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Characterization of moisture-induced swelling in timber joining utilizing hygroscopic dimensional change as an assembly mechanism for wood-to-wood connections

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Abstract

This research investigates the structural behavior of timber joints under moisture-induced dimensional change and explores the potential of hygroscopic swelling as a mechanism for wood-to-wood joinery. The study is framed as a proof-of-concept for climate-activated timber connections that could support prefabricated construction systems in humid environments such as rural Colombia. The methodology combines material experiments, digital fabrication tests, structural analysis, and mechanical testing. First, the dimensional response of selected timber species was measured under controlled humidity conditions. Second, the manufacturability and assembly behavior of traditional joinery types were evaluated using CNC fabrication. Finally, mechanical tests were conducted on mortise–tenon joints and cross half-lap joints to assess the influence of different humidity conditions on the structural performance on these connections. Across the investigated configurations, specimens conditioned at higher relative humidity consistently reached higher peak loads than corresponding control samples. These observations indicate that moisture-induced swelling can increase contact pressure and friction within timber joints, thereby influencing load transfer behavior. The study provides initial findings that hygroscopic dimensional change can be used as an active parameter in timber joinery and may support the development of climate-responsive, prefabricated construction systems.

Keywords Wood-to-wood joints · Timber joinery · Hygroscopicity · Dimensional change · Mortise-tenon · Half-lap

Introduction

Housing crisis and contextual challenges in Colombia

The global housing shortage, intensified by rapid urbanization and social inequality, has led to increasing pressure

on housing systems worldwide. In Latin America, this challenge is particularly pronounced, where informal settlements represent a large portion of the housing stock. Colombia illustrates this situation clearly. The country faces one of the highest levels of internal displacement globally, with more than 8.3 million people affected by armed conflict over the past five decades. At the same time, significant socio-economic inequality persists, particularly in rural regions where poverty rates exceed 40% [1].

These conditions create an urgent need for affordable, adaptable housing solutions capable of being implemented in regions with limited infrastructure and restricted access to industrial construction technologies.

Self-build has historically functioned as an important route to housing access for lower-income and working-class households. It enables entry into home ownership by substituting financial capital with “sweat equity”, where households invest their own labor and time in the construction process [2]. More broadly, self-build involves cases

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“where the first occupants arrange for the building of their own dwelling and, in various ways, participate in its production” [3]. In this way, self-build can reduce costs and expand access to housing for those otherwise excluded from conventional market provision.

Industrialized building systems and prefabrication have been widely discussed as strategies to address housing shortages by enabling faster and more efficient construction processes. However, successful implementation depends on careful adaptation to local environmental conditions, material availability, and construction practices, particularly in self-build contexts.

Local building traditions

Timber has long been an important construction material in Colombia. Traditional techniques developed by Indigenous communities and later influenced by Spanish carpentry rely on timber frameworks combined with earth-based materials [4]. Hybrid systems such as bahareque demonstrate the integration of structural timber logic with local material resources.

These systems employ a structural logic comparable to post-and-beam construction, where loads are transferred through a sequence of beams and columns. Timber joinery techniques such as mortise and tenon, dovetail joints, and splice connections play a central role in these structures [5]. They enable efficient load transfer while reducing the need for additional connectors and illustrate the potential of wood-based systems that combine structural performance with simplified assembly [6].

Manufacturing technology and self-build

Recent developments in digital fabrication, particularly CNC milling, have enabled the precise production of timber components and the reintroduction of complex joinery into contemporary construction [7]. Prefabricated timber systems can reduce construction time, improve accuracy, and minimize material waste.

At the same time, self-build systems such as WikiHouse demonstrate how prefabricated components can be assembled by users with limited construction experience [8]. However, in Colombia, construction remains dominated by concrete and masonry, and digitally fabricated timber systems have not yet been widely adopted. Previous attempts highlight challenges related to contextual adaptation, logistics, and assembly complexity [9].

Timber materials and climatic conditions

Industrial timber construction often relies on engineered wood products such as CLT or LVL, which offer high dimensional stability. In Colombia, these materials remain limited in availability. At the same time, locally available species such as *Acacia mangium*, *Pinus patula*, and *Pinus caribaea* are widely used.

Colombia’s tropical climate is characterized by relatively stable temperatures but high and variable relative humidity, often exceeding 80%. Timber, as a hygroscopic material, exchanges moisture with its environment, leading to dimensional change. This behavior is anisotropic and varies along tangential, radial, and longitudinal directions.

Understanding and managing this behavior is essential for the development of timber systems adapted to the Colombian context.

Climate-activated assembly concept

The spatial separation between controlled production environments and high-humidity assembly sites creates an opportunity to rethink timber joinery. Components manufactured with precise tolerances may undergo dimensional change when exposed to higher humidity during transport or assembly.

Rather than treating this behavior as a limitation, it can be used as a design parameter. Moisture-induced swelling can increase contact pressure within joints and enhance their tight fit without relying on metal fasteners or adhesives.

This approach suggests a link between material behavior, fabrication processes, and environmental conditions, and forms the basis of this research.

Background

Traditional carpentry and structural behavior of timber joints

Several authors emphasize the structural redundancy inherent in traditional timber-to-timber joinery, which often functions as a statically indeterminate system. For instance, [10] highlight the challenges associated with empirically verifying the strength requirements of mortise-and-tenon joints in miter gates; despite these analytical difficulties, historical evidence suggests that such connections rarely exhibit catastrophic failure in practice.

In timber joinery systems, the failure of a single component leads to a redistribution of internal forces across adjacent members and joints, thereby preserving the overall structural integrity of the assembly. This behavior is primarily attributed to the semi-rigid nature and high ductility of traditional connections, which enable controlled deformation and energy dissipation [11].

