Technical Note

Long-Term Moisture Monitoring Results of an Eight-Story Mass Timber Building in the Pacific Northwest

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Abstract: In 2017, a moisture monitoring study was initiated on an eight-story, mass timber building located in Portland, Oregon. A detailed description of the monitoring program and initial monitoring results from the first year of the program were published previously. It was discovered that by the end of Year 1, some of the mass timber components had not dried below 19% moisture content (MC). This technical note is a follow-up to the original paper to examine how the building changed over its first 3 years after construction. All of the locations monitored over 3 years have reached stable moisture contents between 10% and 15%, which are acceptable for building functionality and performance. The main conclusion from this study is that mass timber buildings can naturally recover from construction wetting provided that such buildings are properly enclosed and further moisture intrusion is prevented. **DOI:** 10.1061/(ASCE)AE.1943-5568.0000497.

Introduction

Mass timber and tall wood construction has attracted increasing attention for building projects in the USA during the last decade. Investors are interested in this new construction type due to its esthetics and sustainable aspects of raw materials. On the contrary, the longevity of large-scale mass timber buildings is of concern because modern mass timber buildings have not been around long enough to provide validation data from real projects. Moisture content (MC) of wood building components is one of the metrics that can affect the long-term performance of mass timber buildings. A handful of moisture monitoring studies have been conducted on mass timber buildings, including a study on the 18-story-tall wood building at the University of British Columbia (Mustapha et al. 2017) and a monitoring program on Peavey Hall at Oregon State University (Riggio et al. 2019). In general, no major concerns were discovered related to moisture performance assuming that adequate detailing and ventilation are allowed for these buildings.

Adding to the body of literature, this paper presents long-term findings from a moisture monitoring study on an eight-story mass timber building located in Portland, Oregon. A previous paper by Kordziel et al. (2019) introduced the details on the monitoring program and the challenges for on-site monitoring, presenting approximately 1 year of moisture monitoring data (November 2016–January 2018). One distinct characteristic of this project is the extreme level of precipitation in Portland during the construction causing significant wetting of the mass timber materials. Some of the sensor locations were still reading above 19% moisture content (considered *wet* for wood engineering) by January 2018. These data left several unanswered questions as to the drying behavior of the building. This paper summarizes the data through December 2020 with the objective of presenting the long-term trend on these sensors.

Brief Description of Building and Sensors

A very detailed description of the monitored building configuration and sensor placement was provided in the previous paper by the authors (Kordziel et al. 2019). Only a brief summary is presented in this technical note. The building of interest is an eight-story residential building (the first floor houses commercial offices) with a glulam (GL) and cross laminated timber (CLT) gravity system (Fig. 1). The lateral force-resisting system is a steel-braced frame at the stair core. The building envelope walls are nonstructural and framed using treated dimension lumber. Three main types of wood structural components were monitored, namely, CLT panels (floors and roof), glulam members (columns and beams), and fire-retardant treated wood studs (exterior walls). Specifically, a few sensors were installed on the CLT roof panel starting from the CLT manufacturing facility to monitor the MC-level change over transportation.

During installation, construction, and close to 3 years of occupancy, a large number of sensors became damaged. Some of the sensors were replaced when damage occurred during construction (the research team had access), but the ones that stopped functioning after occupancy were not replaced. In total, 104 sensors were installed and only 38 remain functional after about 4 years. Table 1 provides a summary of the status of all sensors installed on the project. Detailed information about the weather and sensor damage

