4. MATERIALS AND ASSEMBLIES

4.1 Methodology

To investigate the performance of different materials and wall assemblies under hydrostatic forces, full-scale wall assemblies were constructed and tested for this research. Referred to as test pods within this document, each wall assembly was different, and built within an outdoor flood tank. Eleven test pods were observed during two separate flood simulations with water depths of 36" for a 24-hour period of time. Water penetration measurements, visual observations and electronic moisture content readings were collected during flood simulations. The data collected from the first flood simulation was used to inform new iterations of wall assemblies tested during the second flood simulation.

The flood tank was filled a total of three times during the research: one test fill followed by two monitored flood simulations. During the test fill, the tank was filled with the purpose of testing the performance of the flood tank and the effectiveness of the moisture sensors, along with other methods of observation. This was followed by flood simulation 1, where six uniquely constructed test pods were observed for a 24-hour period of time. After this simulation, test pods were left to dry for two weeks, during which time moisture levels were measured and documented, using embedded sensors. A few months later, the second flood simulation tested five test pods that were revised or retrofitted based on knowledge gained from flood simulation 1. Fig. 4.1 below chronicles the flood testing timeline.

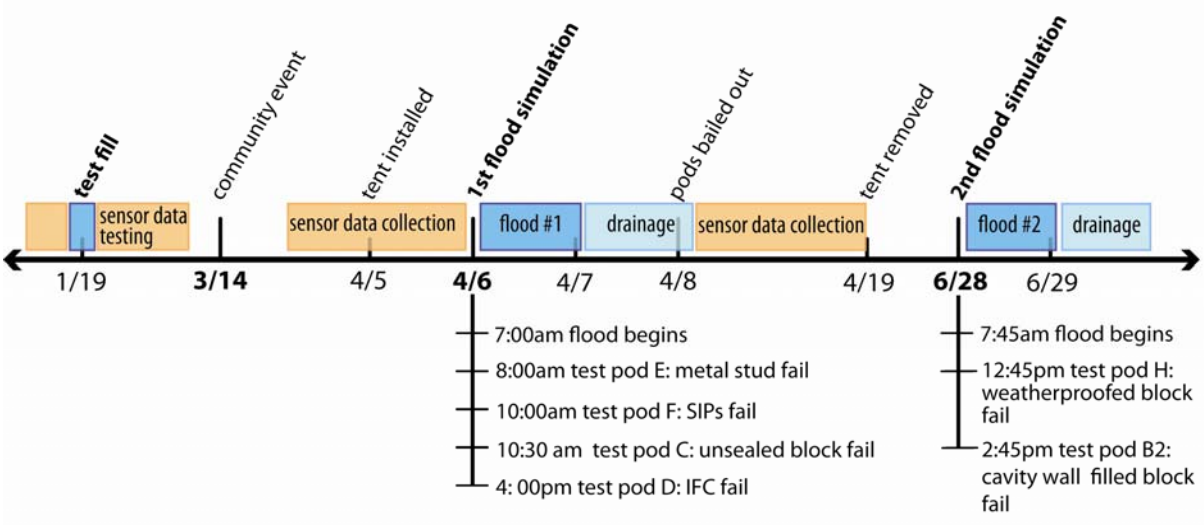


Fig. 4.1. DIAGRAM: Chronology of flood testing.

Efforts to minimize cost and complexity were made throughout the selection and testing of materials and wall assemblies. Material choices were often made with input from local developers, builders, designers and officials. This was an important way to keep dry floodproofing methods applicable to the groups affected by Hurricane Katrina and subsequent BFE changes.

It was important to create a depth of knowledge about a variety of materials and assemblies. Developing a variety of strategies was important to this research because dry floodproofing techniques need to be flexible in order to be combined with a variety of other challenges involved in the design of a building. Potential designers would be best served by having access to a variety of dry floodproof methods with different characteristics. Therefore within the context of research, it was more helpful to consider several methods of dry floodproofing, rather than a singular solution.

4.1.1 Test Facility Description

The flood tank (see Fig. 4.2) was constructed using Hesco Bastion Containers, otherwise referred to as Hesco boxes. Hesco boxes are welded wire mesh boxes with a geotextile lining for sand or gravel fill. Each box has a 3′ by 3′ base and is 4′ tall, linked together to create a 4′ tall 40′ by 40′ test tank. After the test fill, the tank was lined with heavy plastic sheets to increase its ability to hold water. A walkway was installed for easy access and observation of the test pods. A large open air tent was installed over the tank (see Fig. 4.3) during the flood simulation and drying period.

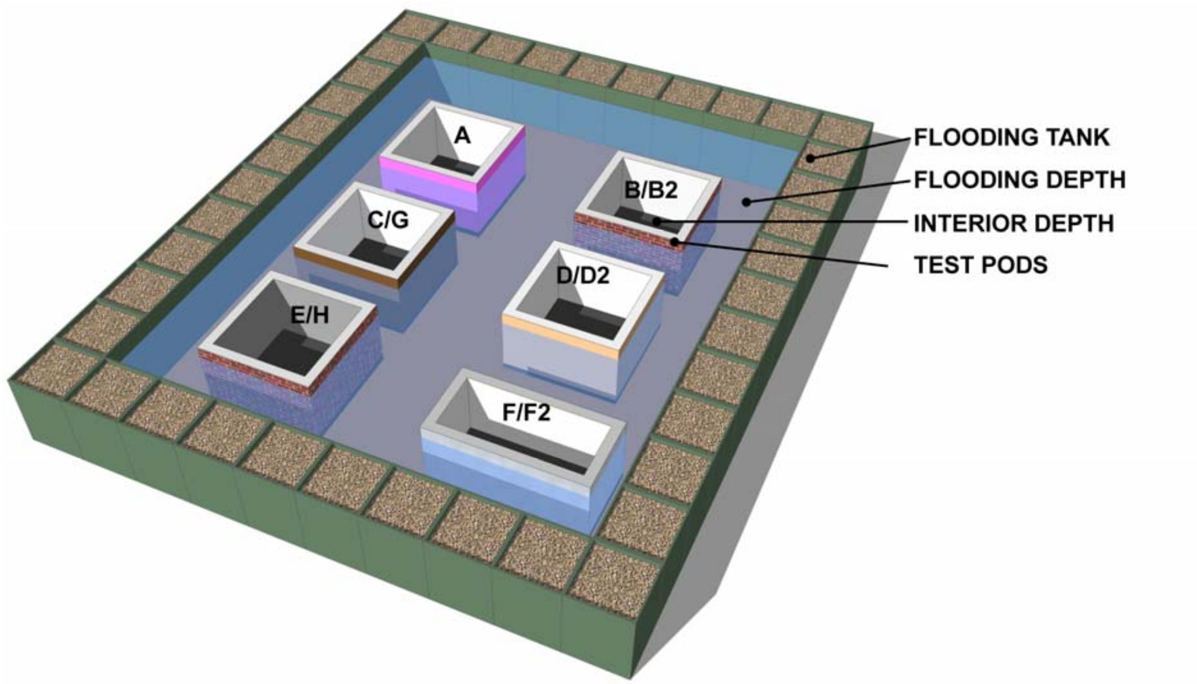


Fig. 4.2. DIAGRAM: Flood tank.

Working outside had several advantages. The size of the testing tank accommodated up to six pods to be tested at once, allowing for direct comparison between the results. Full scale mock-ups built outdoors approximated the construction quality that could be expected during construction of an actual dry floodproof building. Because actual construction can be inconsistent, it was important to work with full scale mock-ups to test the assembly's redundancies to flood resistance.

Fig. 4.3. PHOTO: Flood tank prior to flood simulation 1.

4.1.2 Test Pod Description

Each test pod was built by a local contractor with the exception of the Structurally Insulated Panels (SIPs) assembly. The construction was intended to simulate practices which could be achieved during the construction of an entire building. The standard of construction quality was an important issue for this architectural research. Critical performance systems, such as dry floodproofing, have to be designed to be redundant to mitigate inconstancies in field construction, which often has greater tolerances than laboratory assemblies.

Each pod was built on a concrete slab inside the flood tank. Each concrete slab measured 6′ x 6′, except for the slab which attached to the SIPs, which was 4′ x 8′ at the manufacture's request. Several of concrete pads had block or brick ledges, to accommodate the construction type above.

4.1.3 Testing Protocols

During each flood simulation, a flood depth of 36″ above the finished floor was maintained for a period of 24 hours. The length of the flood during Hurricane Katrina along the Mississippi Gulf Coast lasted hours not days. This, in combination with the precedent of the USACE criteria led the research team to use a 24-hour period for flood simulation. In *Flood Proofing Regulations*, dry floodproofing is defined in the following statement:

"Type B waterproofing construction shall be substantially impermeable but may pass water vapor and seep slightly during flooding to the RFD [Regulatory Flood Datum] … In no case shall there be permitted the accumulation of more than four inches of water depth in such as space during a 24-hour period if there are no devices provided for its removal.(502.1)"

By using a 24-hour test period GCCDS staff was able to simply measure the depth of the water on the interior of the test pods to ascertain if the assembled materials had preformed to the USACE's criteria for Type B dry floodproof construction. (See Fig.4.4)

Fig. 4.4. PHOTO: Data collection during flood simulation 1.

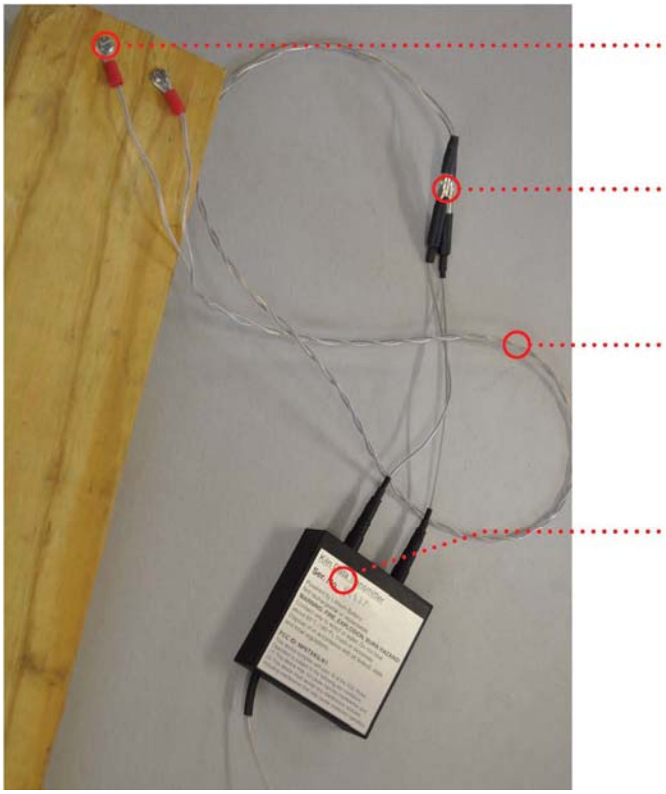
During flood simulations, GCCDS staff members were able to monitor results through measuring water depths inside the test pods, through photographing and videotaping the flood simulations, and through creating a written record of changes in test pod performances. Observations continued as the tank was emptied and water from inside the test pods drained out of the assembly. A two-week drying period followed the first simulation during which moisture content sensors and relative humidity sensors were embedded at various points and depths in the test pods. The final step of the observation protocol was to disassemble several portions of the test pods to look for possible moisture points of intrusion (Fig. 4.5).

Fig. 4.5. PHOTO: Partial demolition of test pod after flood simulation 1.

4.1.4 Instrumentation

Moisture content and relative humidity sensors (Fig. 4.6) were installed in the test pods both before and after the first flood simulation (Fig. 4.7). The use of automated sensors to record moisture over time created an accurate record of how water infiltrated and later dried out of the wall assemblies. Moisture content sensors measure the amount of water held within wood and gypsum products, by measuring the time it takes an electrode to move between two metal contacts. Once calibrated to the specific material, the data collection software can calculate the amount of water in the material as a ratio of the maximum moisture that material can hold. The amount of water soaked into materials during the flood simulation could be estimated by comparing pre-flood and post-flood moisture content measured from the sensors imbedded before and after the flood simulation.

To measure the amount of moisture in concrete, a relative humidity sensor is placed into a small hole which creates a sealed environment from which the sensor can measure the amount of moisture in the air. The data collection software calibrates for temperature and is able to calculate the amount of moisture in the air relative to the maximum capacity of the air to hold moisture. The moisture in the materials which surround the trapped air can be inferred based on this information. All sensor readings are contextualized by climate data gathered from a weather station on Kessler Air Force Base, located two miles from the test site. In order to keep the wireless equipment from becoming damaged during the flood simulations, the equipment was removed from the test pods just prior to the flood simulation, and subsequently returned to the same locations after the flood simulation was completed.



sensors
dry-wall screws pictured. Longer probes are usefull for measuring wood. Proper placement is key to accurate readings.

banana clips
attach to probes or extension wires as shown here

extension wire
length does not effect or measurement

wireless transmitter
collects and transmits data. This sensor collects moisture content information by measuring resistance. Other sensor can measure moisture, temperature, and humidity.

Sensor Equipment
Measuring and Transmitting
all equipment from Lignomat U.S.A.

Fig. 4.6. DIAGRAM: Sensor equipment.

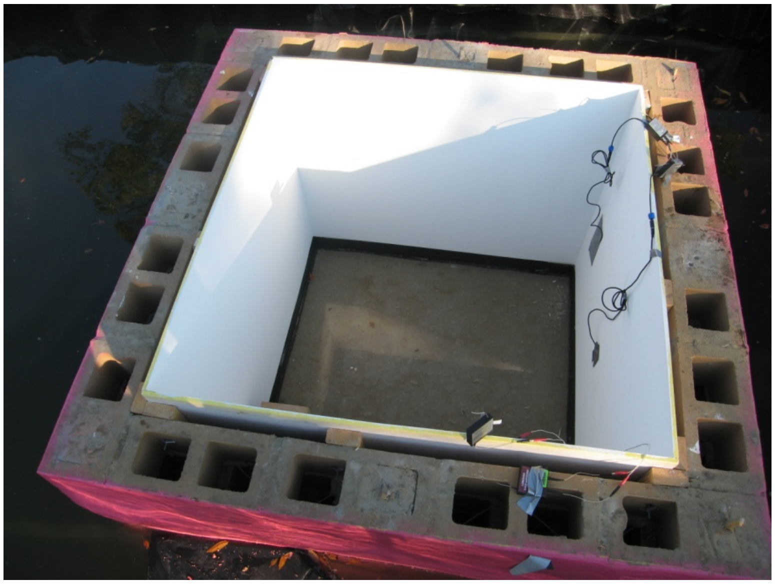


Fig. 4.7 PHOTO: Placement of sensor equipment within test pod assembly.

4.1.5 Documentation

The flood simulations were documented with video, still photography, written reports and digital data collected through the wireless sensors. Written reports were made on log sheets. Water depth inside the tank was referred to as “flood depth”. Water depth inside the test pods due to infiltration through the wall assemblies was referred to as “interior depth.” Measurements of water depths and photographs of the test pods were taken hourly during the filling of the tank, and the first half (first 12 hours) of the 24-hour flood simulation. Additional reports were made during the early stages of the flood simulation due to the high amount of change in the interior depths. After the first 12 hours of the flood simulation, reports were made every 2 hours without significant loss of data due to the relatively slow rate of change. After the test simulations, graphs, logs and presentations were created from analyzed data. A portion of this gathered data is highlighted in this section under section “3.3 Dry Floodproof Testing Under Flood Simulations” and “3.4 Summary of Results”. A more detailed set of results can be found in Appendix A “Complete Flood Simulation Results”.