Further evidence of this ductile performance is provided by studies on traditional Japanese joinery [12]. Their research demonstrates that the seismic resistance of historical timber structures relies on the rotational restoring capacity of column–tie beam joints, which exhibit enhanced ductility due to internal embedding friction within the connection geometry.

These studies demonstrate the complex mechanical performance of timber joints, depending on multiple parameters, including joint geometry, member dimensions, fiber orientation, and contact conditions. As a result, accurately describing their behavior often requires a combination of analytical and numerical approaches.

Hygroscopic behavior of wood

Timber is a hygroscopic material that continuously exchanges moisture with its surrounding environment. Changes in relative humidity lead to variations in moisture content, which in turn result in dimensional changes. This behavior is anisotropic and occurs at different rates along the tangential, radial, and longitudinal directions of the wood fibers.

The dimensional response of wood to moisture changes is typically considered a challenge in construction, as it can lead to deformation, cracking, or loss of precision. Consequently, many industrial timber systems aim to minimize or stabilize these effects, for example through the use of engineered wood products with reduced moisture sensitivity.

At the same time, traditional craftsmanship demonstrates that this behavior can be actively used. Timber elements are often produced under controlled conditions and assembled in environments with higher humidity, allowing dimensional changes to improve the fit of joints. Techniques such as controlled pre-drying or mechanical compression (e.g. *kigoroshi*) make use of this principle to achieve tighter connections after assembly [13, 14].

Moisture-induced joining in existing research

In contemporary research and industrial applications, moisture-induced swelling has mainly been explored through the use of additional connectors, such as swelling dowels in engineered wood systems [15]. These approaches

demonstrate that hygroscopic behavior can be used to create strong, metal-free connections.

However, most existing systems rely on discrete elements that are inserted into otherwise conventional assemblies. The integration of moisture-induced dimensional change directly into the geometry of timber joints remains less explored. Previous studies on mortise–tenon connections and shrink-fit techniques indicate that controlled dimensional change can improve joint performance [16–18]. Nevertheless, challenges remain in achieving precise tolerances, controlling moisture content, and understanding long-term behavior.

Research Gap

While both traditional carpentry and modern research demonstrate the relevance of moisture-induced dimensional change, there is limited work that systematically investigates its integration into timber joinery [19]. In particular, the mechanical effect of moisture-induced swelling on timber connections and the potential of combining CNC-based fabrication with moisture-responsive behavior as an assembly mechanism has not been sufficiently explored.

This gap is especially relevant in contexts where high-precision manufacturing and low-tech assembly conditions coexist. The possibility of using environmental humidity as an active component in the joining process suggests a shift from treating hygroscopic behavior as a constraint to considering it as a design parameter.

This study therefore investigates moisture-induced dimensional change as a mechanism for wood-to-wood joining and examines how it can be integrated into the design, fabrication, and performance of timber connections, with the goal of implementation on a self-build system in the Colombian context as a proof-of-concept.

Research Objective

The aim of this research is to investigate moisture-induced dimensional change in timber as a mechanism for wood-to-wood joinery. The study explores how the hygroscopic behavior of wood can be intentionally used to generate tight-fitting connections through controlled swelling.

Rather than treating dimensional change as a material limitation, the research examines its potential as an active design parameter in the formation and performance of timber joints. The focus lies on understanding how material behavior, joint geometry, and environmental conditions interact to influence the behavior of connections.

To address this aim, the research is structured around three main objectives:

Material behavior

To analyze the hygroscopic properties of selected timber species and quantify their dimensional response under controlled humidity conditions.

Joinery fabrication and assembly

To evaluate the manufacturability and assembly behavior of different joint geometries in relation to moisture-induced dimensional change, with particular attention to tight-fitting connections.

Structural response

To assess the influence of moisture-induced swelling on load transfer mechanisms and the mechanical performance of timber joints.

While the research is contextualized within prefabricated construction and self-build scenarios, these serve as an application framework. The primary contribution lies in the investigation of moisture-induced joining as a material-driven approach to timber connections.

Materials and methods

To address the research objectives outlined in Sect. 3, the study combines literature review, material experiments, structural testing, and research-by-design methods. The methodological approach corresponding to each research objective is described in the following sections.

Material behavior: Selection and hygroscopic characterization

Material selection

The material selection aimed to identify timber species with suitable hygroscopic and mechanical properties for moisture-responsive joinery. Particular emphasis was placed on selecting species that exhibit measurable dimensional response to changes in relative humidity while maintaining sufficient structural capacity.

Due to the limited availability of Colombian timber specimens in the Netherlands, European species were selected as proxies. The selection was based on a comparative evaluation of material properties derived from literature and industry data, ensuring that the chosen species reflect characteristics relevant to the Colombian context.

Two main criteria guided the selection process. First, hygroscopic behavior was assessed through shrinkage

characteristics, including tangential, radial, and volumetric shrinkage. Tangential shrinkage was considered particularly relevant, as it represents the dominant direction of dimensional change in wood. Second, mechanical performance was evaluated using the modulus of rupture (MOR) as an indicator of bending strength.

Hygroscopic characterization

To investigate hygroscopic behavior, timber specimens following the defined selection criteria were subjected to controlled environmental conditions simulating variations in relative humidity and temperature. Three specimens per species were prepared with nominal dimensions of 65 mm × 65 mm × 65 mm and oriented to measure tangential dimensional change.

The initial moisture content (MC) of the specimens was approximately 10% ± 2%. Relative humidity was controlled using a saturated potassium chloride (KCl) solution. Moisture content and dimensional changes were recorded using a moisture meter and digital calipers, respectively, with measurements taken weekly over a period of 30 days.

Three environmental conditions were defined to simulate different stages of production and assembly:

- 1) High-humidity condition – production stage (23 °C – 85% RH),
- 2) Elevated temperature condition – assembly stage (32 °C – 85% RH), and
- 3) Control condition (23 °C – 40% RH).

