Poka-Yoke - A Window Manufacturer's Response to Leakage and Quality Control

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ABSTRACT HEADING

Replacement windows installed in commercial and residential buildings are subject to potential quality control issues during fabrication, shipping, storage, and installation. Quality control procedures employed by the manufacturer during fabrication may not be known or understood by the Architect. Proper employment of these procedures is imperative to achieve specified performance levels. In situ window testing performed at a building that included replacement of 990 windows (consisting of over 6,250 individual sashes) revealed multiple fabrication deficiencies, related to sealant and gasketed joints as well as window assembly component fabrication and orientation. These deficiencies were not initially identified by the manufacturer through their quality control procedures and resulted in an extensive investigation, on-site remediation, and testing program. This paper presents the findings developed through this case study and provides recommendations for assessing manufacturer's quality control plans, methods to quickly identify quality control lapses, and enhancing quality control procedures to prevent reoccurrences.

1.0 INTRODUCTION

Architects are frequently engaged to replace windows that have reached the end of their service life. Construction documents and industry standards are used to establish appropriate performance criteria based on exposure conditions and building type. As a manufactured assembly, the performance of the window is as fundamental to the overall success of the project as the Architect's design for integration with the facade and the installation steps performed by the contractor. Manufacturing deficiencies, if not identified at the plant, can result in significant problems in the field, particularly if the windows have already been installed. Many possible remedies to correct deficiencies cannot be easily or effectively implemented once the window is installed. Additionally, field modifications, because they may be implemented externally, are not as durable as corrective actions that can be undertaken at the plant. Ideally these corrections are quickly addressed and production processes modified before they become widespread.

1.1 Previous Work / Background

Quality assurance is the philosophy, program, and organization defining activities to ensure that the quality

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control program is being effectively implemented. Quality control is the planned system of activities whose purpose is to provide a level of quality that meets the needs of the owner. Quality assurance (process-oriented and focused on defect prevention) and quality control (product oriented and focused on defect identification) must be approved by the owner or the owner's representative. The owner's desired level of quality may depend on the building function, the ease of repairing deficiencies after construction, and the consequences of failures due to the quality of the system. Quality control is normally specified to be the responsibility of the manufacturer during fabrication and to the contractor during installation. Those involved in fabrication of window assemblies should understand how the assembly functions and be able to identify which components are critical to the success of the window.[1] Quality management systems are a tool that is used to improve quality during manufacturing but is not normally considered for building construction where each building is considered to be unique and the construction teams usually change for each project.

Focuses of quality management systems include improving the tools used to measure or assess quality and using the network of processes necessary to transform raw materials or sub-assemblies to a finished product to prevent defects. The Poka-Yoke method was introduced by Shiego Shingo in 1961 and is translated as "resistance to errors" or "avoid errors resulting from inattention".[2] Historically, quality management systems were understood to be a detriment to production costs and efficiency. Mistake proofing is conceptually different. The goal is to eliminate the possibility of mistakes or at least perform inspections soon after processes occur, so they can be immediately understood and corrected by production personnel. Each stage in the manufacturing process is analyzed for potential problems with the intent that through better implementation of those processes defects that arise as a result of human errors can be prevented.

2.0 QUALITY MANAGEMENT IN THE WINDOW INDUSTRY

Window specifications generally reference American Architectural Manufacturers Association (AAMA) standards. In particular, AAMA/WDMA/CSA 101/I.S.2/A440-11[3] is used to define testing and performance parameters through a 'gateway' set of primary requirements that define the minimum allowable performance levels that windows, doors, and skylights are required to achieve. This document is also used to define required performance levels for third-party certification of these products, though the standard itself does not dictate process control requirements or internal quality management systems, which are the prevue of independent certification programs. Installation of windows is required to be performed in accordance with the manufacturer's documented instructions.

Three agencies are noted in AAMA as providing third-party certifications: AAMA, the Window and Door Manufacturers Association (WDMA), and the Canadian Standards Association (CSA). Certification through the AAMA Gold Label Certification or the WDMA Hallmark Certification programs are performed by administrators who review product test reports, perform semi-annual audits of manufacturing plants, and sample materials or assemblies for subsequent testing. Both the AAMA and WDMA programs are accredited by the American National Standards Institute (ANSI) and require that window samples undergo third-party testing in accordance with the requirements of AAMA/WDMA/CSA 101/I.S.2/A440-11. Test requirements include air and water leakage through the assembly, structural resistance to loads, durability, and thermal performance.