4.2 Wall Sections and Material Choices

For the propose of understanding the difference in walls of each test pod, it is best to focus on the four elements which most effect dry floodproof performance in walls: the structure, the flood (bulk water) resistive layer, the thermal resistive layer and the exterior finish. The structure supports all the materials and is able to resist or distribute the hydrodynamic, hydrostatic and all other loads. The flood resistive layer consists of a water proofing membrane or other resistive element and must retain its integrity under hydrostatic loads despite possible inconsistencies. The flood resistive layer separates the portion of the wall intended to be exposed to water and the portion of the wall intended to stay dry. The exterior finish is the exposed face of the building, generally an attractive material, which protects the flood resistive layer from degradation from the sun or other environmental factors, while accommodating inspection and repair of the flood resistive layer.

The flood resistive layer is often but not always placed between the exterior finish and the structure. The exterior finish often needs attachments to the structure; these attachments often must penetrate through the flood resistive layer, thereby causing difficulties with floodproofing efforts. Also critically important for dry floodproof performance is the quality of the attachment between the membranes and the surface of the structure. Some test pods did not have an exterior finish installed for the flood simulations, but the connection pieces which could be used between the structure and the exterior finish were installed though the flood resistive layer so that the performance of the flood resistive layer could be accurately measured. Alternative modular or panelized systems such as SIPs or ICFs can integrate more than one of the four elements discussed above within the same material or component.

A total of eleven unique wall assemblies were tested. The test fill was conducted with test pod A: sealed block installed. The first flood simulation was conducted with test pods A through F installed and observed. The second flood simulation was conducted with test pods A, B2, G, D2, H and F2. Detailed architectural drawings of each pod can be found in Appendix B. Table 2 shows the order in which pods were tested during three flood simulations.

Table 2. Testing order.

Test Fill	Flood 1	Flood 2
A: sealed block	A: sealed block	A: sealed block
	B: cavity wall	B2: cavity wall filled block
	C: unsealed block (control)	G: sheet membrane block
	D: ICF	D2: ICF
	E: metal stud (control)	H: weatherproofed block
	F: metal SIPs	F2: metal SIPs

4.2.1 Test Pod A: Sealed Block

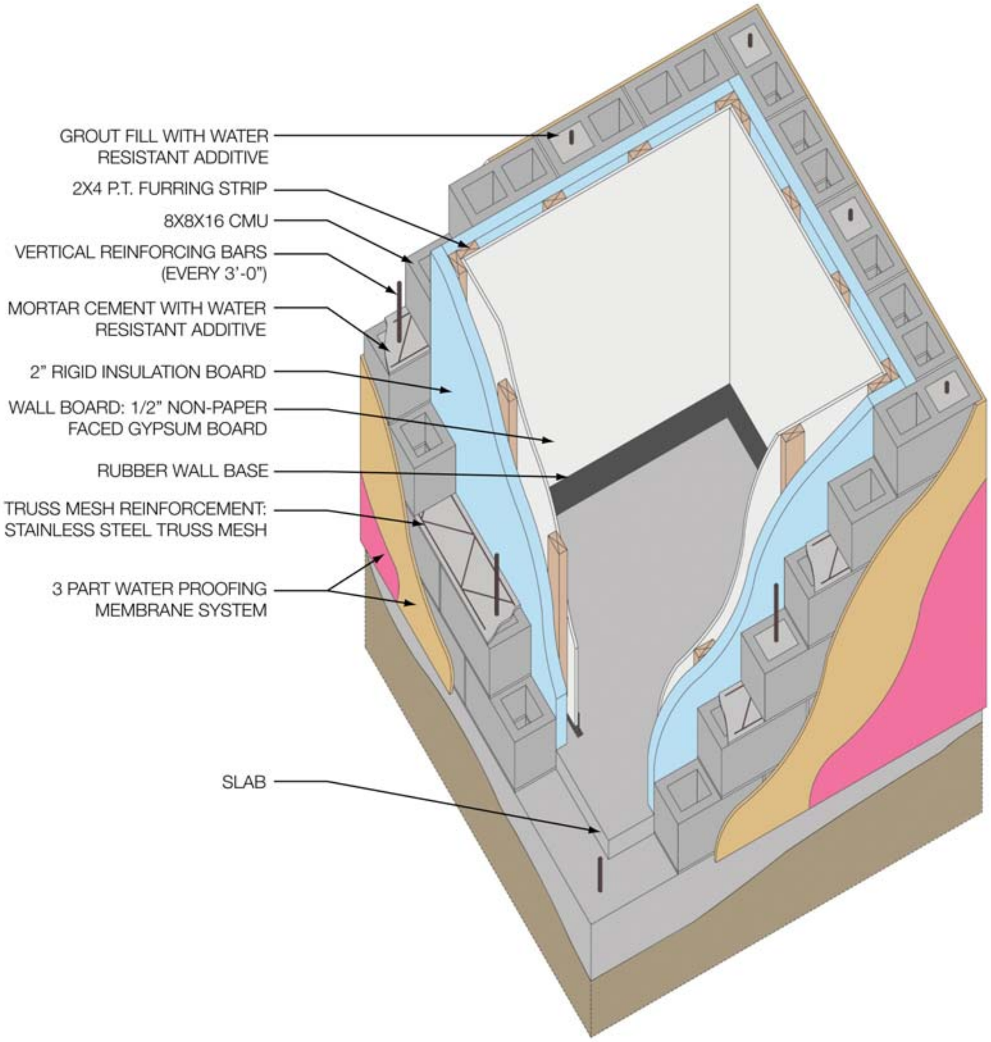


Fig. 4.8. DIAGRAM: test pod A: sealed block.

Test pod A: sealed block was a concrete masonry unit (CMU) wall structure with a layered polymer membrane exterior coating (Fig. 4.8).

- First course (8″ in height) of CMU cells filled with grout with water resistant additive.
- Fully grouted CMU cells located at corners and in at the middle of each wall.
- Three-layered multi-component sealant system most often used in industrial or infrastructure applications.
- Wall assembly did not have exterior finish façade although one would be required for actual install.

4.2.2 Test Pod B: Cavity Wall

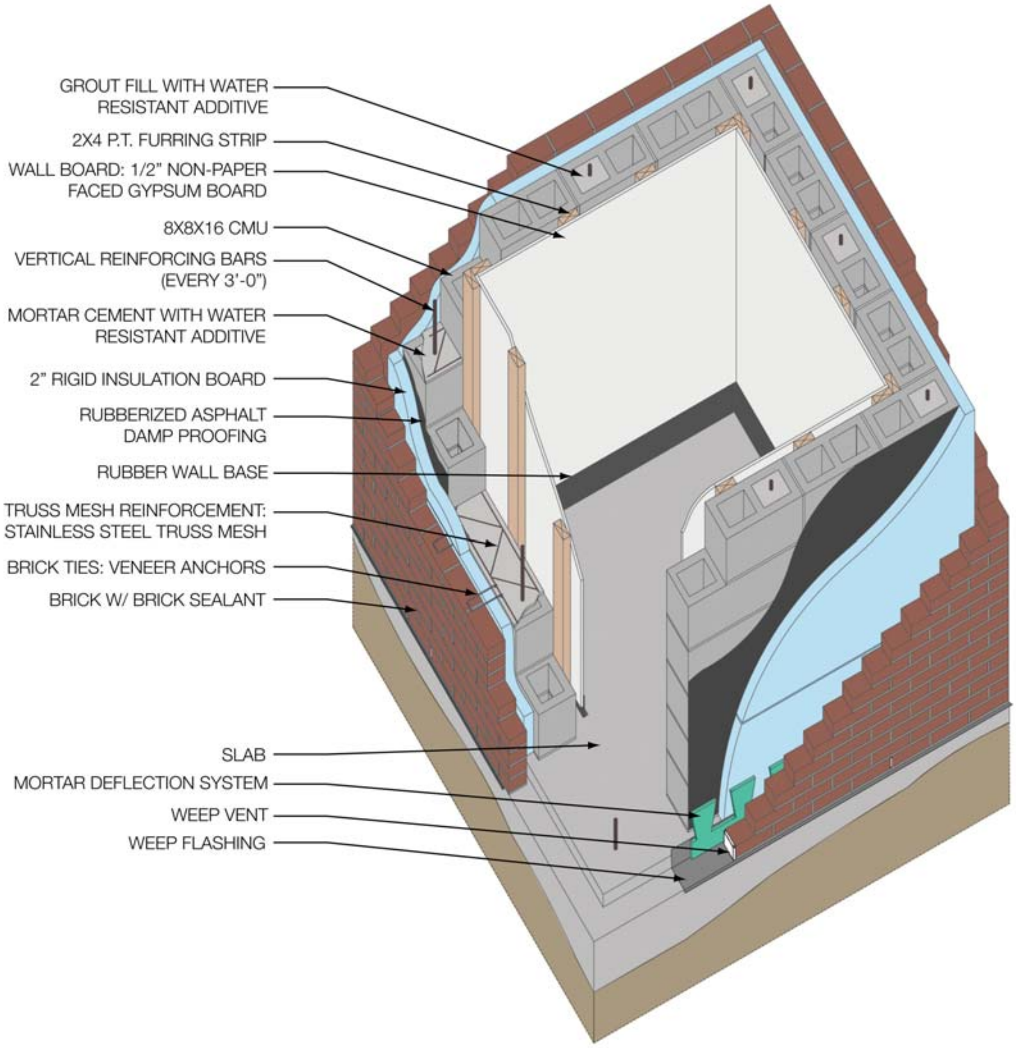


Fig. 4.9. DIAGRAM: test pod B: cavity wall.

Test pod B: cavity wall (Fig. 4.9) was a CMU wall structure with a fluid-applied rubberized asphaltic emulsion coating between the exterior of the CMU face and the brick exterior finish.

- First course (8″ in height) of CMU cells filled with grout with water resistant additive.
- Fully grouted CMU cells located at corners and in at the middle of each wall.
- Brick was connected to CMU; asphaltic membrane was painted on CMUs around metal connectors.
- A 2″ cavity between the bricks and the rubberized asphalt. This cavity contained the thermal barrier and allowed for good drainage during normal use.

4.2.3 Test Pod C: Unsealed Block

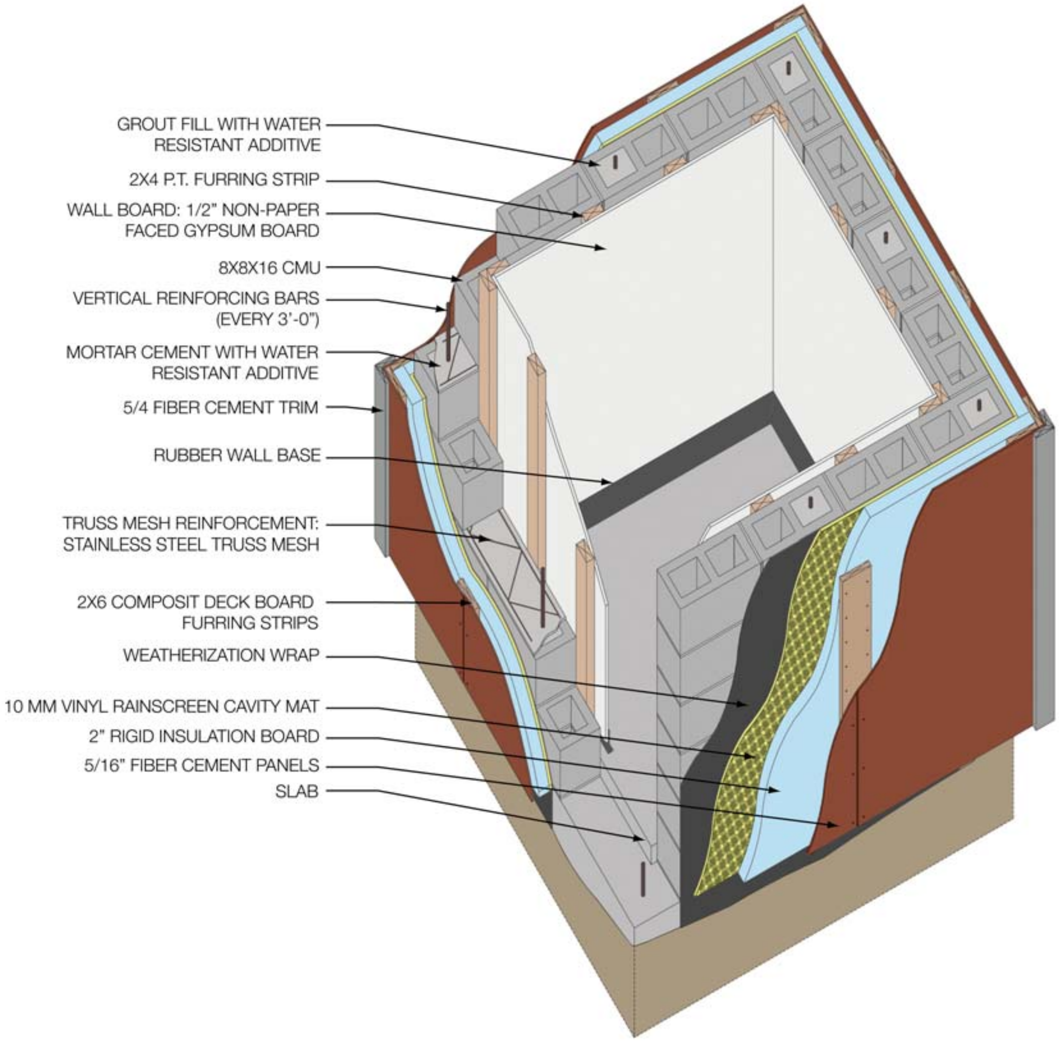


Fig. 4.10. DIAGRAM: test pod C: unsealed block.

Test pod C: unsealed block (Fig. 4.10) was a CMU wall structure with a non-adhesive weather barrier wrapped around the block under fiber cement panels.

- First course (8″ in height) of CMU cells filled with mortar.
- Fully grouted CMU cells located at corners and in at the middle of each wall.
- A non-adhesive weather barrier was wrapped around the wall. This provides little protection against flood waters.
- A plastic drainage mat was placed between the insulation and the membrane to keep water from getting trapped in the assembly.
- Vertical furring strips connect the exterior panels to structure via masonry screws which penetrate the membrane.

