690	690
2	12500	0	0.00	690	690
3	12500	0	0.00	690	690

No	$G_{yz,mean}$ [N/mm ²]
1	50
2	50
3	50

Mechanical properties - 5% quantile values

No	$E_{0,05}$ [N/mm ²]	$E_{90,05}$ [N/mm ²]	$G_{xy,05}$ [N/mm ²]	$G_{xz,05}$ [N/mm ²]	$G_{yz,05}$ [N/mm ²]
1	10500	0	580	580	42
2	10500	0	580	580	42
3	10500	0	580	580	42

Limit stresses

No	$f_{m,0,k}$ [N/mm ²]	$f_{m,90,k}$ [N/mm ²]	$f_{t,0,k}$ [N/mm ²]	$f_{t,90,k}$ [N/mm ²]	$f_{c,0,k}$ [N/mm ²]	$f_{c,90,k}$ [N/mm ²]
1	24.0	24.0	14.5	0.400	21.0	2.50
2	18.2	24.0	14.5	0.400	20.6	2.47
3	24.0	24.0	14.5	0.400	21.0	2.50

No	$f_{xy,k}$ [N/mm ²]	$f_{v,k}$ [N/mm ²]	$f_{vR,k}$ [N/mm ²]	$f_{tor,k}$ [N/mm ²]
1	4.00	4.00	1.30	2.50
2	4.00	4.00	1.30	2.50
3	4.00	4.00	1.30	2.50

Tension and bending, x - 6.2.3

Panel: 'TP.1.1', Layer: '2', LC: 'LC1ULS', $k_{mod} = 0.60$, Coordinates [m]:{ 3.84; 0.00; 0.00}

$$\frac{\sigma_{t,0,d}}{f_{t,0,d}} + \frac{|\sigma_{m,0,d}|}{f_{m,0,d}} = \frac{1.89}{6.96} + \frac{|0.00|}{8.76} = 0.27 \leq 1.00 \quad (6.17) - \text{OK}$$

Tension and bending, y - 6.2.3

Not relevant

Compression and bending, x - 6.1.4, 6.2.4

Panel: 'TP.1.1', Layer: '1', LC: 'LC1ULS', $k_{mod} = 0.60$, Coordinates [m]:{ 4.80; 0.00; 0.00}

$$\frac{|\sigma_{c,0,d}|}{f_{c,0,d}} = \frac{|-7.14|}{10.08} = 0.71 \leq 1.00 \quad (6.2) - \text{OK}$$

$$\left(\frac{\sigma_{c,0,d}}{f_{c,0,d}}\right)^2 + \frac{|\sigma_{m,0,d}|}{f_{m,0,d}} = \left(\frac{-7.14}{10.08}\right)^2 + \frac{|0.00|}{11.52} = 0.50 \leq 1.00 \quad (6.19) - \text{OK}$$

Compression and bending, y - 6.1.4, 6.2.4

Not relevant

Shear, xy - 6.1.7

Panel: 'TP.1.1', Layer: '1', LC: 'LC1ULS', $k_{mod} = 0.60$, Coordinates [m]:{ 4.80; 0.00; 0.00}

$$\frac{|T_{xy,d}|}{f_{xy,d}} = \frac{|-0.71|}{1.92} = 0.37 \leq 1.00 \quad (6.13) - \text{OK}$$

Shear, xz - 6.1.7

Panel: 'TP.1.1', Layer: '1', LC: 'LC1ULS', $k_{mod} = 0.60$, Coordinates [m]: { 3.84; 0.00; 1.20}

$$\frac{|T_{xz,d}|}{f_{v,d}} = \frac{|0.00|}{1.92} = 0.00 \leq 1.00 \quad (6.13) - \text{OK}$$

Shear, yz - 6.1.7

Panel: 'TP.1.1', Layer: '1', LC: 'LC1ULS', $k_{mod} = 0.60$, Coordinates [m]: { 3.84; 0.00; 1.20}

$$\frac{|T_{yz,d}|}{f_{R,d}} = \frac{|0.00|}{0.62} = 0.00 \leq 1.00 \quad (6.13) - \text{OK}$$