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[1] Slaton, Deborah and David S. Patterson, "Making Quality Control a Part of the Design Process". The Construction Specifier, Construction Specifications Institute, January 2013, p.82.

[2] Dudek-Burlikowka, M. and D. Szewieczek, "The Poka-Yoke Method as an Improving Quality Tool of Operations in the Process". Journal of Achievements in Materials and Manufacturing Engineering, JAMME, v. 36, no. 1, September 2009.

[3] NAFS 2011 - North American Fenestration Standard/Specification for Windows, Doors, and Skylights. AAMA/WDMA/CSA 101/I.S.2/A440-11, 171 p.

Other agencies responsible for third-party certifications include multi-national corporations. The National Fenestration Rating Council (NFRC), as a non-profit is responsible for energy ratings. NFRC was founded to address concerns that manufacturers were making unsubstantiated claims about how much energy their products would save.[4] NFRC provides the sole source of energy ratings through analysis and physical testing by an NFRC-accredited laboratory.

2.1 Specific Window Manufacturer Quality Management Systems

Quality manuals for two window manufacturers were compared. The third party agency certifying these programs is a multi-national corporation that currently performs certifications for over one hundred different manufacturers of architectural products in addition to other laboratory and field-testing services. Manufacturers develop their own plant-specific quality programs that meet the minimum requirements of the certifying agency. Both of the quality manuals follow *Acceptance Criteria for Quality Documentation* (AC10)[5], which establishes the requirements for documenting quality control systems together with additional requirements of the certifying agency. As such, the underlying structure of the quality manuals is similar, though individual tasks or procedures vary slightly to accommodate the specific production processes of the plants.

General Requirements. This section includes the requirements for consistent labeling, product assembly drawings and specifications (including tolerances), an organizational chart that defines the responsibilities to personnel involved in the quality program, information on packaging and storage, and record keeping.

Incoming Materials. The requirements for incoming materials should be defined in the specifications. The responsibility of the plant is to confirm that these requirements are met by confirming mill test reports or certificates of compliance provided by the manufacturer of the incoming material, through in-house tests, or through third-party tests. If the compliance of incoming materials is not known, a means of segregating this material should be provided until confirmation or testing is performed and the material is determined to be in compliance. Incoming materials may be expected to include aluminum, glass, gaskets, sealant, and coatings that are governed by various Association for Testing Materials (ASTM) standards that identify critical material or physical properties that those materials should meet. Incoming materials may include sub-assemblies, such as an insulating glass unit (IGU). Storage and handling of these materials should be known and controlled. For example, materials that are sensitive to ultraviolet rays or moisture should not be stored outdoors.

In-Process Quality Control. In-process quality control includes monitoring of process operations and product characteristics such that it is within the allowable tolerances. Work instructions are typically used to define the manufacturing steps in each process and define one or more critical requirements to be confirmed prior to the product being released to the next step. Some processes, such as fabrication of frame component extrusions, the primary characteristic may be dimensional. For IGU fabrication, the process operation defines the orientation and sequence of coatings on the glass. Fabrication of window frames requires visual observation of joinery seals that are internal to the product and may be concealed at the time of final assembly. In all cases, the critical criteria must be understood by personnel performing the inspections and a process for containing products that are not in compliance must be established, including review of additional components within the production lot. Furthermore, corrective actions should be implemented so that out-of-compliance conditions do not repeat. Products are considered acceptable when they are released to the next operation in the process.

[4] NFRC Annual Report. National Fenestration Rating Council, 22 p.
[5] Acceptance Criteria for Quality Control Manuals (AC10). ICC Evaluation Service, Inc., 2004, 5 p.

Final Inspections. Final inspections should include testing on some proportion of the products sampled. Labeling of products may be used to demonstrate that all steps in the quality control process have been satisfied and the product is ready to ship. Some processes, such as sealant installation, may require time before the material achieves its final properties. Storage, handling, and shipping after final inspections are performed must be performed in a manner that will not cause subsequent damage prior to arrival and installation on site.

Non-Conforming Materials. Non-conforming materials must be segregated until they are disposed of or can be reworked, such that they are acceptable. In some cases, manufacturers may use a material that does not meet the performance requirement if the overall window specification can be maintained.