4.2.4 Test Pod D: ICF

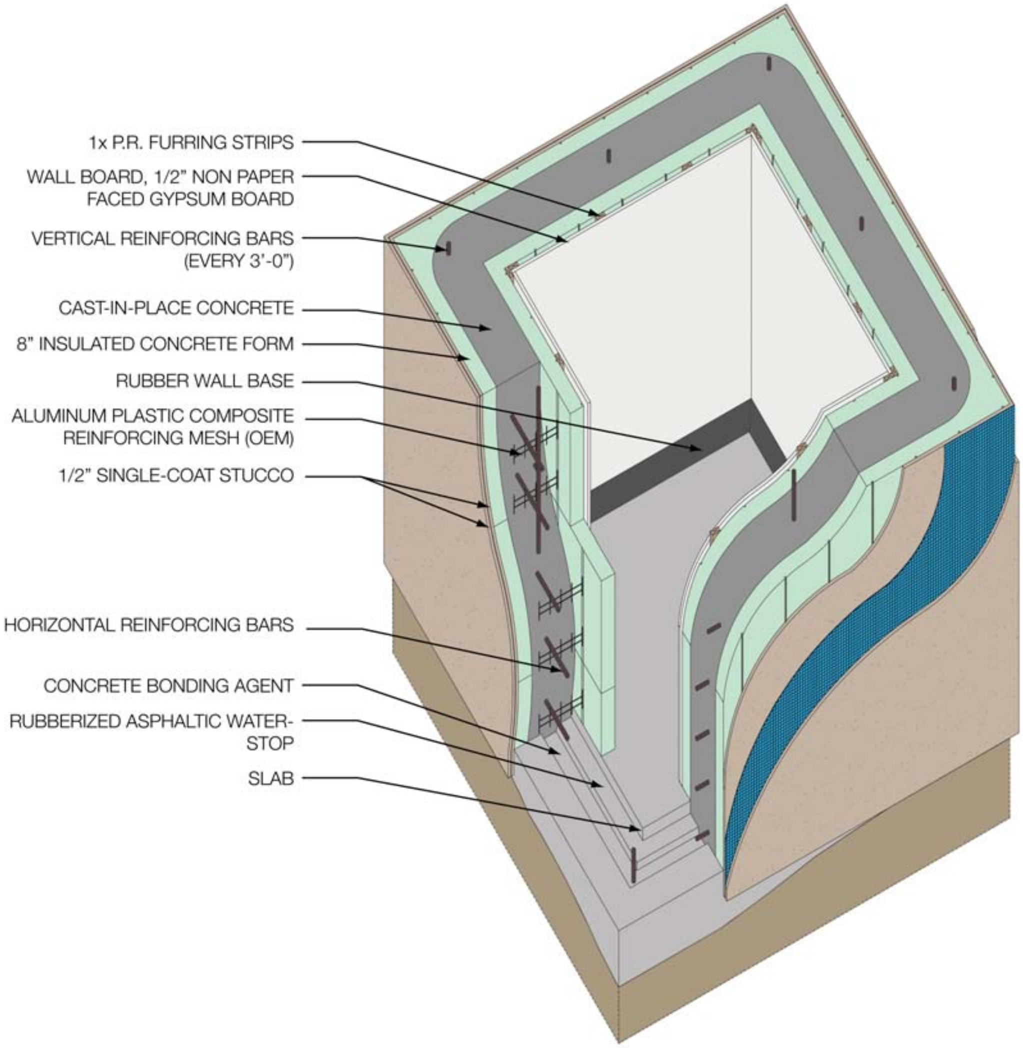


Fig. 4.11. DIAGRAM: test pod D: ICF.

Test pod D: ICF (Fig. 4.11) was constructed using ICF with a stucco exterior finish.

- ICF is a system of formwork for concrete that stays in place as a permanent thermal resistive layer.
- ICF was made from polystyrene foam
- A channel in the foundation slab was used to “key” the wall into the slab.
- The joint between the concrete slab and the concrete core of the wall was filled with a rubberized asphaltic emulsion.
- Stucco finish is water permeable.

4.2.5 Test Pod E: Metal Stud

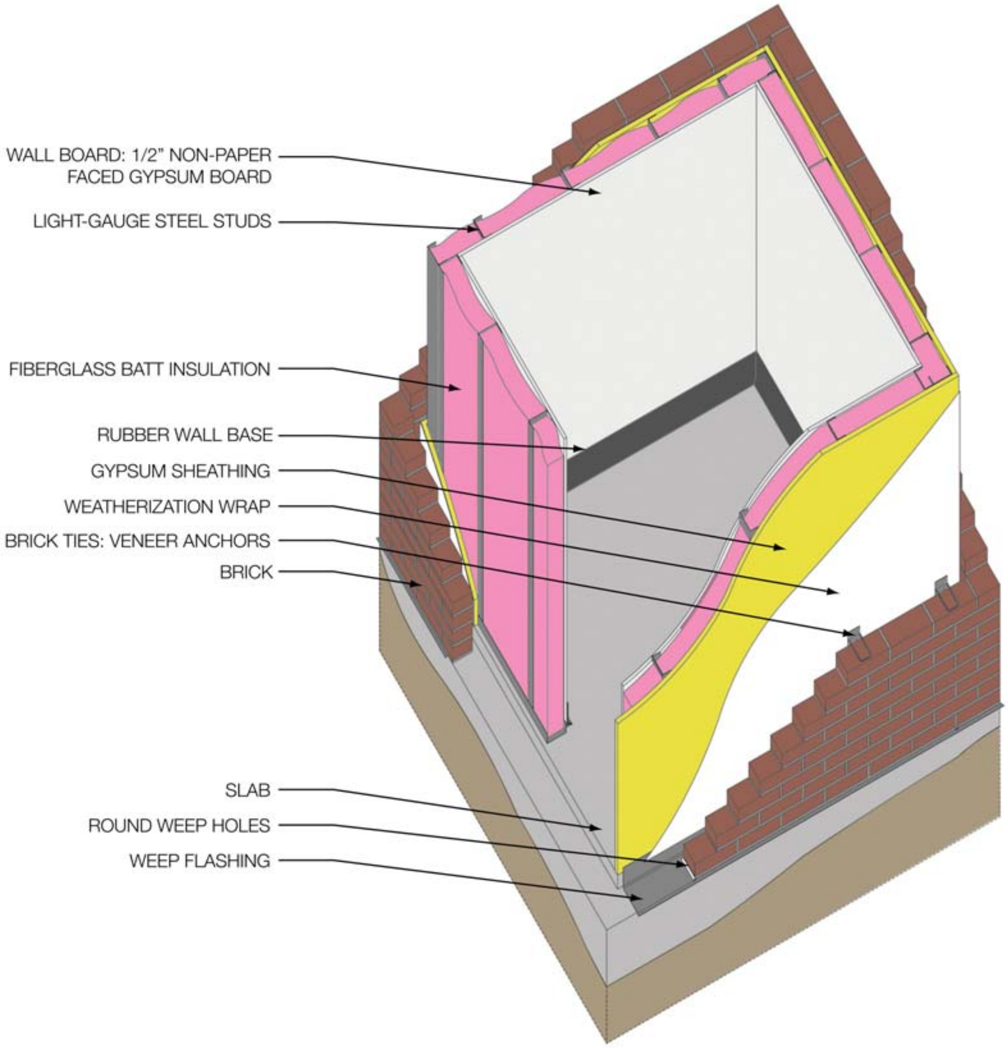


Fig. 4.12. DIAGRAM: test pod E: metal stud.

Test pod E: metal stud (Fig. 4.12) was a metal stud structure with a non-adhesive weather barrier wrapped around the sheathing beneath the brick façade.

- Same weather barrier as test pod C.
- Built as a "Control Pod" to observe how local building might perform during a flood event.
- This assembly is an example of commercial construction common in the Mississippi Gulf Coast.

4.2.6 Test Pod F: Metal SIPs

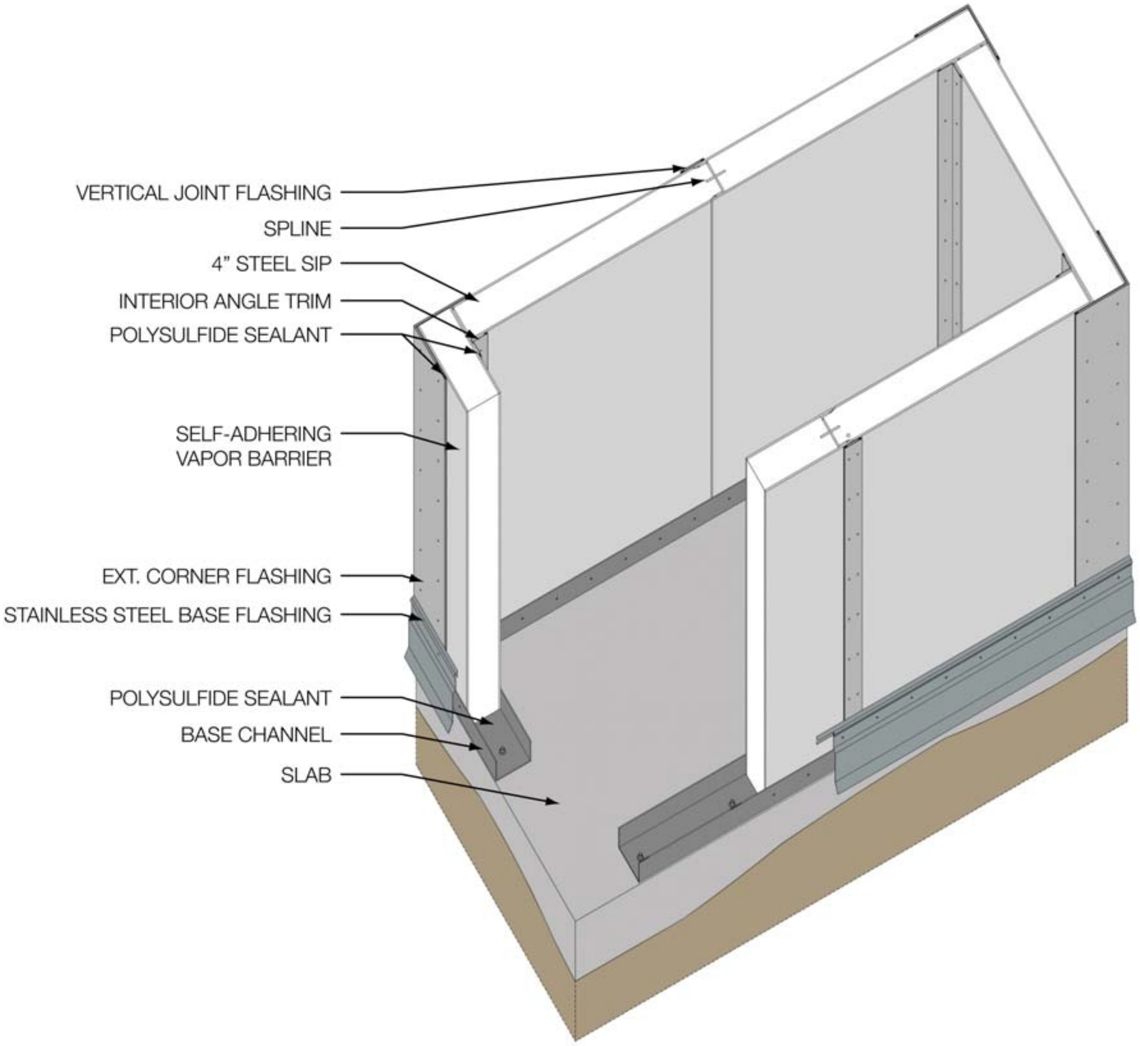


Fig. 4.13. DIAGRAM: test pod F: metal SIPs.

Test Pod F: metal SIPs (Fig. 4.13) was constructed using metal SIPs set in a steel channel, which had been bolted to the concrete slab.

- Metal SIPs were made by sandwiching a core of rigid foam insulation between two metal panels.
- Joints were covered with metal flashing and caulked.
- No exterior finish or water resistive layer was used. It was intended that the SIPs would be the structure, water resistive layer, thermal layer and exterior finish.

4.2.7 Test Pod G: Sheet Membrane Block

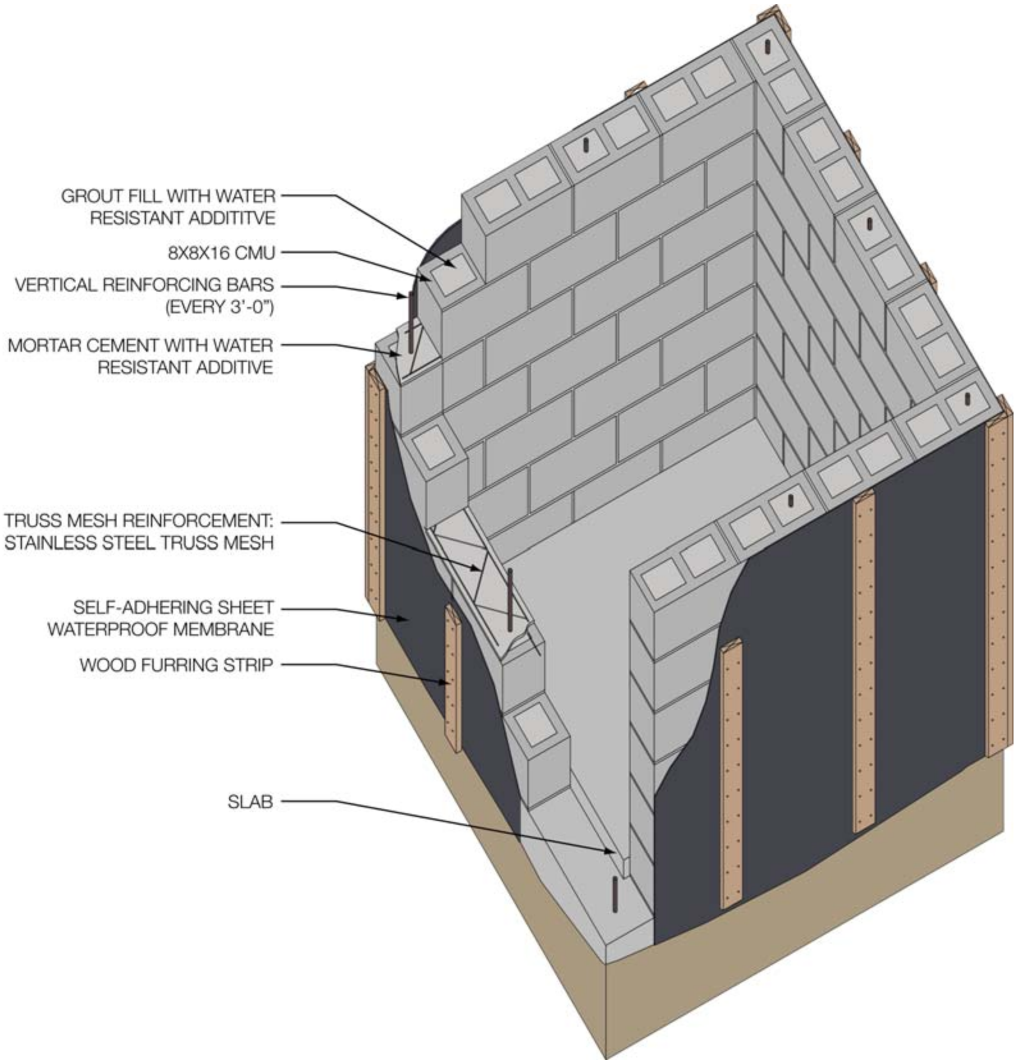


Fig. 4.14. DIAGRAM: test pod G: sheet membrane block.

Test Pod G: sheet membrane block (Fig. 4.14) was a retrofit of test pod C: unsealed block with a self-adhering rubberized asphalt/polyethylene membrane sheet applied to the exterior face of the CMU.

