Building Design and Construction

Using physical mockups to identify curtain wall design flaws

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A recent mockup test found design and manufacturing flaws in this curtain wall system

In my first article I referenced the four most-common causes of cladding system failure: inadequate design, material failure, poor workmanship and acts of nature.

Mockup testing is a popular and effective way to evaluate the design of a custom curtain wall system and to confirm its ability to meet the specified performance criteria.

For those not familiar with curtain wall mockup testing, it involves constructing a full-scale, representative section of a curtain wall system and subjecting it to a battery of tests prior to full-scale production of the curtain wall components. It is important to perform the mockup testing well in advance of fabrication, assembly, and installation so that any design changes can be incorporated into the production of panels.

Typically, the test specimen is selected by the curtain wall consultant or architect to ensure it incorporates all critical components of the curtain wall, including stack joints, inside and outside corners, operable vents, maximum glass sizes, and mullion spans. The consultant or architect will also develop a test procedure, which almost always includes air infiltration testing, water penetration resistance testing (using both static and dynamic pressures), and structural load testing.

Depending on the complexity of the curtain wall system, the building design, and building location, three additional tests may be incorporated in the mockup testing: cycled temperature testing, inter-story differential movement testing, and impact resistance testing. (See sidebar below for a sample test procedure.)

The following case study demonstrates how a mockup for a custom curtain wall successfully identified design inadequacies in the connections of the curtain wall to the structure. The failure of critical anchorage components resulted in a progressive collapse of the mockup and subsequent redesign of the connections. Without a mockup test, the building would have been constructed with connections that were unable to resist modest suction forces on the cladding created by the wind. All company names and locations are withheld to protect the client.

A custom curtain wall was designed by a U.S. curtain wall subcontractor for a high-rise office tower that was planned to be built in Asia. The unitized stainless-steel-clad curtain wall was to be fabricated, assembled, and glazed in a factory in Asia, and then shipped to the site for erection.

Prior to construction, as per the project specifications, the curtain wall subcontractor was required to demonstrate the ability of the wall to meet the specified performance criteria by performing a full-scale mockup. For authenticity, a representative portion of the façade was manufactured by the Asian company that would eventually produce all of the modules and shipped to Florida for testing.

Testing was performed on a 22.7-meter-wide-by-12-meter-high curtain wall mockup incorporating a straight wall, arc, column cladding, and 90-degree outside corner.

After satisfactorily passing static pressure air infiltration testing, static pressure water penetration resistance testing, dynamic pressure water penetration resistance testing, and inter-story differential movement testing, the mockup was subjected to positive and negative structural load tests. During the structural load tests, a section of the curtain wall's anchorage failed when subjected to a negative load of -2.5 kPa (-52 psf)—simulating suction forces caused by wind. The end result: four unitized curtain wall frames separated and fell to the ground from the second floor.

As the curtain wall consultant for the project, we were part of the investigative team asked to determine why the failure occurred.

Sample mockup test procedure

1. Preload to 50% of positive pressure design load
2. Static pressure air infiltration test (ASTM E283)
3. Static pressure water penetration test (ASTM E331)
4. Dynamic water penetration test (AAMA 501.1)
5. Inter-story differential movement test
    a. Horizontal movement parallel to wall
    b. Horizontal movement perpendicular to wall
    c. Vertical slab deflection
    d. Simultaneous horizontal and vertical movement
6. Structural load test (ASTM E330)
    a. 50% positive load
    b. 100% positive load
    c. 50% negative load
    d. 100% negative load
7. Repeat static pressure air infiltration test
8. Repeat static pressure water penetration test
9. Repeat dynamic water penetration test
10. Safety factor load test (1.5x design load)
    a. 50% positive safety factor load
    b. 100% positive safety factor load
    c. 50% negative safety factor load
    d. 100% negative safety factor load
11. Cycled temperature test
12. Repeat static pressure air infiltration test
13. Repeat static pressure water penetration test
14. Window washing equipment load test

Understanding the problem

The first thing we did was inspect the four curtain wall panels that fell from the simulated building while subjected to negative loading. As any forensic investigator would do, we inspected and photographed the mockup curtain wall and collected and labeled samples of various anchorage components. We also recovered deformed anchor clips and noted signs of movement at several supporting rods.

