EE14-2 FUNCTIONAL PERFORMANCE TESTING WITHIN THE BUILDING ENVELOPE COMMISSIONING PROCESS

Kevin D. Knight[1], John A. Runkle[2], Bryan J. Boyle[3]

ABSTRACT

With the growing need to construct energy efficient and durable buildings, building owners mandate a means to ensure that the building envelope is designed and constructed to meet the desired performance requirements. Commissioning the entire building envelope, from the design concept through to the completion of construction, is the most effective means to ensure that the building envelope is constructed to meet the design intent, expected service life, code requirements, and to aid in the prevention of complications that otherwise might arise during the construction process. One of the most significant, misunderstood, and often overlooked, aspects of the building envelope commissioning process is functional performance testing, and the development, integration and implementation of complete and effective functional performance testing protocols into the building envelope commissioning program.

This paper will discuss the many aspects of functional performance testing, from pre-construction laboratory materials and assembly testing, to mockup testing, through to quality control and quality assurance onsite field testing, focusing primarily on the air, water, structural and thermal performance of fenestration and cladding components used on building envelopes. This will include a discussion of the desired end results of functional performance testing, the different test methods and procedures commonly utilized both in laboratory material and system testing and field component and assembly and whole building testing, mockup testing versus field testing and the common ways that minute field alterations have significant effects on performance, and sampling procedures. The paper hopes to dispel some of the myths regarding these tests, and discuss some common misunderstandings about the test procedures and their effectiveness. The paper will conclude with a discussion on the interpretation of test results and identify some common examples of how test results can be misinterpreted.

---

[1] Kevin D. Knight, Architectural Testing Inc., York, PA.

[2] John A. Runkle, Architectural Testing Inc., York, PA

[3] Bryan J. Boyle, Retro-Specs Consultants Ltd., Winnipeg, MB

INTRODUCTION

Over the past several years, building envelope commissioning has become recognized as an effective and essential means to aid in the assurance of building performance over its expected life cycle. It is not surprising that the inclusion of building envelope commissioning in commercial construction project specifications continues to increase in prevalence given the demand for improved energy efficiency and longer life cycles in today's buildings. The National Institute of Building Sciences (NIBS) Guideline 3-2006 Exterior Enclosure Technical Requirements for the Commissioning Process defines commissioning as "a quality-oriented process for achieving, verifying, and documenting that the performance of facilities, systems, and assemblies meets defined objectives and criteria." As it pertains to the commissioning of building envelope systems, it can be defined as a systematic process of ensuring that the building envelope performs interactively according to the Basis-of-Design (BOD) and the Owner's Performance Requirements (OPR) through verification of the system's performance. The objectives of the commissioning process are driven by several factors, including building type, expected life cycles, geographic location, climatic considerations, desired energy efficiency, acoustical requirements, budgetary constraints and tolerance for leakage, which all may vary considerably between projects. While the precise tasks comprising the commissioning process differ from project to project, Annex F of the NIBS Guideline 3-2006 contains a comprehensive list of the roles and responsibilities which remains consistent throughout the commissioning process.

The building envelope commissioning process commences at BOD, and continues through the duration of the project to completion. The tasks comprising the process are typically separated into five phases: *Pre-Design*, *Design*, *Pre-Construction*, *Construction*, and *Operations and Maintenance (O&M)*. While the importance of the Pre-Design and Design phases cannot be understated, one emerging and disturbing trend is the reliance on the tasks conducted during these two phases to comprise most or all of the building envelope commissioning process, whereas tasks typically conducted during the Pre-Construction and Construction phases – specifically, functional performance testing of the building envelope system and its individual components - are minimized or omitted altogether. This approach toward commissioning often does not fulfill the main requirement of verifying building envelope performance because without comprehensive and customized performance testing, it is impossible to confirm that performance criteria outlined in the OPR has been satisfied.

It is often joked in the building envelope consulting industry is that individuals have "calibrated eyes". Even though one may be able to accurately guess dimensions, a tape measure is obviously more accurate and required for verification of dimensions. Experienced building envelope experts can review a set of architectural drawings and conclude, with a good comfort level, certain aspects of anticipated building envelope performance, including dew point locations within wall cavities, effective R-values of wall assemblies, large potential air leakage locations, and possible areas of water infiltration. But does this review, even if follow-up field inspections are performed, provide verification that the desired performance criteria identified in the OPR have been achieved sufficient to provide a letter of compliance confirming as much? Consider a summary of the OPR on a recent project:

- 100 year design life
- LEED Gold
- Air leakage for the entire building not to exceed 0.1 cfm/sf
- Few-to-no water leaks
- An energy efficient building
- Achieve designed R-values
- No loss of use of interior spaces from anticipated hot or cold weather
- Consistent durable finishes on exterior cladding elements
- Acoustic performance in excess of code minimums

It may be possible to review a set of drawings and perform inspections during the construction process to establish a sense of how the building will perform against the above performance requirements. But without testing, verification of performance is simply not possible. Further, without verification of performance, the objectives of the comprehensive building envelope commissioning program have not been achieved.