- Sheet applied directly to CMU
- The self-adhering sheet is covered with 1mm (.04”) of rubberized asphalt/polyethylene
- Sheets overlap 2”
- For structure description see test pod C

4.2.8 Test Pod H: Weatherproofed Block

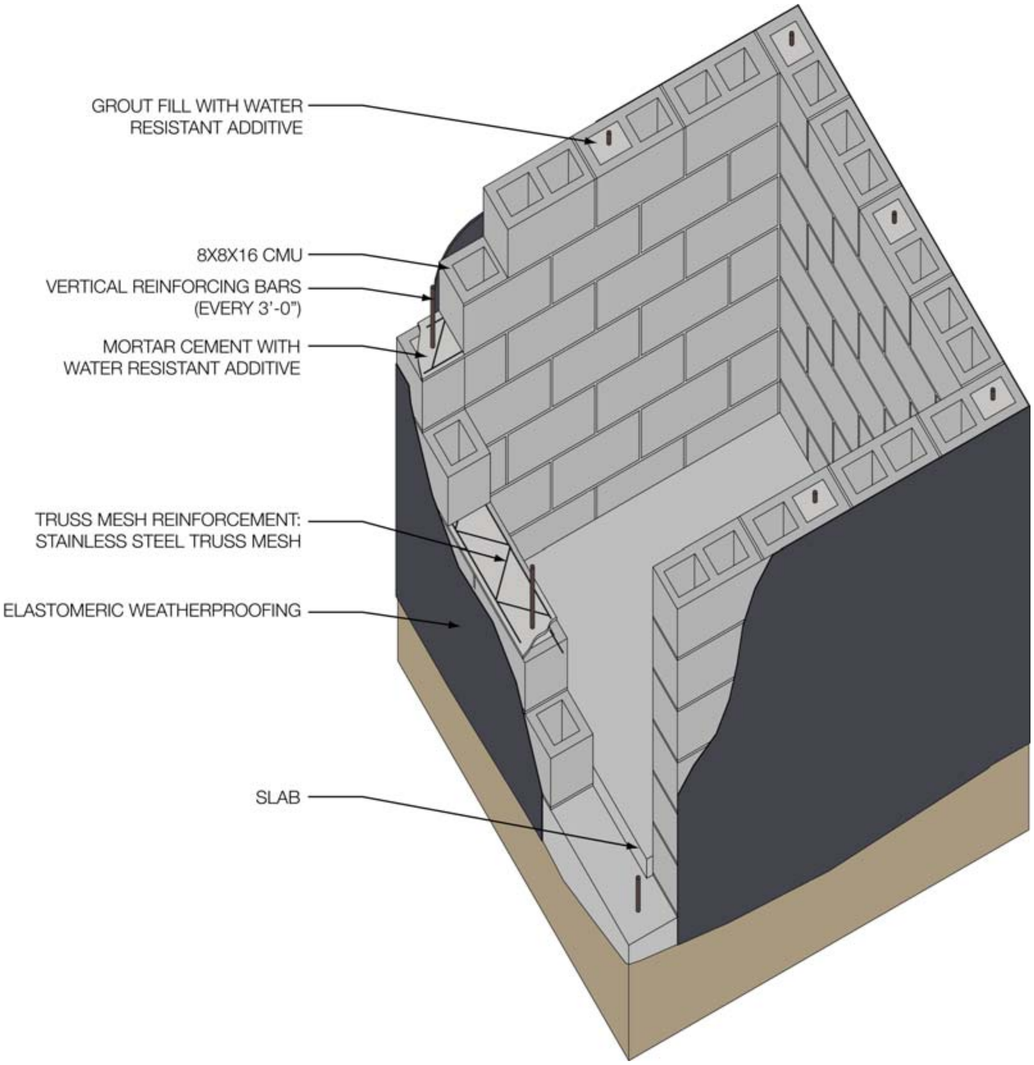


Fig. 4.15. DIAGRAM: test pod H: weatherproofed block.

Test pod H: weatherproofed block (Fig. 4.15) was a CMU block structure with a liquid membrane sprayed on to the exterior of the CMU face.

- First course (8″ in height) of CMU cells filled with mortar.
- Fully grouted CMU cells located at corners and in at the middle of each wall.
- The flood resistive layer was an elastomeric waterproofing coating for masonry and concrete, applied in four thick coats.
- Design was developed as inexpensive alternative to test pod A: sealed block which performed well with a high-end spray-applied water resistive layer.
- Elastomeric coating was applied with a residential sprayer.

4.2.9 Test Pod B2: Cavity Wall Filled Block

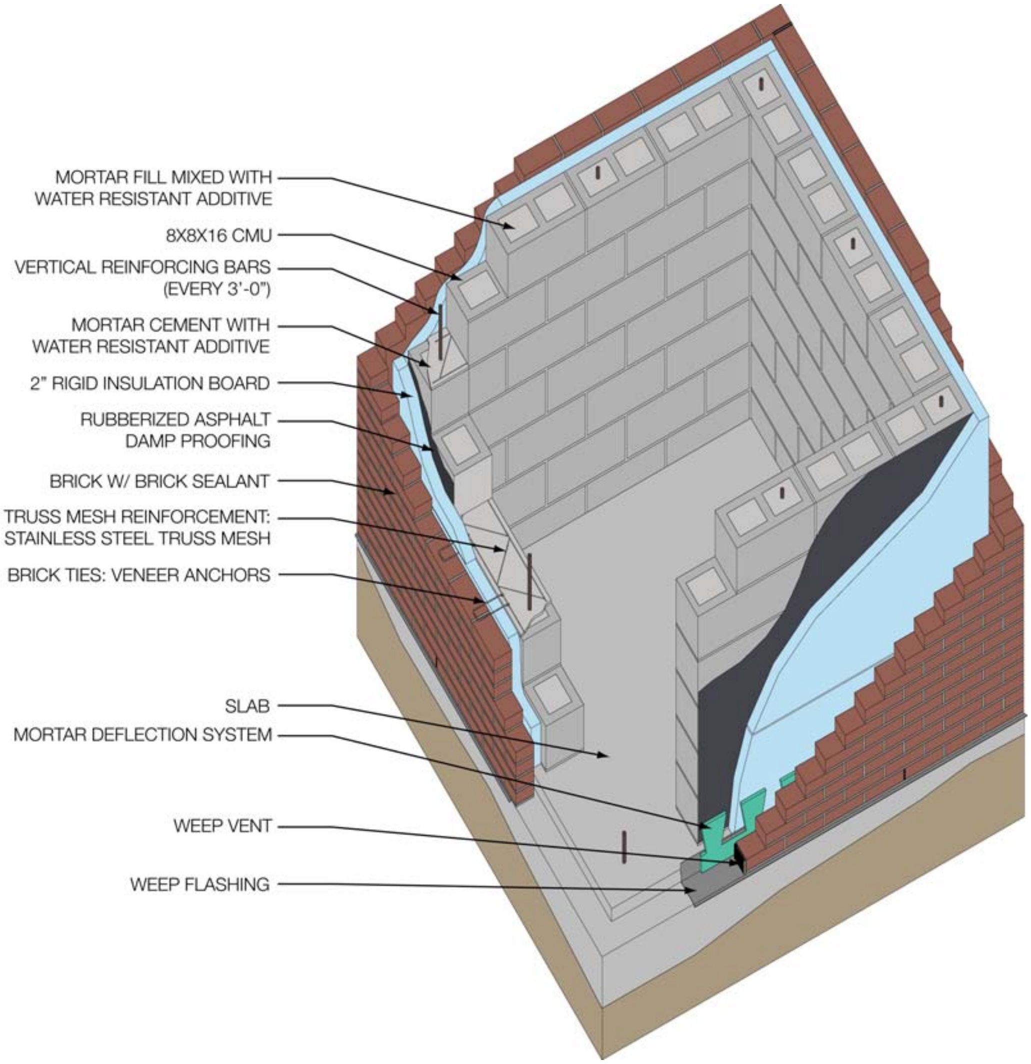


Fig. 4.16. DIAGRAM: test pod B2: cavity wall filled block.

Test pod B2: cavity wall filled block (Fig. 4.16) was a retrofit of test pod B: cavity wall.

- Each cell of the CMU was completely filled with grout for the entire height of the wall.
- For a description of the rest of the construction of the wall, see test pod B: cavity wall description.

4.2.10 Test Pod D2: ICF

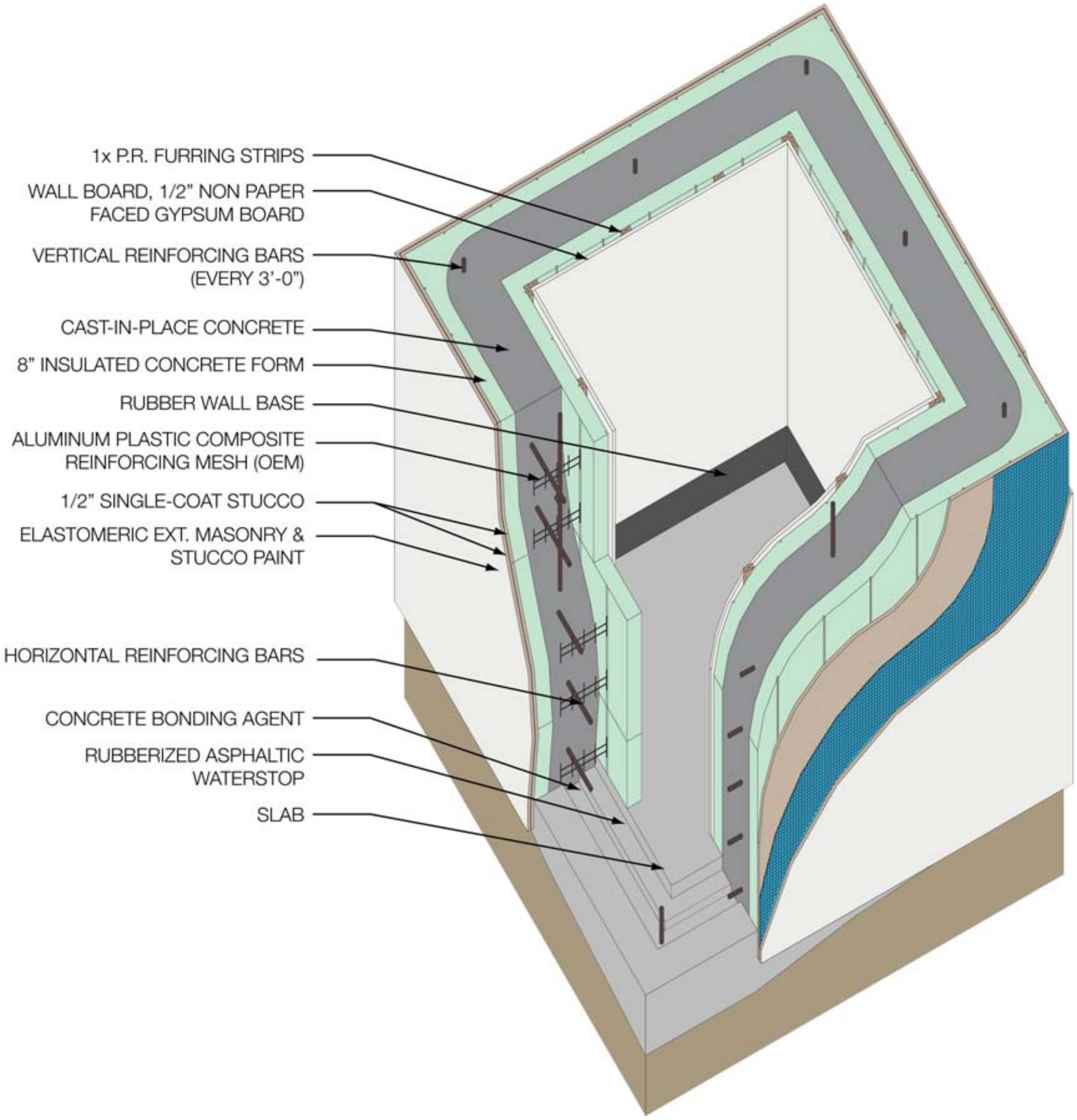


Fig. 4.17. DIAGRAM: test pod D2: ICF.

Test pod D2: ICF (Fig. 4.17) was a retrofit of test pod D: ICF with an elastomeric paint applied to the exterior of the stucco.

- The elastomeric paint is partially impermeable to water
- For a description of the rest of the construction of the wall see test pod E: ICF description.

4.2.11 Test Pod F2: Metal SIPs

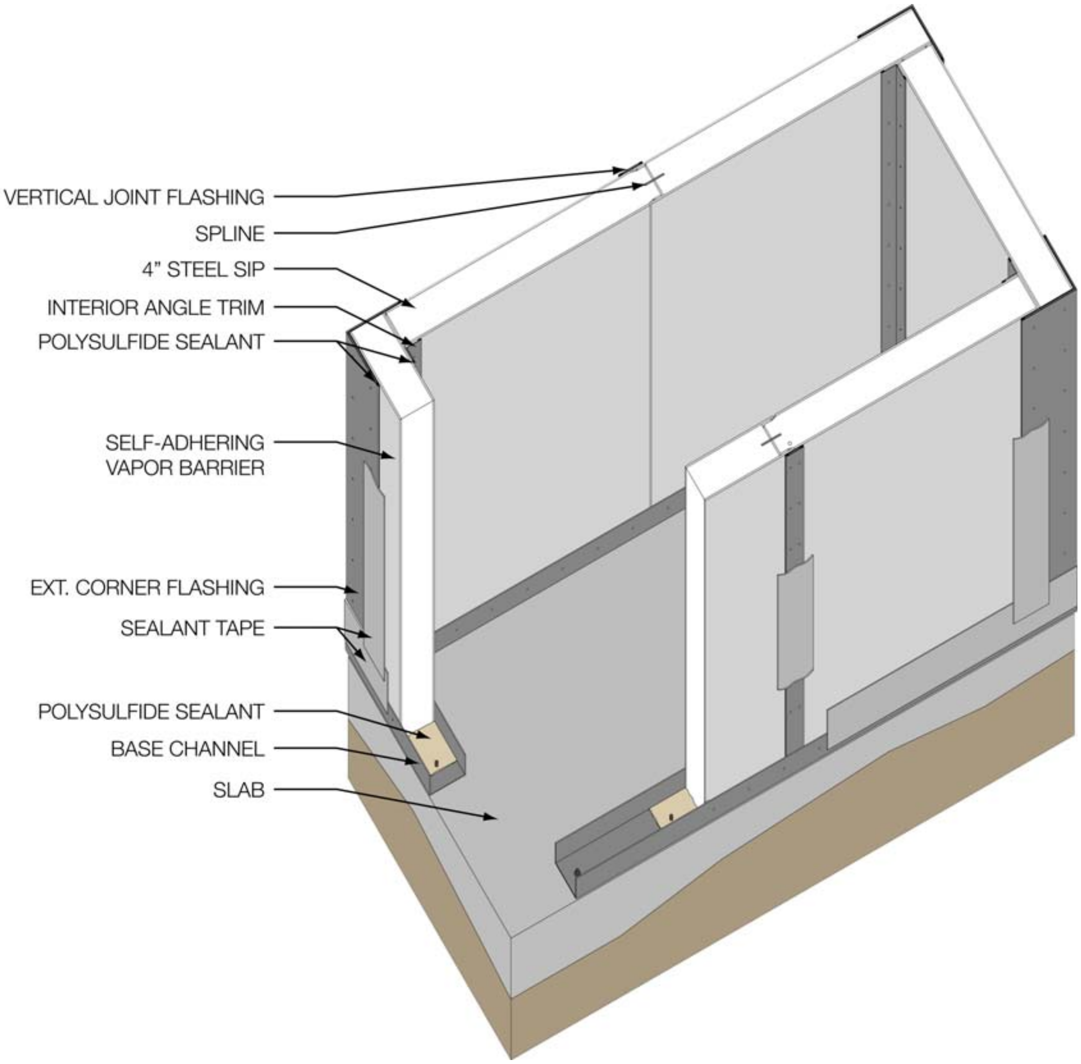


Fig. 4.18. DIAGRAM: test pod F2: metal SIPs.

Test pod F2: metal SIPs (Fig. 4.18) was a retrofit of test pod F: metal SIPs with an updated SIP-to-foundation detail that created a more robust seal between the panels and the slab.

- A much larger amount of sealant was placed into the base channel before the SIPs were set into it.
- Butyl tape was used to seal the vertical and horizontal joints.
- For a description of the other aspects of the wall see test pod F: metal SIPs description.

4.3 Dry Floodproof Testing Under Flood Simulations

The test fill, which was a test for the facility, equipment and protocols, took place on January 19th 2011. The sensors were installed into the test pods to collect pre-flood data on March 15th 2011. Flood simulation 1 began on April 6th, 2011. ON April 8th any remaining water in the test pods were completely drained and the sensors were placed back in the walls. Flood simulation 2 took place on June 28th and 29th 2011. There was not a drying period measured with sensors after the second flood simulation. (See Fig. 4.1 for timeline)

4.3.1 Test Fill Results

During the test fill a water depth of 36” within the tank could not be maintained for an entire 24 hour period. Water leak through the tank lining and Hesco boxes at a high rate making it too difficult to maintain proper depth. Only pod A: sealed block had been installed at the time of the test fill. The interior water depth in the test pod was 2” after 20 hours of flood simulation at water depths ranging from 24” to 40”. After the flood tank had been evacuated, an inspection of the exterior coating of test pod A: sealed block revealed that a 6”x 2” strip of the layered polymer membrane had broken off the wall near the bottom (Fig.4.19). This hole in the sealant material was patched using the same liquid-applied asphaltic sealant used in test pod B: cavity wall, prior to the next flood simulation.