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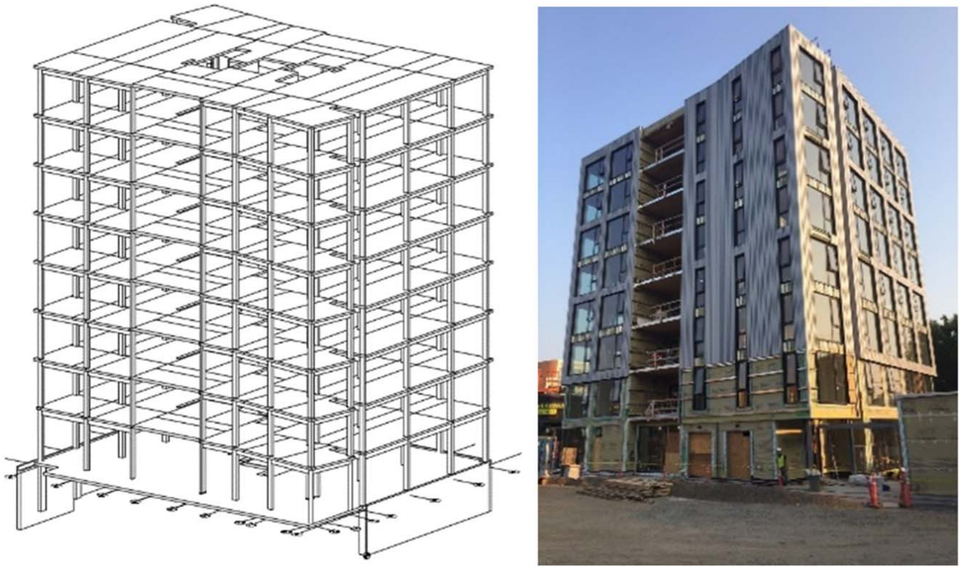

Fig. 1. Structural framing of the monitored building. (Reprinted from Kordziel et al. 2019, © ASCE.)

Table 1. Summary of installed sensors and current status (as of 11/2020)

Sensor location	Total sensor	Operational	Maximum MC record[a]	Current average MC (only functional sensors)
Columns @ ground floor	13	6	40%	11.75%
Columns @ upper floors	3	0	35%	N/A
Exterior wall studs (Floors 2, 4, and 8)	24	16	68% (>40%)	11.4%
CLT diaphragm Floor 4	25	4	48% (>40%)	11.1%
CLT diaphragm roof	39	12	47% (>40%)	11.3%

Note: See Appendix for detailed information and the status of all sensors.
[a]The sensors used for this study were rated up to 40% MC; thus, the recording above 40% shall be interpreted as greater than 40% MC to be accurate.

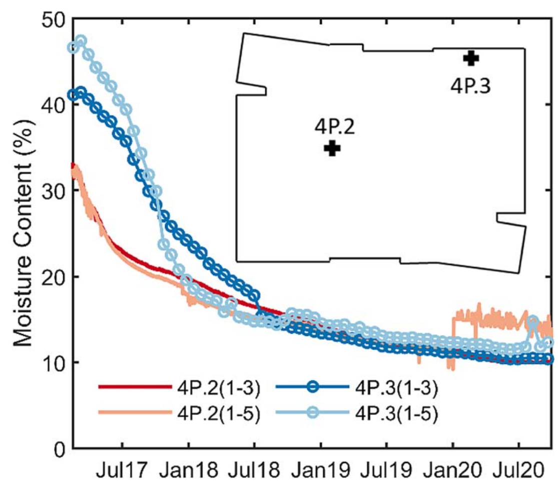

Fig. 2. Moisture Content for Locations 4P.2 and 4P.3.

due to exposure that happened during the early stage of monitoring can be found in Kordziel et al. (2019).

Long-Term Moisture Content Monitoring Results

The main objective of this paper is to present all moisture content data from functional sensors on the building from 2016 to the present day. The naming convention for sensor locations used here is consistent with that of the previous study by Kordziel et al. (2019). The sensors are marked as AB.X, where A is the floor number, B is the building component being monitored (P-CLT panel, W-wall stud, and C-glulam column), and X is the location on the floor shown in the floor layout. For CLT panels, there are numbers within parentheses after X that indicate the layer (within 5-ply CLT, 1-top layer, and 5-bottom layer) that the sensor is measuring.