Shear interaction

Panel: 'TP.1.1', Layer: '1', LC: 'LC1ULS', $k_{mod} = 0.60$, Coordinates [m]: { 4.80; 0.00; 0.00}

$$\left(\frac{T_{xy,d}}{f_{xy,d}}\right)^2 + \left(\frac{T_{xz,d}}{f_{v,d}}\right)^2 = \left(\frac{-0.71}{1.92}\right)^2 + \left(\frac{0.00}{1.92}\right)^2 = 0.14 \leq 1.00 - \text{OK}$$

Tension and shear

Panel: 'TP.1.1', Layer: '2', LC: 'LC1ULS', $k_{mod} = 0.60$, Coordinates [m]: { 4.80; 0.00; 0.00}

$$\frac{\sigma_{t,90,d}}{f_{t,90,d}} + \frac{|T_{yz,d}|}{f_{R,d}} = \frac{0.00}{0.19} + \frac{|0.00|}{0.62} = 0.00 \leq 1.00 - \text{OK}$$

Compression and shear

Panel: 'TP.1.1', Layer: '2', LC: 'LC1ULS', $k_{mod} = 0.60$, Coordinates [m]: { 4.80; 0.00; 0.00}

$$\frac{|\sigma_{c,90,d}|}{f_{c,90,d}} + \frac{|T_{yz,d}|}{f_{R,d}} = \frac{|0.00|}{1.19} + \frac{|0.00|}{0.62} = 0.00 \leq 1.00 - \text{OK}$$

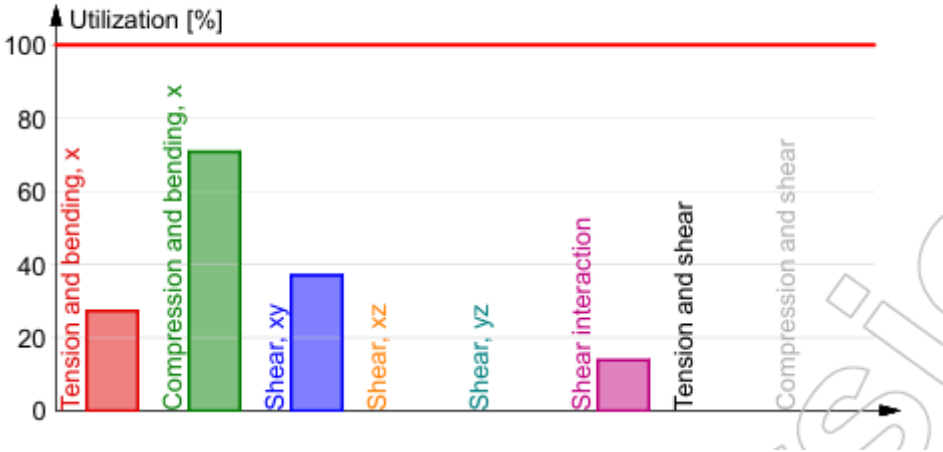
Buckling

Not relevant

Torsion

Not relevant

Summary



Panel properties (C2_PUR_W)

Service class: 1, $\gamma_{M,ult.} = 1.25$, $\gamma_{M,acc./seis.} = 1.00$, $k_{sys} = 1.00$

No	Material	Thickness [mm]	Θ [°]	ρ [kg/m ³]
1	C24	30	0	420
2	C24	40	90	420
3	C24	30	0	420

Mechanical properties

No	$E_{0,mean}$ [N/mm ²]	$E_{90,mean}$ [N/mm ²]	ν_{xy} [-]	$G_{xy,mean}$ [N/mm ²]	$G_{xz,mean}$ [N/mm ²]
1	12500	0	0.00	690	690
2	12500	0	0.00	690	690
3	12500	0	0.00	690	690

No	$G_{yz,mean}$ [N/mm ²]
1	50
2	50
3	50

Mechanical properties - 5% quantile values

No	$E_{0,05}$ [N/mm ²]	$E_{90,05}$ [N/mm ²]	$G_{xy,05}$ [N/mm ²]	$G_{xz,05}$ [N/mm ²]	$G_{yz,05}$ [N/mm ²]
1	10500	0	580	580	42
2	10500	0	580	580	42
3	10500	0	580	580	42

No	$f_{m,0,k}$ [N/mm ²]	$f_{m,90,k}$ [N/mm ²]	$f_{t,0,k}$ [N/mm ²]	$f_{t,90,k}$ [N/mm ²]	$f_{c,0,k}$ [N/mm ²]	$f_{c,90,k}$ [N/mm ²]
1	24.0	24.0	14.5	0.400	21.0	2.50
2	23.1	24.0	14.5	0.400	21.0	2.45
3	24.0	24.0	14.5	0.400	21.0	2.50