Review and evaluation of original design intent
We analyzed the structural calculations for the curtain wall and its supporting anchorage to determine if there were any errors in the design of the system resulting in the inability of the anchors to resist the specified negative design loads. Our review confirmed that the anchorage system should have been adequate to resist the applied forces.

We also reviewed the project specifications relating to the curtain wall and confirmed the design loads and performance criteria were appropriate, including a requirement for the curtain wall to be designed to prevent progressive failure should any single component fail.

During onsite tests, unitized curtain wall frames failed when exposed to negative loads.

Verify as-built condition
Since the mockup was essentially a brand new installation, we combined two steps—verification of as-built and current conditions—into one. Framing members and anchorage components were inspected to identify any deviations from the approved shop drawings and calculations. We confirmed that the curtain wall framing members and anchorage components were sized, configured, and installed as indicated on the approved drawings and calculations.

Identification of deviations
While it was noted that several of the supporting hooks had failed, we also observed that not all of

the hooks had failed. Some of them had slipped off of the ends of the supporting rods that allowed the curtain wall frames to fall.

Through the process of reconfirming the design drawings, calculations, and product specifications, and analyzing the physical evidence collected at the scene, two potential failure scenarios were identified:

• Movement of the wall during testing allowed the anchorage hooks to slip from the supporting rod, transferring forces in excess of the design capacity to the remaining hooks, causing them to deform.

• The hooks failed prematurely under load, allowing movement of the segments, which pulled the remaining intact hooks off of the supporting rods.

Diagnostic investigation revealed that some hooks failed while others did not.

Movement of hooks off the pin observed on undamaged anchors.

Diagnostic testing

The metal hooks and rods we recovered were sent to a metallurgy laboratory to verify the alloys of the materials used for various anchor components. Lab results indicated that the aluminum alloy used for the curtain wall attachment hooks did not match the alloy specified in the curtain wall design calculations. A weaker alloy had been used by the manufacturer for unknown reasons.

Once it was confirmed that a weaker alloy was used for the curtain wall attachment hooks, we re-analyzed the loading capacity of the anchorage assembly utilizing the substituted material. Calculations confirmed that the weaker metal would have been unable to resist the loads applied to it during testing.

Deformed anchor hook – analysis would reveal that hook was manufactured using an incorrect alloy.

Trial repairs

The curtain wall subcontractor redesigned and re-fabricated the attachment hooks using the proper alloy and replaced all of the hooks on the mock-up. The structural load test was repeated and no failure occurred.

In addition, to address the failure of the system to prevent progressive failure, the supporting rods were redesigned. The rods were made longer and flanges were added to their ends to prevent the hooks from slipping off.

To test the new design, one of the new hooks was cut with a hack-saw, simulating structural failure, and the test load was applied. The load was adequately transferred from the “failed” hook to adjacent hooks. No failure occurred and the design adequacy was confirmed.

Based on the analysis of the system failure and the successful testing of the revised design, it was determined that the curtain wall anchorage system was adequately designed to withstand the specified design requirements. As a result, not withstanding an agreement for enhanced quality control monitoring of the aluminum alloys used for the project, the anchorage systems were approved for production.

In this case, through mockup testing, an inadequately designed and manufactured anchorage assembly was identified and corrected before it was mass produced and installed on an actual high-rise building. Without the mockup, the flaws would not have been identified until a major failure occurred. While mockup testing is an additional expense and can add time to the curtain wall schedule, it does provide a unique opportunity to evaluate and improve upon new designs with very little risk.

About The Author

Mark Baker is president of IBA Consultants, (www.ibaconsultants.com) a leading building envelope consulting firm specializing in the identification and elimination of potential and existing wall cladding, glazing, glass, roofing, and waterproofing system failures. Baker serves as vice chair of the American Society of Civil Engineers (ASCE), Construction Quality Management and Inspection Committee. He can be reached at mbaker@ibaconsultants.com or (888) 550-4422.

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