



Vertical Deformations in Tall Timber Buildings: Sources and In-Field Estimations

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Abstract. Tall timber building 'structural components may undergo severe vertical deformations due to the action of different loads/load combinations during their lifetime. These deformations, basically unusual or negligible for low and mid-rise buildings 'components, could harshly affect the overall stability of TTBs; therefore, specific estimation methods and mitigation intervention must be established. A deeper understanding of the short- and long-term deformation behavior of large span and highly loaded components is crucial for improving future design possibilities for TTBs, particularly concerning serviceability during both construction and operational phases. In the following paragraphs, an overview of the current analytical formulations and experimental methods for the estimation of vertical deformations is provided. Firstly, since for practitioners it is essential to adopt clear formulation, the provision included in the main standards are discussed. Secondly, the discussion concerns the experimental methodology for the assessment of in-situ vertical deformations.

Keywords: Vertical deformations · Axial shortening · Axial shrinkage · Connection settlements · Brittle failures

1 Introduction

In the context of developing high-rise structures, the vertical carriers play a predominant mechanical role (Fig. 1). Differential shortening in high-rise building structures is a well-documented phenomenon in the literature [1–3]. It arises from two primary factors: (i) variation in axial loading/moisture conditions within structural elements, and (ii) differences in the design of adjacent vertical load bearing elements. Due to these differences, the reaction of the adjacent vertical structural elements expressed as length change can be different [4]. At the serviceability limit state, the cumulative compressive deformation generates vertical displacements that can no longer be ignored or neglected [5].

In the following, an overview of deformation methods provided by Standards is discussed, with the aim to highlight the current situation and the gap of knowledge: Then, novel proposals and experimental campaigns carried out in situ are summarized.



Fig. 1. Example of timber structure. Figure reproduced from [6] under the terms and conditions of a CC-BY license agreement.

2 Source of Vertical Deformations

According to [7] the main sources causing vertical deformations in tall mass timber structures can include: axial shortening including creep, shrinkage on beams, columns and panels, crushing perpendicular to the grain on beams and panels, connection tolerances and joint settlements.

2.1 Axial Shortening

The main source of short-term axial shortening on columns are gravity loads acting on them. A variable that can affect column axial shortening is the fire-resistance rating (FRR) of the column, which can require a cross-sectional area oversizing for fire purposes. The considerations for shortening of mass timber bearing walls are similar to those for mass timber columns, although the magnitude of anticipated vertical movement will likely be lower. Due to the continuous nature of these systems and their uniformly supported loads, vertical movements would be expected to be low. For systems such as CLT, vertical movement is typically restrained by horizontally oriented laminations, making for a more dimensionally stable wall panel [7]. An additional contribution to columns 'axial shortening is due to creep effect under long-term loading conditions. Three primary components contribute to the total creep deflection of a structural timber element. These three components are: (i) time-dependent or viscoelastic creep which mostly depends on the stress-level, the temperature and moisture, (ii) mechano-sorptive creep due to moisture changes and (iii) pseudo-creep that is attributed to swelling and shrinkage of the timber.

2.2 Axial Shrinkage

Another source of deformation comes from the shrinkage of timber. This change of dimensions is due to the hygroscopic behavior of timber which absorbs and releases moisture from the surrounding environment.

Due to the cellular structure of wood, shrinkage in timber elements occurs primarily perpendicular to grain, meaning that shrinkage effects on a timber member are much more significant in its width and depth than its length. This means that the main deformation due to shrinkage would affect beams or floor joist which will shrink in their cross-section dimensions while their length will remain unchanged. In multi-story buildings, wood shrinkage is therefore concentrated at the wall plates, floor and roof joists, and rim boards. The total shrinkage in conventional framed buildings can be determined by summing the estimated shrinkage of horizontal lumber members in walls and floors, such as wall plates and floor joists [8].

The American Softwood Lumber Standard (PS 20) offers a general guideline for calculating shrinkage in most softwood species. It specifies that for every 4% point reduction in moisture content below the fiber saturation point, there is a corresponding 1% shrinkage. This corresponds to a shrinkage coefficient of 0.0025.

Nevertheless, the shrinkage S , could also be calculated as Eq. (1):

$$S = D \cdot M \cdot C \quad (1)$$

Being D one of the dimensions of the cross section, M the change in moisture content expressed as percentage and C the shrinkage coefficient.

In wood-frame buildings of three or more stories, cumulative shrinkage can be significant and have an impact on the function and performance of finishes, openings, mechanical/electrical/plumbing (MEP) systems, and structural connections.

Since the column-to-beam zone is one of the most critical for vertical movement due to shrinkage in the beam cross section, [7] provided an alternative solution to the “traditional” platform-frame detail in which the upper column stands on the floor panel supported by the beam. The suggested choice would imply to notch the lower column to create a shelf to host the beam or to use a steel device to connect the upper and lower column and so eliminate the cross-grain shrinkage zone.

