FIELD MEASUREMENT OF VERTICAL MOVEMENT IN WOOD CONSTRUCTION

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ABSTRACT

Vertical movement in buildings due to changes in environmental conditions and loads must be considered at the design stage to ensure structural safety, serviceability, and building envelope durability. For a wood or wood-hybrid building, considerations for differential movement occurring between wood and rigid components (e.g., concrete / masonry elevator shaft, masonry cladding), between different environments (e.g., interior and exterior walls), and between different materials (e.g., solid-sawn, engineered wood) becomes particularly important for mid-rise and taller buildings due to its cumulative effect. Vertical movement in a wood structure is primarily caused by shrinkage resulting from wood drying and load-induced deformation, with the former typically being dominant and loads contributing only a small amount. For purposes of assessing the impact of various factors involved and improving the prediction of vertical movement in design, field measurement of vertical movement in four buildings, including 4-, 5-, 6-storey light wood-frame buildings in Metro Vancouver, and a 6-storey mass timber building (Wood Innovation and Design Centre) in Prince George were carried out using sensors installed after topping out of the structure. It was found that the amount of vertical movement was affected by the type of structure (e.g., light platform-frame, mass timber), materials (e.g., dimension lumber, engineered wood products), construction season and MC, and loads. For example, the movement amount reached 45 mm (i.e., about 11 mm/floor or 0.41%) at an interior partition wall of the 4-storey building, framed under wet weather conditions. In the 6-storey wood-frame building built with engineered wood floor joists, the shortening of interior walls was about 6 mm/floor (0.21%). In the 6-storey mass timber building using glulam columns and cross-laminated timber walls for bearing loads, two glulam columns each showed vertical movement below 3 mm (i.e., 0.04%) with a height of over 5 m and 6 m, respectively. The cumulative shortening of the six glulam columns along the height of the building is expected to be approximately 11 mm (i.e., 2 mm/floor).

INTRODUCTION

Vertical movement in buildings must be considered at the design stage to ensure structural safety, serviceability, and building envelope durability. Almost all building materials move slightly resulting from changes in environmental conditions and loads. The vertical movement of wood in a gravity load path of a building is caused by shrinkage or swelling due to moisture content (MC) changes, and load-induced deformation including instant compression and time-dependent deformation, i.e., creep (Wang and Ni, 2012). In addition, vertical movement over the height of a wood-frame building is caused by closing of the gaps between elements arising from manufacturing and construction tolerances under loads.

The relative contributions of MC change and loads were assessed by measuring vertical movement under changing MC conditions using two simulated loaded platform frame structures in laboratory, and it confirmed that wood shrinkage was a major cause and loads had a smaller effect (Wang and King, 2015). Related to the design and construction of a wood or wood-hybrid building, differential movement is the concern and it can occur between wood and rigid components (e.g., concrete / masonry elevator shaft, masonry cladding), between different environments (e.g., interior and exterior walls), and between different materials (e.g., solid-sawn, engineered wood). Taking into account differential movement in design becomes particularly important for mid-rise and taller buildings due to its cumulative effect. It was identified to be one of the major concerns of design when the building code was changed in British Columbia in 2009 to allow 5- and 6-storey wood-frame residential construction (Professional Engineers and Geoscientists of BC and Architectural Institute of BC, 2009).

FPInnovations started a vertical movement monitoring project in 2010 to assess the impacts of climate, structural type, material use, and construction methods on vertical movement, and help validate movement estimation methods; very little data were available at that time (Wang and Ni, 2012). This paper provides an overview about field measurement in four buildings, including 4-, 5-, 6-storey light wood-frame buildings in Metro Vancouver and a 6-storey mass timber building, i.e., the Wood Innovation and Design Centre (WIDC) in Prince George and comparisons between measured building shortening and calculated wood shrinkage to help improve the prediction of vertical movement in design.

MATERIALS AND METHODS

Construction Information

4-, 5-, and 6-Storey Wood-Frame Buildings

The three light wood-frame residential buildings, 4, 5, and 6 storeys tall, respectively were built with similar platform-frame structure by the same company in the same coastal climate of British Columbia (Wang et al., 2013; Wang and Ni, 2014; Wang, 2016). The buildings used similar materials of "S-Dry" dimension lumber, mostly with nominal 2 in. by 6 in. (in actual dimensions of 38 mm by 140 mm) for wall plates and studs. The major difference in material use was dimension lumber floor joists (nominal 2 in. by10 in. with actual dimensions of 38 mm by 235 mm) were used in the 4-storey building as a common practice in low-rise wood-frame construction in Canada, but engineered wood floor joists including laminated strand lumber rim joists and I-joists (with OSB as the web and laminated veneer lumber as the flange, with an actual depth of 235 mm) were used in the 5- and 6-storey buildings to reduce vertical movement. "S-Dry" is a lumber designation in North America indicating that the MC is 19% or below when it is planed or surfaced to the standard lumber dimensions. The Canadian building code requires that the MC of lumber shall be not more than 19% at installation (NRC, 2010). This is usually interpreted in practice that the MC of wood shall be not more than 19% at enclosure. Being similar among these three buildings, double-stud party walls were built between suites and staggered-stud walls were built for hallways. The buildings all had double layers of top and bottom plates except on the first floor. Movement of sill plates was not measured nor discussed in this paper[1]. Plywood was used for

[1] It is estimated that a single layer of wall plate has vertical movement of about 0.8 mm (Table 3).

subflooring. Table 1 summarizes the major wood members used in these three buildings that could contribute to vertical movement, together with their dimensions. In addition to material use, construction seasons, which affect the MC of wood during construction (Wang, 2017), varied. The 4-storey building was framed from September to December, 2010 and the wood was exposed to excessively wet weather before it was sheltered by the roof and exterior walls. The 5-storey building had two phases, with Phase A framed from February to June, 2011 under wet weather conditions and Phase B, framed from June to October, 2012, in much drier weather. The 6-storey building was mostly framed over the summer of 2014 but with the last framing stage exposed to wet weather. The MC of dimension lumber remained on average about 20% when exposed to the wet weather in the winter in the coastal climate, and about 15% under warmer and drier conditions in the summer (Wang et al., 2013; Wang and Ni, 2014; Wang, 2016).