The experimental results were subsequently compared with reference values reported in the literature.

Joinery fabrication and assembly

To evaluate joinery configurations focusing on their manufacturability and assembly behavior in relation to moisture-induced dimensional change, three evaluation criteria were defined:

Manufacturing feasibility Compatibility with CNC-based fabrication processes, including tool diameter, milling depth, and fixation requirements.

Assembly behavior Ease and robustness of assembly, with particular attention to tight-fitting connections.

Material efficiency Stock utilization and material waste during fabrication.

The evaluation was conducted in two steps. First, fabrication tests assessed the feasibility of producing the selected

joints using CNC milling. Second, comparative tests evaluated assembly behavior and material efficiency across different joint typologies.

Structural response: Analytical and numerical evaluation

The structural characterization of the selected joint typologies—cross-half lap, mortise and tenon, and T-joint—was conducted using a sequential evaluation framework combining analytical modelling, numerical simulation, and mechanical testing. This approach enables a consistent assessment of joint behavior across different levels of abstraction, from theoretical prediction to experimental verification.

Analytical modelling

A mathematical framework was developed to relate joint geometry to load-carrying capacity. The model is based on established approaches by [10, 20], allowing for a consistent comparison of different joinery configurations.

The modulus of rupture (MOR) was used as the primary material parameter, with a reference value of 66.9 N/mm² for Douglas fir. The influence of fiber orientation and anisotropic behavior was considered. Detailed equations are provided in Appendix 9.2.

Numerical simulation

Finite element simulations were performed using Ansys Workbench 2021 to analyze stress distribution and verify analytical results.

The simulation model incorporated cross-sectional geometry, material properties, fiber orientation, and MOR. Douglas fir was used as the reference material with a cross-section of 76 mm × 76 mm. Simulations were conducted under dry conditions to establish a structural baseline.

In parallel, a material assessment conducted at the Heritage Laboratory of Delft University of Technology led to the exclusion of *Quercus robur* (oak) for the physical prototypes. Ultimately, this dual-method evaluation aimed to identify the optimal joint configuration for the final design.

Evaluation of structural performance of moisture-induced swelling

To evaluate the influence of moisture-induced swelling on the performance of timber joints, a series of mechanical tests was conducted under controlled humidity conditions.

Two humidity levels were defined: 65% relative humidity (control condition) and 85% relative humidity

(conditioned state), representing environments with increased moisture exposure.

The experimental program was structured into three test configurations:

- 1) Mortise–tenon joints tested in tension.
- 2) Cross half-lap joints tested in compression.
- 3) Cross half-lap joints tested in tension with varying fiber orientations.

For the cross half-lap joints, two fiber orientation configurations were investigated: radial–tangential (RT) and tangential–tangential (TT) (Fig. 1).

Each specimen was assigned a unique identifier indicating joint type, humidity condition, and test configuration. Specimen dimensions, material allocation, and test parameters are summarized in Table 1.

Due to the exploratory nature of the study, one specimen was tested per configuration.

All mechanical tests were performed using a Zwick Roell universal testing machine with a load capacity of 100 kN. Custom test setups were developed for both tensile and compression loading in order to ensure stable boundary conditions during testing (Fig. 2).

Force–displacement behavior was recorded for all specimens, with particular attention to maximum load (F_{max}) and displacement at peak load.

Results

Material behavior

Material selection

Based on the defined hygroscopic and mechanical evaluation criteria, a set of European timber species was identified as suitable proxies for Colombian wood species for use in the experimental phase of this research. The selection

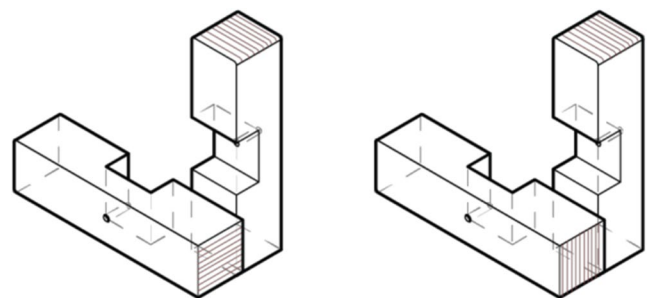
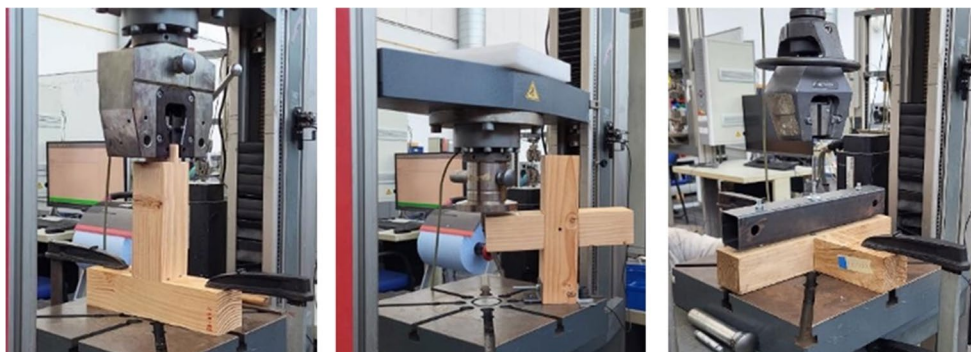


Fig. 1 two different fiber orientation configurations in the cross half-lap joints in Experiment 3, left: HL-RT, right: HL-TT

Table 1 Investigated joint configurations, sample identifiers, humidity conditions, fiber orientations groups, species and dimensions for the three tests

