Moisture Movement and Condensation Control in Exterior Wall Assemblies

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ABSTRACT

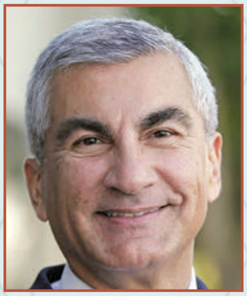
Due to energy code changes, better enforcement, and as a matter of good practice, we are making buildings more and more airtight. Humidity and condensation control go hand in hand with mechanical ventilation of conditioned space. This presentation will focus on the increasing number of interior wall assemblies (and roofs) that are experiencing excessive condensation damage and specific cases that our team of forensic experts have observed over the past several years.

Understanding and predicting moisture movement within and through exterior wall systems is one of the most important factors affecting enclosure performance. Condensation issues can occur with or without designed air barriers, and it is important to understand the role ventilation plays in the design.

This presentation will include forensic studies of moisture movement and condensation control utilizing data loggers to measure moisture movement. The author will review *Wärme Und Feuchtetransport Instationär* or Transient Heat and Moisture Transport (WUFI®) analysis of actual assemblies in actual buildings to understand how buildings behave in real time versus design parameters. Discussion will include mechanical ventilation involved in condensation control, including make-up air versus exhaust. This presentation will also provide an analysis of code requirements versus actual system performance.

The nature of these failures includes design defects and failures related to changes the industry has made for energy efficiency, including cost-cutting measures and system design issues.

SPEAKER



Karim P. Allana is the CEO and senior principal of his firm. He earned a B.S. in civil engineering from Santa Clara University and is a licensed professional engineer in California, Hawaii, Nevada, and Washington. Allana has been in the A/E and construction fields for 30+ years, specializing in forensic analysis and sustainable construction of roofing, waterproofing and the building enclosure. He has acted as a consultant and expert witness in 450+ construction defect projects, as lead plaintiff or defense expert, or in defense of subcontractors and manufacturers. He is a frequent speaker and presenter at professional forums.

Moisture Movement and Condensation Control in Exterior Wall Assemblies

Due to energy code changes, better enforcement, and as a matter of good practice, we are making buildings more and more airtight. Humidity and condensation control in buildings go hand in hand with exterior enclosure, air barriers, and mechanical ventilation. This paper will focus on the increasing number of interior wall assemblies that are experiencing excessive moisture damage due to a combination of moisture diffusion and condensation.

We discuss lessons learned from investigation and analysis of projects in California, where we utilized WUFI model studies, as well as actual data logger information.

Understanding and predicting moisture movement within and through exterior wall systems is one of the most important factors affecting envelope performance today. Condensation and moisture diffusion damage can occur with or without designed air barriers, and it is important to understand the role ventilation plays in the design.

This paper will include forensic studies of moisture movement and condensation control where data loggers were used to measure moisture movement, alongside WUFI analysis of actual assemblies in occupied buildings. This allows us to understand how buildings behave in real time versus through design parameters. The discussion will include mechanical ventilation involved in condensation control, including make-up air and exhaust mechanisms. This paper will also provide an analysis of code requirements for ventilation and actual system performance.

The nature of these moisture intrusion failures includes construction defects and changes the industry has made for energy efficiency, including air barriers and vapor retarders.

CASE STUDY #1

In 2017, Allana Buick & Bers, Inc. (ABBAE) was retained to investigate reported leaks and water intrusion at a 186-unit apartment complex in San Ramon, CA. The five-building, three-story apartment complex was built in 2011. The wall assembly consists of wood sheathing over wood framing, two layers of 60-minute weather-resistive barrier (WRB), and a three-coat stucco system.

Case Study #1 - Background

There were reports of mold and moisture damage on the interior walls of one stack of three units. Water damage and biological growth were reportedly uniform in nature and varied between heavy damage on the first floor and less damage on the third floor. Management believed there was a deficiency with the cement plaster so they hired a contractor to replace all the plaster assembly in a three-story-high unit stack of the façade. The interior and exterior were fully remediated prior to ABBAE's involvement, so the original evidence was lost. Approximately one year before our investigation, the same stack of units that were originally remediated failed, repeating the development of mold and biological growth on the inside face of the exterior walls. In the second go-around, the client and contractor hired us to perform an investigation to understand the factors that were not understood.

As part of our initial study, we were given access to eight apartment units and we performed visual inspections of the interiors. All the units selected for visual inspection were vacant units.

We were not given access to the original stack of units that had the previously repaired damage. Out of the eight units that we were given access to, we observed damage in one unit in Building 1500, at a wall that matches the same elevation at the northwest corner as the previously repaired unit stack in Building 1400. Our staff documented high moisture readings (96% relative humidity [RH] and 73-degree temperature) in this unit, even though it had been vacant for several years.

> Understanding and predicting moisture movement within and through exterior wall systems is one of the most important factors affecting envelope performance today. Condensation and moisture diffusion damage can occur with or without designed air barriers, and it is important to understand the role ventilation plays in the design.

We began by investigating around the windows (as is our standard protocol). Next, we investigated the corner areas of the units. The contractor who did the original repairs suspected that the gutter penetrations were causing the water intrusion. Once we noticed how extensive the visible damage was, we extended our investigation.

Figure 1 – Decay on back side of OSB sheathing.

Figure 2 – Water under concrete slab.

We opened up gypsum board in the various units available to us and observed severe damage to the exterior oriented strand board (OSB) sheathing. Based on our visual observations, we identified several potential sources of wall and window leaks and proceeded to perform water testing to identify the sources of the leaks. We removed the interior gypsum board and observed severe damage inside the wall cavities. Most of the damage was on the back side of the exterior wood sheathing as seen in *Figure 1*.

ABBAE staff spent two days performing extensive water testing and invasive forensic testing of the windows and wall assemblies. Windows were tested under ASTM E1105 under differential pressure and the exterior stucco façade was tested with a spray rack with no differential pressure; however, we did not observe any liquid water penetrating the interiors of these units.

We tested wood moisture levels with a Delmhorst probe before, during, and after the six hours of testing; the moisture levels did not change.

Based on not finding any water or moisture directly coming through the stucco walls, we investigated the slabs on grade to see if they were contributing to the elevated humidity levels. We performed concrete coring and calcium chloride testing of the slabs on grade to understand if the under-slab vapor barrier was installed and to check for water traveling under the slab. Calcium chloride tests indicated an elevated moisture content of between 3.7 and 5.7 lbs./1,000 sq. ft.

Our investigation found that the foundation wall was allowing water from the landscape irrigation system to migrate under the slab, increasing vapor movement through the slab and potentially contributing to high interior humidity. Based on water testing of the foundation wall, liquid water migrated on top of the vapor barrier (as seen in *Figure 2*). We observed improper termination of the under-slab vapor retarders.