The development, integration and implementation of complete and effective functional performance testing protocols can be one of the most effective and reliable means within the commissioning process to help ensure the functionality and durability of the envelope. The objective of functional performance testing is to verify that each building envelope component or assembly is operating according to the documented BOD and OPR by facilitating the transition of the material or assembly from a state of substantial completion to full operation. By identifying areas of deficient performance that can then be corrected, the operation and functioning of the building envelope system can be improved and performance characteristics subsequently verified. And yet, functional performance testing remains one of the most misunderstood and often overlooked aspects of the building envelope commissioning process.

ROLE OF THE BUILDING ENVELOPE COMMISSIONING AGENT

Since functional performance testing is an integral part of the building envelope commissioning process in providing quality assurance of on-site installations, development of the functional performance testing protocols, including test methods, parameters, and frequency, falls under the scope of the Building Envelope Commissioning Agent (BECA). The BECA's involvement during actual physical testing depends on the breadth of the commissioning process employed on a particular project, as follows:

- Testing of building envelope components may fall under the scope of the contractors' Quality Control programs, with the BECA observing the tests as they are conducted and reviewing all reporting documentation to ensure compliance to the test protocol and assurance that the system as tested meets the specified performance requirements.

- All inspection and testing may fall under the Quality Assurance regime of the BECA, to be conducted by the BECA or independent testing agency approved by the Owner and/or BECA.

- It may be a combination of the above, where routine and simple testing of individual components or assemblies is conducted by the contractors and reviewed by the BEC, with more advanced and complex tests conducted on a more holistic scale by the BEC.

CATEGORIES OF FUNCTIONAL PERFORMANCE TESTING

For simplicity, the functional performance testing process can be grouped into three categories: (1) *laboratory testing* for general evaluation of product and assembly performance; (2) *mock-up testing* for evaluating project-specific performance prior to the onset of construction; and (3) *field testing* for evaluating project-specific performance during the construction process. These phases are not necessarily mutually exclusive, and within each performance category, there may be several phases of testing that typically occur.

Laboratory Testing

Laboratory testing, as it is referred to in this document, is testing performed on materials and assemblies outside of the context of a specific project, primarily to provide submittal and marketing information that demonstrate generic product performance. Unlike mock-up and field testing, it is the manufacturer that determines what products to test, the test protocol, and what test results to share, whereas mock-up and field testing typically evaluate the performance of components, assemblies, or the entire building against project-specific performance as built under project-specific labor and conditions.

While the responsibility of performing or observing the laboratory testing itself usually falls outside of the scope of the building envelope commissioning program, it is the responsibility of the BECA to review the data submittals for building envelope materials and assemblies to assess compliance to the bid documents. The BECA must ensure that all submitted material is current, and reflects the material in its current state, both in chemical and physical composition. The BEC must also review all material test result data to check that the parameters under which the material or assembly was tested – test method, load constraints, and test sample construction and composition – are consistent with those parameters identified in the project specifications. It is common to see, especially in airtightness testing results, similar type materials being tested under different test methods and to different pressure differentials than what is called for in the bid documents, and where the construction of the test sample not only differs from how the assembly will be built relative to the specific project, but also built using components that may influence the test results.

Mock-up Testing

Mock-ups are full-size structural models comprised of the exact construction techniques, materials, and technicians that will be used on a project, providing the project team the opportunity to assess a three-dimensional representation of a design, and serving as a means to evaluate functionality, determine compliance with project documents, assess aesthetics, and enhance workmanship. The primary objectives of mock-up testing are to confirm project-specific performance requirements and verify that design details will function per the design intent by: (1) determining performance characteristics of components and assemblies and measuring this performance against project requirements; (2) assessing the skill level of the installers; (3) assessing the feasibility of proposed construction sequencing; (4) establishing a benchmark for the standard of workmanship and aesthetics to be replicated throughout the project; and (5) recognizing and resolving issues and potential areas of conflict prior to the commencement of construction to minimize disruption to the critical path of construction.

The different types of mock-ups can be summarized into four categories:

- *Off-site Laboratory Mock-ups*: full-scale mock-ups constructed, examined and tested in a laboratory setting under controlled conditions.
- *Stand-alone Mock-ups*: free-standing mock-ups generally constructed, examined and tested at the building site that are separate from the building itself.
- *Integrated Mock-ups*: mock-ups constructed directly onto the building structure that may be incorporated into the final construction.
- *Mini-Mock-ups or Detail Mock-ups*: small mock-ups constructed for review of details that could not be included as a part of other mock-ups.

There are pros and cons to each of the mock-up types. While discussion of these characteristics falls beyond the scope of this paper, a combination of these mock-up types is typically specified to receive maximum benefit from this phase of the commission process. The type and quantity of mock-ups required is governed by several factors, such as building type and function, building and building envelope performance requirements, complexity and uniqueness of design details, life cycle expectancy, ambient conditions, owners' expected level of diligence, budgetary constraints, and cost to repair. As a general rule, the greater the expected performance level of the building, or the greater the complexity of the detailing, the more diligent the pre-construction phase of the commissioning process, and therefore the more thorough the mock-up requirements.