CLT Panel Data

Four sensors were still functional on the fourth floor diaphragm at the time of writing this paper. Two of the sensors are located near the perimeter of the building, while the other two are at an interior location. The location and overall time history of the monitored MC levels are illustrated in Fig. 2. Specifically, the sensor data indicate that the wetting is more severe at the perimeter location, registering an MC above 35% during construction. After about 18 months, all readings on the fourth floor fell below 19% and stayed below that level thereafter. The MC for these sensors seems to stabilize between 10% and 15% in the long term. The high-frequency variation at the end of the monitoring period was believed to be caused by loose instrument probe contact. The sensors are not very sensitive under 10% MC [i.e., a loose probe (open circuit) will show a reading of around 7%–8% MC] based on information provided by the sensor manufacturer. The floor diaphragm was constructed using 5-ply CLT. One can see from Fig. 2 that the four remaining sensors belong to two panel location groups but were measuring different layers of the CLT material.

The roof of the building was heavily instrumented in this project because it was exposed to weather for an extended period of time and experienced appreciable wetting. Due to a limited number of channels, different locations on the roof were monitored with different number of sensors across the thickness of the CLT panel. After 3 years, only six locations on the roof still had functional sensors, including one location with all five layers of data [RP.3, Fig. 3(a)], one with three layers [RP.5, Fig. 3(b)], and four locations

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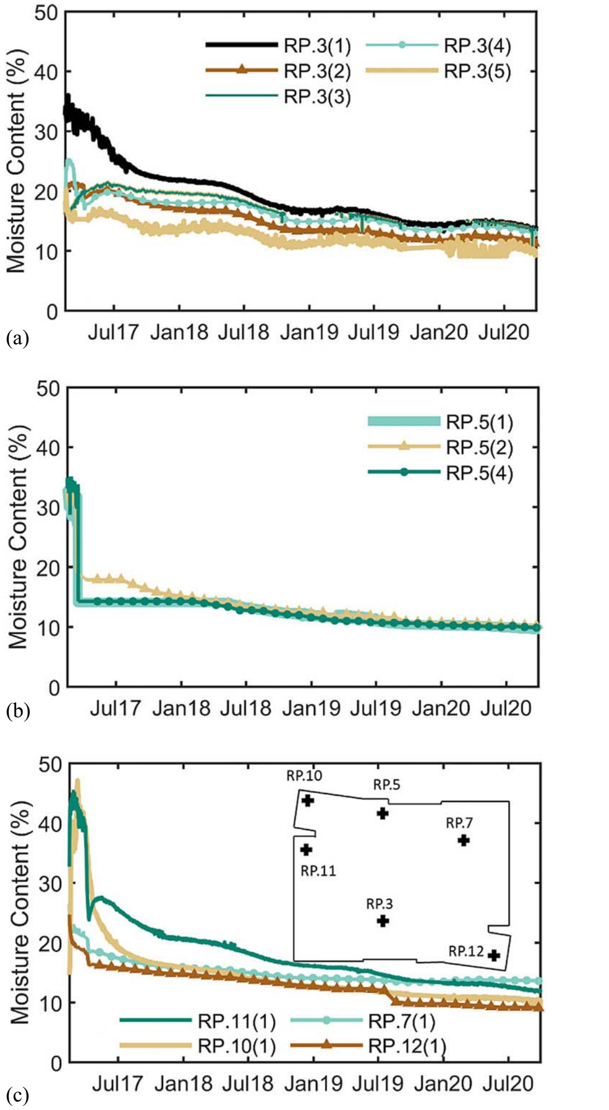

Fig. 3. Moisture Content for Locations: (a) RP.3; (b) RP.5; and (c) RP.7 through RP.12.