Fig. 4.19. PHOTO: Damage to test pod A: sealed block during the test fill.

4.3.2 Flood Simulation 1 Results

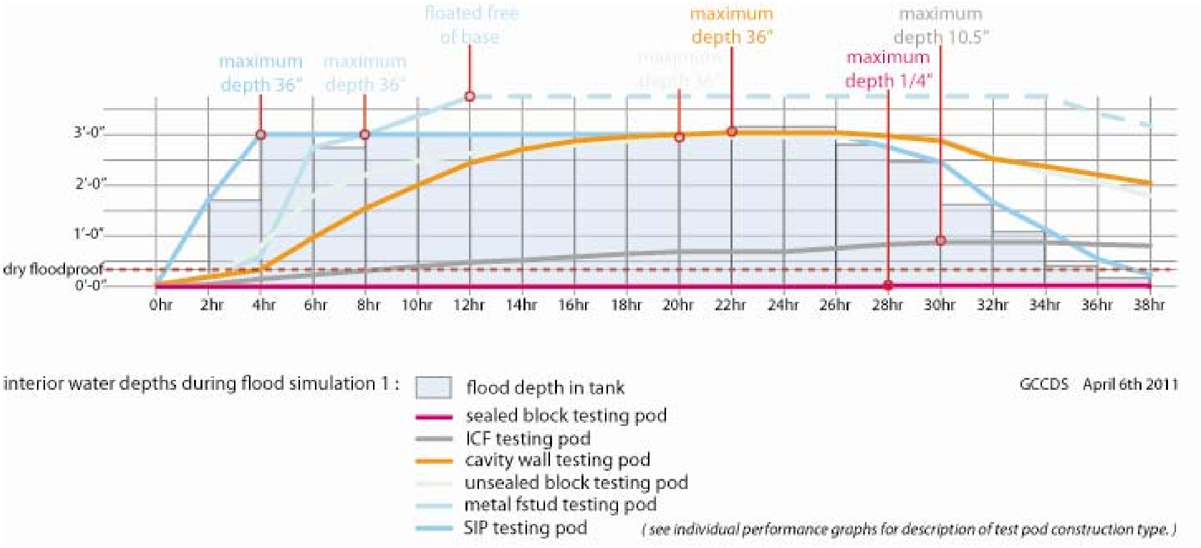


Fig. 4.20. GRAPH: Interior depths: flood simulation 1.

The following is a condensed version of the report from flood simulation 1, which highlights the significant events during the simulation. For a more complete report of the simulation see Appendix A: "Full Test Results". Above (Fig. 4.20), a graph shows the interior depths that infiltrated the test pods during the flood simulation 1.

<u>April 6th</u>

0:00 (7:30am) - The flood simulation began. The approximate rate of water entering the flood tank was 200 gallons per minute. Two hoses were used to fill the flood tank and were positioned to avoid creating hydrodynamic forces on the test pods.
0:25 - The interior depth in test pod E: metal stud surpassed the 4" mark. The flood depth in the tank was 10" at that time.
2:23 – Test pod F: metal SIPs interior depth reached 4". The flood depth was 28" at this time.
2:55 – The interior depth in test pod C: unsealed block rose to 6 ½", surpassing the 4" mark. The flood depth in the flood tank had risen to 33".
3:20 – The flood depth reached the targeted 36" depth. At this time, the test pod A: sealed block had no measurable interior depth; only a small amount of seepage could be seen. Test pod B: cavity wall had 4" of interior depth. Test pod C: unsealed block had 9.5" of interior depth. The interior depth for test pod E: metal stud had equalized with the flood depth at 36". Test pod D: ICF had 1.75" of measurable interior depth. Test pod F: metal SIPs had an interior depth of 7".
8:03 – The water inside test pod D: ICF reached a depth of 4.25", passing the dry floodproof threshold.

10:30 - Test pod F: metal SIPs floated free of the metal base channel which remained connected to the concrete slab. Test pod F: metal SIPs had at least 33″ of interior water depth when this happened.

April 7th
17:30 to 19:30– Test pod B: cavity wall and test pod C: unsealed block had equal interior depth and flood depth at 36″.
23:30 - The contractor began to empty the tank. The flood tank emptied at an average rate of 5″ to 5.5″ inches an hour.
27:30 - The interior water depth in the test pod A: sealed block reached a level of ¼″. This was the maximum interior depth for this test pod.
29:46 – Test pod D: ICF reached an interior depth of 10 ½″. This was the maximum interior depth for this test pod.
32:30 –The flood tank was almost completely empty.

April 8th
52:30 – GCCDS staff bailed out the remaining water in all six test pods and placed the moisture content and relative humidity sensors back into the wall assemblies. The remaining interior depths prior to bailing were .25″ in test pod A: sealed block, 17.75″ in test pod B: cavity wall, 13.25″ in test pod C: unsealed block, 7.25″ in test pod D: ICF. Test pods E: metal stud and test pod F: metal SIPs were not holding standing water at this time.

April 19th
The tent was removed after two weeks of observation.

4.3.2.1 Test pod A: sealed block

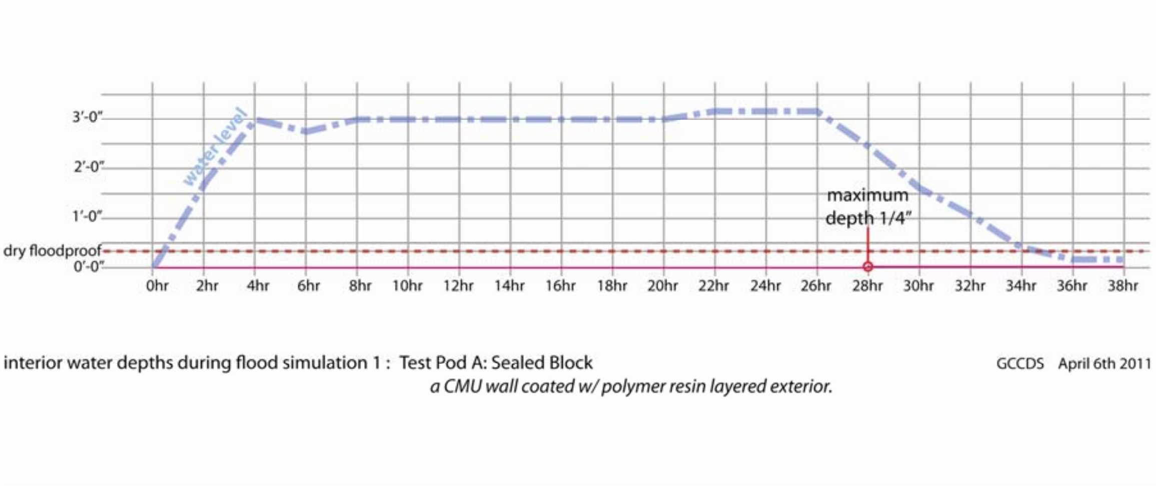
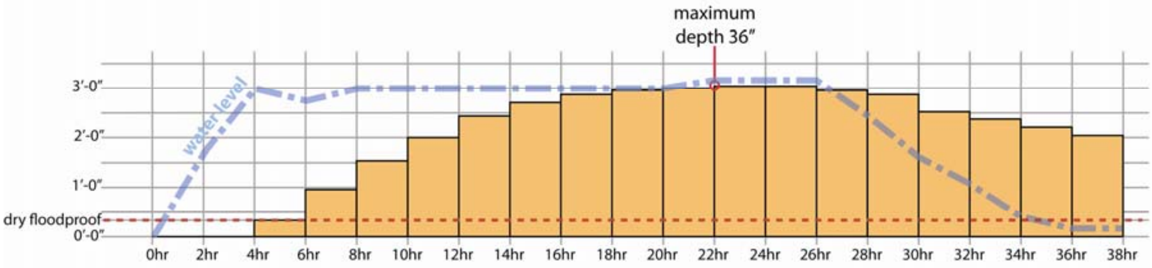


Fig. 4.21. GRAPH: Interior depths: test pod A: sealed block, flood simulation 1.

The test pod A: sealed block never had an interior depth of more than ¼″ of water at any point during flood simulation 1 (Fig. 4.21). The water that did seep into this test pod did so at a continuous rate starting from the middle of the west wall of the pod. This location corresponds with the 6″ x 2″ section of the layered polymer membrane which had been damaged and repaired prior to flood simulation 1.

4.3.2.2 Test pod B: cavity wall



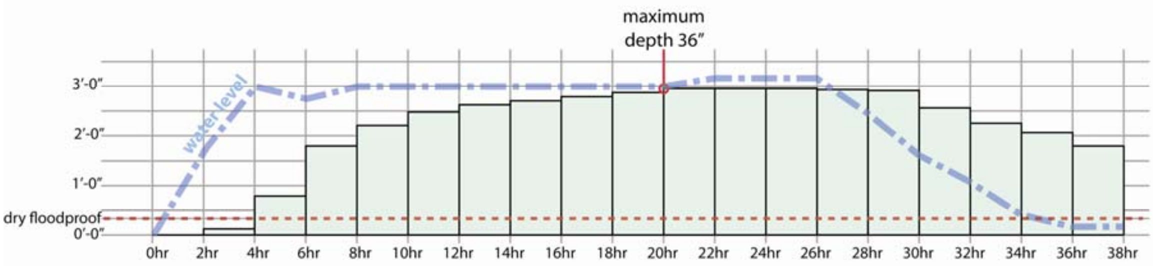
interior water depths during flood simulation 1 : Test Pod B: Cavity Wall GCCDS April 6th 2011

a CMU wall w/ a liquid applied asphaltic membrane applied to the exterior of the block face between it and the brick cavity.

Fig. 4.22. GRAPH: Interior depths: test pod B: cavity wall, flood simulation 1.

Test pod B: cavity wall maintained 4″ or less of interior depth for the first 6 hours, eventually equalizing with the flood depth after 18 hours (Fig. 4.22). Water was observed filling different CMU cells at different rates during the test. A CMU block is 8″ tall; 8″ was often the difference between the depth of water in neighboring CMU cells. Because of this observation, it was concluded that penetration of water between CMU cells happened through the joints rather than the blocks themselves.

4.3.2.3 Test pod C: unsealed block



interior water depths during flood simulation 1 : Test Pod C: Unsealed Block (control) GCCDS April 6th 2011

a CMU w/ non-adhesive wrap membrane wrapped around the block under the panels.

Fig. 4.23. GRAPH: Interior depths: test pod C: unsealed block, flood simulation 1.

Overall, test pod C: unsealed block had similar performance to the test pod B: cavity wall, but filled at a quicker rate (Fig. 4.23). The difference in performance between the two test pods can be attributed to the difference in membranes used in the test pods, as represented by the darker shaded areas in Fig. 4.24. Test pod C: unsealed block was a CMU wall without a membrane. When compared to test pod B: cavity wall, the results show that the presence of the asphaltic membrane in test pod B made little headway towards floodproof performance. The comparison of test pods B and C led the GCCDS research team to conclude that the asphaltic liquid membrane applied with a brush was not a viable option for investigation of dry floodproofing.

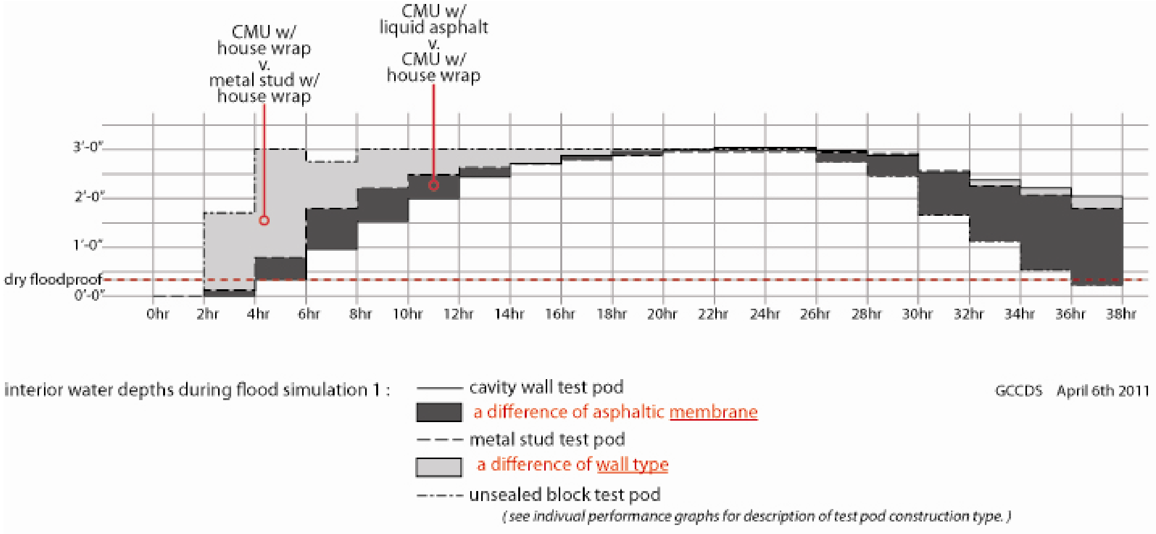


Fig. 4.24. GRAPH: Int. depths: differences between membranes and wall assemblies.

4.3.2.4 Test pod E: metal stud

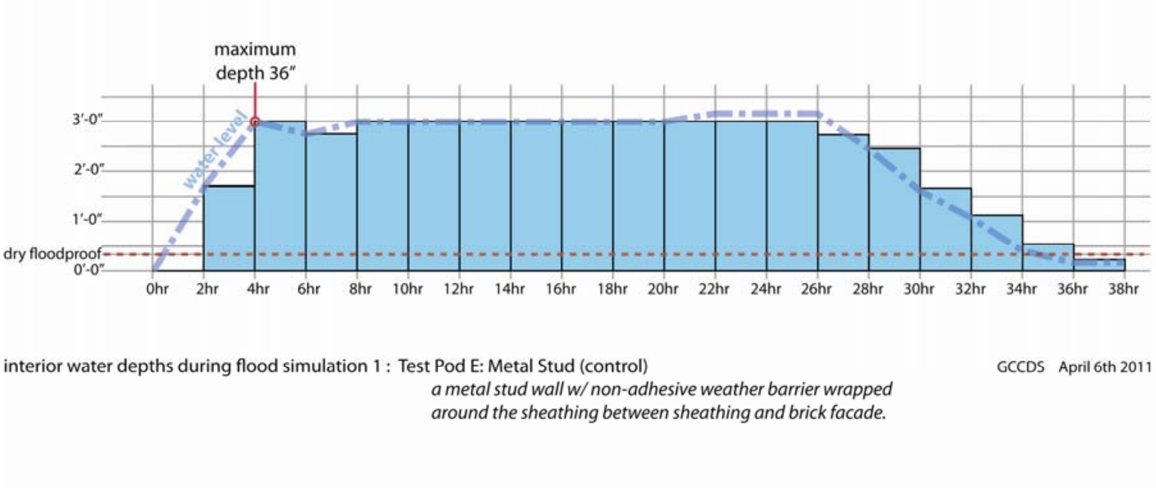


Fig. 4.25 GRAPH: Interior depths: test pod E: metal stud, flood simulation 1.