Measuring and Test Equipment. Requirements for maintaining and properly calibrating test equipment is a requirement of the standard. Typically, this equipment is required to be calibrated at specific intervals, in accordance with traceable standards, such as those of the National Institute of Standards and Technology (NIST).

Inspection and Test Records. Inspection and test records may include checklists, standardized forms, or reports that are used to document observations and/or measurements. These reports are normally retained so that, should a problem occur, the cause(s) may be assessed based on information collected during the manufacturing process. Additionally, internal quality audits may be performed to confirm that each quality activity is effective and is performed in accordance with the requirements of the quality control program.

3.0 RESPONSIBILITIES OF THE ARCHITECT

The initial responsibility of the architect is to recognize the owner's project requirements, goals, and budget. Based their understanding of the owner's objectives, the architect will create contract documents, including drawings and specifications. Once the design phase is complete, the architect will likely be involved throughout the construction process. Construction period services may include reviewing shop drawings, responding to requests for information (RFIs), on-site field inspections, coordination of field testing, and other items that can significantly improve the possibility of a successful outcome for a window replacement project.

3.1 Design Phase

Drawings and specifications convey the architect's design by defining the project requirements, the quality of materials, and the relationships between the replacement windows and the adjacent conditions. Construction drawings should include elevations, sections, and details as needed to clearly and concisely show what is to be built and how it relates to the existing site or building. The architect must have a clear perception of the construction of the existing window assembly, its attachment to the building structure, and the construction of the surrounding facade assemblies. If there are no original drawings of the building available, on-site investigation may be required to gather this information. Apart from developing a cohesive assembly on paper (or in model space), the architect must ensure that the work defined in the construction documents is constructible.

Specifications delineate the project requirements for the materials, products, installation, and quality. It is critical that the specifications are thorough and well thought out. There are several types of specifications, the most typical for window replacement projects are the prescriptive specification and the performance specification. Prescriptive specifications dictate detailed information about the products and materials required for the project and also has detailed installation instructions. A performance specification, on the other hand, specifies the operational requirements of the completed component or installation.

Defining appropriate performance criteria is a very important part of any window replacement specification.

Requirements for air infiltration and water penetration, energy performance, deflection capabilities, structural capacity, wind load and/or seismic performance should be clearly stated in the specification. There may be multiple sets of requirements, for example, one set for operable windows and another for fixed. When testing is required by the performance specification, the pass/fail criteria must be stated, for example:

Air Infiltration: Test according to ASTM E 283 for infiltration as follows:

1. Fixed Framing and Glass Area:
    a. Maximum air leakage of 0.04 cfm/sq. ft. at a static-air-pressure differential of 1.57 lb./sq. ft.

Aside from performance requirements, the specification will likely include requirements for the warranty, installer qualifications, quality assurance, mock-ups, and field quality control. The architect should define the size, scope, and inspections requirements of the mock-ups. Field quality section(s) clarify the specific testing required, frequency of testing, who is to perform the testing, reporting requirements and also observation of mock-ups, testing, and construction.

How pass/fail criteria is defined is critical to a field-testing program. What constitutes failure may be harder to define with some testing, such as water infiltration testing. Some standards allow windows to pass testing with a small amount of water leakage, others allow no observed water infiltration. The architect must understand the referenced standards and add clarification to the specifications when needed. What happens after a failed test should be clearly defined; is there a mandatory retest? At which party's expense does the test occur? Does failure trigger additional testing at other locations?

3.2 Construction Phase

In many cases, the architect is involved in the construction phase and will play a key role in the quality process. It is the architect's responsibility to work with the contractor and owner to answer questions, review construction submittals and shop drawings, and clarify the construction documents if needed with additional sketches.

The architect may also play a role on-site, typically this would include attending meetings, periodically reviewing on-going construction for performance and aesthetics, and observing field testing. Based on the size and scope of the project the architect may also perform on-site inspections at the glass or window manufacturer's plants.

4.0 FIELD TESTING

Ideally, deficiencies, if they exist, will be identified and remediated by the manufacturer during fabrication. In some cases, deficiencies are not discovered through the manufacturer's quality process or the deficiency occurred subsequent to the final inspection. In addition to testing individual sashes, field testing is used to identify problems related to integration with the window perimeter or the joints between multiple sashes within the same opening. As such, the mock-up and testing phases of construction are essential to evaluate these additional conditions while also providing additional opportunity that may lead to the identification of non-conforming work. This program of field testing should be determined by the architect based on the owner's performance requirements, expectations, and budget. The scope of the testing program must be well defined in the specifications so that all parties understand the requirements and responsibilities involved.