2.3 Crushing Perpendicular-to-the-Grain

Due to the reduced strength of timber members in the direction perpendicular to the grain, they are susceptible to isolated crushing. This must be accounted when designing structural components, especially given the potential vertical movements that may arise from the aforementioned factors. Certain configurations, such as steel-on-timber bearing conditions where timber is loaded perpendicular to the grain, increase the likelihood of crushing. This configuration is typical of TTBs with post and beams and diagonals as lateral load resisting system, in particular the joint made of slotted-in steel plates that connect diagonals to the continues beams generates on it pressure in the direction perpendicular to the grain which can cause crushing. This issue can partially be solved by using steel plates on top of and underneath the beam at the location of the connection to spread the force over a larger area [9].

2.4 Joint Settlement

According to the National House Building Council (NHBC) [10] provisions, joints should be detailed to accommodate the expected amount of shrinkage or expansion

safely and provide an additional allowance for the residual thickness of any compressible filler materials after movement has occurred. Nevertheless, quantifying the joints vertical movement in the design phase is challenging firstly due to the complexity to estimate the connections ‘stiffness’ and then to their interaction with the surrounding structural and non-structural components. Due to the nature of timber and other construction materials (i.e. concrete) it is never actually possible to create fully fixed end conditions on timber members which compose the systems and most often connections are semi-rigid [11].

Additionally, although mass timber is often fabricated with exceptionally tight tolerances for overall size, as well as size and locations of holes, notches and any other alterations, and can be constructed to within as little as ± 1.58 mm. of the specified dimensions, this tolerance cannot be overall settled since the attachment of mass timber elements to other materials could require larger tolerances [12].

3 Standard Formulations and Main Gap

3.1 US Codes

Council (ICC) [13] provides at Chapter 35 a list of referenced standards, which represent consensus on how a material, product or assembly is to be designed, manufactured, tested or installed to achieve a specified level of performance.

For timber the aforementioned standards are the National Design Specification (NDS) for Wood Construction published the American Wood Council (AWC) [14] and the product standards for cross laminated timber (ANSI/APA PRG 320) [15] and glulam (ANSI 190.1) [16]. Additionally, regardless of the framing type, IBC Section 2304.3.3 requires that designs for buildings over three stories consider the fact that wood shrinks as it dries. It stipulates that shrinkage in a wood building not have adverse effects on systems such as roof drainage, electrical, mechanical, or other equipment.

None of the current standards explicitly address vertical movements in TTBs or consider the effects of creep and long-term behavior in compressed elements. For instance, Chap. 3.5.1 and Annex F of the NDS only account for the additional deformation caused by long-term loading in the deflection formulation for bent members. In such cases, the total deflection Δ_T is calculated according to Eq. (2):

$$\Delta_T = K_{cr} \cdot \Delta_{LT} + \Delta_{ST} \quad (2)$$

Being K_{cr} the time dependent deformation creep factor, Δ_{LT} the immediate deflection due to the long-term component of the design load and Δ_{ST} the deflection due to the short-term or normal component of the design load.

3.2 Eurocode 5

Eurocode 5 integrates the effect of creep on the long-term behavior of wood structures only in the case of the calculation of the deflection of bending elements and in the long-term stiffness of fasteners. This consideration has been reflected by an amplification of the deflections through a coefficient k_{def} modulated by the duration of the given loading and service class [7].

3.3 Gap of Knowledge

The aforementioned codes and standards lack explicit guidance on certain aspects of vertical movement in tall timber structures. For instance, they do not provide detailed procedures for calculating shrinkage in wood members or the creep factor for axial shortening in columns. Consequently, engineers must rely on supplementary analyses and assumptions to address these critical design considerations [7, 8].

Concerning the choice of the creep coefficient, most of the design engineers use creep coefficients determined for bending also for the calculation of the axial shortening.