Test pod E: metal stud provided the least resistance to the penetration of water into the interior (Fig. 4.25). The interior depth of test pod E: metal stud was nearly constant and equal to the flood depth throughout flood simulation 1. The interior depth was higher than the flood depth during the evacuation of the flood tank. Likely, this was a result of the external hydrostatic pressure slowing the drainage of the water from inside the test pod. This observation led GCCDS staff to conclude that the majority of water was penetrating the assembly along the base of the test pod, where hydrostatic forces were strongest, causing quick filling and slow draining of the test pod.

4.3.2.5 Test pod D: ICF

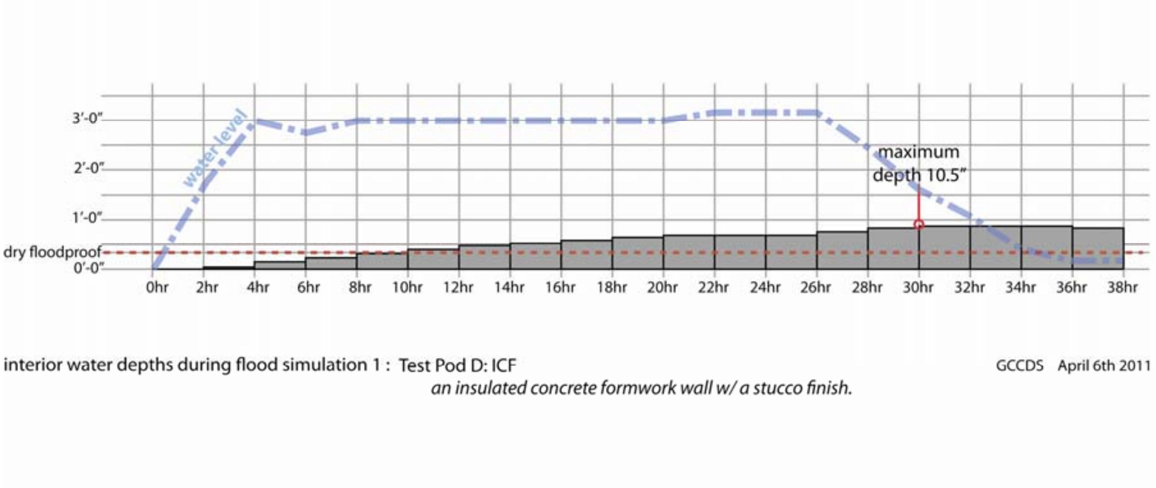


Fig. 4.26. GRAPH: Interior depths: test pod D: ICF, flood simulation 1.

Test pod D: ICF displayed a constant rate of water penetration into the assembly system, even after flood depths began to drop (Fig. 4.26). The interior depth surpassed the 4” dry floodproof threshold at approximately 4.5 hours after the 36” flood depth was reached. The maximum interior depth for test pod D: ICF was 10.5”, 26 hours after the flood simulation began. The final interior depth was much lower than systems which obviously failed, implying that the assembly continuously maintained some resistance to flood waters throughout the test. The slow rate of change in the interior depth suggested that the accumulated water was likely due to seepage through material rather than leakage through gaps in connections.

4.3.2.6 Test pod F: metal Structural Insulated Panels (SIPs)

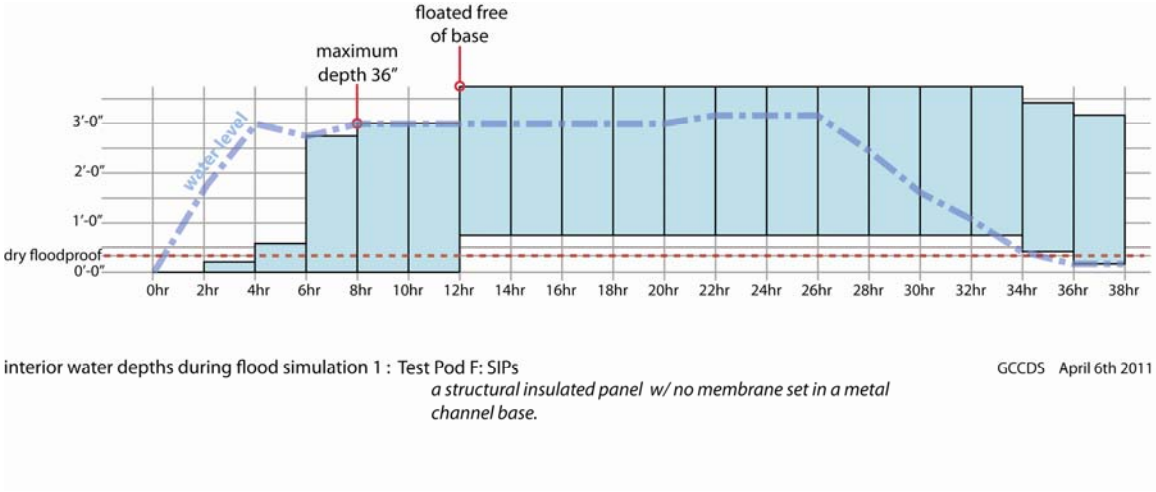


Fig. 4.27 GRAPH: Interior depths: test pod F: metal SIPs, flood simulation 1.

Test pod F: metal SIPs was unable to resist both vertical and horizontal hydrostatic forces during the first flood simulation. Once the flood depth reached 36”, the test pod quickly filled up with water (Fig 4.27). Water could be seen flowing to the interior along a path which followed the connection between the U-shaped channel and panel. Water was not seen passing through the vertical seams between panels. By the 12th hour of the test, the entire test pod floated free from the foundation slab. The vertical hydrostatic (buoyant) forces acting on the wall were too great for the caulk, which was the sole component in the assembly connecting the channel to the SIPs. Likely, the buoyant forces stressed the caulk early in the simulation, to where the caulk was no longer an effective barrier against the passage of water.

4.3.3 Two-Week Drying Period

After flood simulation 1 was complete, and all the water had been evacuated from both the flood tank and the test pods, the wireless sensors were placed back into the test pods at the same locations as before the simulation. Each sensor recorded moisture content for a two-week drying period. During this time the flood tank was covered with a tent to keep out the weather, but allowed outside air flow. Four data sets are presented in this chapter: the drying period of a wall classified as dry floodproof, the drying period of a wall not classified as dry floodproof, a comparison of drywall in all test pods, and a comparison of the mortar joints 24 hours before and after the flood simulation. For more sensor graphs and analysis, refer to Appendix A.

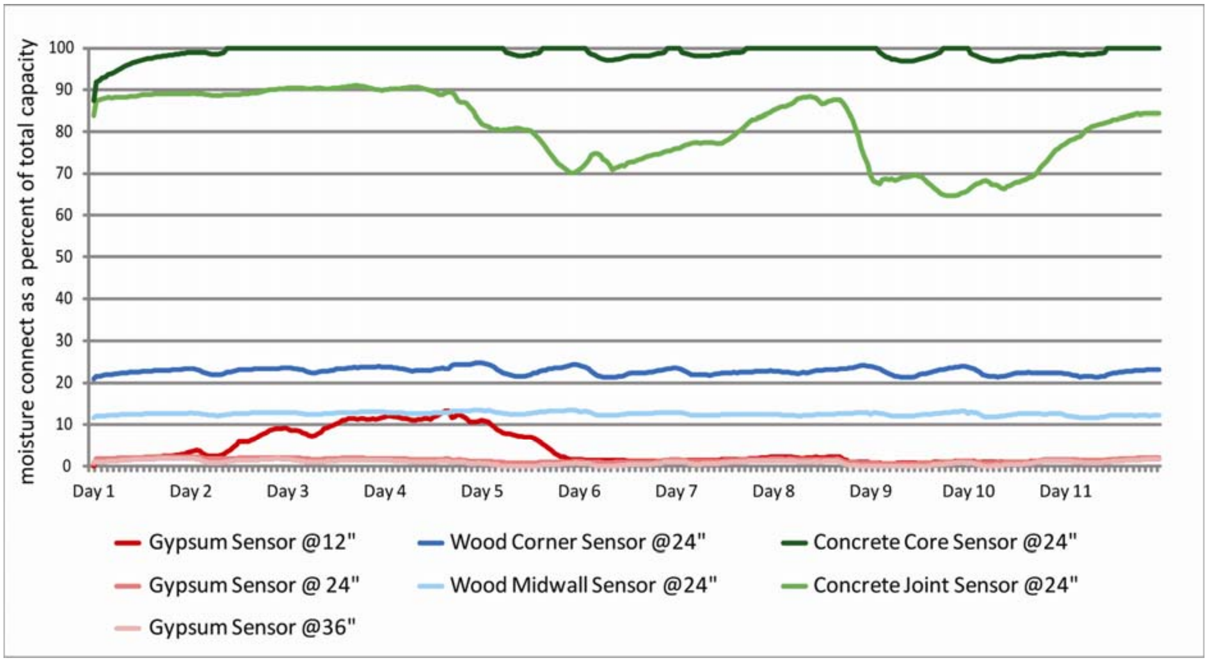


Fig. 4.28. GRAPH: Drying period test pod A: sealed block, flood simulation 1.

The sensor readings for test pod A: sealed block are exemplary of the moisture levels within an assembly classified as dry floodproof (Fig 4.28). This sensor reading data provides information regarding the moisture collection within an assembly. The concrete sensors (upper green lines) show that the concrete dried little during the two-week drying period. The fluctuations in the moisture level of the concrete cavity sensor represent daily temperature change. The concrete joint sensor fluctuates similarly, however over a two-day cycle. The cause of this is unclear. The wood sensors were placed between the interior face of the CMU block wall and the backside of the gypsum board, embedded into the wood furring strips. The readings (middle red lines) show that the moisture level within the furring strips hovered around 10% and 20% for the duration of the drying period. However, these post-flood moisture levels match the pre-flood moisture levels, indicating that the moisture content was constant and unrelated to the flood simulation. The average moisture content for all wood products in the test pods prior the flood simulation was 12%.

The lower blue lines in the graph represent the three moisture sensors embedded at various heights into the gypsum board. Sensors were placed at 12”, 24” and 36”above the slab, aligned vertically (Fig. 4.29). Since only .25” of water penetrated the interior of the pod, none of the gypsum sensors were in direct contact with water during the flood simulation. The increase in moisture content reading from the gypsum sensor embedded 12″ above the slab is most likely the result of water wicking, as a result of capillary action, from the base of the gypsum board. Note that it took several days for the moisture to migrate to this height, and subsequently dried out within one week. Moisture was not able to reach the height of sensors at either 24″ or 36″. These results are constant with the gypsum data shown in subsequent readings.

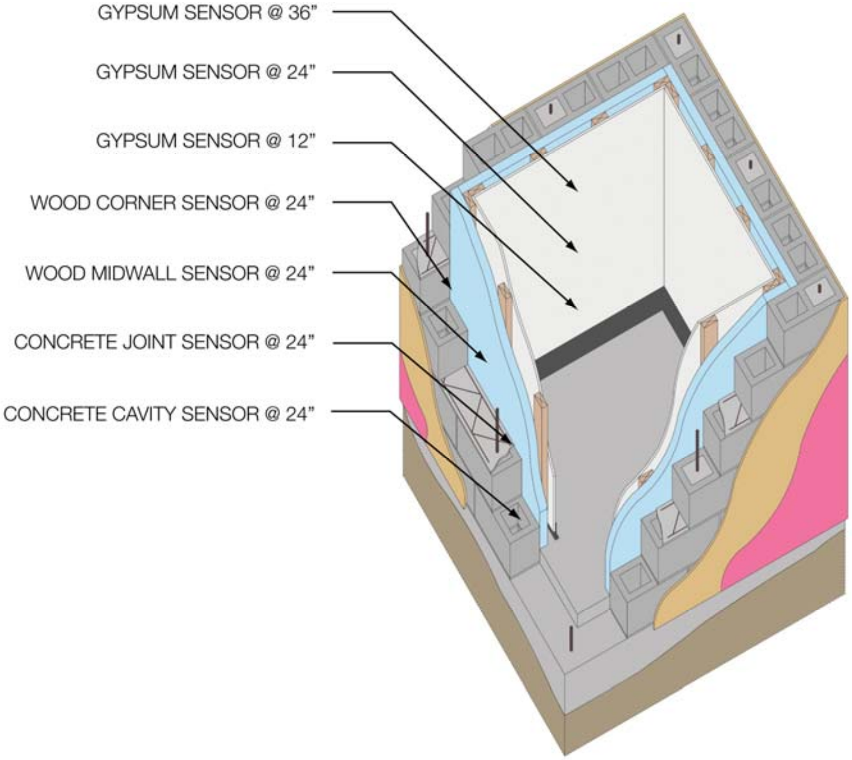


Fig. 4.29. DIAGRAM: Sensor locations: test pod A: sealed block, flood simulation 1.

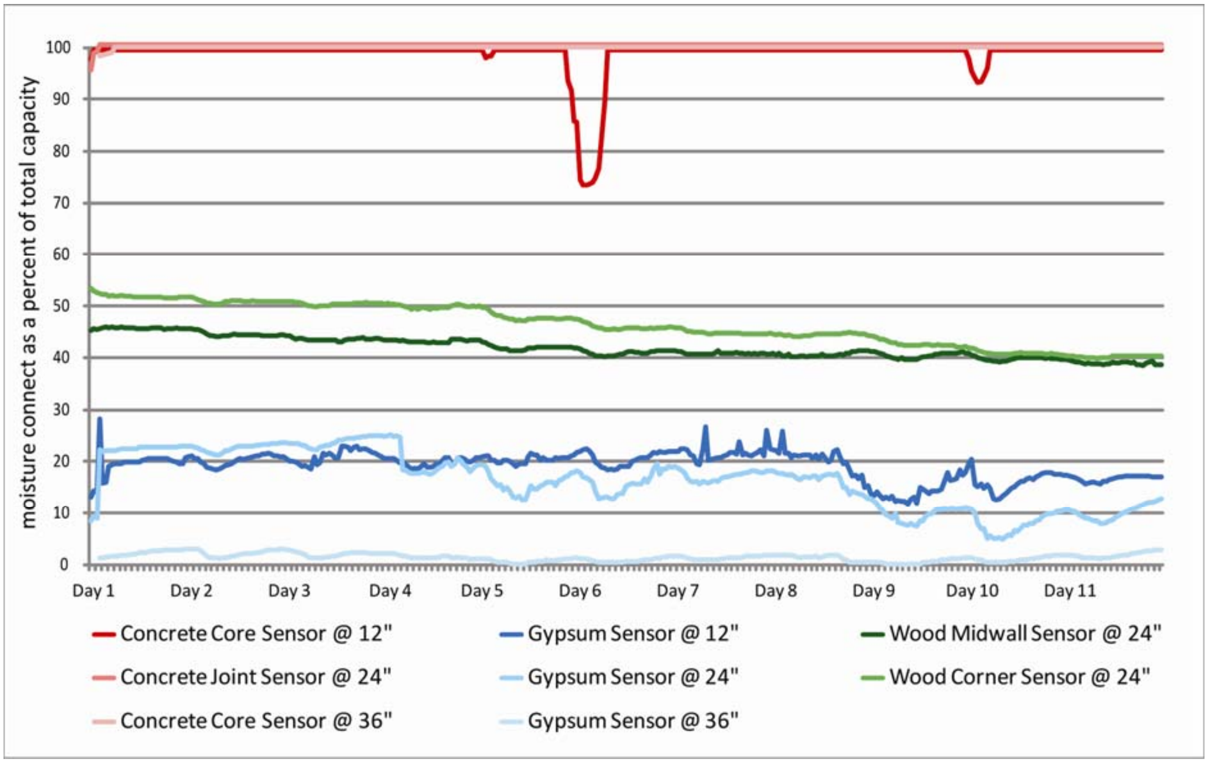


Fig. 4.30. GRAPH: Drying period: test pod B: cavity wall, flood simulation 1.