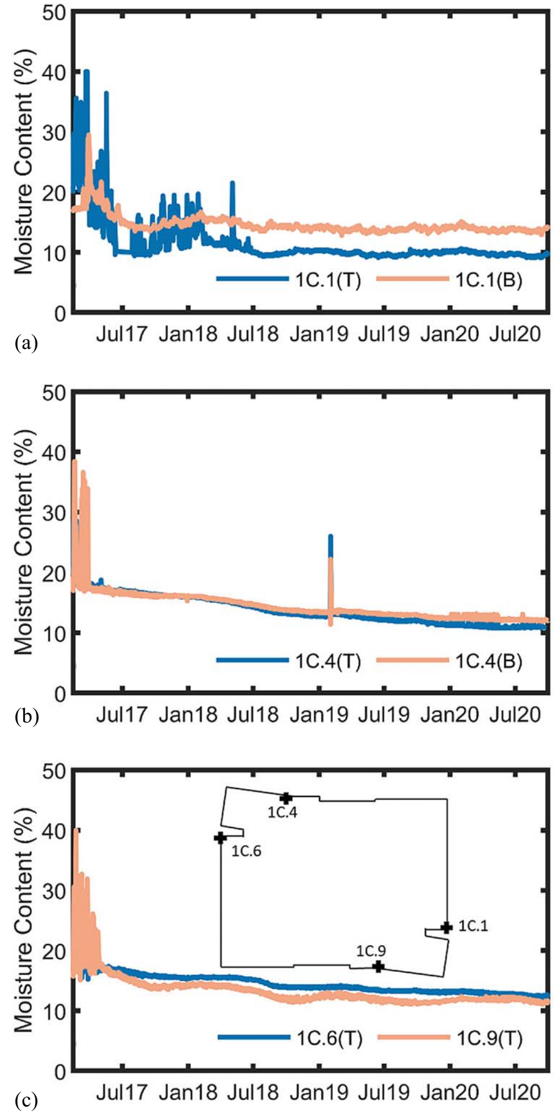

Fig. 4. Moisture Content data for (a) Location 1C.1; (b) Location 1C.4; and (c) Locations 1C.6 and 1C.9.

with a single sensor in the first layer [various, Fig. 3(c)]. The time history of the MC recording for all these locations is shown in Fig. 3. The straight line jumps shown in the data were due to data loss over that period of time.

MC data from all locations on the roof indicated the drying of roof panels over time. While the roof panels were exposed to heavy rain during construction and remained very wet at the time of applying roofing membrane and insulation, all of the locations monitored dried out to under 19% MC after about 18 months from the start of construction. There have been some concerns on the effect of a vapor-impermeable membrane on the long-term drying process of CLT. However, it is clear from some of these sensors [especially the top layer sensor from Fig. 3(a)] that the CLT monitored in this building was able to continuously dry out even with the membrane applied when the wood was still wet. After 3 years, the MC of all monitored locations on the roof was below 15%, with most locations showing a continued drying trend (i.e., MC data showing a negative slope over time).

Glulam Data

Unlike CLT panels that are protected either by the roofing membrane and insulation or by concrete overlay, the glulam columns monitored in this study were exposed to the environment. All of the functional glulam-MC sensors were located at the first-story (ground floor) columns. The long-term MC data for all these columns are illustrated in Fig. 4. It can be seen that all column locations started very wet due to exposed construction, but these members dried very fast after the building was completed and enclosed. This is expected because such members are exposed and vertical, therefore leaving little chance of sustained rainwater absorption. All glulam monitoring locations reached a stable MC after 18 months after construction, with some moisture spike events likely due to accidental wetting during occupancy. However, the wetting effect very quickly dissipated by itself, demonstrating the drying benefit of the exposed wood members.

Stud Wall Stud Data

Moisture sensors were also installed on the 2×6 studs inside of the exterior walls at three different floors. Compared with the fully exposed glulam and CLT floor exposed on the bottom, these elements were protected from the environment by wall sheathing and finishes in a concealed space. Also, these wall studs were chemically