While the stucco assembly and the interior slab were not causing direct water intrusion into the units, they were contributing to an increase in interior humidity levels. The original design of the HVAC system showed that the building was designed to have a fresh-air intake duct connected to the fan coil unit. We wanted to fully understand the source of the continued high humidity in the units, so we installed data loggers to track temperature, humidity, and actual moisture levels in exterior sheathing of several units. Two to three data loggers were installed in three units—both inside the wall cavity and within the living spaces—to measure ambient levels. We also installed data loggers in the exterior covered hallways to measure exterior temperature and humidity levels. Analysis of the exterior data loggers (see *Figure 3*) allowed us to pinpoint areas of high moisture and humidity where mildew and mold could grow. We also calculated moisture contribution from human activity as part of our investigation. Finally, we used WUFI modeling to analyze the as-built and as-designed conditions.

Based on the data logger information showing high humidity and poor air circulation, we decided to further study the individual units' HVAC systems.

Our investigation included review of the original mechanical construction documents, on-site verification of the installed mechanical systems, air flow measurement of the bathroom exhaust fans, air flow measurement of the fan coil unit outside air intakes, and blower door air barrier tests. The construction drawings indicated a fresh-air duct connected to the interior fan coil unit. We performed additional destructive testing to see if the fresh-air duct had been properly installed and if it was functioning properly.

We found that the installed indoor fan

Omnisense Readings							
Unit	Location	Temp (Daily Low)	Temp (Daily High)	%Int. Hum (Daily Low)	%Int. Hum (Daily High)	%WME (Daily Low)	%WME (Daily High)
1100-100 East	BD 1	66.9	77.7	48.9	71.1	10.6	12.6
1100-100	Hall	73.9	77.3	46.8	51.1	7.6	8
1100-100 North	Master	67.3	79.4	55	77.7	11.8	14.4
1400-100 South	BD 1	67.2	83.4	49	72.2	10.1	12.5
1400-100	Hall	72.3	79.7	44.8	52.8	6.5	7.4
1400-100 East	Master	66.8	81.9	57.1	76.2	10.1	12.1
1500-311	Hall	74	80.1	39.5	48.9	6.3	7.1
1500-311 South	Master	65.5	80.5	51	75.8	8.4	10.5
1800-202 East	BD 1	68.3	83.7	53.7	82.6	9.4	13.1
1800-202	Hall	75.4	80.1	53.1	56.5	8.3	8.7
1800-202 East	Master	63.1	88.1	43.3	73.8	6.4	8.6
1100-115	Hall	54.2	79.1	45.6	74.7	9.6	20
1100-115 East	Master	54.7	89.1	45	98.7	9.6	21.5
1100-115 East	Master Ceiling	54	87	45.8	80.3	10.1	20.1
1100-115 South	Master Closet	53.7	80.5	45.4	77.1	7.7	18.8
1500-100 North West	BD 1	54.4	76.9	45.8	68.7	10.1	18.6
1500-100	Hall	54.3	78.4	40	60.2	8	18.6
1500-100 North East	Living Room	53.8	79	39.5	66.1	8.8	18
1500-100 West	Master Closet	50.8	80.6	39.6	73.7	9.2	18.9

Figure 3 – Analyzed data logger information showing highest levels of humidity in red.

coil system did not comply with the existing mechanical construction documents. The system did not allow for a fresh-air duct to be connected to the fan coil unit. The fresh-air intake duct as designed by the mechanical engineer was not installed. Had the ducted fresh-air inlets been per design, it would have resulted in a ventilation rate of 1.5 to 1.7 air changes per hour (ACHs).

Furthermore, the bathroom exhaust fans were found to be undersized and also did not match the mechanical construction documents' specifications. The original design exhaust fans were specified to flow at 110 cfm (two exhaust fans per residential unit). Our calculations indicate that a minimum of 1.5 ACHs can be achieved with the originally designed 110-cfm fans (at full-rated flow). The 80-cfm units installed can only achieve 0.8 ACHs at full-rated flow as built.

Construction	Climate Zone	Interior Source Moisture	Exterior Source Moisture	Mechanical Ventilation Rate
• ¾-in. stucco (bright paint) • 60-min. building paper (two layers) • ½-in. OSB • 3½-in. fiberglass batt insulation (1.2 pcf) • ⅝-in. interior gypsum board (painted)	San Ramon, CA	0.83 lbs./hr. (two-bedroom residence per WUFI)	None	1.5 ACH

Table 1 – Parameters of as-designed model for Case Study 1.

Mold Index	Sheathing Moisture Content
0	11%

Table 2 – Outcomes of as-designed model for Case Study 1.

Case Study #1 – WUFI Modeling

WUFI is a software suite designed to realistically calculate heat and moisture transport in multilayered building components, such as exterior walls. It simulates the accumulation and dissipation of moisture through the building materials over a period of time.

We began our WUFI hygrothermal analysis by modeling the existing construction using project-specific interior and exterior climate data.

WUFI Model – As Designed

This model shows the hygrothermal behavior of the building exterior as designed. If the mechanical ventilation had been installed per the construction documents, this model would be expected to match the collected data logger information.

We chose the north-facing elevation for all our WUFI runs because north-facing elevations typically take longer to dry out and are more exposed to rain and environmental conditions.

The as-designed model uses the parameters shown in *Table 1*.

The as-designed model generated the outcomes in *Table 2*.

The results of the as-designed WUFI run were good. This raised a red flag since the results did not match field measurements of the sheathing moisture content and observed mold growth.

While investigating this discrepancy, we discovered that the ventilation systems were improperly installed. This also led us to run additional WUFI models to include alternative sources of moisture to account for actual conditions per the data logger information.

WUFI Model – Run 1 (As Built)

WUFI Run 1 models the hygrothermal behavior of an exterior, as-built, north-facing wall assembly. We modeled the ventilation based on the understanding that the mechanical ventilation designed for the project had not been properly installed. Therefore, the ACHs we used were significantly below the original design intent.

This model also added to the interior

source moisture to account for occupant activity, since this issue was not isolated to the vacant units investigated.

This model uses the parameters shown in *Table 3* with the assembly shown in *Figure 4*.

This model generated the outputs shown in *Table 4*.

Figure 5 shows the mold index for this building exterior configuration. The mold index predicts mold growth based on the building materials, temperature, and RH. A mold index below 1.0 indicates low mold growth probability. With a mold index of 1.0, this model indicated a medium probability for mold growth.

Figure 6 shows the modeled moisture content of the OSB sheathing. We can see that the OSB moisture content went as high as 15% during the winter season, according to the model.

The WUFI results for Run 1 look good, but they do not represent actual site conditions. This is an example where "typical or default" input into the software will output results that do not represent real-world conditions.

Based on our data loggers, we were able to monitor changes in moisture and humidity conditions before and after rain events. Changes in humidity during a rain event allowed us to model how much "leakage" was

Construction	Climate Zone	Interior Source Moisture	Exterior Source Moisture	Mechanical Ventilation Rate
• ¾-in. stucco (bright paint) • 60-min. building paper (two layers) • ½-in. OSB • 3½-in. fiberglass batt insulation (1.2 pcf) • ⅝-in. interior gypsum board (painted)	San Ramon, CA	0.83 lbs./hr. (two-bedroom residence per WUFI)	None	0.5 ACH

Table 3 – Model Run 1 parameters for Case Study 1.