On laboratory mock-ups or larger free-standing or integrated mock-ups, it is not common to find multiple assemblies such as windows and opaque walls contained in a single mock-up, as this not only allows for testing multiple assemblies under a single protocol, but also the interface between the assemblies. In fact, when citing a 'building envelope mock-up', one is most commonly referring to a mock-up containing both a window unit or curtain wall section and the adjoining opaque wall and its typical components (air barrier, masonry ties, insulation, etc.).

Ultimately, the desired result from mock-up evaluation is to be able to take a proven assembly or system and replicate its installation onto the building. Lessons learned during mock-up construction and evaluations are transferred to the job-site such that mistakes made during the mock-up phase are not repeated during actual site construction. This speaks to several important notions:

- As much as practically possible, the mock-up must be representative of the site conditions, constructed using the same materials, labor, and supervisors, that will be employed during actual construction.

- Mock-up testing procedures should verify compliance with all of the OPR and not just select test procedures that are easy to complete that have little relevance in simulating actual performance.

- The goal of the mock-up should not simply be to ‘pass’, but to pass the *first time* using reasonable construction practices. In the occurrence of a failure, determine the cause of that failure and adjust the design, materials, and/or installation practices accordingly. Too often, when a mock-up fails initial testing, the mock-up is continually remediated and re-tested until a pass result is finally achieved, without determining the underlying cause of the failures. The same flawed practices are then carried over to the job site, resulting in installations that do not satisfy project specifications.

Field Testing

Mock-ups are used to ascertain performance levels of certain assemblies, which may or may not be representative of the actual building conditions. While one of the pre-requisites of mock-up testing is that the mock-up simulate, as closely as possible, the conditions that will be encountered on the job site, rarely does that simulation remain 100% accurate over the course of the project. Changes in labor, materials, construction, and sequencing conditions among others can all be expected to occur during the construction process. It is therefore necessary to validate the installation throughout the project in order to ensure that desired performance requirements are achieved. Field testing is therefore performed on the actual structure being commissioned on assemblies that are complete and intended to be functional without modifications. The primary objectives of field testing are to verify component or assembly performance against the OPR, BOD, bid document requirements, and performance benchmarks established during mock-up testing, and show compliance or non-compliance of said components or assemblies to these constraints, under actual project conditions. Note that many of the field testing standards or procedures are the same or similar to those used during mock-up testing.

It is both important and necessary that in order to achieve sufficient coverage on a project, the functional performance testing protocol must include field testing *throughout* the construction process. Often, the Owner or Specifier’s notion of ‘commissioning’ is a whole building test performed at the completion of construction; while in certain instances this can be a valuable test, it can, when utilized in lieu of any other field testing, be a very risky proposition. Consider a whole building airtightness test conducted at building completion, one of the most common building envelope end-tests. What recourse is there if the building fails the test? As the plane of airtightness is often inaccessible at this stage of completion, it is virtually impossible to pinpoint the precise location(s) and cause of the air leakage. Even if this could be determined, the cost of repair could be exorbitant.

CATEGORIES OF FUNCTIONAL PERFORMANCE

There are numerous ways to classify functional performance, but within the building envelope, it is typically broken down into the following:

- Airtightness

- Energy Efficiency (combination of air, thermal and material property testing)
- Water-tightness
- Thermal/Energy
- Acoustical
- Structural/Blast

Airtightness

It is accepted that uncontrolled air leakage through the building envelope can have significant negative impacts upon a building's long-term durability and energy efficiency, and the comfort and health of the building occupants. The development and implementation of more stringent government regulation for air barrier systems in buildings, and the increasing awareness of the need to build 'airtight', has resulted in airtightness testing common to the building envelope commissioning process having undergone more substantial modifications from laboratory to field testing when compared to all of the other performance classifications.

Airtightness testing as it relates to building envelope performance, most commonly refers to the performance of the air barrier - the sheet or panel type materials intended to provide the principal resistance to air leakage - and the adjoining fenestrations that comprise the air barrier system. Any materials designated as the air barrier should have an air leakage characteristic not greater than 0.02 $L/(s \cdot m^2)$ (0.004 cfm/ft^2) under a pressure differential of 75 Pa (0.3 in. water). Furthermore, it is recommended that these materials be joined in a system such that the system is airtight under different environmental conditions.

For inclusion on most commercial projects, manufacturers of commonly used air barrier membranes must supply material air permeance characteristics, based upon laboratory test data, for both material air permeance (tested in accordance with ASTM E283, ASTM E2178) and assembly air leakage (ASTM E2357).