The sensor readings for test pod B: cavity wall are exemplary of moisture levels found within an assembly that completely failed to perform as dry floodproof (Fig 4.30). During the flood simulation, water filled all cavities within the assembly. The sensor readings provide information regarding the degree of water infiltration, and the drying rate of the materials during the two-week drying period.

The graph shows that the concrete dried very little during the two-week drying period. The moisture levels in the concrete were similar to the moisture levels found in test pod A: sealed block. Likely, this is because the concrete still had high moisture content from being poured approximately a month before the testing began. However, neither of data sets gathered from the concrete in test pod B fluctuated similar to the data sets gathered from the concrete materials in test pod A: sealed block. An explanation for this difference may be that while the concrete materials in both test pods were holding the maximum amount of moisture the material was capable of, (100% reading) the concrete products in test pod B: cavity wall were also surrounded by water, as water was trapped within the assembly. This explanation was supported by evidence of water found within the interior of other CMU block walls during partial demolition (Fig 4.5).

The wood sensor readings shown in the mid-section of the graph represent moisture data collected from the sensors embedded in wood furring strips located behind the gypsum board. Over the drying period the wood fu4rring strips dried approximating 10 percentage points. At around 40% moisture content, neither wood furring strip came close to returning to pre-flood simulation moisture levels (at around 12%).

The three lower readings represent data collected from moisture sensors embedded in the gypsum board. The two sensors located closest to the slab showed a moisture content of around 20 percentage points higher than the sensor located 36” above the slab. The sensors recorded slight drying in the gypsum during the two-week drying period; they also showed significant variation over that same period. This variation may be the result of moisture trapped within crevices within the wall assembly, which were subject to temperature and vapor level variation during an average day.

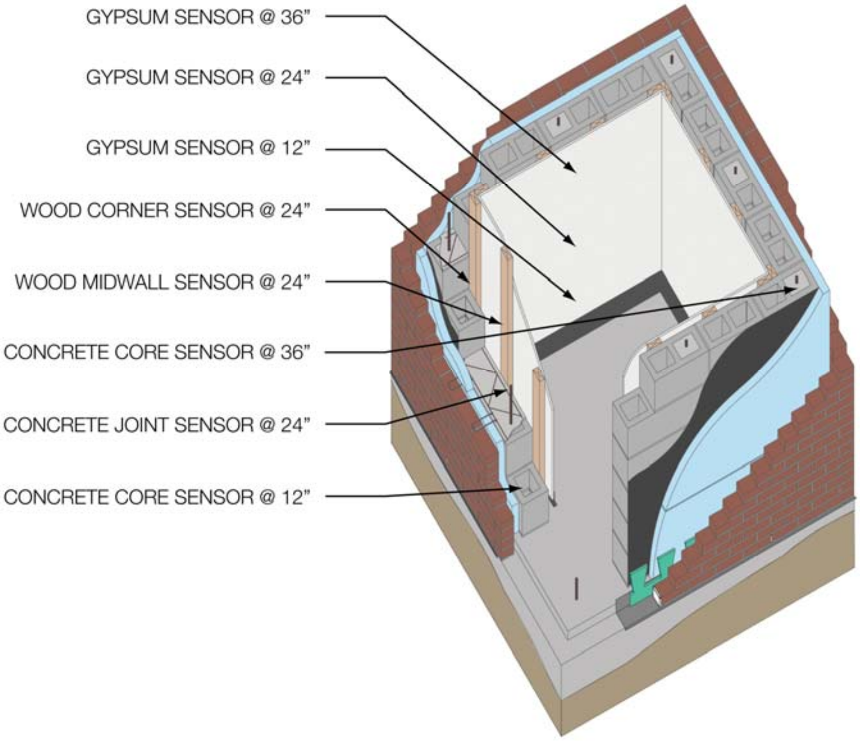


Fig. 4.31. DIAGRAM: Sensor locations: test pod B: cavity wall, flood simulation 1.

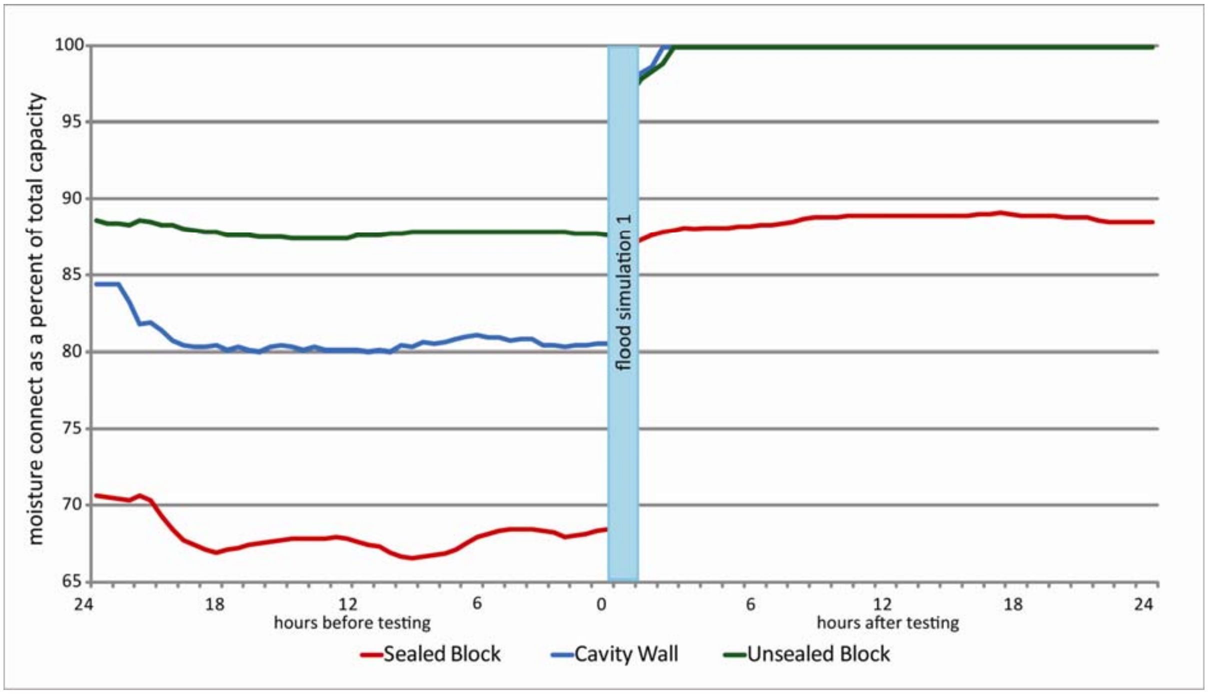


Fig. 4.32 GRAPH: Moisture levels in mortar: before and after flood simulation 1.

Fig. 4.32 shows the data collected by sensors embedded in the mortar joints of three test pods for 24 hours before and after the flood simulation. The data collected from test pod A: sealed block shows that even though the test pod demonstrated interior depths compatible with dry floodproof construction, the cement-based products in the wall accumulated additional moisture during the flood simulation. Mortar joints in the other two test pods behaved similarly to each other. While in all cases an approximate increase of 15 percentage points is recorded after the flood simulation, in the case of materials which were fully submerged during the flood simulation, the mortar material reached a level of 100% moisture content. Data from sensors embedded in submerged materials showed the mortar material maintaining a 100% moisture content during the entire two-week drying period. It is unclear how long drying period would have had to continue to record some amount of drying in these materials.

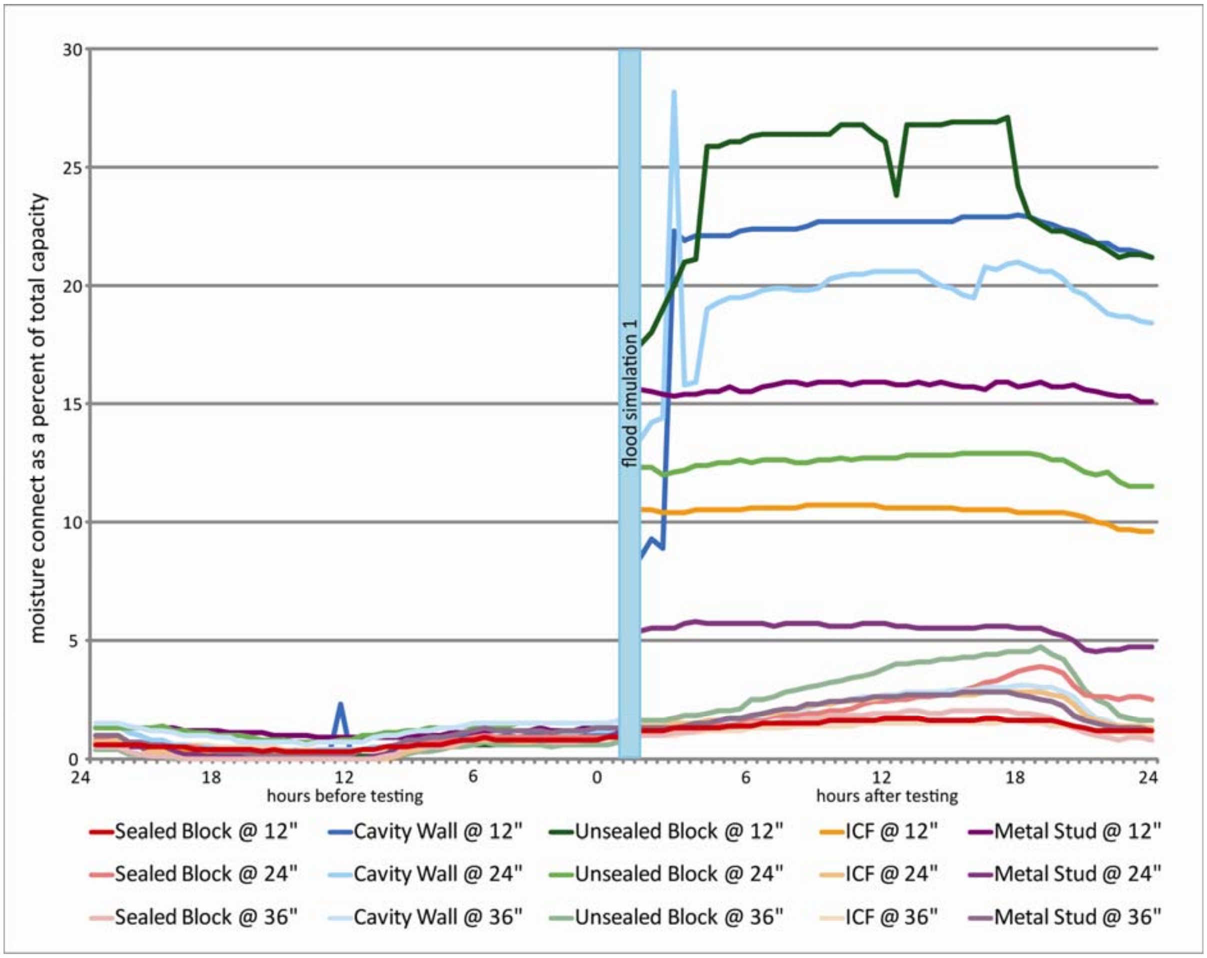


Fig. 4.33. GRAPH: Moisture levels in gypsum: before and after flood simulation 1.

Data collected from five of the six test pods (test pod F: metal SIPs had no sensors embedded) shows that the gypsum products gained an average of 15% moisture content after flood simulation 1. Data also showed that the amount of moisture gain was not related to the length of time it took for the assembly to reach an interior depth of 36″. Sensors which recorded more than a 5% increase in moisture content where located below final interior depths. Sensors that reported less than a 5% increase were above the final interior depth. Data collected over the two-week drying period showed no significant drying of the gypsum. Material observations taken on-site indicated that gypsum boards which held 10-20% of moisture content were still intact, but had peeling paint. Test pod E: metal stud had gypsum board installed as the exterior sheathing of the structure. This gypsum board on the exterior had a moisture level of 80% after the flood simulation and had become crumbly and infirm.

4.3.4 Flood Simulation 2 Results

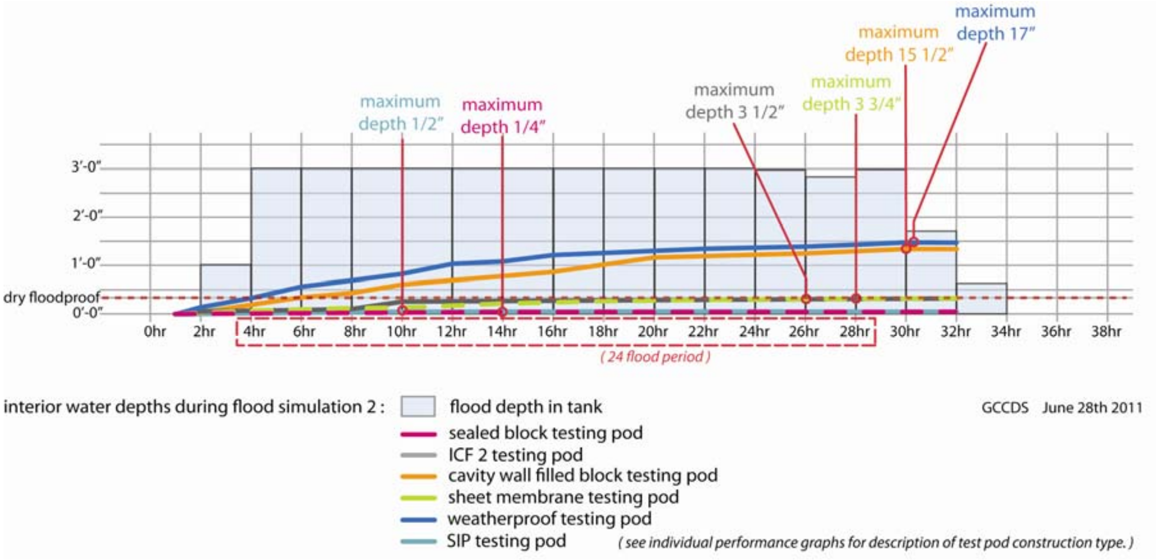


Fig. 4.34. GRAPH: Interior water depths, flood simulation 2.

The following is a condensed version of the report from flood simulation 2, highlighting the significant events during the simulation. For a list of the test pods used in flood simulation 2, see Table 2 on page 48. Descriptions of these test pods can be found in Section 4.4 "Wall Sections and Material Choices". For the second flood simulation, the flood tank and test site were arranged the same as the first simulation. Observation through the use of wireless sensors of the drying of assemblies was not performed after the second flood simulation; the primary goal of the second flood simulation was to test simple detail changes in the test pod assemblies to achieve dry floodproof performance. The gypsum board was removed from some of the assemblies so that moisture movement could be better observed in test pods B2, C2, and D2. For a more complete report of the simulation see Appendix A: "Full Flood Simulation Results". Above (Fig. 4.34) a graph shows the interior depths of water infiltration during the second flood simulation.

<u>June 28th</u>
0:00 (7:45am) –Flooding began
0:50 – Flood depth at 10", some seepage was observed in test pod G: sheet membrane block, test pod D2: ICF and test pod F: metal SIPs.
3:00 - Flood depth at 36", observations for 24 hour dry floodproof testing began. Test pod H: weatherproofed block had an interior depth of 1.5". Test pod B2: cavity wall filled block and test pod D2: ICF both had interior depths of 0.5". Test pod G: sheet membrane block and test pod F2: metal SIPs both had interior depths of .25". Test pod A: sealed block and test pod B2: cavity wall filled block had no measurable interior depths of water.