Mold Index	Sheathing Moisture Content
1.1	15%

Table 4 – Outputs from WUFI model Run 1 for Case Study 1.

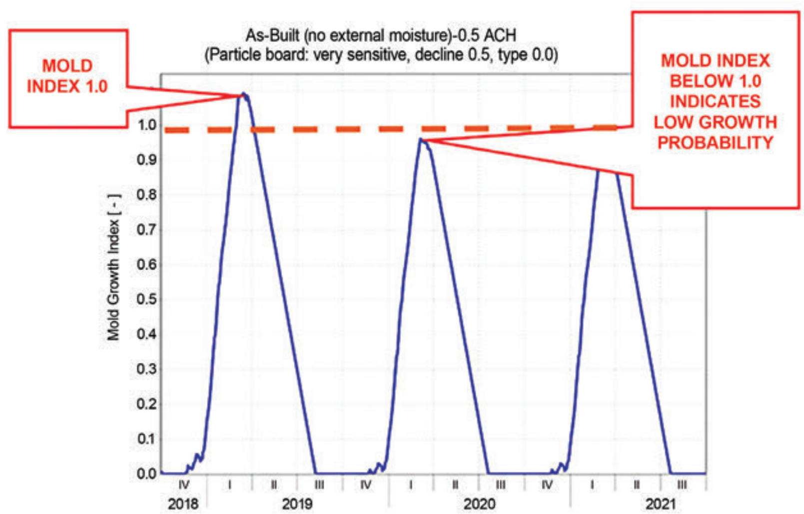


Figure 5 – WUFI model Run 1: mold index.

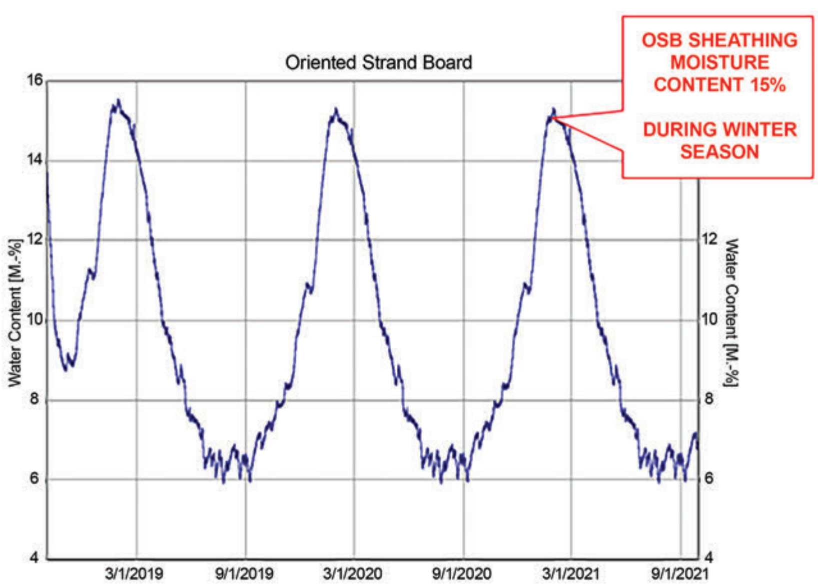


Figure 6 – WUFI Run 1: sheathing moisture content.

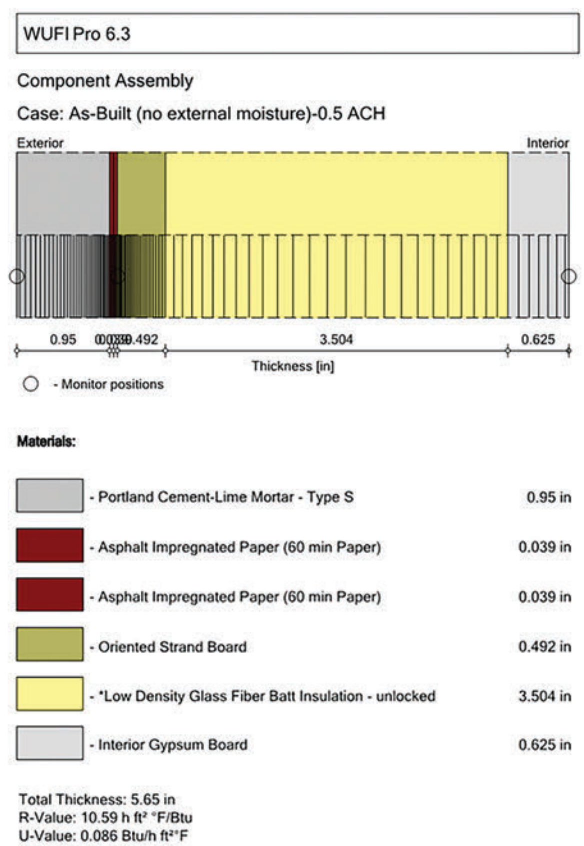


Figure 4 – WUFI model Run 1: component assembly.

occurring through the exterior wall assembly. While the leakage was not in liquid form passing through the interior finishes, there was moisture diffusing through the exterior sheathing due to the WRB getting damp from leakage through the stucco. Damp building paper was acting like a wet towel against the OSB sheathing, and the moisture gradually absorbed through the OSB and started to dry through the wall cavity. Humidity levels in the stud cavity increased and diffused through the gypsum board and increased the interior humidity levels.

Based on the data loggers, we were able to adjust the WUFI model to include an exterior wall vapor permeability (or air "leakage" rate) to model the actual conditions. Once wall leakage rates were known, we could model how much ventilation was needed to dry out the high humidity levels inside the apartments to mitigate condensation. We modeled a number of ventilation rates, including those mandated by building code to see if it was adequate to mitigate condensation. We also modeled the ventilation as designed by the mechanical engineer to see if that would adequately mitigate the interior condensation.

WUFI Model – Run 2

In Run 2, we modeled the impact of the reservoir cladding by adjusting the leakage rates of the stucco and the concrete floor slab until the WUFI model mirrored the site conditions established by data loggers, moisture meters, etc. A reservoir cladding is a cladding, such as stucco, brick, wood, etc., that stores rainwater.

This model shows the hygrothermal behavior of the same as-built, north-facing wall assembly, and it uses the same parameters as in Run 1—with the addition of exterior source moisture to account for the air leakage.

This model uses the parameters shown in *Table 5.*

This model generated the outputs shown in *Table 6.*

The OSB moisture content for this model peaked at 18% during winter seasons. The mold index for this model peaked at over 1.7, indicating a medium probability for mold growth.

The results of WUFI Run 2 represent the final output from numerous incremental adjustments in exterior source moisture. Run 2 results matched the conditions we verified within the test units for moisture content monitored by the data loggers over time.

