# Impact of Cyclic Moisture on Shrinkage of Glue-Laminated Softwood

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**Abstract.** Glulam softwood, widely used in construction due to its strength-to-weight ratio and sustainability, undergoes dimensional changes under varying moisture conditions. Cyclic moisture exposure accelerates these changes, potentially affecting its long-term performance. This study investigates the impact of cyclic moisture exposure on the shrinkage behaviour of glue-laminated (glulam) softwood, which affects structural integrity and dimensional stability in engineered wood products. The experimental methodology involves fabricating glulam specimens using industry-standard adhesives and softwood laminations. Samples are subjected to controlled cyclic moisture conditions, alternating between wetting (85% relative humidity) and drying (30% relative humidity) in a controlled environmental chamber. Shrinkage strains are measured periodically. The testing duration spans up to 20 cycles, simulating natural seasonal variations. Preliminary results indicate that cyclic moisture exposure exacerbates anisotropic shrinkage, with tangential shrinkage being up to three times higher than radial shrinkage. This study aims to validate these findings while examining the influence of adhesive type and lamination orientation on shrinkage rates. The results are expected to provide a quantitative relationship between cyclic moisture levels and shrinkage behavior, offering insights for optimizing glulam manufacturing and service life prediction models. This research contributes to improving the resilience and sustainability of wood-based materials in modern construction practices. Unlike prior studies that focused on individual softwood specimens, this research investigates glulam as a structural composite, considering adhesive effects and lamination orientation under cyclic moisture exposure

**Keywords:** Glulam, Cyclic humidity, Dimensional Change Coefficient, Fibre Saturation point, Timber structures

Timber glulam, also known as glued laminated timber, is an engineered wood product made by bonding together multiple layers of solid lumber with high-performance adhesives. It consists of individual pieces of lumber (lamellas) that are typically arranged in a parallel configuration and bonded together along their wide faces to form larger structural members such as beams or columns. Glued laminated timbers combine the strength and durability properties found in natural wood with enhanced performance characteristics achieved through engineering techniques. Timber species commonly used for producing glue-laminated components include spruce, pine, fir, larch, oak or hardwoods like beech. One significant advantage of timber glulam is its favorable strength-to-weight ratio compared to solid sawn beams or traditional materials like steel or concrete. By assembling different lengths and sizes into uniform sections using well-designed adhesive connections between lamellas during production process can result in stronger and stiffer members than equivalent-sized single-piece alternatives obtained from sawmills. Glued laminated timber is highly durable when properly manufactured with protective treatments like preservatives that increase resistance against insects, decay, fungi etc.

However, the durability of wood as a structural element is hindered by various issues. These include defects such as cracking, delamination of glulam beams, and attacks from fungi and insects in these structures. These result in a deterioration of the strength of glulam beams and can sometimes lead to structural failure. Excessive moisture content (MC) is often the main factor contributing to such defects, particularly variations in MC or cycles of wetting/drying (W/D) caused by climatic conditions [26]. These W/D cycles induce repetitive shrinkage/swelling mechanisms in the material, weakening its mechanical strength. Additionally, creep behavior also plays a significant role in the durability of timber structures. When wood is subjected to both mechanical loading and climatic cycles, its time-dependent deformation increases over time and can eventually cause failure (known as duration-of-load effect). All these phenomena significantly impact the lifespan of timber structures. Therefore, it becomes necessary to establish a relationship between the durability of glulam timber structures and their exposure to W/D cycles throughout their lifespan in order to predict residual life accurately and optimize maintenance operations [35].

To investigate the durability of structural timber under natural climatic conditions, researchers typically expose specimens to outdoor environments. However, this approach requires a lengthy testing period. Therefore, it is often necessary to conduct accelerated ageing tests to assess durability more efficiently. These tests commonly involve subjecting the material to controlled humidity and temperature conditions since moisture significantly affects hydrophilic materials like wood. The hydric ageing cycles used in these tests gradually lead to mechanical degradation due to heterogeneous shrinkage/swelling mechanisms within the wood [1]. Furthermore, the presence of moisture in the material reduces the glass transition temperature of its constituent polymers, resulting in changes in its mechanical properties as well.