Figure 1: Light wood platform-frame construction

Table 1: Major wood elements and their dimensions in three light wood-frame buildings

Building Element	4-Storey Building	5-Storey Building	6-Storey Building
Bottom/top plates	Dimension lumber, 2-layers at each location, 38 × 14 = 532 mm	38 × 18 = 684 mm	38 × 22 = 836 mm
Floor joists	Dimension lumber, 235 × 3 = 705 mm	Engineered wood, 235 × 4 = 940 mm	Engineered wood, 235 × 5 = 1175 mm
Wall studs	Dimension lumber, 2440 × 4 = 9760 mm	2440 × 5 = 12200 mm	2440 × 6 = 14640 mm
Subflooring	Plywood, 15.8 × 3 = 47.4 mm	15.8 × 4 = 63.2 mm	15.8 × 5 = 79 mm
Total height	11,044 mm	13,887 mm	16,730 mm

6-Storey Mass Timber Building

Vertical movement was measured in the WIDC building, a 6-storey mass timber building located in Prince George (Wang et al., 2016). The building has a height of 24.5 m for its main six floors, with a total height of 29.5 metres including the roof-top mechanical room. This building showcases the applications

and capacities of various wood products, including cross-laminated timber (CLT) core structure of an elevator shaft and staircases, glued-laminated timber (glulam) columns, CLT floors and roof structure, parallel strand lumber transfer beams, and laminated veneer lumber columns and structurally insulated panels (SIPs) in the exterior walls. Related to vertical movement, this building primarily uses glulam columns, which are connected using metal connectors along the height for bearing gravity loads, and CLT shear walls in the core of the building for bearing lateral loads.

Figure 2: Glulam columns and beams, and CLT panels in the roof structure of the WIDC building (courtesy of Michael Green Architecture)

Field Measurements

Similar instruments were installed in these four buildings to measure vertical movement. A type of draw wire displacement sensors, with a measurement range of 50 mm (Model WPS-50-MK30-P50) was used. Most sensors were installed after the roof sheathing was installed and the building was sheltered from rain in order to protect the sensors from water damage. The monitoring locations and the number of sensors installed in each building are summarized in Table 2. In the three light wood-frame buildings, a displacement sensor was installed for each floor to measure vertical movement at selected monitoring locations (Figure 3). The sensors for measuring the bottom floors each covered wood members including two bottom plates, wall studs, one floor joist, subflooring, and two top plates. The sensors for the top floor in each building only covered wall studs and top plates between the roof trusses and the wall studs below.

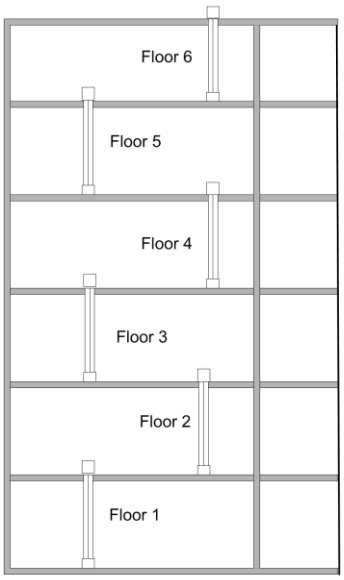

Figure 3: Illustration of installed displacement sensors on each floor in the 6-storey light wood-frame building

In the WIDC building built with mass timber, it was not possible to have a continuous measurement of vertical movement throughout the height of the building. There was a challenge of aesthetically concealing instruments using existing building elements. Unlike light wood frame construction, many members in the WIDC building, such as glulam columns, were designed to be fully exposed to the interior. Given the limited space available, measuring vertical movement was focused on glulam columns, with the displacement sensor covering the CLT floor above in a few cases at three locations (i.e., Locations 1, 3, 4 in Table 7; Figure 4). These measurements were focused on the three lower floors of the building. The major reason was that the top three floors were built to be tenanted spaces without interior finishes provided upon building completion; therefore concealing instruments within these unfinished areas became almost impossible. Design theory and previous research also supports that the vertical movement at lower floors will generally be greater than the upper floors due to the effect of gravity loads (Wang et al., 2013; Wang and Ni, 2014; Wang, 2016). In addition to glulam columns, the CLT wall of the core structure (Location 5, Table 7) was measured for vertical movement on the top five floors, where the CLT wall was to be covered with drywall after the instrumentation. A displacement sensor was installed from the CLT floor up to the ceiling, or up to the ledger below the ceiling on these floors. The CLT wall on the first mezzanine floor was not measured since the double high CLT wall was designed to be fully exposed to the interior. The original distance (gauge length) covered by each displacement sensor was measured to estimate the ratio between vertical movement and gauge length, and consequently the movement of the entire CLT wall. All sensors were connected to data loggers with data collected and transmitted hourly through a laptop installed inside each building.