Construction	Climate Zone	Interior Source Moisture	Exterior Source Moisture	Mechanical Ventilation Rate
• ¾-in. stucco (bright paint) • 60-min. building paper (two layers) • ½-in. OSB • 3½-in. fiberglass batt insulation (1.2 pcf) • ⅝-in. interior gypsum board (painted)	San Ramon, CA	0.83 lbs./hr. (two-bedroom residence per WUFI)	• 20% of driving rain at stucco • 2% of driving rain at building paper • 0.15 lb./ft.^{2} moisture at floor slab	0.5 ACH

Table 5 – Model Run 2 parameters for Case Study 1.

Mold Index	Sheathing Moisture Content
1.7	18%

Table 6 – Outputs from WUFI model Run 2 for Case Study 1.

WUFI Model – Run 3

Once we were confident that our WUFI model was replicating the real-life existing conditions occurring at the project, we began running cases that implemented corrective solutions. Run 3 models the units with added exhaust and with new fresh-air intake as components of the repair solution.

This model uses the parameters shown in *Table 7.*

This model generated the outputs shown in *Table 8.*

This model indicates that with the higher ventilation, there is no probability for mold growth. The mold index for this

Construction	Climate Zone	Interior Source Moisture	Exterior Source Moisture	Mechanical Ventilation Rate
• ¾-in. stucco (bright paint) • 60-min. building paper (2 layers) • ½-in. OSB • 3½-in. fiberglass batt insulation (1.2 pcf) • ⅝-in. interior gypsum board (painted)	San Ramon, CA	0.83 lbs./hr. (two-bedroom residence per WUFI)	• 20% of driving rain at stucco • 2% of driving rain at building paper • 0.15 lb./ft.^{2} moisture at floor slab	1.5 ACH

Table 7 – Model Run 3 parameters for Case Study 1.

Mold Index	Sheathing Moisture Content
0.0005	14%

Table 8 – Outputs from WUFI model Run 3 for Case Study 1.

Construction	Climate Zone	Interior Source Moisture	Exterior Source Moisture	Mechanical Ventilation Rate
• ¾-in. stucco (bright paint) • 60-min. building • 40-mil WRB • ½-in. exterior-grade plywood • ⅝-in. interior gypsum board (painted)	San Ramon, CA	0.83 lbs./hr. (two-bedroom residence per WUFI)	• 20% of driving rain at stucco • 2% of driving rain at building paper • 0.15 lb./ft.^{2} moisture at floor slab	0.5 ACH

Table 9 – Model Run 4 parameters for Case Study 1.

Mold Index	Sheathing Moisture Content
0.35	15%

Table 10 – Outputs from WUFI model Run 4 for Case Study 1.

model is 0.0005, well below the index 1.0 threshold. The OSB moisture content for this model peaked at a safe 14% during the winter season.

The results of WUFI Run 3 represent the final output from numerous incremental adjustments in the air changes per hour. Run 3 results indicate that the moisture issues can be addressed through mechanical ventilation alone.

The analysis shows that by maintaining residential unit ventilation at a minimum of 1.5 ACH, a significant reduction in moisture accumulation and moisture-related damage to the exterior wall components would occur. We concluded that the construction defects introducing moisture through the exterior walls and floor slabs, combined with missing ducted fresh-air intakes and undersized and underperforming exhaust fans, were causing the high levels of moisture to build up in these units. The high humidity caused condensa-

Case Study #1 – WUFI Inputs					
	As Designed	Run 1	Run 2	Run 3	Run 4
Const.	• ¾-in. stucco (bright paint) • 60-min. building paper (two layers) • ½-in. OSB • 3½-in. fiberglass batt insulation (1.2 pcf) • ⅝-in. interior gypsum board (painted)	• ¾-in. stucco (bright paint) • 60-min. building paper (two layers) • ½-in. OSB • 3½-in. fiberglass batt insulation (1.2 pcf) • ⅝-in. interior gypsum board (painted)	• ¾-in. stucco (bright paint) • 60-min. building paper (two layers) • ½-in. OSB • 3½-in. fiberglass batt insulation (1.2 pcf) • ⅝-in. interior gypsum board (painted)	• ¾-in. stucco (bright paint) • 60 min. building paper (two layers) • ½-in. OSB • 3½-in. fiberglass batt insulation (1.2 pcf) • ⅝-in. interior gypsum board (painted)	• ¾-in. stucco (bright paint) • ⅜-in. drain mat • 40-mil WRB • ½-in. plywood exterior grade • ⅝-in. interior gypsum board (painted)
Climate Zone	San Ramon, CA	San Ramon, CA	San Ramon, CA	San Ramon, CA	San Ramon, CA
Interior Source Moisture	0.83 lbs./hr.	0.83 lbs./hr.	0.83 lbs./hr.	0.83 lbs./hr.	0.83 lbs./hr.
Exterior Source Moisture	None	None	• 20% of driving rain at stucco • 2% of driving rain at building paper • 0.15 lb./ft.^{2} moisture at floor slab	• 20% of driving rain at stucco • 2% of driving rain at building paper • 0.15 lb/ft.^{2} moisture at floor slab	• 20% of driving rain at stucco • 2% of driving rain at building paper • 0.15 lb/ft.^{2} moisture at floor slab
Mech. Vent. Rate	1.5 ACH	0.5 ACH	0.5 ACH	1.5 ACH	0.5 ACH
Case Study #1 – WUFI Outputs					
	As Designed	Run 1	Run 2	Run 3	Run 4
Mold Index	0	1.1	1.7	0	0.35
Sheathing Moisture Content	11%	15%	18%	14%	15%

Table 11 – Case Study 1 WUFI summary.

tion in the exterior walls during the winter, resulting in significant damage.

WUFI Model – Run 4

We then began running cases with a hybrid approach, controlling the moisture load into the unit, as well as the addition of improvements to the ventilation. The impact of the stucco cladding as a moisture source was addressed by modeling the stucco installed in a rainscreen configuration.

Run 4 models the hygrothermal behavior of the exterior, rainscreen-configured, north-facing wall assembly. Since this model is already changing the building structure by adding a rainscreen, we also modeled the planned upgrading of the sheathing system to exterior-grade plywood, since it provides superior durability over OSB.

The rainscreen WUFI modeling is based on Modeling Enclosure Design – 2016 by Building Science Corp.

This model uses the parameters shown in *Table 9*.

This model generated the outputs shown in *Table 10*.

The mold index for Run 4 was 0.35, well below the 1.0 index threshold. This indicates no probability for mold growth with this configuration. The moisture content of the OSB sheathing moisture content was 15% during the winter season.

The analysis shows that by controlling the exterior source moisture, the ventilation requirements to manage moisture were dramatically reduced. This illustrates the need for reservoir claddings to be installed in a rainscreen configuration over vapor-permeable WRB. Otherwise, the ventilation design for the space needs to anticipate the impact of exterior source moisture and be designed accordingly. See the Case Study 1 summary in *Table 11*.