While previous studies have focused on small clear wood specimens, limited research exists on how cyclic moisture affects shrinkage at a structural scale in engineered glulam softwood. This study aims to bridge this gap by systematically analyzing shrinkage behavior under cyclic wet and dry conditions. Understanding moisture-induced shrinkage in glulam is critical for optimizing design strategies in construction, reducing maintenance costs, and improving long-term durability [13]

## 1 Equilibrium Moisture Content

The equilibrium moisture content (EMC) of softwood is the moisture stage at which the timber stabilizes with its surrounding surroundings. normally, smooth-woods exhibit an EMC range between eight% and 15%, prompted through factors consisting of species, temperature, relative humidity, and geographic vicinity. it's miles essential to renowned that EMC values may additionally range barely across specific softwood species. maintaining manipulate over the moisture content of softwood is critical to ensuring dimensional stability and stopping defects like warping or cracking in its applications.

at some point of the lifespan of wood structures, fluctuations in ambient temperature and relative humidity result in versions in the EMC of structural wooden components. The moisture content (MC) of wooden performs a big role in determining its physical and mechanical conduct. wooden keeps moisture in forms: unfastened water gift within cellular cavities and certain water within the cell partitions. The Fibre Saturation factor (FSP) is reached while all unfastened water has been eliminated, leaving handiest sure water in the cell structure. normally falling among 25% and 30%, the FSP is drastically higher than the average MC of structural wooden, that's commonly around 12% [3]. This discrepancy underscores the susceptibility of structural wooden to environmental fluctuations.

### 1.1 Coefficients of Moisture Expansion/Contraction:

The moisture content (MC) of wood plays a crucial role in determining its physical properties, leading to either swelling or shrinkage, which are reflected in dimensional changes. The speed at which these changes happen is measured using the coefficients of moisture expansion (CME) and contraction (CMC), respectively. Because wood has an uneven structure, these coefficients are usually determined along three main directions: the direction of the wood's surface, the direction perpendicular to the surface, and the direction parallel to the surface. Extensive research has demonstrated that various wood species display unique CME and CMC values [11].

In significant timber structures, the radial and tangential directions are frequently combined and regarded as a single perpendicular direction to the grain for ease of analysis. Unfortunately, there has been very little research conducted on how temperature affects the swelling and shrinking of timber. To forecast long-term performance in changing environmental conditions, fixed values for shrinkage and swelling are typically used. Accurately evaluating CME and CMC across various temperature ranges is crucial for comprehending moisture-induced stresses in wood-based structural applications [26].

A.A. Chiniforush et al. conducted an extensive experimental study to investigate the influence of moisture and temperature on the shrinkage and swelling behavior of softwood glued-laminated (glulam) timber. Unlike previous research that primarily examined small, clear wood specimens, this study focused on larger samples at a structural scale. It provided an in-depth analysis of wood anatomy and the anisotropic characteristics of hygro-expansion and contraction. The findings, derived from tests on Slash Pine glulam at two distinct temperatures—15°C and 50°C—are discussed in this work.

## 2 Dimensional Changes

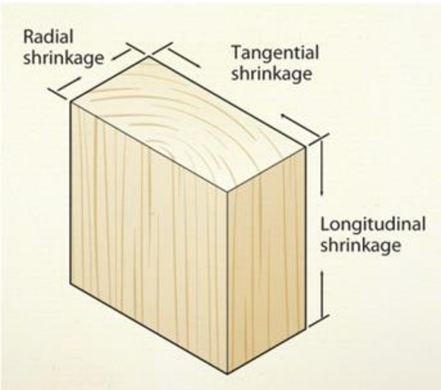


**Fig. 1.** Principal Direction of shrinkage in a small sample of wood.

The hygroscopic nature of timber products, attributed to the non-uniform composition of wood cell walls and their complex hierarchical structure, presents several challenges. Moisture-driven expansion and contraction can result in defects such as checking and splitting, significantly impacting lumber quality during the drying process and subsequent applications. It is important to note that hygro-expansion and contraction are influenced not only by moisture content but also by the density of the wood.

The overall volumetric expansion of wood due to moisture uptake is considerably lower than that of individual cell-wall components, primarily because the outer layers impose constraints. Research has shown that the maximum shrinkage and swelling of wood cell walls follow a linear relationship with both the fibre saturation point (FSP) and specific gravity. Stamm and Loughborough demonstrated that even when the cell wall exhibits anisotropic behavior, volumetric shrinkage and swelling are not affected by void fraction but instead correlate linearly with wood density. This supports the hypothesis that during the processes of swelling and shrinkage, the volume of cell cavities remains largely unchanged. Multiple studies have reinforced this hypothesis, consistently finding that moisture-induced volumetric expansion is directly related to wood density, with FSP serving as the proportionality constant.