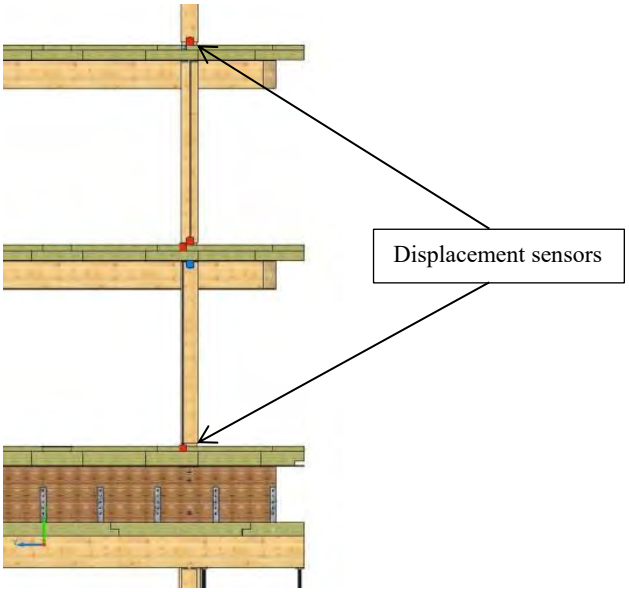

Figure 4: Displacement sensors installed in the WIDC building to measure vertical movement of glulam columns and CLT floors

Table 2: Measurements of vertical movement using displacement sensors in four buildings

Instrumentation Information	4-StoreyBuilding	5-Storey Building	6-Storey Building	6-Storey WIDC
Measurement locations	An interior hallway wall, an interior partition wall, an exterior wall	An interior hallway wall, an interior partition wall, an exterior wall in both Phases A and B	An interior party wall, a hallway wall, and a partition wall, plus bottom two floors of an exterior wall	Two glulam columns, glulam column together with CLT floor at three locations, and CLT wall on each floor from 2nd to 6th floor
Number of displacement sensors	One sensor for each floor, 12 sensors in total	One sensor for each floor, 30 sensors in total	One sensor for each floor, 20 sensors in total	14 sensors in total
Period of monitoring	17 months	21 months for Phase A and 17 months for Phase B	24 months	14 months

RESULTS AND DISCUSSION

Vertical Movement in Three Light Wood-Frame Buildings

A displacement sensor records any movement (i.e., vibration, shrinkage / swelling, load-induced closing of gaps and deformation, etc.) in the direction measured. Its readings in a long term, however, show downward movement, i.e., shortening resulting from wood shrinkage and load-induced movement in the building (Wang et al., 2013; Wang and Ni, 2014; Wang, 2016). Overall the displacement readings tend to have high fluctuations during the construction, resulting from vibration due to various construction activities adjacent to sensors (Figures 5-7). The downward movement, i.e., building shortening at this stage was primarily caused by the increase in loads resulting from installation of drywall and other interior and exterior finishing materials, before the wood could dry. Increased loads accelerate closing of

gaps between elements in the gravity load path, together with a small amount of deformation (i.e., compression). The displacement readings became more consistent, with reduced fluctuations after the major construction stages. The mechanisms for shortening gradually shifted towards wood shrinkage under warmer and drier service environments, for example, after the building was occupied, particularly when space heating was provided. In general the vertical displacement amounts levelled off after over one year in service, typically after the first heating season. The movement amounts of the bottom floors were generally higher than those of the upper floors at each line of measurement (Figures 5-6), and the interior walls had higher amounts of movement than the exterior wall (Figure 7). These differences are believed to be caused by differences in wood MC and loads. For example, exterior walls typically have higher MC than interior walls (Wang, 2016) and lower floors bear higher gravity loads than upper floors. The movement readings also showed seasonal changes, e.g., slight swelling due to higher indoor humidity in the summer. It appears that such changes were most obvious in the interior walls and on lower floors (Figures 6-7).

Both shrinkage and creep of wood in normal building service are slow movements and do not cause sudden changes and large fluctuations in vertical movement measurements. The readings from a number of displacement sensors installed in these three buildings started drifting with high fluctuations after the sensors were in service for over one year, probably due to loosening of the wire inside the sensor. For calculation purposes an estimate of vertical movement was provided to replace the displacement readings based on trend of the curve for each of those sensors. Summing up the measured movement amount of each floor, it was found that from top of sill plates to underside of roof trusses, the building shortening in the 4-storey wood-frame building reached about 43 mm at the interior hallway wall, 45 mm at the interior partition wall, and 34 mm at the exterior wall after a monitoring period of 17 months. In the 5-storey building, the downward vertical movement in two interior walls reached about 39 mm when it was framed in a wet construction season, and about 21 mm when it was framed under warmer and drier conditions. In the 6-storey building, the building shortening reached approximately 34 mm at the party wall, 35 mm at the hallway wall, and 37 mm at the interior partition wall, with an average of 35 mm for these three interior walls after a monitoring period of 24 months. The movement amounts of interior walls in these three buildings were assembled in Tables 4-6, together with calculated average building shortening per floor and the percentage of shortening relative to the total height of wood members (listed in Table 1).

The average building shortening per floor was the highest, reaching about 11 mm / floor in the 4-storey building, likely resulting from a combination of wet construction season and use of dimension lumber floor joists. The importance of construction season, i.e., wood MC during construction to building movement was clearly revealed by monitoring the two phases of the 5-storey building. The shortening/floor reached about 7.8 mm when it was framed in wet weather (Phase A) but only 4.2 mm when it was framed in warm and dry weather (Phase B), with engineered wood floor joists used in both phases. The shortening was about 5.8 mm / floor in the 6-storey building, i.e., between those measured from the two phases of the 5-storey building, when the same engineered wood floor joists were used but the construction season transitioned from dry to wet conditions. This work confirms that use of engineered wood floor joints and framing in dry weather are both important solutions to reducing building movement in light wood-frame construction. Related to this study, a modified balloon-frame structure was used in Sweden to reduce the amount of horizontal wood members in the load path of a 5-storey wood-frame building in order to reduce vertical movement, with measured shortening of about 4 mm /

floor based on five months' measurements (Thelandersson and Martensson, 2006). A similar amount of building shortening was reported for the 6-story platform-frame building built with specially dried lumber with an initial MC below 12% under sheltered conditions in the TF 2000 Project conducted in the United Kingdom (Grantham and Enjily, 2000).