Test	Sample ID	Joint Type	Test Type	Fiber Orientation	RH [%]	Group	Species	Dimensions (L *W*H) [mm]
1	MT-C	Mortise–Tenon	Tension	-	65	Control	Douglas Fir	400 * 72 * 72
1	MT-M	Mortise–Tenon	Tension	-	85	Conditioned	Douglas Fir	400 * 72 * 72
2	HL-C	Cross Half Lap	Compression	-	65	Control	Douglas Fir	400 * 65 * 65
2	HL-M	Cross Half Lap	Compression	-	85	Conditioned	Douglas Fir	400 * 65 * 65
3	HL-RT-C	Cross Half Lap	Tension	Radial–Tangential	65	Control	Oak	400 * 65 * 65
3	HL-RT-M	Cross Half Lap	Tension	Radial–Tangential	85	Conditioned	Oak	400 * 65 * 65
3	HL-TT-C	Cross Half Lap	Tension	Tangential–Tangential	65	Control	Oak	400 * 65 * 65
3	HL-TT-M	Cross Half Lap	Tension	Tangential–Tangential	85	Conditioned	Oak	400 * 65 * 65

Fig. 2 Custom setup for joint testing, left: mortise-tenon in tension, middle: cross half-lap in compression, left: cross half-lap in tension

focused on species exhibiting comparable shrinkage behavior and structural performance, as determined through literature review and industry data.

Douglas fir (*Pseudotsuga menziesii*), elm (*Ulmus spp.*), oak (*Quercus robur*), and meranti (*Shorea spp.*) were selected as representative candidates. These species cover a range of hygroscopic responses, particularly in terms of tangential and radial shrinkage, while also meeting structural requirements based on modulus of rupture values (Appendix Table 4). This selection enabled the systematic investigation of moisture-induced dimensional changes under controlled conditions.

Hygroscopic characterization

All investigated timber species exhibited measurable tangential dimensional change after exposure to increased relative humidity over a period of 30 days.

Starting from an initial dimension of 65 mm, the samples reached final dimensions of 65.4–65.5 mm for oak, 65.3 mm for elm, 65.2 mm for Douglas fir, and 65.1–65.2 mm for meranti. These values correspond to tangential swelling of 0.62–0.77% for oak (mean 0.72%), 0.46% for elm, 0.31% for Douglas fir, and 0.15–0.31% for meranti (mean 0.20%). The relative magnitude of swelling follows the sequence oak > elm > Douglas fir > meranti.

Published data indicate tangential dimensional changes of approximately 8–10% across the full shrinkage range of

most structural timber species, corresponding to moisture content variations of roughly 30% (Forest Products Laboratory, 2000). Assuming an approximately proportional relationship below the fiber saturation point, the applied moisture increase (approximately 8–10% MC) corresponds to an expected dimensional change of roughly 0.2–1.0%.

The experimentally observed swelling values fall within this range. In addition, the relative sequence of dimensional change among the investigated species corresponds to trends reported in the literature.

Due to the limited number of samples per species ($n=3$), the results are interpreted as indicative observations of general moisture-induced behavior.

Manufacturing and assembly evaluation of joinery configurations

The fabrication tests demonstrated that CNC production of joinery in sawn timber is feasible, but influenced by machine and setup conditions.

The limited milling height restricted the maximum cross-section of processable elements, while the available tool diameter constrained the geometry of internal joint features. In addition, stable fixation of the timber elements proved essential for maintaining machining accuracy.

A comparative evaluation of three joint typologies, mortise–tenon, T-joint, and cross half-lap, was conducted with respect to material efficiency and assembly behavior.

The mortise–tenon joint achieved a stock utilization of 87.7%, corresponding to approximately 12% material waste. However, post-processing was required due to alignment issues during assembly.

The T-joint showed a comparable material efficiency, with 88% stock utilization and 12% waste. The fabrication process required more extensive routing, and assembly proved difficult when attempting to achieve a tight-fitting connection.

The cross half-lap joint demonstrated the highest material efficiency, with 91.5% stock utilization and 8.5% waste. The joint required no post-processing and showed the simplest assembly behavior among the tested configurations.

Across all evaluated criteria, the cross half-lap joint showed the most favorable overall performance.

Structural characterization of joint types

The analytical evaluation revealed clear differences in structural performance between the investigated joint configurations.

Mathematical models

Among the investigated configurations, the cross half-lap joint exhibited the highest structural capacity, followed by the mortise and tenon joint, while the T-joint showed the lowest bending resistance (Table 2).

Numerical simulations

The finite element simulations showed stress distributions consistent with the analytical predictions. Localized stress concentrations were observed at critical regions, particularly at notched sections and contact interfaces.

Across all configurations, similar load transfer patterns were observed, with higher stress accumulation in areas of reduced cross-section. The relative performance ranking identified in the analytical modelling was confirmed by the simulation results.

Table 2 Analytical results of load-carrying capacity for the investigated joint typologies, including ultimate bending moment and corresponding force capacity

Joint type	Ultimate Bending Moment [kN*m]	Force Capacity [kN]
Mortise -Tenon	1.74	2.90
Cross Half-Lap	2.45	4.04
T-Joint	1.54	2.41

Mechanical testing of moisture-induced joining

The mechanical experiments investigated the influence of moisture-induced swelling on the structural behavior of timber joints under different loading conditions.

The measured peak loads and corresponding displacements are summarized in Table 3.

In addition to the measured values, the table also includes the relative difference between conditioned and control specimens, calculated based on the maximum load (F_{max}). Due to the exploratory nature of the study, one specimen was tested per configuration. The results therefore represent observations of the tested configurations under the defined experimental conditions rather than statistically representative values.