### 2.1 Dimensional Change Coefficient

According to the research conducted by Richard Bergman, dry wood exhibits minimal dimensional changes when subjected to normal fluctuations in relative humidity. When the humidity is higher, there is a slight increase in size, whereas lower humidity levels cause a slight decrease in size. These changes are much smaller compared to the shrinkage that occurs from the green condition. Equation 2 can be employed to calculate dimensional changes resulting from shrinking and swelling, utilizing the total shrinkage coefficient from green to oven-dry conditions. Nevertheless, this equation assumes a linear relationship between shrinkage and moisture content (Comstock 1965). In real-world scenarios, moisture content variations usually stay within a narrow range of 6% to 14%, where the relationship between shrinkage and moisture content follows a linear pattern. As a result, a set of dimensional change coefficients (DCCS) derived from equation1 was created using the linear portion of the shrinkage-moisture content curve. The tangential direction, determined by the dimension at 10% mc, is calculated as follows.

$$C_T = \frac{1}{\left(\frac{100FSP}{S_T}\right) - FSP + M_I} \quad (1)$$

where ST is tangential shrinkage (%) from green to oven-dry (based on dimension at green condition), CT is DCC tangential direction (for radial direction, use CR), FSP is fiber saturation point (assumed at 30% MC unless noted otherwise), and MI is 10% MC. The corresponding equation can be used for the radial direction.

### 2.2 Change in Dimension in Dry State

The change in dimension (ΔD) can be calculated using the dimensional change coefficient (CT or CR) for either the tangential or radial direction, respectively [15-17]. A satisfactory estimation of dimensional changes within the moisture content range of 6% to 14% can be achieved by utilizing a dimensional change coefficient derived from the dimension at 10% moisture content:

$$\Delta D = D_I[C_T(M_F - M_I)] \quad (2)$$

The initial dimension at the start of the change is represented by DI, while MF and MI denote the moisture content (%) at the end and start of the change, respectively. The values for CT and CR can be obtained from total shrinkage measurements. If MF < MI, then (MF - MI) will yield a negative value indicating a decrease in dimension. Conversely, if MF > MI, it will result in a positive value indicating an increase in dimension [2-3].

## 3 Experimental Methodology

As per the study conducted, softwood samples of glulam, specifically Slash Pine (SP, Pinus elliottii), were prepared. Two sets of samples were conditioned at different temperatures, namely 15°C and 50°C, to investigate swelling and shrinkage during sorption and desorption cycles. Each set consisted of 126 samples. Half of these samples were oven-dried while the other half were water-saturated to facilitate sorption and desorption cyclic tests.

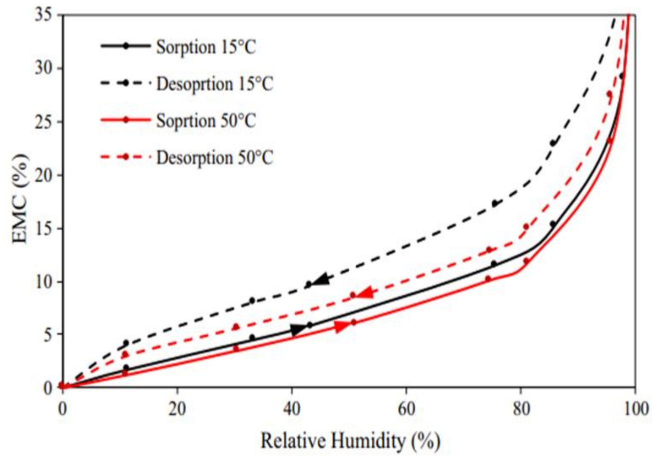


**Fig.2.** Sorption-desorption isotherm (Equilibrium Moisture Content (EMC) vs Relative Humidity) for SP glulam [2]

During the sorption process, half of the Slash Pine (SP) glulam samples were oven-dried at 104°C, with their weights recorded at successive intervals. After drying, the samples were placed in a sealed desiccator containing silica gel to prevent moisture reabsorption. Once stabilized, their dimensions were measured before being gradually conditioned to achieve the target moisture content levels. This was done using different aqueous salt solutions, as detailed in Table 1, to regulate humidity.

**Table.1.** Equilibrium relative humidity obtained using various aqueous salt solutions [2]

| Salt Solution | $15^0$C | $50^0$C |
|---|---|---|
| Lithium Chloride | 11.3 | 11.1 |
| Magnesium Chloride | 33.3 | 30.5 |
| Potassium Carbonate | 43.2 | - |
| Sodium Bromide | - | 50.9 |
| Sodium Chloride | 75.6 | 74.5 |
| Potassium Chloride | 85.9 | 81.2 |
| Potassium Sulphate | 97.9 | 95.8 |

The samples were stored in desiccators with maximum stabilization times of less than one week at 50°c and two weeks at 15°c, as determined by successive weighting measurements. After conditioning, all samples achieved saturation by being immersed in undisturbed water after each weighting measurement.