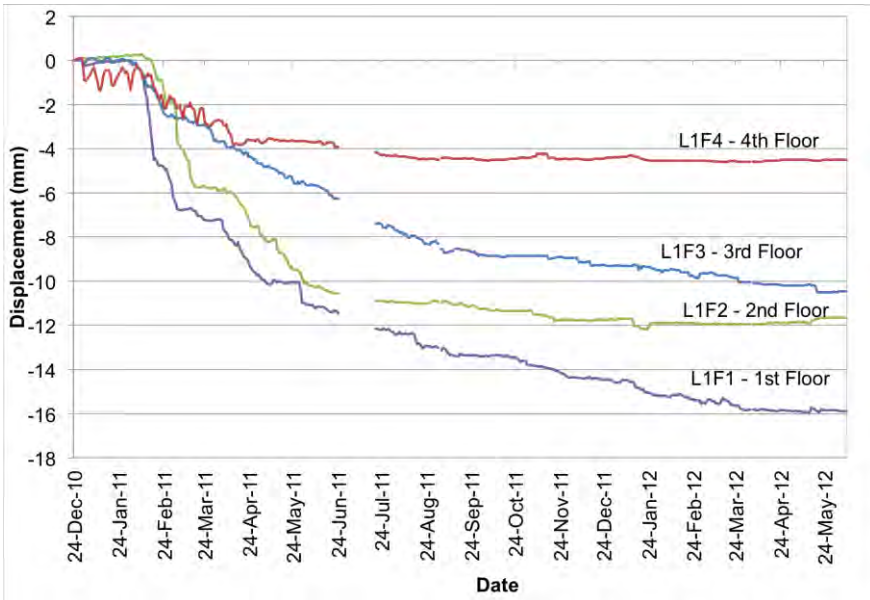

Figure 5: Vertical movement measured on each floor of the hallway wall of the 4-storey wood-frame building for 17 months

(Negative readings indicate building shortening)

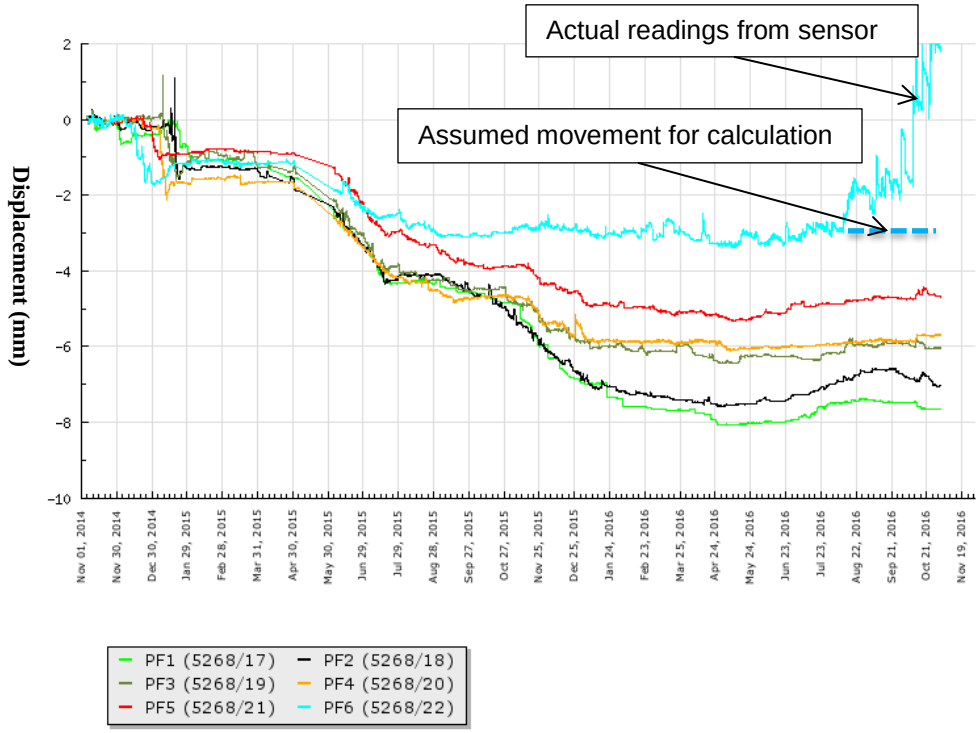

Figure 6: Vertical movement measurements at the party wall of the 6-storey wood-frame building for 24 months

(Chart legends: "PF" means "party wall" and the number in each label means the floor level. Negative readings indicate building shortening)