Case Study #1 – Ventilation Solutions

Improvement to the existing ventilation was proposed in two options. The goal was to achieve the best performance possible, combined with those repairs having the least impact on each rental unit, and managing cost.

Option 1: Preferred solution (See *Figure 7*.)

- Ducted supply to existing fan coil unit
  - From covered walkway side of building
  - With in-line blower fan
- Controls with humidity sensor
  - To trigger fan coil, in-line fan, and bathroom exhaust fan
- Larger bathroom exhaust fan
  - Existing 4-in. duct to remain

Option 2:

- Larger bathroom exhaust fan
  - Existing 4-in. duct to remain
- Controls with humidity sensor
  - To trigger bathroom exhaust fan
- Passive outside air vent
  - From outside of building, ideally into at least two rooms

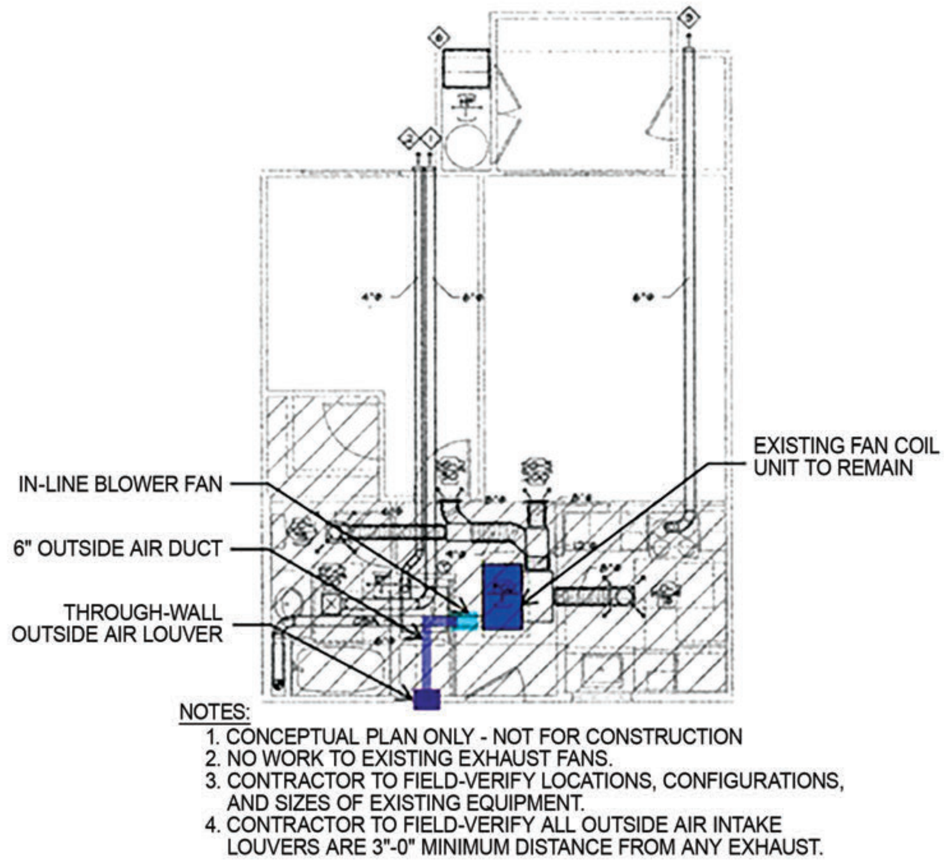


Figure 7 – Option 1 layout of new fresh-air intake similar to original design intent.

CASE STUDY #2

In 2015, ABBAE was retained to investigate water intrusion at a 60-unit apartment complex in Redwood City, CA. The complex was originally built in 2006 and consists of two three-story apartment buildings and a single-story clubhouse. The wall assembly consisted of wood framing, wood sheathing, exterior gypsum board, and stucco or panel siding, depending on the elevation or floor.

Case Study #2 – Background

Water intrusion was reported by the building owners at 12 of the residential units and at several areas of the clubhouse. ABBAE performed interior visual surveys to review damage at windows, walls, and private balcony decks. As part of this investigation, we pulled carpet back to observe any damage to carpet tack strips. There was very little damage found in the unit interiors during visual observations, limited to damaged carpet tack strips under a few windows.

As part of our building investigation, we removed the interior gypsum board and batt insulation in several units as part of our protocol for water intrusion testing of the windows and walls. In one unit stack in particular, dark staining and biological growth was observed on the back side of the wood sheathing and batt insulation prior to testing the windows.

Upon removal of the interior gypsum board in Unit 209, we still did not observe much damage. It was once the batt insulation was removed that damage was uncovered on the back side of the wood sheathing. The wood sheathing had biological growth

Figure 8 – Biological growth on back side of wood sheathing after removing gypsum board.

on the surface, and there were severely corroded fasteners through the exterior wood sheathing (*Figure 8*).

We performed several water intrusion tests on the exterior wall, and no leaks were found on the interior to correlate to the extensive damage found.

Observations on the exterior showed possible signs that water could get behind the siding and stucco panels (leakage to the WRB). We observed open sealant joints, window head flashings that were improperly installed, and open transitions between siding and stucco. We proceeded to remove layers of the wall assembly in search of leak sources. Removal of the siding panels exposed the WRB over the exterior gypsum board. Removal of the WRB exposed an exterior gypsum board (DensGlass) with a fiberglass facer that did not show signs of damage. The fasteners, however, were severely corroded when pulled out of the gypsum board, indicating that while the sheathing is capable of years of wetting and drying cycles, the fasteners obviously were not.

The overdriven and corroded fasteners indicated that the board had been wet for long periods of time. We removed the gypsum board and exposed the wood sheathing, which had heavy staining and damage. The damage was most evident around windows, where water was most likely to get behind the siding. The gypsum board served as a "reservoir" for water, preventing direct water intrusion to the interior finishes, despite the fact that the water had gone through the designed and installed weather-resistive barrier.

We proceeded to install data loggers in several units' wall cavities around the property to measure humidity, temperature, dew point, and moisture in the wood sheathing. Correlating the data with weather events showed that the humidity and moisture increased during heavy rains. There was also some correlation of higher moisture with north-facing units that were shaded for larger portions of the day. *Figure 9* shows part of a data set that analyzes the effect of weather events in determining moisture levels inside the units. The cumulative nature of multiple rain events during the winter months increased the humidity inside the units to the point where mold and mildew were allowed to grow.