No	$f_{xy,k}$ [N/mm ²]	$f_{v,k}$ [N/mm ²]	$f_{vR,k}$ [N/mm ²]	$f_{tor,k}$ [N/mm ²]
1	4.00	4.00	1.30	2.50
2	4.00	4.00	1.30	2.50
3	4.00	4.00	1.30	2.50

Tension and bending, x - 6.2.3

Panel: 'TP.1.1', Layer: '2', LC: 'LC1ULS', $k_{mod} = 0.60$, Coordinates [m]: { 3.84; 0.00; 0.00}

$$\frac{\sigma_{t,0,d}}{f_{t,0,d}} + \frac{|\sigma_{m,0,d}|}{f_{m,0,d}} = \frac{1.89}{6.96} + \frac{|0.00|}{11.11} = 0.27 \leq 1.00 \quad (6.17) - \text{OK}$$

Tension and bending, y - 6.2.3

Not relevant

Compression and bending, x - 6.1.4, 6.2.4

Panel: 'TP.1.1', Layer: '1', LC: 'LC1ULS', $k_{mod} = 0.60$, Coordinates [m]: { 4.80; 0.00; 0.00}

$$\frac{|\sigma_{c,0,d}|}{f_{c,0,d}} = \frac{|-7.14|}{10.08} = 0.71 \leq 1.00 \quad (6.2) - \text{OK}$$

$$\left(\frac{\sigma_{c,0,d}}{f_{c,0,d}} \right)^2 + \frac{|\sigma_{m,0,d}|}{f_{m,0,d}} = \left(\frac{-7.14}{10.08} \right)^2 + \frac{|0.00|}{11.52} = 0.50 \leq 1.00 \quad (6.19) - \text{OK}$$

Compression and bending, y - 6.1.4, 6.2.4

Not relevant

Shear, xy - 6.1.7

Panel: 'TP.1.1', Layer: '1', LC: 'LC1ULS', $k_{mod} = 0.60$, Coordinates [m]: { 4.80; 0.00; 0.00}

$$\frac{|T_{xy,d}|}{f_{xy,d}} = \frac{|-0.71|}{1.92} = 0.37 \leq 1.00 \quad (6.13) - \text{OK}$$

Shear, xz - 6.1.7

Panel: 'TP.1.1', Layer: '1', LC: 'LC1ULS', $k_{mod} = 0.60$, Coordinates [m]:{ 3.84; 0.00; 1.20}

$$\frac{|T_{xz,d}|}{f_{v,d}} = \frac{|0.00|}{1.92} = 0.00 \leq 1.00 \quad (6.13) - \text{OK}$$

Shear, yz - 6.1.7

Panel: 'TP.1.1', Layer: '1', LC: 'LC1ULS', $k_{mod} = 0.60$, Coordinates [m]:{ 3.84; 0.00; 1.20}

$$\frac{|T_{yz,d}|}{f_{R,d}} = \frac{|0.00|}{0.62} = 0.00 \leq 1.00 \quad (6.13) - \text{OK}$$

Shear interaction

Panel: 'TP.1.1', Layer: '1', LC: 'LC1ULS', $k_{mod} = 0.60$, Coordinates [m]:{ 4.80; 0.00; 0.00}

$$\left(\frac{T_{xy,d}}{f_{xy,d}}\right)^2 + \left(\frac{T_{xz,d}}{f_{v,d}}\right)^2 = \left(\frac{-0.71}{1.92}\right)^2 + \left(\frac{0.00}{1.92}\right)^2 = 0.14 \leq 1.00 - \text{OK}$$

Tension and shear

Panel: 'TP.1.1', Layer: '2', LC: 'LC1ULS', $k_{mod} = 0.60$, Coordinates [m]:{ 4.80; 0.00; 0.00}

$$\frac{\sigma_{t,90,d}}{f_{t,90,d}} + \frac{|T_{yz,d}|}{f_{R,d}} = \frac{0.00}{0.19} + \frac{|0.00|}{0.62} = 0.00 \leq 1.00 - \text{OK}$$