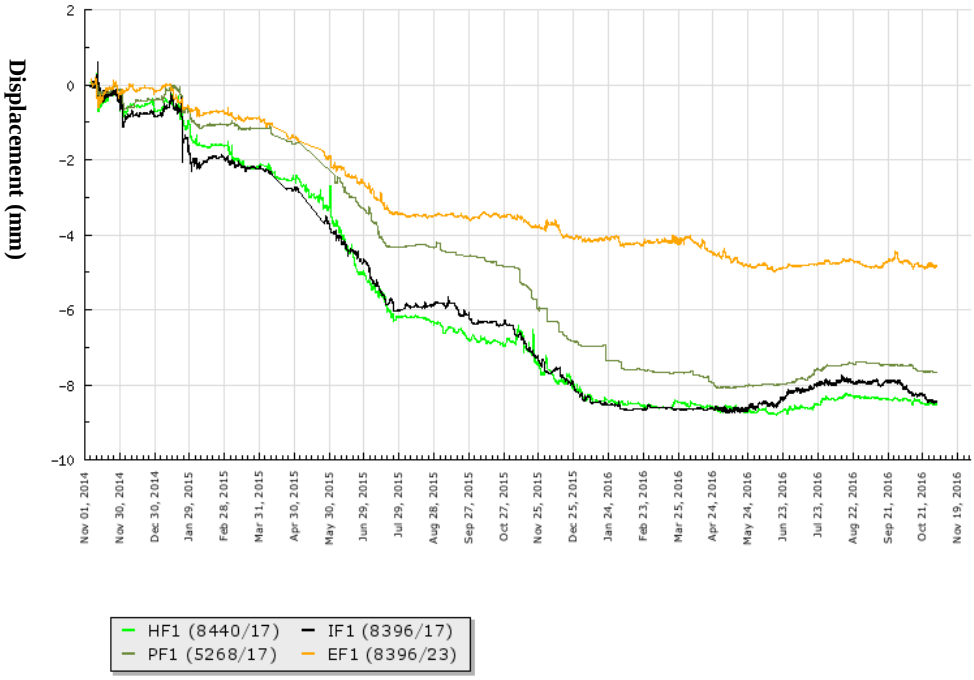

Figure 7: Vertical movement measured on the first floor of three interior walls and one exterior wall of the 6-storey wood-frame building for 24 months

(Chart legends: "HF" means "hallway wall", "IF" means "interior partition wall", "PF" means "party wall", and "EF" means exterior wall. Negative readings indicate building shortening)

The major purpose of this paper is to compare measured vertical movement and calculated shrinkage based on a calculation method commonly used in design. The effect of loads on vertical movement is required to be considered in engineering calculation in Europe (CEN 2004); however, it is not yet required based on relevant standards and design books commonly used in North America (CWC, 2011; Breyer et al., 2006; CSA, 2014). When predicting vertical movement of a wood-frame building, a designer typically calculates only the shrinkage of horizontal dimension lumber members (e.g., wall plates, floor joists). The contribution of engineered wood products, such as engineered wood floor joists, is typically ignored since those products have reduced dimensional changes compared with dimension lumber and solid-sawn timber. Moreover, little information is available for design use about their shrinkage coefficients or changes in MC during construction[2]. The contribution of vertical wall elements, such as wall studs, is also usually ignored in design of low-rise buildings due to wood's high dimensional stability in the longitudinal direction. However, the shrinkage of wall studs is often taken into account for a mid-rise building due to the accumulative effect over the increased building height (CSA, 2014).

Wood shrinkage was therefore predicted in this paper as the vertical movement in these three light wood-

[2] FPInnovations has a project underway to assess physical properties including sorption and dimensional changes of wood-based composite materials.

frame buildings, without taking into account load-induced movement or other factors (Table 3). The calculation accounted for only wall plates and studs, both dimension lumber elements, by using the following equation.

$$\mathbf{S = D \times C \times M}$$

Where S is the shrinkage amount (mm), D is the actual dimension of wood members in the load path (mm), C is the shrinkage coefficient (percentage per 1% change in MC), and M is the percentage of MC change (%), i.e., the difference between the MC during construction and the MC in service. A shrinkage coefficient of 0.2% per 1% change in MC was used to calculate the shrinkage of horizontal dimension lumber elements based on design recommendations (CWC, 2011; Breyer et al., 2006; CSA, 2014) and a coefficient of 0.005% per 1% change in MC was used for wall studs (FPL, 2010). The calculation used an initial MC of 19% given the use of "S-Dry" lumber and a service MC of 8% based on field measurements and design recommendations for this climate (CWC, 2011; Wang and Ni, 2014). The contribution of engineered wood floor joists was ignored. As another common practice in design, the contribution of plywood subflooring was also ignored because of its small dimension in the load path and the expected overall small contribution to vertical movement. There was also a lack of information for predicting the shrinkage and compression of subflooring materials.

Comparing the measured movement amounts and the predicted shrinkage showed that the measured building shortening exceeded the predicted shrinkage in all these three buildings, except for Phase B of the 5-storey building. The percentage points of underestimation ranged from 24% for the 6-storey building, 26% for the 4-storey building, to 44% for Phase A of the 5-storey building. For Phase B of the 5-storey building, which was framed under warm and dry weather conditions, the measured movement and the predicted shrinkage were very close. One reason should be that a higher initial MC, i.e., 19% was used for the prediction, instead of the lower actual MC (about 15%) during construction. This validation exercise suggests that the shrinkage calculation method used in this paper may severely underestimate building shortening that could occur in platform-frame construction, mid-rise buildings in particular. Given the contributions of loads and engineered wood members to vertical movement, a good margin of safety is therefore recommended for the design of mid-rise wood-frame buildings in order to avoid underestimation of vertical movement and to prevent potential consequences of differential movement. This was strongly recommended in the APEGBC Technical and Practice Bulletin on mid-rise wood-frame construction (Professional Engineers and Geoscientists of BC, 2011).

Table 3: Prediction of wood shrinkage for each wood member in a gravity load path of three light wood-frame buildings

Wood members covered by each displacement sensor	Dimension in load path (mm)	Shrinkage coefficient	Initial MC (%)	Service MC (%)	Calculated shrinkage (mm)
Wall plate	38	0.002	19	8	0.8
Wall stud	2440	0.00005	19	8	1.3
Dimension lumber floor joist	235	0.002	19	8	5.2
Engineered wood floor joist	235	-	-	-	0
Plywood subflooring	15.8	-	-	-	0

Table 4: Comparison between the measured vertical movement from two interior walls and the calculated shrinkage for the 4-storey wood-frame building

4-Storey	Hallway wall	Interior partition wall	Average measured movement (mm)	Calculated shrinkage (mm)	Difference (mm)	Underestimation (%)
1	15.9	14.2	15.1	9.9	5.2	34.2
2	11.7	17.1	14.4	9.9	4.5	31.3
3	10.5	11.3	10.9	9.9	1.0	9.2
4	4.5	2.6	3.6	3.0	0.6	15.5
Entire building	42.6	45.2	43.9	32.7	11.2	**25.5**
/Floor (mm)	10.7	11.3	11.0	8.2	2.8	-
Shortening ratio (%)	0.39	0.41	0.40	0.30	-	-