Unit	Int. Absolute Humidity	%WME (Average, BDR Closed)	%WME (Average, LVR Closed)	%WME (Average, Hall Open)	Int. Temp	Significant Climate Event	Exterior AH (High)	Exterior AH (Low)
205	40	9.9	9.6	10.4	72	None	40	31
209	40	10.5	10.8	10.35	72			
212	40	10.6	10.3	10.15	72			
203	40	9.35	11.1	11.45	72			
208	40	11.75	11.6	11.65	72			
209	40	11.5	11.6	11.6	72			
205	65	14.1	15.05	9.7	71	After Rain	32	20
209	81	26.7	20.1	10.85	73			
212	54	8.65	9.4	7.85	85			
203	38	9.5	8	9.4	65			
208	58	8.8	8.8	8.55	74			
209	40	15.25	14.25	9.55	62			
205	56	14	13.4	10	69	Before Rain	58	45
209	60	23.6	17	10.7	67			
212	57	8.5	7.9	7.9	74			
203	48	9.7	7.8	9.1	68			
208	57	8.8	8.1	9.6	69			
209	45	14.1	11.6	9.6	64			
205	82	14.2	13.6	10.1	72	Rain Event	72	50
209	55	23.5	17	10.7	64			
212	62	8.4	7.9	8	75			
203	42	9.4	7.8	9.2	65			
208	60	8.8	7.9	9.8	62			
209	49	14	11.8	9.5	68			
205	76	14.4	14	10.3	72	After Rain	64	53
209	61	23.5	17.1	11.1	65			
212	67	8.8	7.8	8.1	77			
203	46	9.6	7.9	9.2	66			
208	71	9.2	8.2	9.9	76			
209	75	14.2	12	9.7	71			

Figure 9 – Analyzed data logger information showing highest levels of humidity in red.

Case Study #2 – WUFI Modeling

We began our WUFI hygrothermal analysis by modeling the existing construction using project-specific interior and exterior climate data.

WUFI Model – As Designed

This model shows the hygrothermal behavior of the building exterior as designed. If the mechanical ventilation had been installed per the construction documents, this model would be expected to match the collected data logger information.

As with Case Study #1, we chose the north-facing elevation for all of our WUFI runs because north-facing elevations typically take longer to dry out and are more exposed to rain and environmental conditions.

The as-designed model uses the parameters shown in *Table 12*.

This model generated the outputs shown in *Table 13*.

The results of the as-designed WUFI run were good. Just as in Case Study #1, this raised a red flag, since the results did not match field measurements of the sheathing moisture content and observed mold growth.

While investigating this discrepancy, we discovered that the ventilation systems were undersized and underperforming. This also led us to run additional WUFI models to include alternative sources of moisture to account for actual conditions per the data logger information.

Construction	Climate Zone	Interior Source Moisture	Exterior Source Moisture	Mechanical Ventilation Rate
• ¾-in. stucco (bright paint) • 60-min. building paper (two layers) • ½-in. OSB • 3½-in. fiberglass batt insulation (1.2 pcf) • ⅝-in. interior gypsum board (painted)	Redwood City, CA	0.83 lbs./hr. (two bedroom residence per WUFI)	None	1.5 ACH

Table 12 – As-designed parameters in Case Study 2.

Mold Index	Sheathing Moisture Content
0	14.5%

Table 13 – Outputs from the WUFI run for Case Study 2.

Construction	Climate Zone	Interior Source Moisture	Exterior Source Moisture	Mechanical Ventilation Rate
• ¾-in. stucco (bright paint) • 60-min. building paper (two layers) • ½-in. OSB • 3½-in. fiberglass batt insulation (1.2 pcf) • ⅝-in. interior gypsum board (painted)	Redwood City, CA	0.83 lbs./hr. (two-bedroom residence per WUFI)	None	0.5 ACH

Table 14 – WUFI Model Run 1 parameters for Case Study 2.

Mold Index	Sheathing Moisture Content
1.8	18%

Table 15 – Outputs from WUFI Run 1 for Case Study 2.

WUFI Model – Run 1

Run 1 models the hygrothermal behavior of an exterior, as-built, north-facing wall assembly.

We modeled the ventilation based on the understanding that the mechanical ventilation designed for the project was underperforming. Therefore, the ACHs we used were significantly below the original design intent.

This model uses the parameters shown in *Table 14*.

This model generated the outputs shown in *Table 15*.

The mold index for this building exterior configuration predicts mold growth based on the building materials, temperature, and RH. A mold index below 1.0 indicates low mold growth probability. With a mold index of 1.7, this model indicated a medium probability for mold growth.

The modeled moisture content of the OSB sheathing went as high as 18% during the winter season, according to the model.

WUFI Model – Run 2

Run 2 models the hygrothermal behavior of an exterior, as-built, north-facing wall assembly.

We modeled the impact of the reservoir cladding by adjusting the porosity (and leakage rates) of the stucco until the WUFI model mirrored the site conditions established by data loggers, moisture meters, etc.

This model uses the parameters shown in *Table 16*.

This model generated the outputs shown in *Table 17*.

The OSB moisture content for this model peaked at 18% during winter seasons. The mold index for this model peaked at over 1.8, indicating a medium probability for mold growth.

The results of WUFI Run 2 represent the final output from numerous incremental adjustments in exterior source moisture. Run 2 results matched the conditions we verified within the test units for moisture content monitored by the data loggers over time.

Construction	Climate Zone	Interior Source Moisture	Exterior Source Moisture	Mechanical Ventilation Rate
• ¾-in. stucco (bright paint) • 60-min. building paper (two layers) • ½-in. OSB • 3½-in. fiberglass batt insulation (1.2 pcf) • ⅝-in. interior gypsum board (painted)	Redwood City, CA	0.83 lbs./hr. (two-bedroom residence per WUFI)	• 20% of driving rain at stucco • 2% of driving rain at building paper	0.5 ACH

Table 16 – WUFI Model Run 2 parameters for Case Study 2.

Mold Index	Sheathing Moisture Content
1.8	18%

Table 17 – Outputs from WUFI Run 2 for Case Study 2.

Construction	Climate Zone	Interior Source Moisture	Exterior Source Moisture	Mechanical Ventilation Rate
• ¾-in. stucco (bright paint) • 60-min. building paper (two layers) • ½-in. OSB • 3½-in. fiberglass batt insulation (1.2 pcf) • ⅝-in. interior gypsum board (painted)	Redwood City, CA	0.83 lbs./hr. (two-bedroom residence per WUFI)	• 20% of driving rain at stucco • 2% of driving rain at building paper	1.5 ACH

Table 18 – WUFI Model Run 3 parameters for Case Study 2.

Mold Index	Sheathing Moisture Content
0.0005	15%

Table 19 – Outputs from WUFI Run 3 for Case Study 2.

If the proposed design allows significant moisture gain within the building that is not properly addressed with ventilation, then high moisture content, humidity, and biological growth can be expected.

WUFI Model – Run 3

We initially began running WUFI cases with ventilation improvements only. We began with the "as originally designed" ventilation as a starting point. We adjusted the ventilation further, increasing air exchanges, until we achieved performance that managed the impact of moisture and significantly reduced mold potential.

Run 3 models the hygrothermal behavior of an exterior, as-built, north-facing wall assembly.