Compression and shear

Panel: 'TP.1.1', Layer: '2', LC: 'LC1ULS', $k_{mod} = 0.60$, Coordinates [m]:{ 4.80; 0.00; 0.00}

$$\frac{|\sigma_{c,90,d}|}{f_{c,90,d}} + \frac{|T_{yz,d}|}{f_{R,d}} = \frac{|0.00|}{1.18} + \frac{|0.00|}{0.62} = 0.00 \leq 1.00 - \text{OK}$$

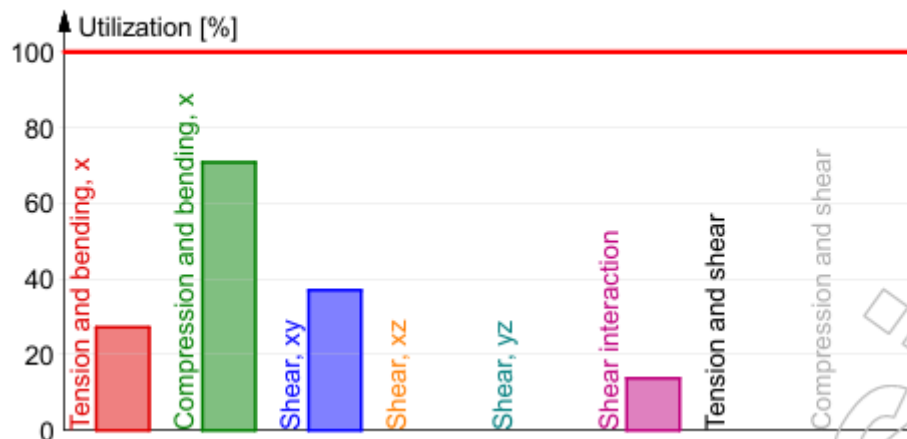
Buckling

Not relevant

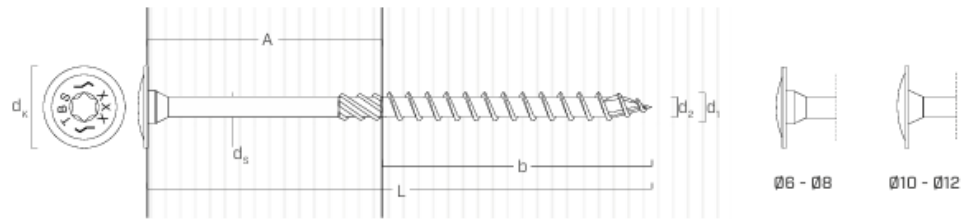
Torsion

Not relevant

Summary



■ GEOMETRIE EN MECHANISCHE EIGENSCHAPPEN



GEOMETRIE						
Nominale diameter	d_1	[mm]	6	8	10	12
Diameter kop	d_k	[mm]	15,50	19,00	25,00	29,00
Diameter schroefkern	d_2	[mm]	3,95	5,40	6,40	6,80
Diameter schacht	d_s	[mm]	4,30	5,80	7,00	8,00
Diameter voorboring ⁽¹⁾	$d_{v,s}$	[mm]	4,0	5,0	6,0	7,0
Diameter voorboring ⁽²⁾	$d_{v,h}$	[mm]	4,0	6,0	7,0	8,0

⁽¹⁾ Voorgeboord gat voor naaldhout (softwood).
⁽²⁾ Geschikt voor hardhout (hardwood) en beuken LVL.

KENMERKENDE MECHANISCHE PARAMETERS						
Nominale diameter	d_1	[mm]	6	8	10	12
Treksterkte	$f_{tens,k}$	[kN]	11,3	20,1	31,4	33,9
Vloeimoment	$M_{y,k}$	[Nm]	9,5	20,1	35,8	48,0

			naaldhout (softwood)	naaldhout-LVL (LVL softwood)	voorgeboord beuken-LVL (Beech LVL predrilled)
Karakteristieke parameter voor uittrekweerstand	$f_{ax,k}$	[N/mm ²]	11,7	15,0	29,0
Karakteristieke parameter voor penetratie van de kop	$f_{head,k}$	[N/mm ²]	10,5	20,0	-
Gekoppelde dichtheid	ρ_a	[kg/m ³]	350	500	730
Berekeningsdichtheid	ρ_k	[kg/m ³]	≤ 440	410 + 550	590 + 750

Zie ETA-11/0030 voor toepassingen met andere materialen.