Mortise–tenon tension

The control specimen (65% RH) reached a peak load of 0.74 kN, while the conditioned specimen (85% RH) reached 1.34 kN. In addition to the higher maximum load, the conditioned joint exhibited a larger displacement at peak load, increasing from 4.91 mm to 15.49 mm. Both curves show a similar initial loading behavior, followed by a higher peak load and extended deformation range in the conditioned specimen (Fig. 3.).

Cross half-lap compression

The control specimen reached a peak load of 15.58 kN, while the conditioned specimen reached 18.84 kN. The displacement at peak load increased from 11.22 mm in the control sample to 19.34 mm in the conditioned specimen.

Both curves show a similar initial loading behavior, followed by a higher peak load and increased deformation capacity in the conditioned specimen (Fig. 4).

Cross half-lap tension

The tensile behavior of cross half-lap joints was evaluated for two fiber orientation configurations: radial–tangential (R/T) and tangential–tangential (T/T).

For the R/T configuration, the control specimen reached a peak load of 1.41 kN, while the conditioned specimen reached 2.75 kN. The displacement at peak load increased from 1.32 mm to 1.87 mm.

For the T/T configuration, the control specimen reached 1.73 kN, whereas the conditioned specimen reached 3.06 kN. The displacement at peak load increased from 2.03 mm to 3.31 mm.

Table 3 Summary of mechanical test results including maximum load (F_{max}), displacement at peak load, and relative difference between conditioned (85% RH) and control (65% RH) specimens for the investigated joint configurations

Test	Joint Type	Test Type	Fiber Orientation	Condition	RH [%]	F_{max} [kN]	Displacement at F_{max} [mm]	Increase in F_{max} [%]
1	Mortise–Tenon	Tension	–	Control	65	0,737	4,91	–
1	Mortise–Tenon	Tension	–	Conditioned	85	1,338	15,49	81,5
2	Cross Half-Lap	Compression	–	Control	65	15,579	11,22	–
2	Cross Half-Lap	Compression	–	Conditioned	85	18,838	19,34	20,9
3	Cross Half-Lap	Tension	Radial - Tangential	Control	65	1,410	1,32	–
3	Cross Half-Lap	Tension	Radial - Tangential	Conditioned	85	2,753	1,87	95,2
3	Cross Half-Lap	Tension	Tangential - Tangential	Control	65	1,727	2,03	–
3	Cross Half-Lap	Tension	Tangential - Tangential	Conditioned	85	3,0573	3,31	77

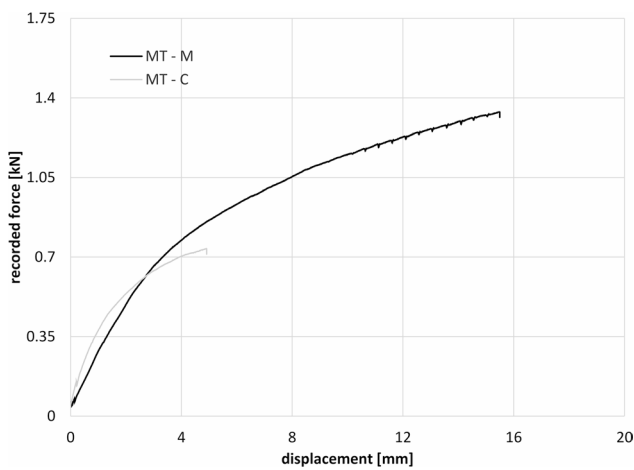


Fig. 3 Force–displacement curves of mortise–tenon joints (MT) tested in tension under control (C) (65% RH) and conditioned (M) (85% RH) humidity conditions

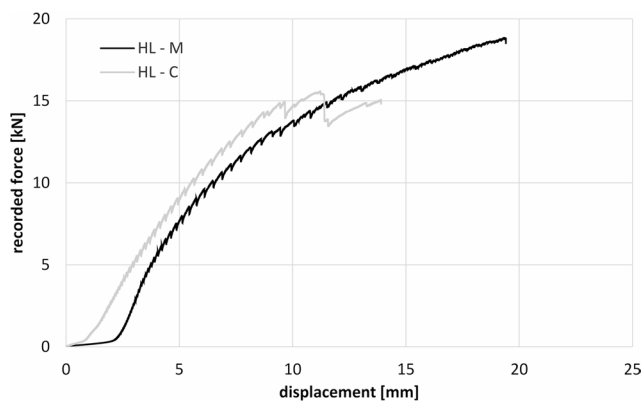


Fig. 4 Force–displacement curves of cross half-lap joints (HL) tested in compression under control (C) (65% RH) and conditioned (M) (85% RH) humidity conditions

Across both configurations, the conditioned specimens reached higher peak loads and larger displacements compared to the control samples (Fig. 5).

Summary of mechanical results

Across all investigated configurations, specimens exposed to higher relative humidity reached higher peak loads than the corresponding control samples.

The relative increase in peak load ranged from approximately 21% for the cross half-lap joint tested in compression to between 77% and 95% for the tensile tests of the cross half-lap configurations. The mortise–tenon joint showed an increase of approximately 82%.

These values provide a comparative overview of the observed differences between humidity conditions. Given the limited number of tested specimens, the results should be interpreted as indicative observations rather than statistically validated results.