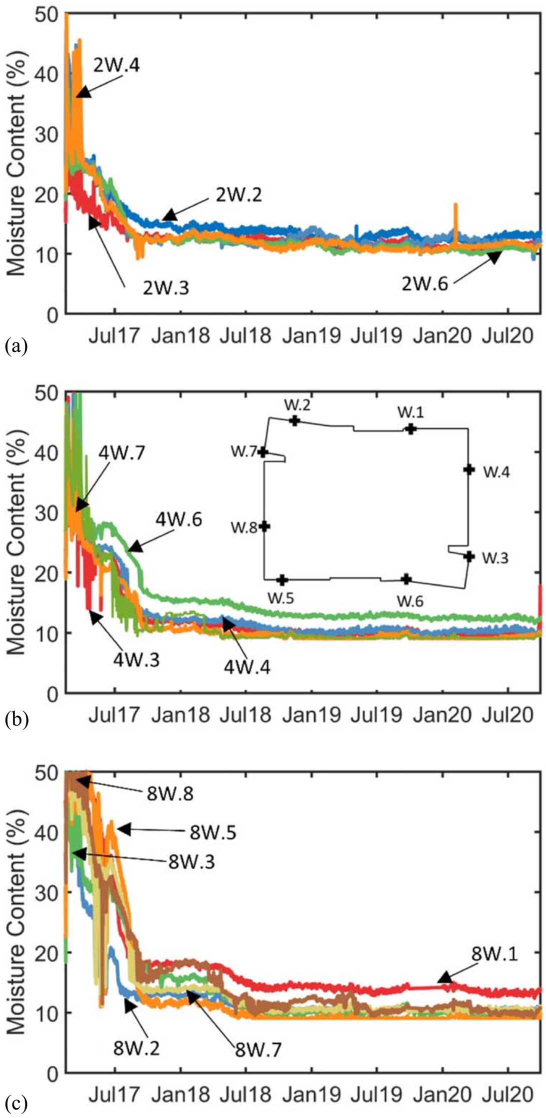

Fig. 5. Stud wall moisture content time history for Floor 2(a); 4(b); and 8(c).

treated for fire, which increases the conductivity of moisture sensors, resulting in higher readings. Therefore, the MC readings presented were a conservative estimation of how wet the wood was. The time history of MC data from all wood stud walls (SWs) is presented in Fig. 5. The MC readings of these studs started quite high, but all fell below 19% after the first year and stayed around 10%–15% throughout the rest of the monitoring period.

The average MC data from all functional sensors over about 3.5 years of monitoring period are plotted in Fig. 6 for different wood products. From the data, it can be observed that the CLT sensor locations exhibit a slower rate of drying than the glulams and stud walls. This agrees with the trend observed in the original paper with only 1 year of data. This is not surprising because CLT panels for this project were covered by a water vapor-impermeable membrane on the top face. It is clear from the long-term data that once all products dried out, the MC levels stabilized and there is no significant difference between the different products.

Fig. 7 illustrates the variability of measurements in different wood products. As expected, the variability for all products is most pronounced in early months, when there is no building enclosure in place. This variability is a direct reflection of different

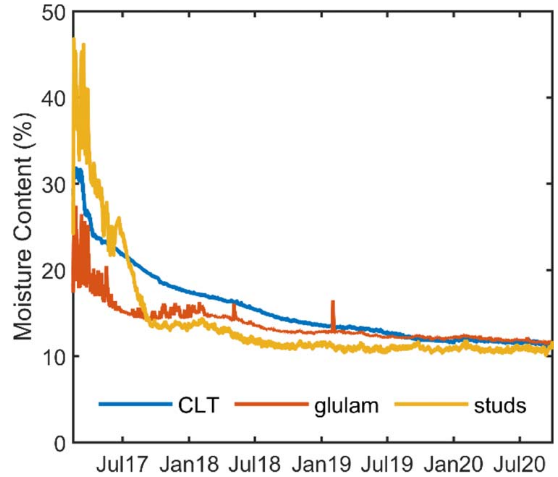

Fig. 6. Average moisture content time history of all data from CLT, stud walls (SWs) and glulam (GL).