Table 5: Comparison between the average vertical movement amounts measured from two interior walls and the calculated shrinkage for the 5-storey wood-frame building

5-Storey	Phase A (wet season)	Phase B (dry season)	Calculated shrinkage (mm)	Phase A, difference (mm)	Phase B, difference (mm)	Phase A, underestimation (%)	Phase B, underestimation (%)
1	11.0	8.0	4.7	6.3	3.3	57.3	41.3
2	9.0	7.0	4.7	4.3	2.3	47.8	32.9
3	7.0	5.0	4.7	2.3	0.3	32.9	6.0
4	9.0	1.0	4.7	4.3	-3.7	47.8	-
5	3.0	0.0	3.0	0.0	-3.0	0.0	-
Entire building	39.0	21.0	21.8	17.2	-0.8	**44.1**	Prediction close to measured movement
/Floor (mm)	7.8	4.2	4.4	3.4	-0.2	-	-
Shortening ratio (%)	0.28	0.15	0.16	-	-	-	-

Table 6: Comparison between the vertical movement amounts measured from three interior walls and the calculated shrinkage for 6-storey wood-frame building

6-Storey	Average measured movement (mm)	Calculated shrinkage (mm)	Difference (mm)	Underestimation (%)
1	8.1	4.7	3.4	42.0
2	6.7	4.7	2.0	30.2
3	6.4	4.7	1.7	26.6
4	5.7	4.7	1.0	17.1
5	5.5	4.7	0.8	14.5
6	2.5	3.0	-0.5	-
Entire building	34.9	26.5	8.4	**24.1**
/Floor (mm)	5.8	4.4	1.4	-
Shortening ratio (%)	0.21	0.16	-	-

Measured Vertical Movement in Mass Timber Building

The WIDC building was located in Prince George, a cold climate (Climate Zone 6 based on the 2011 National Energy Code of Canada for Buildings (NRC 2011); climate Dfb according to the Köppen-Geiger climate classification). Similar to a light wood-frame building, the vertical movement amount primarily depends on MC changes and the consequent drying in such a mass timber building. It was estimated that

the average MC of the CLT panels and the glulam columns installed in the building was about 13% when the timber was installed from fall to spring. After occupation the indoor environment tends to be very dry, without humidification under the heated conditions in this climate. The monitoring of temperature and relative humidity indicated that the wood inside this building could reach a MC close to 4% in the winter (Wang et al., 2015).

Glulam columns are known to be dimensionally stable in the longitudinal direction. The structural design of this building utilized this attribute of wood by connecting glulam columns end-to-end with metal connectors along the height of the building, without cross-section members in the gravity load path (Figure 9). The field measurements confirmed that the glulam columns were extremely stable under compression parallel to grain. The two glulam columns (with about 5 m and 6 m in height, respectively) directly measured by sensors (at Locations 1 and 4, Figure 8) each showed vertical movement of less than 3 mm (i.e., less than 0.04%) during the period of monitoring for 14 months. Neither MC changes nor sustained loads led to considerable downward movement. Therefore the total shortening of the building would be approximately 11 mm, accounting for a total height of 24.5 m for the connected glulam columns, without taking into account the rooftop mechanical penthouse. This movement amount does not take into consideration any potential settlement or deformation at connections between glulam columns, or effects of reduced loads on the top two unoccupied floors. Such a shortening amount is apparently much lower than that measured in light wood-frame buildings, but comparable with the measured movement from a similar 6-storey mass timber building in Quebec City (Munoz et al., 2012).

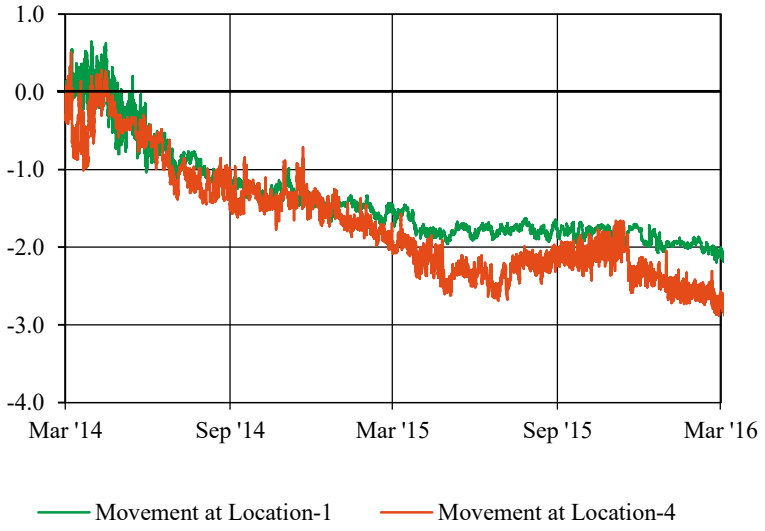

Figure 8: Vertical movement of glulam column at Locations 1 (green) and 4 (orange)

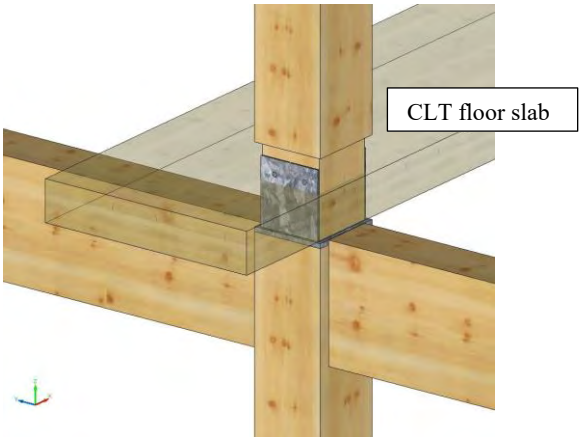

Figure 9: Support of CLT floor slab with glulam column and beam (courtesy of Equilibrium Consulting)