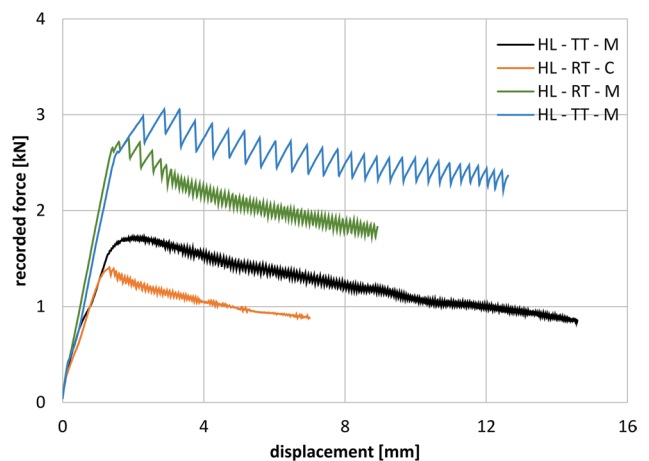


Fig. 5 Force–displacement curves of cross half-lap joints (HL) tested in tension for radial–tangential (RT) and tangential–tangential (TT) fiber orientation configurations under control (C) (65% RH) and conditioned (M) (85% RH) humidity conditions

Conclusion

This study investigated the potential of moisture-induced dimensional change as a mechanism for wood-to-wood joinery. The results demonstrate that hygroscopic behavior can be intentionally utilized to influence the performance of timber connections, rather than being treated solely as a material limitation.

The material experiments confirmed that all investigated timber species exhibit measurable dimensional change under increased relative humidity. The observed swelling values fall within the expected range derived from literature and follow known trends between species. This supports the validity of the experimental setup and indicates that hygroscopic behavior can be reliably activated within controlled environmental conditions. At the same time, the limited number of samples restricts the results to indicative observations.

The fabrication experiments demonstrated that digitally manufactured wood-to-wood joints can be produced with sufficient precision to enable tight-fitting assembly. However, the results also highlight the influence of machine constraints and fabrication setup on joint quality. Among the tested configurations, the cross half-lap joint showed the most favorable performance in terms of manufacturability, material efficiency, and assembly simplicity. In contrast, more complex geometries such as the mortise–tenon and T-joint required additional processing or presented challenges during assembly. These findings indicate that the effectiveness of moisture-induced joining is closely linked not only to material behavior, but also to the geometric and fabrication characteristics of the joint.

The analytical and numerical evaluations revealed consistent differences in load-carrying capacity between the investigated joint configurations. Across both approaches, the cross half-lap joint exhibited the highest structural capacity, followed by the mortise–tenon joint, while the T-joint showed the lowest performance. The agreement between analytical modelling and numerical simulation supports the validity of the adopted evaluation methods and provides a consistent basis for comparing different joint typologies.

The mechanical experiments indicate that increased moisture conditions can influence the structural response

of timber connections. Across all investigated configurations, specimens exposed to higher relative humidity consistently reached higher peak loads than the corresponding control samples. In addition, conditioned specimens generally exhibited increased displacement at peak load, indicating a change in deformation behavior. These observations suggest that moisture-induced swelling increases contact pressure and frictional interaction between joint components, thereby affecting load transfer mechanisms within the connection.

Due to the limited number of tested specimens, the findings should be interpreted as preliminary observations. Nevertheless, the results provide initial evidence that hygroscopic dimensional change can influence the structural behavior of timber joinery and may offer new opportunities for the development of climate-responsive timber construction systems.

It is important to note that the experimental work was conducted using European timber species as proxies for Colombian materials. While the selection was based on comparable hygroscopic and mechanical properties, direct validation using locally available species would be required to fully transfer the findings to the Colombian context. After the research conclusion, a proposal for a self-built system was developed based on the findings of this study.

Future research should therefore focus on expanding the experimental dataset to enable statistical evaluation of the observed effects. In addition, the long-term behavior of moisture-responsive joints under cyclic humidity conditions should be investigated, as well as the influence of different timber species and joint geometries. Further studies at the scale of structural elements and assemblies will be necessary to assess the applicability of moisture-induced joining mechanisms in real building systems.

Despite the exploratory nature of the study, the results provide a proof-of-concept that moisture-induced swelling can be utilized as an assembly mechanism in timber construction. This approach suggests a shift in the understanding of hygroscopic behavior, from a constraint that must be controlled to a material property that can be actively integrated into the design of timber connections.

Appendix

Material selection

Table 4 Summary of physical, mechanical, and hygroscopic properties of investigated timber species, including modulus of rupture, density, and shrinkage characteristics used as selection criteria

Scientific Name	English Name	Spanish Name	Location	Length (m)	Trunk Diameter (m)	Green Weight (kg/m ³)	Dry Weight (kg/m ³)	Modulus of Rupture (MPa)	Elastic Modulus (GPa)	Crushing Strength (MPa)	Radial Shrinkage (%)	Tangential Shrinkage (%)	Volume Shrinkage (%)
Softwood													
Acacia mangium	Acacia mangium	Acacia mangium	Australia	25	0.60		585	98.2	11.07	52.1	2.80	7.80	10.70
Pinus patula	Patula pine	Pino patula	Mexico	35	0.61	960	490	79.3	10.09	35.6	4.10	7.90	12.60
Caribbean pine	Caribbean pine	Pino	Central America	35	0.75	1040	625	133.4	12.03	54.4	6.30	7.80	12.90
Eucalyptus grandis	Eucalyptus	Pino eucalipto	Worldwide	40	1.60	1160	700	107.8	14.15	55.0	5.90	10.10	15.50
Tectona grandis	Teak	Teca	Worldwide	35	1.35	800	570	97.1	12.28	54.8	2.60	5.30	7.20
Hevea brasiliensis	Rubberwood	Caucho	Brazil	26.5	0.65		595	71.9	9.07	42.1	2.30	5.10	7.50
Pseudotsuga menziesii	Douglas fir	Pino Douglas	USA	45	1.20		435	66.9	10.07	34.8	4.10	7.40	11.80
Larix decidua	Larch	Alerce	Europe	35	0.75	810	575	90.0	11.80	52.0	4.20	8.20	12.50
Fraxinus excelsior	Ash	-	Europe	25	1.05	1500	675	103.5	12.00	51.1	4.90	7.80	13.30
Eucalyptus pellita	Eucalyptus	Eucalipto	Southern Mexico	53	1.35		590	80.8	10.06	46.6	2.90	4.30	7.50
Hardwood													
Cordia alliodora	Walnut	Nogal canaleta	Colombia	35	0.90	890	600	77.0	7.81	45.2	3.09	6.62	9.71
Tabebuia rosea	Oak (flor morado)	Roble flor morado	Colombia	40	1.00	950	540	108.0	20.00	62.3	4.60	6.90	11.50
Quercus robur	European oak	Roble europeo	Europe	35	1.15	1040	675	97.1	10.60	46.3	4.70	8.40	13.00
Albizia saman	Monkey pod	Saman	Colombia	35	1.15	1130	530	65.7	7.92	39.9	3.00	5.10	8.10
Mangifera indica	Mango tree	Mango	Colombia	25	1.20		675	88.5	11.53	49.9	3.60	5.50	8.90
Anacardium excelsum	Wild cashew	Caracoli	Colombia	30	1.50	590	370	62.5	8.71	33.9	2.80	5.30	8.50
Shorea spp.	Meranti (dark red)	Meranti	Southeast Asia	30	1.50	1000	675	87.7	12.02	48.8	3.90	7.80	12.50
Ulmus hollandica	Elm	Olmo - negrillo	Europe	19.5	0.80		575	89.7	10.28	43.9	4.90	8.90	13.80
Clarisia racemosa	Tulpay	Aji	Colombia	42	0.45	880	490	89.4	11.20	38.6	2.60	4.90	7.50