Quantitative airtightness testing of windows or curtain wall systems is typically conducted on a mock-up in general accordance with ASTM E283 (laboratory test) or ASTM E783 (field test). Often, this entails construction and pressurization and/or depressurization of either a polyethylene enclosure or a rigid test chamber around the test sample and 'masking' the window unit to obtain a quantifiable rate of air flow through the window unit. In multi-assembly tests where, for example, the test sample contains both a window unit and the adjoining opaque wall, and where the allowable air leakage rate of the two assemblies are different, the rigid chamber method is most effective, as it allows for the elimination of the extraneous air leakage which in turn results in a higher confidence in the numerical data obtained during the test. Even in single-assembly tests, the rigid chamber has proven to be the more reliable method given the inherent characteristics of the polyethylene enclosure that can affect the test procedure. Depending on the placement of the polyethylene enclosure, either pressurization or depressurization may cause the enclosure to come into contact with the test sample, which would be in breach of the test Standard. As well, the polyethylene enclosure may be affected by ambient conditions, such as wind gusts that may cause large fluctuation in the manometer and rotometer resulting in an inaccurate reading, and extreme temperatures which may affect the performance of seals and tapes used to seal the polyethylene enclosure.

ASTM test method E1186 contains numerous test procedures suitable for on-site field testing that are effective in assessing the airtightness of the air barrier system, and that can be performed relatively quickly and with minimal disruption to the construction process. Method 4.2.7 can be used to evaluate the airtightness of air barrier membrane seams, overlaps and T-joints, and penetrations through the membrane such as cast-in-place (and surface-mounted) masonry ties, through-wall piping, and fastener penetrations, proving an immediate pass/fail result for the test sample. Methods 4.2.2 and 4.2.6 involve the use of zone or enclosure pressurization/depressurization and smoke generators to provide a qualitative assessment of the airtightness of the air barrier membrane, fenestration, or both. Both of these methods are particularly effective in pinpointing the precise location of air infiltration or exfiltration, and are often used in conjunction with the ASTM E283 and E783 quantitative tests to provide a more complete diagnosis of component or assembly airtightness. ASTM E2357, though often included in project specifications as a mock-up or field test, is actually a laboratory test that provides a uniform methodology for measuring the air leakage rate of air barrier assemblies as they are typically used in the building envelope.

The OPR often includes a whole building air leakage rate in addition to, and sometimes and mistakenly in lieu of, component or assembly performance requirements. Determining the air leakage rate for the entire building can be useful in estimating the overall air leakage related energy efficiency of the building, in addition to simply ascertaining whether or not the air barrier system is functional. Post-construction end-testing in this manner is usually only performed where one or more of the following conditions are present:

- The building is a high-performance building, where the interior environment must be stable.

- It is required for specification or code compliance.

- It is a requirement in the OPR to confirm that the air barrier system is functional.

Determining the whole building air leakage rate (by ASTM E779, ASTM E1186, CAN/CGSB-149.10-M86, or CAN/CGSB-149.15-96) is becoming an increasingly common component in commissioning plans, as it addresses whole building performance. And while this test can be useful in determining the functionality of the air barrier system, caution should be taken when analyzing the results. Test results exceeding the allowable indicate the presence of air leakage sites, but they do not pinpoint the exact location of leak origins, or identify which component or components may have failed. It is also possible that the numeric results generated indicate that the system has met air leakage requirements even though one or more components have failed. Additionally, specifying this test method in lieu of functional performance testing throughout the construction process limits options in the event of a failure. It is important to remember that in order to reach satisfactory whole building air leakage rates, one much first achieve proper air leakage rates for individual components as well at the interfaces between components.

Water-tightness

When discussing water penetration, it is important to draw the distinction between water penetration and *vapor permeance*, a layer property that describes the ease with which vapor molecules diffuse through it. Vapor permeance is defined at the quantity of vapor flow across a unit area that will flow through a unit thickness under a unit vapor pressure difference, and is typically measured in "perms" (ng/(s·m^2·Pa) or gr/h·ft2·in·Hg). Testing for the vapor permeance characteristic of a material is primarily a laboratory test performed in using ASTM test method E96, and is useful in determining whether a material acts as a vapor barrier (in the U.S., commonly defined as having a maximum air permeance characteristic of 1.0 perm, although some jurisdictions specify a much tighter standard of 0.1 perms), a vapor retarder, or vapor permeable.

Water penetration, on the other hand, refers to the ability of an assembly to impede or manage the infiltration of water in its liquid form. Because the damaging effects of water penetration through the building envelope have been thoroughly researched and well-documented, and that both the damage and the water infiltration itself are often more tangible when compared to the other performance categories, water penetration is a cornerstone of almost every OPR and is often well representing through testing in the commissioning plan. Many current building envelope commissioning professionals have transcended form the waterproofing and envelope consulting community, which typically focuses on preventing water intrusion. Even though preventing water intrusion is often a portion of the OPR, a testing plan or commissioning approach that places more emphasis on waterproofing than other performance requirements is incorrect. An appropriate commissioning plan addresses the OPR as prioritized by the Owner, not out of convenience based on the skill set of the commissioning agent.

Tolerance for water infiltration by end users, especially regarding high-end facilities, is decreasing with time. Acceptable water leakage used to include a few anomalies, but zero tolerance on water infiltration has become the norm. Fortunately, the testing options to identify water intrusion from product through field are plentiful and heavily used. Building codes and specifications typically require performance testing of fenestration products and cladding. This testing often includes water being applied simultaneously with either static or dynamic air pressure differentials through various ASTM and AAMA testing standards and guide specifications including AAMA/WDMA/CSA 101/I.S.2/A440 and ASTM E331. Other means of qualifying resistance to water intrusion, such as the hose stream in AAMA 501.2, are also common.