The desorption process was carried out in reverse order, starting with saturating the samples in distilled water, followed by oven-drying them, and finally allowing them to cool in desiccators containing silica gel. Throughout the sorption and desorption processes, weight measurements were taken at each stage to determine the moisture content (mc), and dimensional changes were recorded to evaluate swelling strain. To guarantee accurate width and height measurements, a modified concrete shrinkage rig, along with steel calibration bars, was employed.

The average changes in size and volume, as well as the overall swelling and shrinkage, were determined. Furthermore, the changes in volume due to moisture content were calculated using the coefficients of moisture expansion and contraction.

## 4 Results & Discussions

Figures 4(a), (b), and (c) demonstrate the expansion and contraction of various wood species in response to variation in moisture content (MC). The incline of the curves in these figures indicates the CME during the process of sorption and the CMC during desorption [2]. At 15°C, a fall in the initial measurement is noted because the first measurement was taken at a higher temperature (104°C) instead of at 15°c. While this temper

related effect is relatively small with respect to the overall dimensional changes—averaging $65\times10^3$ mm/mm—it can be neglected when studying moisture-induced expansion and contraction in the horizontal direction. Figure 4(b) emphasizes this in softwood glulam specimens, especially for MC values below the fibre saturation point (FSP). Raising the temperature from 15°C to 50°C led to a significant decrease in CME values for softwood glulam specimens when placed vertically.

Figure 4(c) suggest varied patterns of expansion and contraction observed in the horizontal and vertical directions. On average, the total shrinkage/swelling strains and CMEs of soft-wood glulam along the longitudinal axis were found to be 35. 6, 41. 4, and 28. 4 times smaller than those recorded in the transverse directions. Nevertheless, at a temperature of 50°C, these values were significantly diminished to 26. 0, 34. 9, and 22. 8 times smaller than their counterparts in the transverse direction.

Unlike the transverse directions, where CME values decreased with increasing temperature, CME in the longitudinal direction increased as the temperature rose

from 15°C to 50°C. At 15°C, CMCs were slightly higher than CMEs along the longitudinal direction, whereas at 50°C, CMCs became smaller than CMEs. This reversal is attributed to the Poisson effect, which dictates that an increase in shrinkage/swelling in the horizontal and vertical directions must be accompanied by a corresponding decrease in the longitudinal direction. Similar trends have been reported in previous studies on specimens exposed to elevated temperatures. The intensified Poisson effect is particularly evident in Slash Pine (SP) glulam during desorption cycles, where it results in a negative slope for MC values above the FSP.

subjected to increased temperatures. The intensified Poisson effect is evident in SP's longitudinal direction during desorption cycles, resulting in a negative slope for MC values above FSP