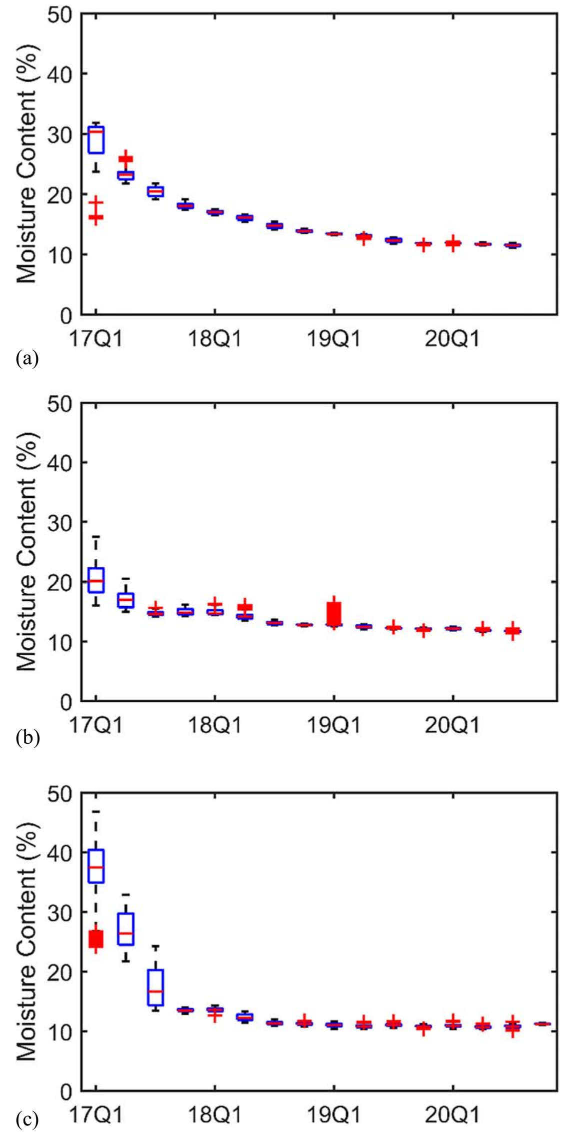

Fig. 7. Box plots of moisture contents by product over time (Qi refers to date quarter from 2017 through 2020): (a) CLT; (b) GL; and (c) SW.

exposures to precipitation. Fig. 7 shows that by the third quarter of 2017, all glulam and stud wall products had below 20% moisture content, a threshold that represents risks for mold and decay (Carll and Highley 1999; Jakes et al. 2013).

Conclusions

Based on the data gathered over 3 years on this multistory mass timber building, the following main conclusions can be reached.

Following significant wetting during construction, a consistent drying trend was observed after the building was enclosed.

CLT roof and floor panels, which were covered on one side with a vapor-impermeable membrane, dried more slowly than glulam columns, which were fully exposed to indoor air.

Once drying was complete, mass timber components reached stable moisture contents under normal operation. All of the monitored points stayed dry (MC between 10% and 15%).

Finally, more attention should be paid to the survivability and long-term reliability of moisture monitoring sensors in future research efforts. It is difficult to conduct monitoring during the construction process, but careful and willful collaboration with the construction crew and owner can be helpful.