It is important to differentiate between dynamic and static water penetration testing. Testing for water penetration under *dynamic pressure* (AAMA 501.1) involves 'creating' the condition of wind-driven rain by spraying water onto the test sample through a spray rig while creating 'wind' using a wind generator apparatus. This test can be used to simulate the most severe conditions, such as hurricane and tornado-force winds and rain. While this test method has historically been primarily utilized in a laboratory setting, it is becoming more common seen in field testing, albeit on a more limited basis. Testing for water penetration under *static pressure* (ASTM E331, ASTM E1105) is the more common method used in the field, and involves the construction of an airtight chamber around the test sample, subsequent pressurization or depressurization of the chamber, and the application of water onto the test sample by way of a spray rig. The appliance of water under the prescribed pressure differential simulates the condition of wind-driven rain; the greater pressure differential, the higher the simulated wind velocity.

There are benefits and limitations to both test methods, and both methods should often be used concurrently to effectively and accurately evaluate water-tightness of fenestrations. A study by Matthews, Bury and Redfearn demonstrated that dynamic testing included behavior modes which a static test could not (e.g. pumping of the seals), produced conditions similar to those which may be encountered in practice (especially water flow) and was repeatable. But even though this test method is becoming increasingly common, there remain a limited number of laboratories that perform the test, and even fewer options for in-field testing when compared to static testing. And although in some ways static testing offers more accurate control over the test conditions, it lacks the pulsations needed to provide joint movement that would be reasonably expected under wind and rain conditions, and the water application method does not provide for higher impact force of water contact. Additionally, static testing may produce misleading test results; the pressure loads applied against the test sample can cause deflection between the frame and the glazing seals, resulting in excessive water infiltration, or a ‘tightening’ of the assembly resulting in a false ‘pass’ result.

In the future, it is anticipated that water penetration testing within the building envelope commissioning process will continue to gravitate toward more accurately simulating naturally occurring precipitation events that the particular project is expected to experience.

Thermal/Energy

The thermal performance of a wall assembly should not be evaluated without first considering all aspects of thermal performance on the façade. The location of dew points within a wall assembly and the associated influence of energy performance should not be ignored when developing the commissioning plan. While locating dew point within a wall assembly has historically been accomplished through calculations and hygrothermal modeling, dew point analysis testing on three-dimensional mock-ups and field testing have steadily increased in prevalence. The goal of these types of tests is to forecast the location of the dew point within a wall assembly given simulated environment conditions.

There are numerous ways to evaluate fenestration thermal performance in the laboratory. One important note is that often, laboratory testing specimens are sealed such that air infiltration has a minimal effect on the thermal test results. It is also unusual for products to be tested with accessories, such as trim, receptors and flashings. Mock-up and field thermal testing often include both these accessories and the effects of air infiltration, which can lead to confusion when interpreting the test results. It is difficult, if not inaccurate, to compare thermal testing results between the laboratory, mock-up and field testing due to these differences. The BECA should understand these differences and adjust the commissioning plan and functional performance testing protocol accordingly.

In addition to the field dew point analysis, thermal cycling through AAMA 501.4 is common in laboratory mock-ups and gaining in popularity for on-site mock-ups. New advancements in thermal testing are making field U-factor testing possible, which will become especially useful as a retro-commissioning testing tool. Other field testing methods such as SHGC and visible light transmittance will also be instrumental in completing commissioning testing plan for retrofit projects in the future as the importance of energy saving continues to gain traction.

Acoustical

Laboratory acoustical testing is common for building components, but field testing is also needed to verify the acoustical performance of the building system. Acoustical evaluation in the commissioning process is especially important in multi-unit buildings such as condominiums, apartments, dormitories, hospitals and hotels. The goal is to meet the performance expectations of the owner while maximizing the quality of life for the occupants. Field tests should be performed during the initial stage of the construction process so that any problems can be remedied and installation practices can be modified.

Laboratory sound transmission loss tests are conducted in accordance with ASTM test method E90 which yields two ratings. The sound transmission class (STC) rating is for interior building partitions that are exposed to speech type noises. The outdoor-indoor transmission class (OITC) rating is for building facades or facade elements that are exposed to transportation (aircraft, highway or rail) noise. The higher the sound rating, the more isolation the products will provide against noise.

For field tests on interior wall partitions or floor/ceiling assemblies, the ASTM E336 test method is used to measure the noise reduction (NR), normalized noise reduction (NNR) or apparent sound transmission loss (ATL). The NR is used to calculate a noise isolation class (NIC) rating, the NNR is used to calculate a normalized noise isolation class (NNIC) rating, and the ATL is used to calculate the apparent sound transmission class (ASTC) rating. The applicable measurement/rating will depend on the partition or floor/ceiling system, the room volumes (and furnishings), and the floor plan.

For field tests on building facades or facade elements, the ASTM E966 test method is used to measure outdoor-indoor noise reduction (OINR) or apparent outdoor-indoor transmission loss (AOITL). The OINR is used to calculate an outdoor-indoor noise isolation class (OINIC) or the AOITL is used to calculate an apparent outdoor-indoor transmission class (AOITC) rating. The applicable measurement/rating will depend on the facade or facade element design, the interior room volume, the facade location, and exterior noise conditions.