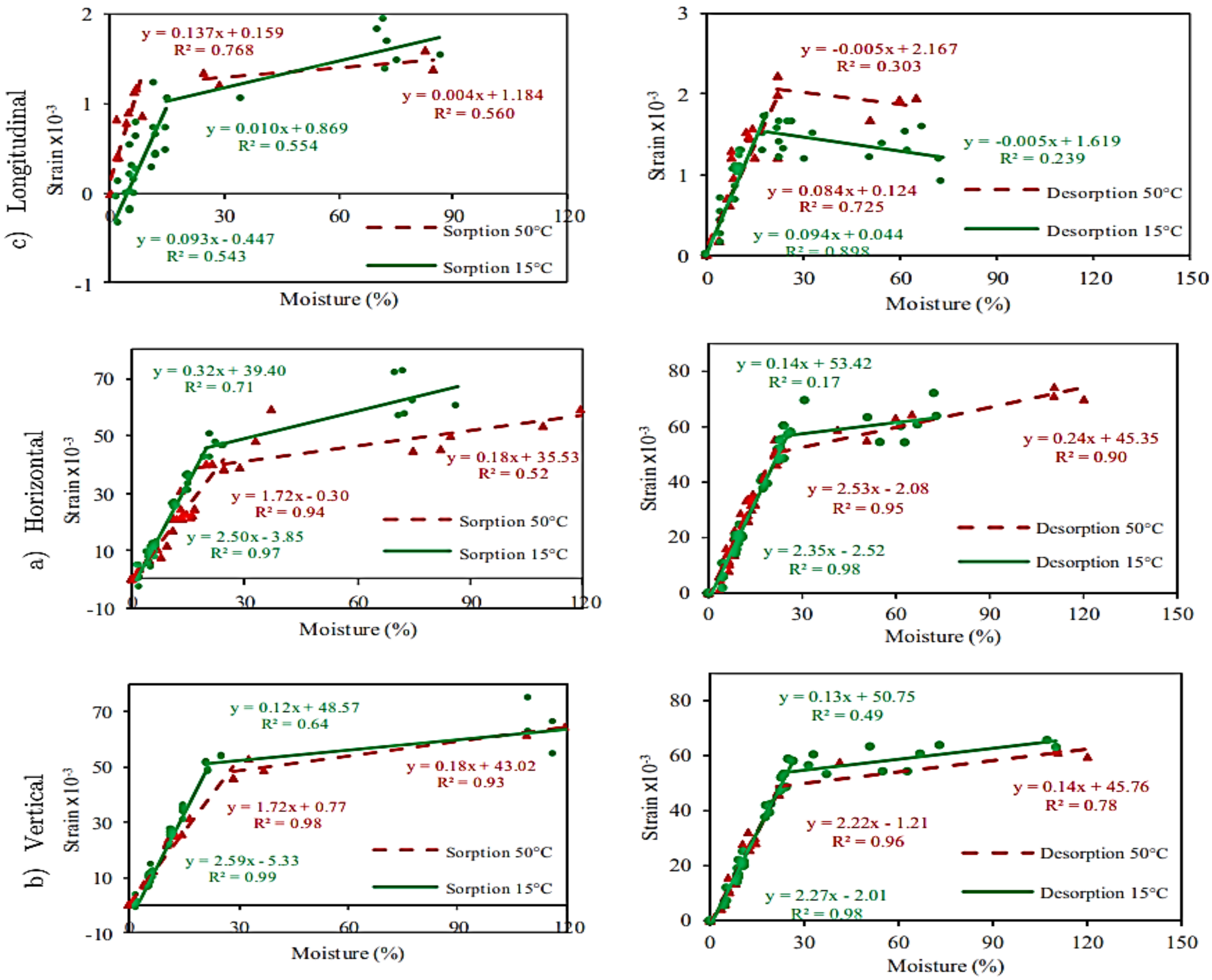


**Fig.3.** Moisture expansion & contraction of Slash Pine (SP) under sorption and desorption cycle (a) horizontal, (b) vertical and (c) longitudinal direction [2]

## 5 Conclusions

This study aimed to determine the fibre saturation point (FSP), coefficient of moisture expansion (CME), coefficient of moisture contraction (CMC), and coefficient of thermal expansion (CTE) for softwood glulam in both transverse and longitudinal directions. The main results from the sorption/desorption tests are summarized as follows:

1. 1. temperature has a negligible effect on the FSP of softwood glulam.
2. Increasing the temperature from 15°c to 50°c resulted in a substantial decrease—up to 65%—in CME and CMC values in the transverse direction. Nevertheless, in the direction of the longitudinal axis, higher temperatures led to higher CME and CMC values. As the moisture content in the wood exceeds the fibre saturation point (FSP), the reduction in CME and CMC becomes more significant.

3. The effects of temperature-induced shrinkage and swelling are more noticeable in the direction of the longitudinal axis than in the transverse directions. In general, the CMEs and CMCs measured along the longitudinal axis were considerably smaller than those observed in the transverse directions. The CMEs and CMCs measured along the longitudinal axis were considered to be smaller than those observed in the transverse directions.
4. The ratio of the height to width (transverse) of softwood glu-lam beams was calculated to be approximately 0. 97 ± 0. 13. This differs from the ratios reported for small clear wood samples with distinct radial/tangential orientations, which typically range from 0. 5 to 0. 6 [2]. The ratio of the tangential to the radial component of the refractive index is a function of the refractive index of the material and the angle of inci-

dence. This difference in expansion may be due to the specific adhesive properties or the combined radial and tangential expansion observed in larger structural samples or laminated engineered wood, resulting in more uniform expansion across the transverse plane.

The study underscores the need for further research using numerical multi-scale models to analyze the interactions between temperature and moisture content. Additionally, it highlights the lack of comprehensive studies that integrate numerical multi-scale modeling with micro-scale experiments to assess the significant influence of temperature on variations in CME and CMC.

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