Appendix. Condition of All Installed Sensors

Detailed information of all sensors installed

CLT sensors					
ID	Install date	Operational	Latest reading date	Max. MC	Last reading
4P.3(1–3)	2/11/2017	Y	Continue	41.9	10.2
4P.3(1–5)	2/11/2017	Y	Continue	47.9	11.5
4P.1(1–3)	2/11/2017	N	5/7/2017 4:46	35.4	31.1
4P.1(1–5)	2/11/2017	N	3/2/2017 14:59	10.6	9.0
4P.2(1–3)	2/11/2017	Y	Continue	34.3	10.0
4P.2(1–5)	2/11/2017	Y	Continue	33.0	7.7
4P.4(1–3)	1/7/2017	N	2/17/2017 8:04	34.3	33.5
4P.4(1–5)	2/11/2017	N	2/21/2017 8:41	35.5	34.8
4P.5(1–3)	2/11/2017	N	2/12/2017 7:03	34.9	34.8
4P.5(1–5)	1/7/2017	N	2/12/2017 11:30	36.2	34.2
4P.1(1)	1/7/2017	N	1/9/2017 12:56	32.9	33.3
4P.1(2)	1/7/2017	N	1/9/2017 13:18	34.0	34.1
4P.1(3)	1/7/2017	N	1/9/2017 12:58	33.5	33.6
4P.1(4)	1/7/2017	N	1/9/2017 14:12	21.3	3.0
4P.1(5)	1/7/2017	N	1/9/2017 12:25	26.7	35.7
4P.2(1–3)	1/7/2017	N	1/9/2017 16:05	16.6	16.6
4P.2(1–5)	1/7/2017	N	1/9/2017 20:07	30.1	29.6
4P.3(1)	1/8/2017	N	1/8/2017 12:18	10.1	10.1
4P.3(2)	1/8/2017	N	1/8/2017 12:48	30.6	31.1
4P.3(3)	1/8/2017	N	1/8/2017 12:50	13.0	12.3
4P.3(4)	1/8/2017	N	1/8/2017 13:09	12.2	12.2
4P.3(5)	1/8/2017	N	11/27/2016 14:07	34.3	10.9
4P.4(1–3)	1/7/2017	N	1/8/2017 20:01	14.5	14.5
4P.4(1–5)	1/7/2017	N	1/8/2017 17:59	36.0	36.0
4P.5(1–3)	1/7/2017	N	1/28/2017 3:22	40.4	34.1
RP.5(1)	1/7/2017	N	11/28/2016 6:13	31.1	31.1
RP.5(2)	1/7/2017	N	11/28/2016 6:25	26.6	26.6
RP.5(3)	1/7/2017	N	11/28/2016 6:25	26.7	26.8
RP.5(4)	1/7/2017	N	11/28/2016 6:22	10.7	10.3
RP.5(5)	1/7/2017	N	11/28/2016 6:25	19.7	19.8
RP.1(1)	2/11/2017	N	2/11/2017 16:58	14.8	14.8
RP.1(2)	2/11/2017	N	2/15/2017 1:13	14.7	14.7
RP.1(3)	2/11/2017	N	2/11/2017 16:59	13.4	13.3
RP.1(4)	2/11/2017	N	2/11/2017 17:00	15.0	14.9
RP.1(5)	2/11/2017	N	2/11/2017 17:01	16.3	16.1
RP.2(1)	2/11/2017	N	2/13/2017 12:39	30.7	28.9

(*Continued.*)

CLT sensors					
ID	Install date	Operational	Latest reading date	Max. MC	Last reading
RP.2(2)	2/11/2017	N	2/13/2017 13:17	30.7	28.5
RP.2(3)	2/11/2017	N	2/13/2017 13:17	24.3	23.6
RP.2(4)	2/11/2017	N	2/13/2017 13:21	18.4	15.8
RP.2(5)	2/11/2017	N	2/13/2017 12:14	22.3	21.4
RP.3(1)	2/11/2017	Y	Continue	36.0	13.2
RP.3(2)	2/11/2017	Y	Continue	21.4	11.1
RP.3(3)	2/11/2017	Y	Continue	21.5	8.2
RP.3(4)	2/11/2017	Y	Continue	25.5	7.0
RP.3(5)	2/11/2017	Y	Continue	20.7	7.0
RP.4(1)	1/7/2017	N	2/9/2017 3:05	9.9	9.4
RP.4(2)	1/7/2017	N	2/11/2017 22:43	36.5	35.9
RP.4(3)	1/7/2017	N	2/9/2017 3:02	13.5	11.8
RP.4(4)	1/7/2017	N	3/13/2017 8:15	29.1	22.4
RP.4(5)	1/7/2017	N	2/11/2017 15:17	40.0	29.7
RP.5(1)	2/11/2017	Y	Continue	34.3	9.6
RP.5(2)	2/11/2017	Y	Continue	33.5	10.0
RP.5(3)	2/11/2017	N	3/28/2017 1:10	38.3	31.1
RP.5(4)	2/11/2107	Y	Continue	37.3	10.0
RP.5(5)	2/11/2017	Y	Continue	40.0	7.6
RP.6(1)	2/11/2017	N	11/12/2020 12:04	37.9	6.6
RP.7(1)	2/11/2017	Y	Continue	32.8	13.6
RP.8(1)	2/11/2017	N	2/13/2017 13:09	31.4	27.9
RP.9(1)	2/11/2017	N	3/26/2017 11:54	43.4	42.5
RP.10(1)	2/11/2017	Y	Continue	47.1	9.4
RP.11(1)	2/11/2017	Y	Continue	45.3	11.8
RP.12(1)	2/11/2017	Y	Continue	27.8	8.9
RP.13(1)	2/11/2017	N	4/11/2017 6:26	31.1	23.5
RP.14(1)	2/11/2017	N	5/23/2017 17:23	39.8	27.7