Traditionally, building assemblies perform differently in the field than in a laboratory environment. In the laboratory, the building component (test specimen) can be easily isolated from all surrounding elements. In the field, the same component is surrounded by other elements that can allow sound to bypass (flank) the installed unit. For demising walls, these flanking paths can consist of common walls, ceiling or floor plenums, air ducts and air gaps between the adjacent units. For exterior walls, these flanking paths can consist of spandrel areas, louvers, PTAC units, or other penetrations through the facade.

If acoustic performance of the building enclosure is critical to the success of the project, the first step is to determine what level of noise will be acceptable inside the building. Most regulations (FAA, EPA, HUD, etc) specify a maximum interior noise level of 45 dBA. Quieter interior noise levels could be required for schools or expensive living units. The next step would be to determine the existing exterior sound pressure levels on site in accordance with ASTM E1503. So, for example, if the exterior noise level is 80 dBA and you need a maximum interior noise level of 45 dBA, then the building facade needs to provide a minimum noise reduction of 35 dBA. It is generally accepted that the OITC rating is equivalent to the facade noise reduction (dBA) when the source is transportation noise. This practice is currently being used in New York City for all new or renovated buildings in “E” designated areas. It would seem appropriate that requirements such as this will be seen in other cities in the future.

It is important to verify the acoustical performance of the whole assembly rather than just meeting the performance requirements of the glass units alone. The STC and OITC ratings of window and curtain wall units (tested in the laboratory) have been known to be anywhere from three to six points lower than the glass-alone data that is prevalent in the fenestration industry. The difference between a laboratory tested product or assembly and a field tested product or assembly can also vary by three or more points if good construction practices are not followed. It is evident that in order to meet the owner's performance expectations, laboratory testing of proposed building elements and field testing of installed assemblies is essential. It is only at the field testing phase of the process can the true acoustical performance of the assembly can be determined, which is often critical to the commissioning process.

There are many opportunities for acoustical evaluation during the commissioning process. ANSI/ASA standard S12.60 currently provides guidelines for noise in school classrooms. This noise can be generated by adjacent classrooms, music rooms, mechanical rooms, HVAC systems and/or outdoor noise sources. Areas of review in the commissioning process could include interior walls, doors and/or floor/ceiling assemblies, facades and/or facade elements (door, windows, unit ventilators, etc), roof systems, and heating, air conditioning and/or plumbing noise.

For multi-family dwellings, the current IBC and IRC codes require that the demising (party) walls and floor/ceiling assemblies between adjacent units have a minimum laboratory STC rating of 50 or achieve a field tested ASTC of at least 45. Some assemblies have not been achieving the acoustical performance that is documented in current publications. This could be due to outdated test data or to changes in materials or manufacturing processes over the years. Architectural and mechanical drawings should be reviewed by an acoustical expert prior to construction and on-site inspections should be performed to verify that constructions comply with the drawings.

Structural/Blast

Component level structural testing is most often performed during laboratory testing. However, many wall components such as fenestration products and claddings are regularly tested for structural load resistance during the mock-up phase using ASTM E330. By exposing the mockup to specified pressure differentials, it can be determined whether the component or assembly structural performance is sufficient to withstand the structural loads under which it can be reasonable expected to be exposed. Small scale field structural testing of some façade components and assemblies such as anchorages, membranes, and concrete are also quite common.

Terrorist attacks on buildings in the United States over the past decade have accelerated research at all levels in the design and construction of buildings such that the potential for progressive collapse under abnormal loading conditions is reduced. Testing and analysis are used by designers, architects, consultants, and manufacturers to mitigate hazards from glass fragmentation, which, apart from extreme circumstances, constitute approximately 75% of all damage resulting from a blast. With the increasing levels of blast protection required for building code compliance and OPR, particularly in pertinent governmental and other high-risk buildings, blast resistance has become an important performance category for building envelope functional performance and should be verified through functional performance testing.

Testing is performed on fenestration products and given a rating in accordance with ASTM F1642 and GSA – TF 01. Testing is conducted in either a shock tube or area-tested. Shock tube testing is useful when conducting convenient and inexpensive testing on single, small test samples. Full scale arena blast testing is more appropriate for larger, project-specific mock-ups and is typically considered more of a real-world environment. However, testing under this method is generally more expensive than shock tube testing, with slightly more variability in the test results. As with other mock-up tests, a portion of the building enclosure can be built, including the roof, in an open area.

Field testing for blast performance is typically limited to small scale anchorage testing.