4 Experimental Tests

The availability of long-term experimental data is a concern for the industry but there has been a significant effort to utilise finite element modelling to predict this behaviour over longer periods of time. Timber is a challenging material to model numerically due to its natural variability in properties and anisotropic behaviour; however, in recent years, timber has been modelled successfully under long-term loading situations thereby increasing the reliability and safety of structural timber design. The recent advances in the modelling of the creep behaviour of timber by [17–19] have resulted in validated fully coupled three-dimensional moisture-displacement models that can be used to predict the long-term behaviour of timber elements under varying climates and relative humidity conditions. Experimental monitoring of the long-term behaviour of engineered wood products is a costly and time-consuming process and the benefits of a validated model will provide a powerful tool to aid the further development of such engineered wood products in the future. This is coupled with a significant effort around the world to instrument and monitor some of the many demonstrator structures using CLT and novel mass timber solutions [20, 21]. Other studies monitoring elements such as CLT shear walls and Timber Concrete Composite (TCC) beams are also being successfully utilised in a number of structures as novel solutions to examine the deformation performance and the vibration criteria. Similar numerical studies of this technology were analysed in [22, 23] with modelling efforts proving successful. Fragiaco & Ceccotti [22] developed a validated model based on two long-term experimental tests in outdoor conditions. Despite some uncertainties in environmental conditions and material properties, a good fit between experimental and numerical results was obtained. Binder et al. [23] examined and compared TCC and CLT panels and demonstrated similar creep behaviour after a 50-year design life based on a numerical study. Baas et al. [24] and Riggio et al. [21] reported on the structural health monitoring data collected during the construction of Peavy Hall, a mass-timber university building which focused on creating a comprehensive building performance dataset, including static and hygrothermal data collected during the phases of building construction. These data were used to validate a proposed methodological approach to structural health monitoring for mass-timber buildings under construction, potentially encompassing aspects related to creep behaviour through the monitoring of wood moisture content, displacements, and tension loss in structural components [24]. This study provides insights into the hygrothermal performance of mass timber structures during construction, which is a critical aspect affecting the long-term structural

behaviour, including creep and future data will aid the design of taller timber buildings, however, there still remains a gap in the knowledge related to the long-term creep performance of timber buildings.

Jockwer et al. [25] examined the long-term behaviour of timber columns in Arbo, a tall timber building with RC core and timber skeleton in Switzerland consisting of 15 floors. Fibre optic sensors were used to measure the strain in the building components over a length covering 8 storeys from the floor on the ground level first floor to the ceiling of the eighth floor (Fig. 2). In Fig. 2 the measurement numbers represent the height of the timber structure during the construction stage: measurement no.1 is associated with 2 floors already realized, measurement no.2 is associated with 4 floors realized,

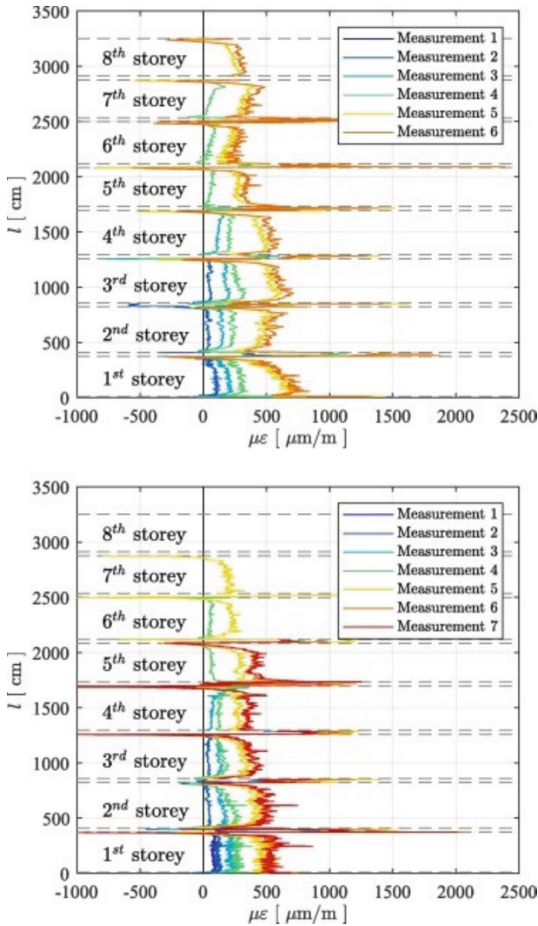


Fig. 2. Experimental strain from the test carried out by [25]. Strain development along the column positions “wall” (top) and “corner” (bottom). Measurement data is expressed in micro-strain ($10^{-4}\%$) and interval length between the individual measurement points is 1.02 cm. Positive measured values correspond to a compression of the elements. Figure reproduced under the terms and conditions of a CC-BY license agreement.

measurement no.3 is associated with 7 floors already realized, measurement no.4 is associated with 9 floors realized and measurement from 5 to 7 were taken with the entire number of floors equal to 15.

Their research demonstrated the increased deformation due to the addition of load during the construction phase within the spruce glued laminated timber columns and beech LVL columns. The deformation of the columns was compared to model calculations to compare the deformation of individual timber elements and the total deformation experienced. Furthermore, their study indicated that approximately 25% and 8% of the total deformation after 420 days of monitoring can be attributed to viscoelastic and mechano-sportive creep, respectively and comparison with current structural design codes show that the conservative results are provided for highly stressed timber columns.

5 Conclusions

Tall timber buildings are subject to significant vertical deformations due to several factors such axial shortening, shrinkage, crushing, and joint settlement. Current design codes offer limited guidance on these long-term effects, particularly for axial components. Experimental studies and advanced numerical models are helping to fill this gap by improving understanding and prediction of deformation behavior. To support the safe growth of tall timber construction, future standards must better integrate these insights for more accurate and reliable design.

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