Wall stud sensors					
Location	Install date	Operational	Latest reading date	Max. MC	Latest reading
2W.1	2/11/2017	Y	Continue	47.1	12.3
2W.2	2/11/2017	Y	Continue	37.0	11.5
2W.3	2/11/2017	Y	Continue	46.3	13.3
2W.4	2/11/2017	Y	Continue	38.9	10.9
2W.5	2/11/2017	N	9/5/2020 20:54	46.0	10.8
2W.6	2/11/2017	Y	Continue	51.6	11.8
2W.7	2/11/2017	N	8/31/2019 17:55	47.9	11.6
2W.8	2/11/2017	N	2/3/2020 14:56	43.9	6.0
4W.1	2/11/2017	N	9/7/2020 0:28	51.8	6.0
4W.2	2/11/2017	Y	Continue	52.1	10.2
4W.3	2/11/2017	Y	Continue	49.5	10.1
4W.4	2/11/2017	Y	Continue	65.3	12.2
4W.5	2/11/2017	N	2/15/2017 0:55	35.4	29.6
4W.6	2/11/2017	Y	Continue	47.8	9.0
4W.7	2/11/2017	Y	Continue	48.4	9.7
4W.8	2/11/2017	N	12/13/2019 13:25	43.8	10.6
8W.1	2/11/2017	Y	Continue	68.3	14.2
8W.2	2/11/2017	Y	Continue	58.1	10.8
8W.3	2/11/2017	Y	Continue	52.8	10.5
8W.4	2/11/2017	N	2/24/2017 14:04	48.9	39.0
8W.5	2/11/2017	Y	Continue	56.0	9.0
8W.6	2/11/2017	N	2/21/2017 10:52	43.0	34.8
8W.7	2/11/2017	Y	Continue	55.6	10.3
8W.8	2/11/2017	Y	Continue	47.1	11.0

Glulam sensors					
Location	Install date	Operational	Latest reading date	Max. MC	Latest reading
1C.1(B)	1/7/2017	Y	Continue	29.5	14.6
1C.1(T)	1/7/2017	Y	Continue	40.0	10.4
1C.4(B)	1/7/2017	Y	Continue	38.4	12.3
1C.4(T)	1/7/2017	Y	Continue	37.9	10.8
1C.5(B)	2/11/2017	N	11/12/2020 11:44	52.5	6.0
1C.6(B)	2/11/2017	Y	Continue	25.8	13.2
3C.2(T)	2/11/2017	N	2/11/2017 15:00	7.1	6.0
8C.3(T)	2/11/2017	N	11/12/2020 11:33	100.0	9.0

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Glulam sensors					
Location	Install date	Operational	Latest reading date	Max. MC	Latest reading
1C.6(T)	1/7/2017	Y	Continue	17.9	13.0
1C.7(B)	1/7/2017	N	2/17/2017 19:11	35.8	30.1
1C.8(B)	1/7/2017	N	2/21/2017 9:02	21.9	21.9
1C.9(B)	1/7/2017	N	4/17/2017 10:38	31.9	17.1
1C.9(T)	1/7/2017	Y	Continue	40.0	11.9
1C.5(B)	1/7/2017	N	1/14/2017 22:16	25.2	20.8
1C.6(B)	1/7/2017	N	2/11/2017 15:57	25.2	18.8
3C.2(T)	1/7/2017	N	2/12/2017 6:53	31.2	7.0

Data Availability Statement

All data, models, and code that support the findings of the study are available from the corresponding author upon reasonable request.

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