5:00 – Test pod H: weatherproofed block had an interior depth of 6″ (this is 2″ above the 4″ dry floodproof threshold). Test pod B2: cavity wall filled block had an interior depth of 2.25″. All other test pods had interior depths of less than 1″.
7:00– Test Pod B2: cavity wall filled block had 4″ of interior depth.
8:00 – Due to the consistent interior water depth in the test pods, observations were changed to two-hour time intervals.

June 29th
27:00– After 24 hours of exposure to a 36″ simulated flood, four of the test pods had maintained an interior depth low enough to be considered dry floodproof. Test pod A: sealed block had an interior depth of 0.25″. Test pod G: sheet membrane block and test pod D2: ICF both had interior depths of 3.75″. Test pod F2: metal SIPs had 0.5″ of interior depth. At this time evacuation of the flood tank began.
30:00– 12″ of flood depth remained. Interior depths of the test pods had remained the same as the previous log entry, except for test pod B2: cavity wall filled block and test pod H: weatherproofed block, which had slightly increased interior depths.
34:00 – The flood tank was completely emptied. No changes were observed in flood depths from the previous log entry in any of the test pods.

4.3.4.1 Test pod A: sealed block

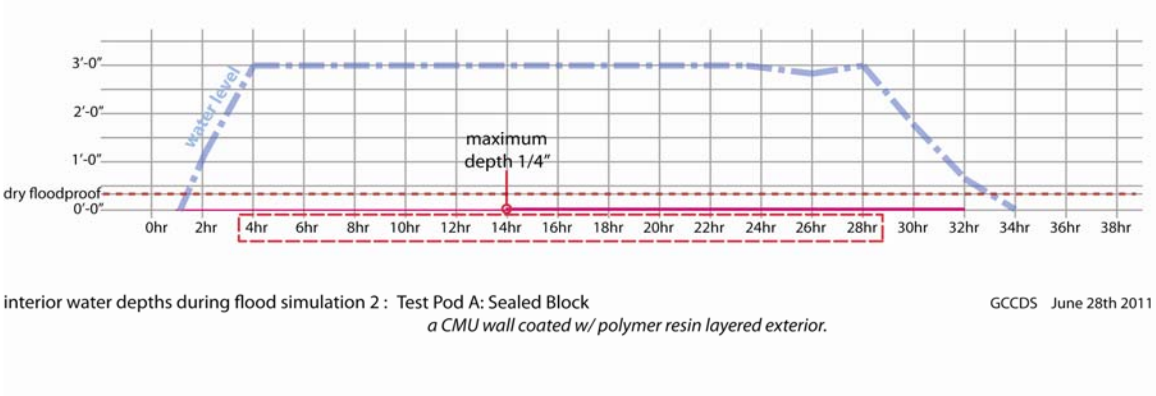
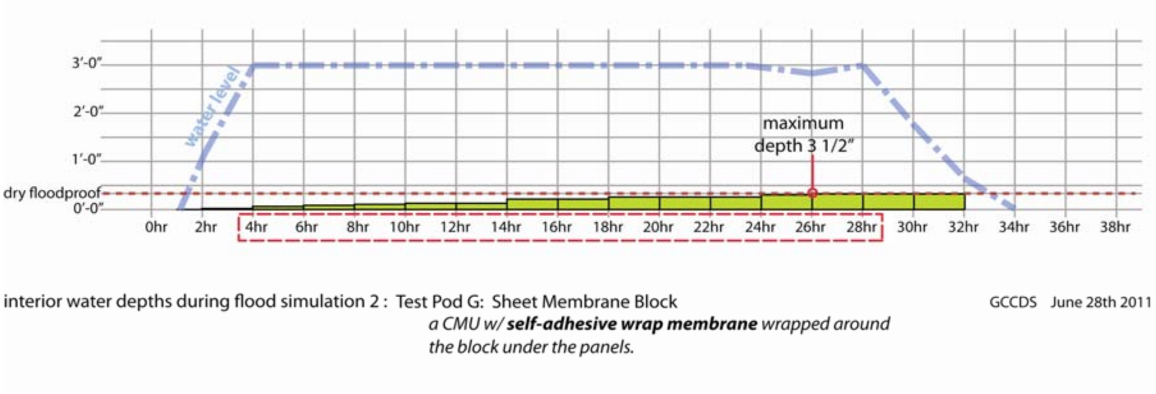


Fig. 4.35. GRAPH: Interior depths: test pod A: sealed block, flood simulation 2.

Test pod A: sealed block performed as well during the second flood simulation as it did during the first simulation (Fig 4.35). The assembly of this pod was exactly the same during both flood simulations. The layered polymer membrane of the exterior coating was beginning to show bubbling and discoloration prior to flood simulation 2, likely due to prolonged exposure to ultraviolet light between flood simulations. However, this did not seem to affect performance of the assembly.

4.3.4.2 Test pod G: sheet membrane block



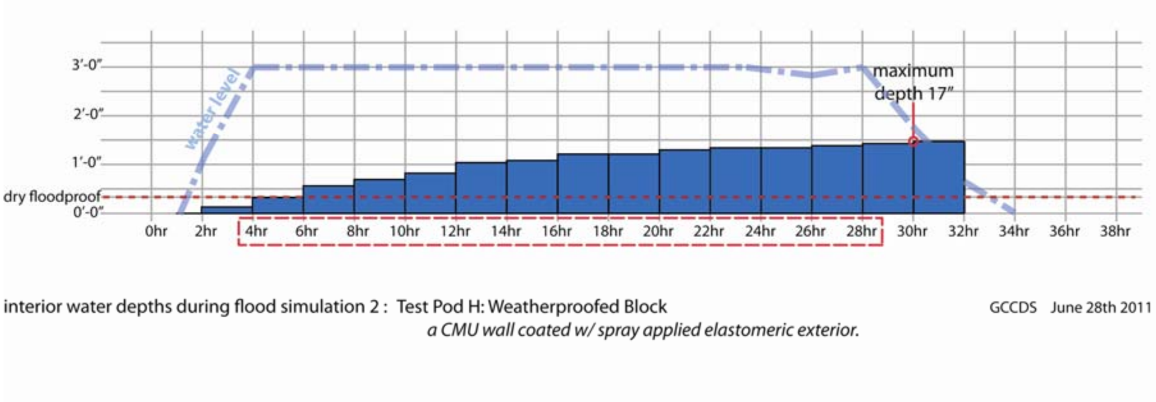
interior water depths during flood simulation 2 : Test Pod G: Sheet Membrane Block GCCDS June 28th 2011

*a CMU w/ **self-adhesive wrap membrane** wrapped around the block under the panels.*

Fig. 4.36. GRAPH: Interior depths: test pod G: sheet membrane block, flood simulation 2.

Test pod G performed well enough during flood simulation 2 to be considered a viable option for dry floodproofing (Fig. 4.36). The increase in dry floodproof performance can be attributed to the impermeability and consistent coverage of the self-adhering rubberized asphalt/polyethylene membrane sheet.

4.3.4.3 Test pod H: weatherproofed block



interior water depths during flood simulation 2 : Test Pod H: Weatherproofed Block GCCDS June 28th 2011

a CMU wall coated w/ spray applied elastomeric exterior.

Fig. 4.37. GRAPH: Interior depths: test pod H: weatherproofed block, flood simulation 2.

During the early hours of flood simulation 2, test pod H: weatherproofed block had an interior depth greater than 4" (Fig. 4.37) . While not considered dry floodproof, the test pod did show a degree of resistance to flood water. The maxium interior water depth of 17" was a significant improvement over the previous results of test pod C: unsealed block in flood simulation 1. The two test pods had similar assemblies; however test pod H: weatherproofed block had an elostameric coating sprayed on the exterior.

4.3.4.4 Test pod B2: cavity wall filled block

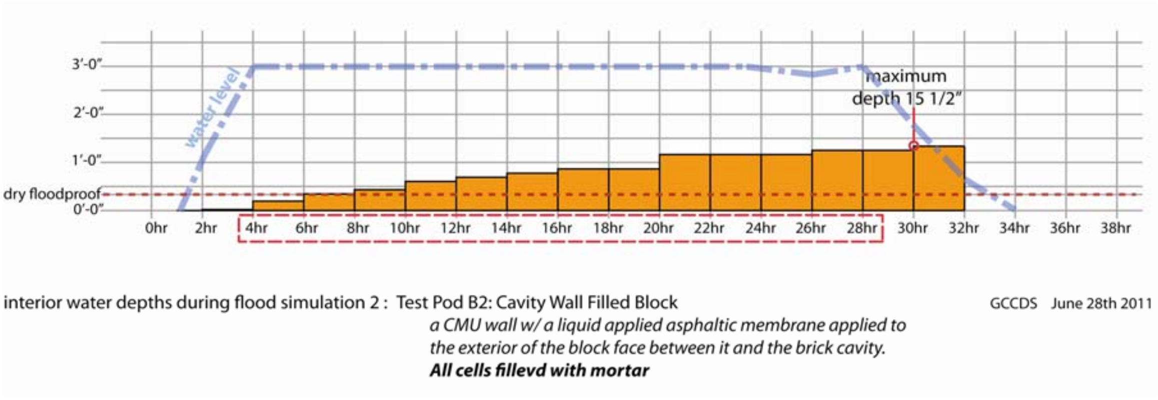


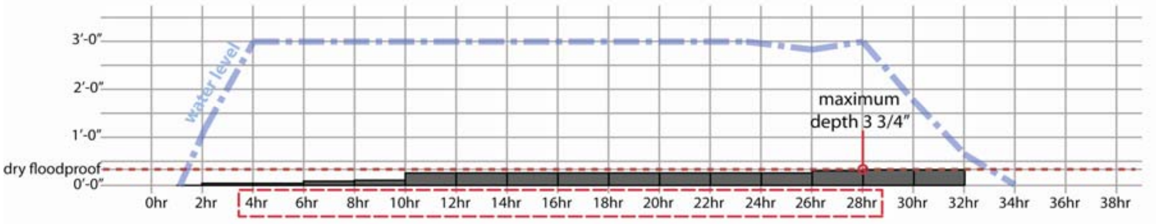
Fig. 4.38. GRAPH: Interior depths: test pod B2: cavity wall filled block, flood simulation 2.

Test pod B2: cavity wall filled block allowed 13" of interior depth to accumulate during the 24 hour dry floodproof test period, with a maximum depth of 15.5" of interior depth that was reached after the flood tank began to drain (Fig. 4.38). These results showed significant improvement over the results of test pod B: cavity wall during the first flood simulation. The only difference between the two assemblies was the addition of continuous grout fill in each CMU cell in test pod B2: cavity wall filled block.

Throughout the second flood simulation, water was observed collecting on several interior faces of the CMU wall, as shown in Fig. 4.39. This accumulation of water was more evident on CMU blocks where cells which had been previously filled for flood simulation 1, rather than those cells which were filled as part of the assembly revisions in flood simulation 2. Despite the improvement in performance in flood simulation 2, this assembly is not a viable option dry floodproofing.

Fig. 4.39. PHOTO: Water seeping into test pod B2: cavity wall filled block, flood simulation 2.

4.3.4.5 Test pod D2: ICF



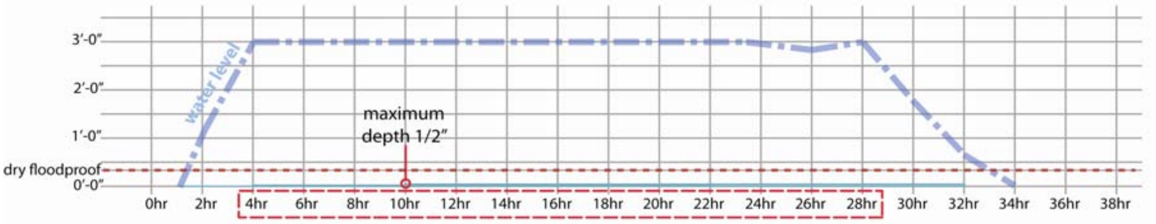
interior water depths during flood simulation 2 : Test Pod D2: ICF
an insulated concrete formwork wall w/ a stucco finish ***coated with elastomeric paint.***

GCCDS June 28th 2011

Fig. 4.40. GRAPH: Interior depths: test pod D2: ICF, flood simulation 2.

Test pod D2: ICF resisted water penetration well enough during the 24 hour test period in flood simulation 2 to be considered a viable option for dry floodproof construction (Fig 4.40). With the addition of an elostameric paint applied to the exterior surface of the assembly, water penetration in the second flood simulation decreased over 50% from the first flood simulation. It is likely that the water which did accumulate on the interior of the test pod during flood simulation 2 was the result of seepage around the base of the wall or through the foundation slab. Further detailing of this joint could potentially reduce the amount of water penetration.

4.3.4.6 Test pod F2: metal SIPs



interior water depths during flood simulation 2 : Test Pod F2: SIPs
a structural insulated panel ***fastened to metal base channel. Channel set with membrane.***

GCCDS June 28th 2011

Fig. 4.41. GRAPH: Interior depths: test pod F2: metal SIPs, flood simulation 2.

Test pod F2: metal SIPs was very resistant to the penetration of water during flood simulation 2. By securely fastening the SIPs with screws to the base channel, buoyancy forces were kept from stressing the caulk, maintaining a water-tight seal. With a maximum interior depth of 0.25" (Fig. 4.41), this wall assembly improved from one of the lesser performing test pods in flood simulation 1 to one of the better in flood simulation 2.

4.4 Summary of Results

Of the eleven wall assemblies tested, four allowed less than 4” of water to accumulate over a 24-hour flood simulation. Using the USACE standards referenced in the beginning of this chapter (USACE Document EP1165-2-314 *Flood Proofing Regulations*), these four wall assemblies would be viable options for a dry floodproof building: test pod A: sealed block, test pod D2: ICF, test pod F2: metal SIPs and test pod G: sheet membrane block.

4.4.1 Protection of Joints Between Materials

During flood simulation 1, water was observed and recorded moving within the wall assembly through gaps in the mortar joints. It could not be observed specifically how the water had entered into the CMU wall, but it may have been through the same type of gap on the exterior face of the wall. This water movement was different during the second flood simulation when test pod B2: cavity wall filled block had all CMU cells filled with grout. During the second flood simulation, water was observed seeping through the CMU faces of the wall. It is unclear if this was happening because CMU cells had been filled or if the CMUs had been damaged during the first flood simulation. One conclusion based on these observations is that fewer joints in an assembly lead to better hydrostatic resistance. However wall assemblies with solid concrete fill did not provide enough resistance to hydrostatic pressure without an additional water resistive membrane, as shown in test pod B2: cavity wall filled block and test pod D: ICF.

4.4.2 Consistency of Coverage

When comparing the performances of test pod B: cavity wall and test pod G: sheet membrane block, the importance of a consistent coverage of a membrane becomes apparent. In test pod B: cavity wall, which had a flood resistive material brushed on, the resistance to flood water was marginally better than an unprotected block assembly as observed in test pod C: unsealed block. Test pod G: sheet membrane block was coated in a similar material to test pod B, but with a consistent depth it performed much better. Test pod H: weatherproofed block, which had a sprayed weatherproof coating, did not perform to dry floodproof standards. However, it did perform better than test pod B: cavity wall which was a similar structure to test pod H, but with a different flood resistive membrane material and application.

4.4.3 Designing Redundancy

Within the testing, the difference between critical failure and minor infiltration was the presence of redundancy within an assembly. In the same way that one designs structural redundancy to prevent failure, a good way to mitigate failure due to substandard installation of a product is to design a wall assembly with redundancies. Test pod A: sealed block, test pod D: ICF, and test pod D2: ICF are good examples of a multi-layered assembly. Unfortunately, system redundancy cannot compensate fully for sub-standard construction; as a result it is paramount that quality is controlled through diligent construction administration practiced on site during the installation of dry floodproof systems. The affects of inconsistencies in dry flood proof construction can be more critical than in other construction systems.