SAMPLING

Given project scheduling and budgetary constraints, it is both impractical and cost-ineffective to test 100% of any installed component or assembly. Multiple identical pieces of assemblies should therefore be tested using a sampling strategy. Significant application differences and significant sequence of functional differences in otherwise identical materials or assemblies invalidates their common identity, although a small size or capacity difference, alone, would not constitute a difference. One common sampling strategy is the “xx% Sampling – yy% Failure Rule” as defined in the following example, where:

> *xx = the percentage of the group of identical materials or assemblies to be included in each sample.*
> *yy = the percent of the sample that, if failing, will require another sample to be tested.*

As an example, consider a 20% Sampling – 10% Failure Rule. The “first sample” would consist of 20% (xx) of each group of identical materials or assemblies, in no case testing less than three units in each group. If 10% (yy) or more of the units in the first sample fail the functional performance tests, another 20% for the group, referred to as the “second sample,” should be tested under the same parameters. If 10% or more of the units in the second sample fail, all remaining units in the whole group should be tested.

While the determination of statistically accurate sampling techniques and adequate sample sizing falls outside the scope of this paper, it is often most effective to perform an increased level of testing at the onset of the project, so that any deficiencies stemming from improper installation techniques, material defect, or other factors, can be identified early on the construction process. It might also be prudent increase the sample size proportionally to the frequency of failed tests on an assembly-by-assembly basis. However, if at any point frequent failures are occurring and testing is becoming more 'troubleshooting' than verification, testing should cease and the contractor should be required to perform and document a checkout of the remaining units prior to continuing with functionally testing the remaining units.

ANALYSIS OF TEST RESULTS

The role of the BECA does not end once a functional performance test has been completed. The significance of the involvement of the BECA becomes apparent during the analysis of failure. It is not only important to identify issues of non-compliance, but also to identify the cause of that non-compliance – be it workmanship, materials, design or other factors - as the deficiency may only be a symptom of a greater issue. In some cases, this is relatively straightforward. Consider a membrane-to-substrate tensile adhesion test conducted on a self-adhesive wall air/vapor barrier membrane, where the project specifications require the membrane to remain adhered to the substrate under a prescribed tensile load. In the event of a failure where the membrane sample detaches from the substrate under a tensile load less than the specified, installation logs can be reviewed and the sample itself can be viewed post-test to assess potential causes of the failure, such as improper substrate preparation, moisture between the membrane, inadequate ambient environmental conditions, etc.

In other cases, establishing causality is not nearly as simple. Determining the entry point and leak path of water infiltration detecting during water penetration testing often requires additional diagnostic testing and/or disassembly of the test unit. Assessing the direct cause of failure in a multi-assembly test is often even more difficult and requires experience and understanding of: (1) material composition, installation, and design of all of the different assemblies; (2) the different diagnostic tools and equipment available, and the associated limitations of each; and (3) how the interaction between the different assemblies affects overall system performance. Of particular interest is item (3), as the interaction of assemblies is often complex and may be counter intuitive. In a multi-assembly test, the presence of one assembly might lead to a failure of a second assembly, where under normal testing parameters each of the two assemblies would pass if tested independently. Consider a system comprised of a window unit and an adjoining metal panel wall assembly subjected to air and water penetration testing, where the test results show the total air/water infiltration through the curtain wall system has exceeded the allowable. Without further analysis of the sample, it may not be possible to determine the exact location of the leakage and whether the breach occurs within the window assembly, or whether the window test results are presenting symptoms from a breach within the interface between the window and adjoining wall assembly where the infiltration would not be present if the window unit were tested as a standalone system.

What may not be as obvious, but is as equally if not more significant is the need for proper analysis of *positive* test results. Test results that appear to be compliant to project requirements, need to be analyzed to ensure that they are truly representative of system performance. In some instances, the prevalence of a deficient condition or failure of a single component might be hidden or appear insignificant when measured as a part of a larger assembly, but can be quite significant when the deficiency is replicated throughout the project. This occurred on a recent project where the measured air flow rate of a window/wall mock-up was found to be approximately 80% of the allowable for the test area, signifying a 'pass' result. Analysis consisting of visual examination and additional diagnostic testing of the test sample determined that the leakage was occurring at breaches in the seals at masonry tie locations, and that only 16% of the masonry ties in the test sample were leaking; in other words, a failure rate of only 16% in one component was accounting for 80% of the allowable air leakage for the whole sample. Given the number of masonry ties that may be installed throughout a large commercial building, this amount of leakage attributable to this component is worrisome if this is representative of the site condition, or worse, if the prevalence of deficient installation increased over the remainder of the project as compared to the mock-up.

In other cases, a significant breach or deficiency occurring at an isolated location may be diluted across the results of the entire test sample. Consider a window/wall mock-up for a recent high-performance laboratory, where the results of air tightness testing conducted in general accordance with ASTM E783, Standard Test Method for Field Measurement of Air Leakage Through Installed Exterior Windows and Doors, showed that the measured air flow rate for both the window, 0.056 L/(s·m^2) at 300 Pa (0.011 cfm/ft^2 at 1.20 in. water), and opaque wall, 0.041 L/(s·m^2) at 75 Pa (0.008 cfm/ft^2 at 0.3 in. water), fell within the allowable leakage rates of 1.016 L/(s·m^2) at 300 Pa (0.2 cfm/ft^2 at 1.20 in. water) and 0.102 L/(s·m^2) at 75 Pa (0.020 cfm/ft^2 at 0.3 in. water), respectively. Qualitative airtightness 'smoke' testing conducted on the sample in general accordance with ASTM E1186, Standard Practices for Air Leakage Site Detection in Building Envelopes and Air Barrier Systems, Method 4.2.6, revealed the air infiltration to be isolated to the plenum area above the soffit. Although this area represented only approximately 20% of the opaque wall sample, the air infiltration at this location was accounting for 40% of the total allowable air leakage for the entire sample area. So while the test sample 'passed', analysis of the results identified a critical area, or *point-failure*, that the installer needed to address.