The addition of a horizontal CLT floor in the displacement measurement for glulam columns greatly increased the vertical movement, as originally expected. The floors of this building were built with two vertically staggered CLT slabs, which were structurally supported by glulam beams at each end. The glulam beams were then supported by glulam columns using concealed dovetail connections (Figure 9). It is believed that the beam should have a minor contribution to the vertical movement measurement since its vertical movement (including shrinkage) is restrained by the column and the connection. Being 5-ply and 169 mm thick, the bottom CLT panel was included in the measurements with a displacement sensor box installed to sit on this panel (i.e., in the space created by the staggered CLT floor slabs). The CLT floor slabs are not major members for bearing gravity loads and there should be no cumulative deformation resulting from compression. Shrinkage of the CLT panel (in thickness) resulting from drying must therefore be a major reason for the measured movement at each location. The measurement indicated that the average shrinkage of the CLT slabs was approximately 5 mm in the thickness of 169 mm (i.e., 3%) (Figure 10; Table 7).

Not relevant to the movement monitoring in this study, the upper 3-ply CLT panels (99 mm thick) of the floors would have incurred shrinkage of another 3 mm under the same environmental conditions. Therefore the total shrinkage amount would exceed 8 mm when these two slabs are stacked. This magnitude of movement could be significant if the floor was, for example, supporting equipment that had rigid service connections attached to the walls or columns, or directly connected to other building components, such as the curtain wall in this building. This expected vertical movement along with building deflection was accounted for in the design of the curtainwall connections by using a vertical slotted connection at the SIPs infill wall panels and curtainwall system (Figure 11). The amount of movement designed for this interface was slightly more than the amount that would be expected for a steel or concrete building with similar details.

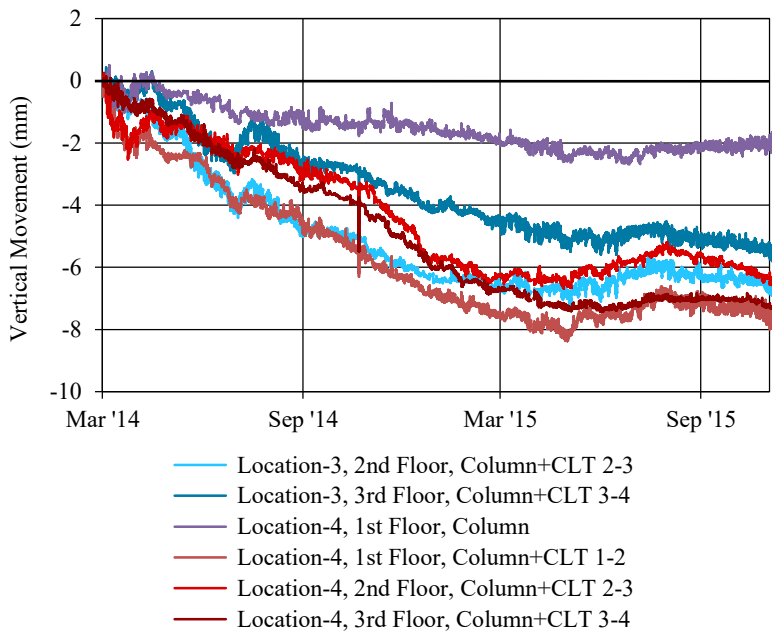

Figure 10: Vertical movement of glulam column (purple) and of column and CLT floor (from Level 1 to Level 3) at Locations 3 (blue) and 4 (orange/red) in the WIDC building

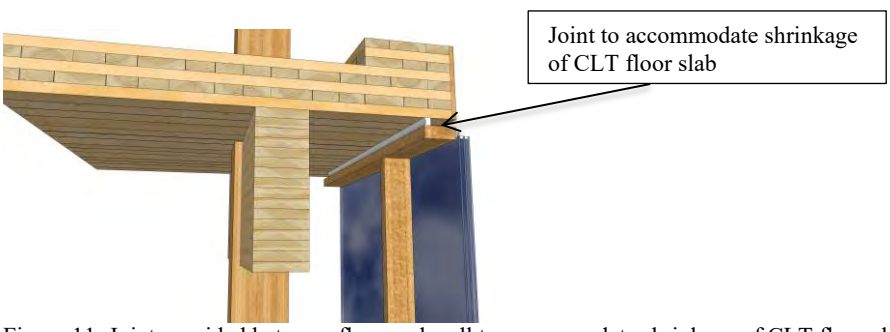

Figure 11: Joint provided between floor and wall to accommodate shrinkage of CLT floor slab (courtesy of RDH Building Science Inc.)

The CLT shear wall located at the core of this building also has a total height of 24.5 m, with two horizontal step joints along the height. As described above, the vertical movement of the CLT wall (location 5) was only partially monitored from Level 2 to Level 6, without covering the portions of the wall concealed by the CLT floors or the ledgers below the ceilings. The displacement sensor on each floor covers approximately 3 m in height of the CLT wall (Table 7). Similar to the measurements of the two glulam columns at Locations 1 and 4, the measurements confirmed that CLT was also highly dimensionally stable in its plane direction (with combined longitudinal and transverse grain). The downward movement amounts measured from the CLT wall ranged from 1.5 mm (i.e., 0.05%) to 2.7 mm (i.e., 0.09%) on each floor after two years in service (Figure 12). The building shortening in general increased over time; however, there was a clear recovery (i.e., swelling) in an amount of over 0.5 mm for each floor in the summer of 2015, the first summer after occupation, when the humidity in the building increased to seasonal summertime levels. For a CLT wall, not all boards inside are bearing gravity loads in the longitudinal direction due to cross lamination of boards. Similarly the increased humidification

levels caused movement in the CLT floor panel thickness (Figure 10) but had less effect on the longitudinal glulam columns (Figure 8). Assuming that wood shrinkage and load-induced deformation were uniform along the height on each floor and the movement amount was proportional to the height of the wall, the measurements showed that the total shortening of this CLT wall, from Levels 1 to 6, would be about 19 mm (i.e., about 0.07%). This appears to be slightly larger than the vertical movement of a glulam line under the same indoor environment; however, this level of differential movement is quite small for such a tall building.