This model uses the parameters shown in *Table 18*.

This model generated the outputs shown in *Table 19*.

This model indicates that with the higher ventilation, there is no probability for mold growth. The mold index for this model is 0.0005, well below the index 1.0 threshold. The OSB moisture content for this model peaked at a safe 15% during the winter season.

The results of WUFI Run 3 represent the final output from numerous incremental adjustments in the ACHs. Run 3 results indicate that the moisture issues can be totally addressed through mechanical ventilation alone.

The analysis shows that by maintaining residential unit ventilation at a minimum of 1.5 ACH, a significant reduction in moisture accumulation and moisture-related damage to the exterior wall components would occur. We concluded that the construction defects introduced moisture through the exterior walls and undersized and underperforming exhaust fans, thus causing the high levels of moisture to build up in the units we investigated. The high humidity caused condensation in the exterior walls during the winter, leading to significant damage.

WUFI Model – Run 4

We then began running cases with a hybrid approach, controlling the moisture load into the unit as well as the ventilation. The impact of the stucco cladding was addressed in two corrective approaches. One was to review the impact of incorporating a moisture-absorption-reducing coating, and the other was reviewing the impact of the stucco being installed in a rainscreen configuration. This approach allowed a reduction in ventilation rates.

As with Case Study #1, we upgraded the sheathing system to exterior-grade plywood since it provides superior durability than OSB, and we are already adding a rainscreen system.

Run 4 models the hygrothermal behavior of an exterior, rainscreen-configured, north-facing wall assembly.

Note that rainscreen WUFI modeling is based on Modeling Enclosure Design - 2016 (by Building Science Corp.).

This model uses the parameters shown in *Table 20*.

This model generated the outputs shown in *Table 21*.

The mold index for Run 4 was 0.425, well below the 1.0 index threshold. This indicates very low probability for mold growth with this configuration. The moisture content of the OSB sheathing moisture content was 15.5% during the winter season.

The analysis shows that by controlling the exterior sources of moisture, the ventilation requirements to manage moisture were dramatically reduced. This illustrates the need for reservoir claddings to be installed in a rainscreen configuration over vapor-permeable WRBs. Otherwise, the ventilation design for the space needs to anticipate the impact of exterior-source moisture and be designed accordingly.

See the Case Study 2 summary in *Table 22*.

Construction	Climate Zone	Interior Source Moisture	Exterior Source Moisture	Mechanical Ventilation Rate
• ¾-in. stucco (bright paint) • ⅜-in. drain mat • 40-mil WRB • ½-in. plywood exterior grade • 3½-in. fiberglass batt insulation (1.2 pcf) • ⅝-in. interior gypsum board (painted)	Redwood City, CA	0.83 lbs./hr. (two-bedroom residence per WUFI)	• 20% of driving rain at stucco • 2% of driving rain at building paper	0.5 ACH

Table 20 – WUFI Model Run 4 parameters for Case Study 2.

Mold Index	Sheathing Moisture Content
0.0425	15.5%

Table 21 – Outputs from WUFI Run 4 for Case Study 2.

Case Study #2 – WUFI Inputs					
	As Designed	**Run 1**	**Run 2**	**Run 3**	**Run 4**
Const.	• ¾-in. stucco (bright paint) • 60-min. building paper (two layers) • ½-in. OSB • 3½-in. fiberglass batt insulation (1.2 pcf) • ⅝-in. interior gypsum board (painted)	• ¾-in. stucco (bright paint) • 60-min. building paper (two layers) • ½-in. OSB • 3½-in. fiberglass batt insulation (1.2 pcf) • ⅝-in. interior gypsum board (painted)	• ¾-in. stucco (bright paint) • 60-min. building paper (two layers) • ½-in. OSB • 3½-in. fiberglass batt insulation (1.2 pcf) • ⅝-in. interior gypsum board (painted)	• ¾-in. stucco (bright paint) • 60 min. building paper (two layers) • ½-in. OSB • 3½-in. fiberglass batt insulation (1.2 pcf) • ⅝-in. interior gypsum board (painted)	• ¾-in. stucco (bright paint) • ⅜-in. drain mat • 40-mil WRB • ½-in. plywood exterior grade • 3½-in. fiberglass batt insulation (1.2 pcf) • ⅝-in. interior gypsum board (painted)
Climate Zone	Redwood City, CA	Redwood City, CA	Redwood City, CA	Redwood City, CA	Redwood City, CA
Interior Source Moisture	0.83 lbs./hr.	0.83 lbs./hr.	0.83 lbs./hr.	0.83 lbs./hr.	0.83 lbs./hr.
Exterior Source Moisture	None	None	• 20% of driving rain at stucco • 2% of driving rain at building paper	• 20% of driving rain at stucco • 2% of driving rain at building paper	• 20% of driving rain at stucco • 2% of driving rain at building paper
Mech. Vent. Rate	1.5 ACH	0.5 ACH	0.5 ACH	1.5 ACH	0.5 ACH
Case Study #2 – WUFI Outputs					
	As Designed	**Run 1**	**Run 2**	**Run 3**	**Run 4**
Mold Index	0	1.8	1.8	0	0.425
Sheathing Moisture Content	14.5%	18%	18%	15%	15.5%

Table 22 – Case Study 2 WUFI summary.

BUILDING CODE REQUIREMENTS

Designing to building code will not always prevent condensation and incidental moisture.

The International Building Code (IBC), and, therefore, the California Building Code, requires that vapor-permeable WRBs be installed over wood sheathing in two independent layers. Further, the layers must be installed such that each layer provides a separate continuous plane and that any flashing intended to drain to the WRB is directed between the layers.

IBC Section 2510.6, Water-Resistive Barriers, reads as follows:

> **2510.6 Water-resistive barriers.** Water-resistive barriers shall be installed as required in Section 1403.2 and, where applied over wood-based sheathing, shall include a water-resistive vapor-permeable barrier with a performance of at least equivalent to two layers of water-resistive barrier complying with ASTM E2556, Type I. The individual layers shall be installed independently such that each layer provides a separate continuous plane and any flashing (installed in accordance with Section 1404.4) intended to drain the water-resistive barrier is directed between the layers.
>
> **Exceptions:**
>
> 1. Where the water-resistive barrier that is applied over wood-based sheathing has a water resistance equal to or greater than that of a water-resistive barrier complying with ASTM E2556, Type II, and is separated from the stucco by an intervening, substantially nonwater-absorbing layer or drainage space.
> 2. Where the water-resistive barrier is applied over wood-based sheathing in Climate Zone 1A, 2A or 3A, a ventilated air space shall be provided between the stucco and the water-resistive barrier.

This revised application requirement creates reverse laps within the WRB, and more opportunities for trapped water within the wall system. Water will collect at locations where the WRB bonds directly to the plaster. Water is also held between layers at crinkles, folds, creases, and puckers in the WRB (*Figure 10*).