As a project rarely transpires where all tested components or assemblies 'pass' on the first attempt, it is important that a well-defined method for evaluating pass/fail criteria, and a procedure in the event of non-conformance be in place. In the event of a failure, the BECA should record all test results and notify appropriate parties of all deficiencies or non-conformance issues. In some cases, corrections of minor deficiencies may be made during the tests at the discretion of the BEC. Typically, while the cost of initial testing is borne by the Owner, the cost of re-testing, and any observation of correction of deficiencies prior to, but related to, the re-testing, should be borne by the contractor responsible for the deficiency or non-conformance issue.

SUMMARY

With the increased complexity of building envelope designs, the onset of new building materials, and increasingly stringent performance demands, a complete building envelope program has become recognized as an invaluable process in ensuring the continued functionality and durability of the envelope. Not only does it ensure that the building envelope is constructed to meet the design intent, code requirements, and expected service life, but it can also assist in preventing many complications that occur during the construction process. As a part of the commissioning process, a thorough functional performance testing protocol can be utilized to verify that the performance criteria as established in the OPR are achieved.

REFERENCES

Aldous, F., Godfryt, J. J. & Lemieux, D. J. 2008. Building Enclosure Commissioning - A Review of "commissioning under the influence.," *National conference on Building Commissioning: April 22-24, 2008.*

Anis, W., "NIBS Guideline 3: Exterior Enclosure Technical Requirements for the Commissioning Process," *Journal of Building Envelope Design*, National Institute of Building Sciences/Building Enclosure Technology and Environment Council, Winter 2008.

Bentz, S. P & Howell, M., "Minimizing Risk with Mock-Ups," *Applicator*, 29.3, Sealant Waterproofing & Restoration Institute, 2007.

Brennan, T. & Clarkin, M., "Characterizing Air Leakage in Large Buildings: Part II," *Journal of Building Envelope Design*, National Institute of Building Sciences/Building Enclosure Technology and Environment Council, Winter 2008.

Hodas, S., "Preconstruction Mock-Ups for Construction Are Becoming Industry Standard Procedure," *New England Real Estate Journal*, 2007.

Knight, K. D. & Boyle, B. J., "Commissioning Airtight Building Enclosures: The Importance of the Pre-Construction Phase Commissioning Process," *Journal of Building Enclosure Design*, National Institute of Building Sciences/Building Enclosure Technology and Environment Council, Winter 2007.

Knight, K. D. & Boyle, B. J., "Commissioning the Building Envelope for Compliance with Part 5 of the National Building Code of Canada," *Building Envelope Forum, 7th Edition Online Newsletter*, January 2007.

Knight, K. D. & Boyle, B. J., "Guidelines for Delivering Effective Air Barrier Systems," Canada Mortgage and Housing Cooperation/Ontario Association of Architects, 2004.

Knight, K. D., Runkle, J. A. & Boyle, B. J., "Effective Utilization of Mock-ups within the Building Envelope Commissioning Process," *2009 Symposium on Building Envelope Technology*, Roofing Consultants Institute, 2009.

Knight, K. D., Runkle, J. A. & Boyle, B. J., “Procedures for Commissioning Building Envelopes,” *2008 Symposium on Building Envelope Technology*, Roofing Consultants Institute, 2008.

Kubal, Michael T., Waterproofing the Building Envelope, McGraw-Hill Professional, 1992.

Lemieux, D. J. & Totten, P. E., “Building Envelope Design Guide – Wall Systems,” *Whole Building Design Guide*, National Institute of Building Sciences, 2009.

Lstiburek, J., “Understanding Vapor Barriers,” *Building Science Digest 106*, Building Science Press, 2006.

Matthews, R. S., Bury, M. R. C. & Redfearn, D., “Investigation of Dynamic Water Penetration Tests for Curtain Walling, *Journal of Wind Engineering and Industrial Aerodynamics*, Volume 60, April 1996.

Morrison Hershfeld Ltd., “Commissioning and Monitoring the Building Envelope for Air Leakage,” Canada Mortgage and Housing Corporation, Ottawa, ON, 1993.

NIBS Guideline 3 Exterior Enclosure Technical Requirements for the Commissioning Process, National Institute of Building Sciences, 2006.

Rosen, Harold J. & Sakhnovsky, A. A., “Testing for Water Penetration,” *Window and Wall Testing: A Symposium Presented at ASTM Headquarters*, American Society for Testing and Materials, 1974.

Taylor, H., “Curtain Wall Mock-up Testing,” *Journal of Building Enclosure Design*, National Institute of Building Sciences/Building Enclosure Technology and Environment Council, Summer 2007.