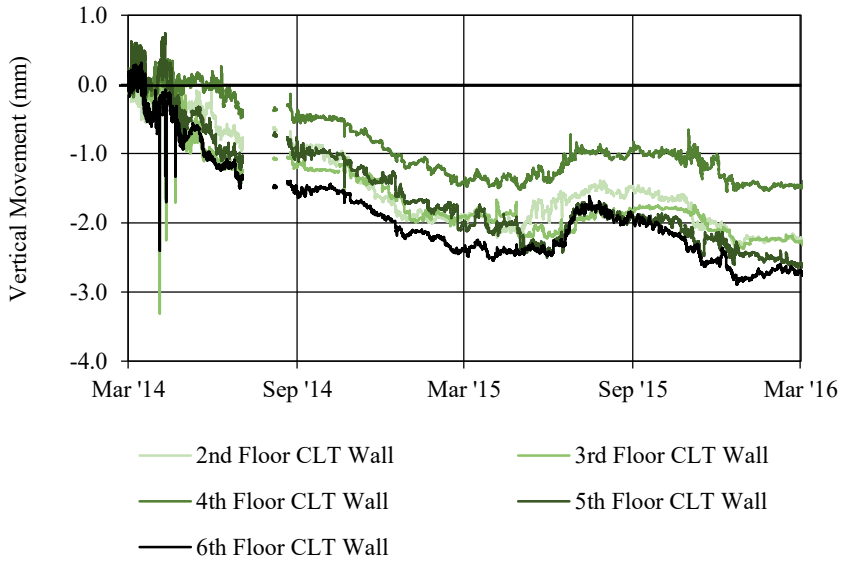

Figure 12: Vertical movement of CLT wall on floors 2-6 in the WIDC building

Table 7: Vertical movement measured from the WIDC building and the potential contributions

Location	Wood members	Vertical distance (mm)	Estimated shrinkage* (mm)	Measured movement (mm)	Shortening ratio (%)
Location 1	Column	5005	2.3	2.2	0.044
Location 3	Column+CLT floor	3290	4.5	7.6	0.23
	Column+CLT floor	3190	4.5	6.0	0.19
Location 4	Column	6160	2.8	2.8	0.045
	Column+CLT floor	6480	6.0	8.0	0.12
	Column+CLT floor	3290	4.5	7.5	0.23
	Column+CLT floor	3190	4.5	8.1	0.25
Location 5, CLT wall	F2 CLT	2870	1.3	2.1	0.073
	F3 CLT	2860	1.3	2.4	0.084
	F4 CLT	3010	1.4	1.5	0.050
	F5 CLT	2890	1.3	2.6	0.090
	F6 CLT	3000	1.4	2.7	0.090
	CLT total	14630	6.6	11.3	0.077

*An assumed composite shrinkage coefficient of 0.005% per 1% change in MC for longitudinal glulam and CLT, of 0.2% per 1% change in MC for out-of-plane CLT, and 9% in MC reduction for estimating shrinkage

CONCLUSIONS

- From top of sill plates to underside of roof trusses, the building movement in the 4-storey wood-frame building, built with dimension lumber floor joists in wet weather was about 43 mm (0.39%) at the interior hallway wall, 45 mm (0.41%) at the interior partition wall, and 34 mm (0.31%) at the exterior wall based on monitoring for 17 months.
- In the 5-storey building built with engineered wood floor joists, the vertical movement in two interior walls reached about 39 mm (0.28%) when it was framed in a wet season, and about 21 mm (0.15%) when it was framed under warm and dry weather conditions.
- In the 6-storey building built with engineered wood floor joists in relatively dry weather, the building shortening reached approximately 34 mm at the party wall, 35 mm at the hallway wall, and 37 mm at the interior partition wall, with an average of 35 mm (0.21%) for these three interior walls after a monitoring period of 24 months.
- The measured building shortening amounts exceeded the predicted shrinkage in all three light wood-frame buildings (except for Phase B of the 5-storey building) by percentage points ranging from 24% to 44%. A good margin of safety should therefore be provided in design of mid-rise wood-frame buildings to compensate for contributions of loads, engineered wood members, and other factors towards vertical movement.
- Lower initial MC of wood resulting from framing under warm and dry weather condition (instead of exposing wood to excessive rain) and use of engineered wood floor joists (instead of dimension lumber floor joists) appear to be effective measures to reducing vertical movement in platform-frame construction.
- In the 6-storey WIDC building built with mass timber, the two glulam columns measured showed very small amounts of vertical movement, each below 3 mm (i.e., 0.04%), for a height of over 5 m and 6 m, respectively. The cumulative shortening of the six glulam columns along the height of the building is estimated to be 11 mm (0.045%), not taking into account deformation at connections.
- The CLT shear wall was found to be also dimensionally stable along the height of the WIDC building. The measurements suggested that the entire CLT wall, from Level 1 to Level 6 with a height of 24.5 m, would shorten about 19 mm (i.e., 0.07%).
- The CLT floor slabs had expected shrinkage in the thickness direction. It was estimated that the bottom CLT slab of the floor structure, 5-ply and 169 mm in thickness, had a shrinkage amount of about 5 mm (i.e., approximately 3%). This resulted in differential shrinkage at the curtainwall and infill SIPs panels on each floor, which was accommodated by a vertical movement joint.

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