Analytical formulation

Governing equations

$$M = \frac{(\sigma * b * d^2)}{6}$$

$$\sigma = \frac{M}{W}$$

$$W = \frac{(b * h^2)}{6}$$

Sample calculation (Douglas fir)

Given:

$$b = 27\text{mm}$$

$$h = 76\text{mm}$$

$$\sigma = \frac{M}{W}$$

Section modulus:

$$W = \left(\frac{1}{6}\right) * 27 * 76^2$$

$$W = (1/6) * 27 * 76^2$$

$$W = 25,992 \text{ mm}^3$$

Bending moment:

$$M = 66.9 * 25,992$$

$$M = 1,738,865 \text{ N}\cdot\text{mm}$$

Remarks

The analytical formulation is based on simplified bending theory and incorporates both geometric parameters and material properties. Fiber orientation is considered through the selection of appropriate strength values.

Building system

The development of an autonomous timber construction system (Fig. 6) addresses the housing deficit in rural Colombia by enabling low-cost, resource-efficient construction independent of heavy machinery. Through the integration of prefabrication and automated manufacturing, the system reduces construction complexity while maintaining high planning accuracy. The structure is conceived as a modular timber skeleton composed of repetitive members connected via standardized cross half-lap joints. The subdivision into small-scale prefabricated components improves handling, transportability, and on-site assembly, while modular coordination ensures structural consistency and scalability.

Conceptual building system illustrating the application of moisture-induced joining in a prefabricated timber structure, showing parts needed, assembly sequence of the load-bearing structure and system components. The system is defined by its construction logic and material integration. Ergonomic autonomy is a key design parameter, with a maximum component weight of 30 kg, allowing all elements to be handled by a single operator without mechanical assistance. This constraint directly informs the dimensional configuration of the system. Material behavior is embedded in the joint design through fiber-oriented alignment of elements, to allow for moisture-induced swelling to increase frictional resistance and enable stable connections without additional fasteners or specialized tools.

Fabrication, assembly, and component integration are developed as an interdependent system. Component dimensions correspond to CNC milling capacities and the constraints of rural transportation, ensuring manufacturability and accessibility under limited infrastructural conditions. The construction process follows a sequential assembly logic, in which a primary structural frame is erected first, followed by the integration of modular floor elements, façade components, and roof elements. Floor modules function as integrated building components, combining structural members with insulation and service layers while remaining compatible with the modular grid.