Additionally, by directing the water between the two layers instead of over the two layers, the code has effectively reduced the protection provided from two layers down to a single layer of Grade D paper standing between the water and the exterior sheathing.

There are two exceptions allowed by the California Building Code that allow the installation of a single layer of WRB. The first exception is the use of an intervening substantially non-water-absorbing layer or drainage space, and the second is a ventilated air space. Both of these exceptions are superior solutions to the base requirement.

With regard to ventilation, the building code does not require taking into account moisture movement through exterior walls. Exterior-source moisture entering the wall assembly is not specifically addressed by standard ventilation design.

CONCLUSIONS

These case studies illustrate the real-life impact of cladding performance on the moisture movement and management within building enclosures. The impact of not properly controlling the amount of wetting of the wall assembly is exhibited by the moisture readings, biological growth, and rot shown throughout the figures included. The case studies also demonstrate the impact of interior air exchanges in controlling moisture build-up within a building.

Installing traditional claddings compactly over WRBs and sheathing, as allowed by the IBC, leads to excessive moisture trapped between the cladding and WRB and results in the issues illustrated within this paper. The water absorbed by the reservoir claddings transfers through each layer of the assembly by capillary action, absorption, diffusion, and/or air exchange. This is compounded when the cladding is highly absorptive and has a significant moisture storage capacity (e.g., gypsum sheathing, and stucco).

Additionally, leaks that allow water through the cladding (installed compactly over WRBs) will be stored within the WRB and between the WRB and the cladding and sheathing.

One method of controlling the vapor transport into a wall assembly with a reservoir cladding is with a vapor control layer that blocks that moisture movement. This control layer is installed between the cladding and the sheathing. However, in climates where an impermeable control layer cannot be used, the introduction of a rainscreen application or an air space or a drainage layer between the cladding and the WRB is the best option to control moisture absorption and diffusion, provide drainage, and allow drying air to circulate from within the wall assembly. Based on the climate conditions of the two case studies, drying is desired in both directions.

Installing the cladding in a rainscreen or drainage configuration (see *Figures 11* and *12*) enhances drainage of bulk water and can allow ventilation behind the cladding. This ventilation will allow airflow behind the cladding that will accelerate drying. The efficiency of the ventilation requires combining the potential for air movement with vents at both the top and the bottom of the wall. The stack effect and wind pressure differentials will effectively

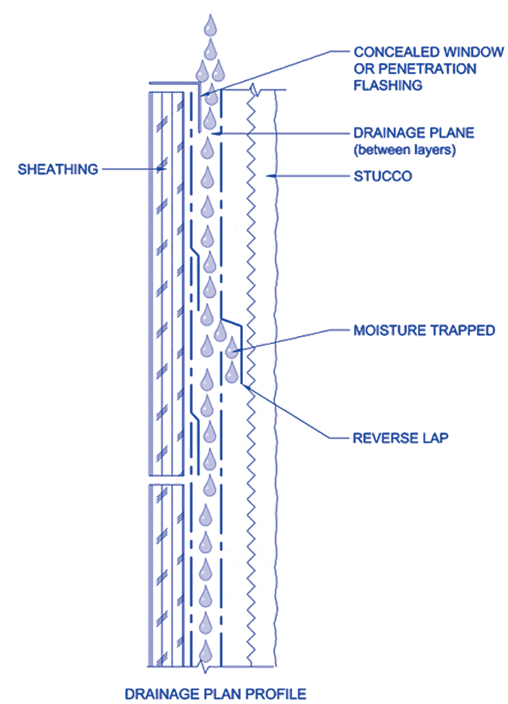


Figure 10 – Impact of WRB installed in separate layers.

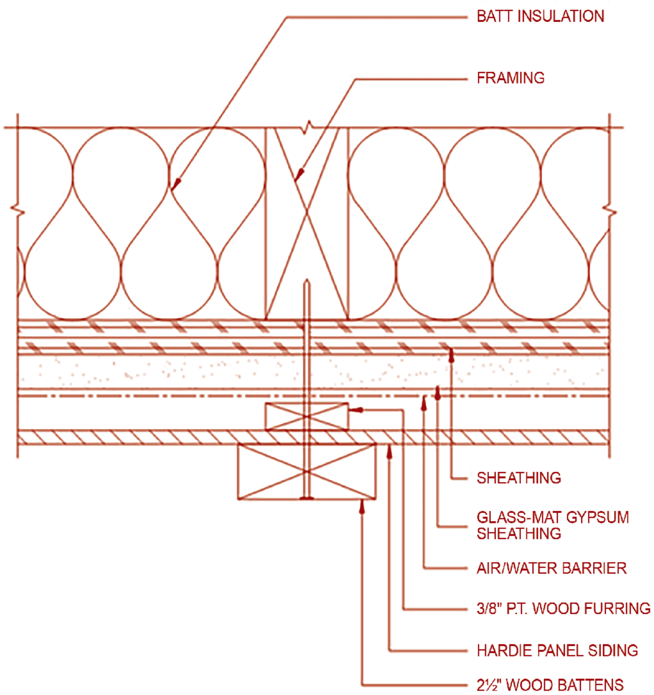


Figure 11 – Plan section of rainscreen siding detail.

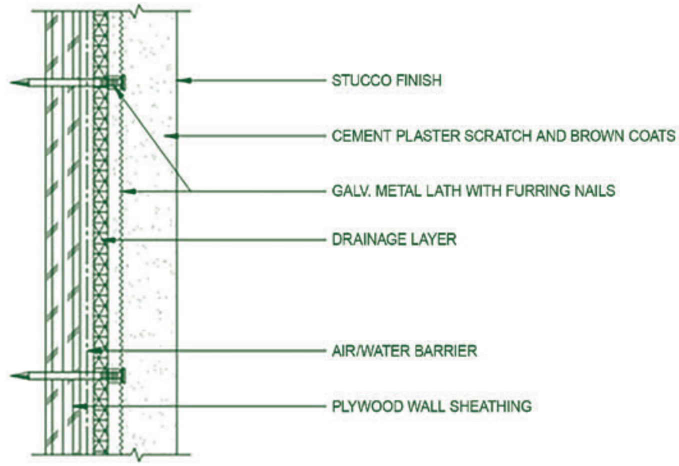


Figure 12 – Rainscreen cement plaster detail.

move air through the air space.

The benefits of a drainage layer or air gap between reservoir claddings and WRBs has been understood for some time. However, the current California Building Code not only ignores the need to uncouple this assembly, but it has also recently reduced the WRB performance with revised installation requirements.

Ventilation required by the California Building Code does not include moisture load from the building enclosure in the engineering calculation. If the proposed design allows significant moisture gain within the building that is not properly addressed with ventilation, then high moisture content, humidity, and biological growth can be expected. With buildings being more efficient and airtight, there is an increased need for less incidental leakage in the exterior wall assembly. Furthermore, while increasing ventilation can reduce the harmful impact of mold formation, it will continue to damage the exterior sheathing, and additional ventilation will increase energy consumption.