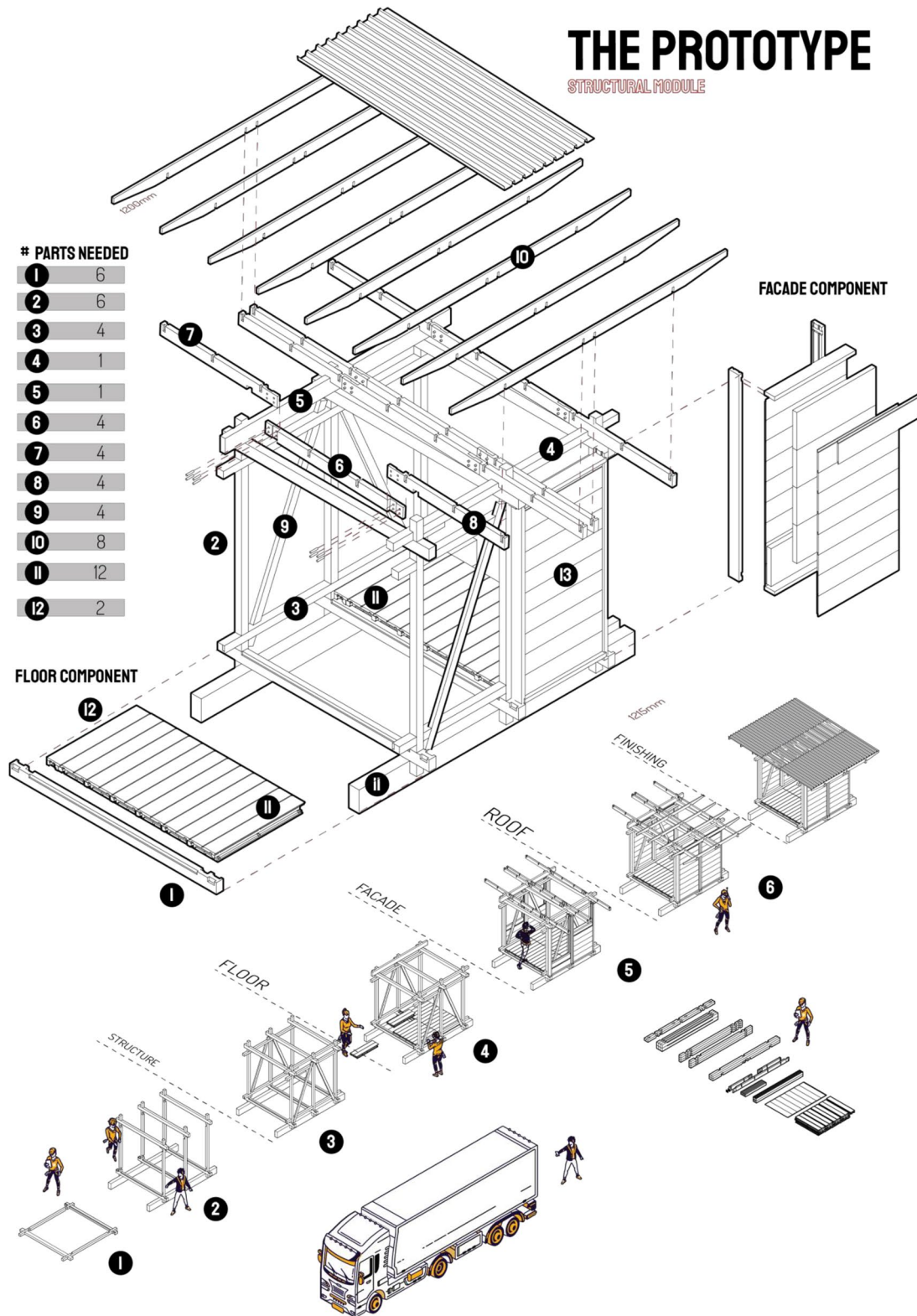


Fig. 6 Conceptual building system illustrating the application of moisture-induced joining in a prefabricated timber structure, showing parts needed, assembly sequence of the load-bearing structure and system components

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Data availability All data supporting the findings of this study are available within the paper or the appendix.

Declarations

Competing interests The authors declare no competing interests.

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References

- World Bank Group (2020) Colombia. World Bank, Washington, DC
- Benson M, Hamiduddin I (2017) Self-build homes: social discourse, experiences and directions. UCL Press, London
- Duncan S, Rowe A (1993) Self-provided housing: the first world's hidden housing arm. *Urban Stud* 30(8):1331–1354. <https://doi.org/10.1080/00420989320081291>
- Gama C (2007) Earthen architecture in Colombia: processes and constructional culture. *Apuntes* 20(2):242–255
- Armar DE De armar. 1899
- Robeller C (2015) Integral mechanical attachment for timber folded plate structures [PhD thesis]
- Weinand Y (2017) Advanced timber structures: architectural designs and digital dimensioning. Birkhäuser, Basel. <https://doi.org/10.1515/9783035604900>
- Albus J, Meuser P (2018) Prefabricated housing: construction and design manual. DOM Publishers, Berlin
- Massara Rocha B, Alvarenga A, Bolssoni G (2021) Open-source social housing architecture: Wikihouse Sr. Manoel. In: Proceedings of the XXV International Conference of the Ibero-American Society of Digital Graphics (SIGraDi 2021)
- van de Kuilen JWG, Otterloo J, Ravenshorst GJP et al (2014) WCTE. Load carrying capacity of large mortise and tenon joints in wooden mitre gates. In: Proceedings of the World Conference on Timber Engineering
- Branco JM, Descamps T (2015) Analysis and strengthening of carpentry joints. *Constr Build Mater* 97:34–47. <https://doi.org/10.1016/j.conbuildmat.2015.05.089>
- Tanahashi H, Suzuki Y (2015) Three effects of mechanisms in traditional timber structures. *IABSE Symp Rep* 104:1–8. <https://doi.org/10.2749/222137815815774656>
- Amino Y (2004) An overview of modern Japanese wood construction: interaction with tradition. In: Proceedings of the Internationales Holzbau-Forum
- Zwerger K (2015) Wood and wood joints: building traditions in Europe, Japan and China. Birkhäuser, Basel
- Sotayo A, Bradley D, Bather M et al (2020) Review of state of the art of dowel laminated timber members and densified wood materials as sustainable engineered wood products for construction and building applications. *Dev Built Environ* 1:100004. <https://doi.org/10.1016/j.dibe.2019.100004>
- Eckelman C, Haviarova E, Tankut A et al (2004) Withdrawal capacity of pinned and unpinned round mortise and tenon furniture joints. *Forest Products Journal* 2004; 54(12):185–191
- Mougel E, Segovia C, Pizzi A et al (2011) Shrink-fitting and dowel welding in mortise and tenon structural wood joints. *J Adhes Sci Technol* 25(1–3):213–221. <https://doi.org/10.1163/016942410X503320>
- Wojcik M (2020) Reframing wood construction: innovation in architecture through activating material properties with the use of digital technologies [Master's thesis]. Oslo School of Architecture and Design
- Salzberger M, Klein T, Hemmerling M et al (2024) Shape-changing wood joints in crafts and industry and their potential for building construction and wood culture: state of the art of utilizing the hygroscopicity and resulting dimensional change of wood for the moisture-induced joining of wooden elements. *Int J Wood Cult* 4(1):58–95. <https://doi.org/10.1163/27723194-bja10031>
- Kasal A (2008) Bending moment and shear force capacities of T-type doweled furniture joints reinforced with different sizes of corner blocks. *J Fac Eng Archit Gazi Univ* 23(2):273–282

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