4.1 Mock-up Testing

Standards, methods, and requirements for field testing are specified by ASTM, AAMA, and ANSI. For larger projects or projects involving curtain wall mock-up testing may include thermal cycling, vertical and lateral inter-story drift, and structural load testing. For the purpose of this paper, we will focus on typical window field testing protocol which involves air infiltration testing, water infiltration testing, and sealant performance testing. The key standards include:

Water Infiltration Testing:

- ASTM E1105-15 Standard Test Method for Field Determination of Water Penetration of Installed Exterior Windows, Skylights, Doors, and Curtain Walls, by Uniform or Cyclic Static Air Pressure Difference
- AAMA 501.1-17 – Standard Test Method for Water Penetration of Windows, Curtain Walls and Doors Using Dynamic Pressure
- AAMA 501.2-15 – Quality Assurance and Diagnostic Water Leakage Field Check of Installed Storefronts, Curtain Walls, and Sloped Glazing Systems

Air Infiltration Testing:

- ASTM E1186-17 Standard Practices for Air Leakage Site Detection in Building Envelopes and Air Barrier Systems
- ASTM E783-02 (2010) Standard Test Method for Field Measurement of Air Leakage Through Installed Exterior Windows and Doors

Comprehensive Test Programs:

- AAMA 502-12 – Voluntary Specification for Field Testing of Newly Installed Fenestration Products
- AAMA 503-14 – Voluntary Specification for Field Testing of Newly Installed Storefronts, Curtain Walls, and Sloped Glazing Systems (Air Infiltration is Optional)

Sealant Testing:

- ASTM C1521-13 – Standard Practice for Evaluating Adhesion of Installed Weatherproofing Sealant Joints

The time when mock-up and field testing occurs during the construction process is critical; this work should be performed as early in the process as possible so that any deficiencies are identified and remediated quickly and efficiently. Often, a freestanding performance mock-up assembly is built for this purpose prior to the start of construction. This allows the owner and architect to review and approve (or reject) the materials, construction, and aesthetics of the new window assembly before construction starts and sometimes before the bulk of the units are manufactured. Initial rounds of field testing would also be performed on this separate mock-up. Alternately, these reviews and testing can be performed on one of the first units installed during the construction. Typically, at this point many of the units have been manufactured therefore any deficiencies that require modification of the units will likely be field modified. It is preferable to have these deficiencies identified earlier so that modifications can be performed during the manufacturing process.

Who performs and who observes field-testing is in large part up to the owner and the architect. In most cases, the testing is performed by a third-party testing company with no affiliation to the design team, manufacturer, or window installer. This testing should be observed by the architect (and the facade consultant), the window installer, and a manufacturer's representative. When all of these parties are able to witness the testing there is a greater opportunity to address any issues or deficiencies efficiently. Requirements for attendance at testing can be specified by the design team if desired. The frequency of testing should be one for each type of product on for projects with less than one hundred units or one percent of the installed products for larger products. If there is a test failure, it is the responsibility of the window installer and manufacturer to determine the cause and recommend remediation. Diagnostic testing of failed assemblies using the AAMA 501.2-15 standard is an effective method to pinpoint issues identified by other performance tests.[6]

4.2 Observations during Construction

Quality reviews at the project site should be performed to ensure installation procedures are consistent with the manufacturer's requirements and the design documents. These reviews should be performed by the architect, manufacturer's representative, or a third party hired by the owner. These quality reviews should always include visual observations or inspection together with field-testing, as can be practiced. Inspections should be performed at critical stages in the construction process. For example, at the time the rough opening is constructed (or repaired) to assess the substrate conditions, when flashings are installed, following completed window installation.

5. CASE STUDY

The building that is the subject of the case study was constructed in 1918 and served as a waterside storehouse for the Army. The building is constructed of reinforced concrete and extends 1,638 ft. in length, 126 ft. in width, and is eight stories tall. Due to current urbanization trends, coupled with a desire to be near the harbor, occupancy within the building was on the rise and new tenants would not accept the leaking and condensation issues associated with the original steel-framed windows. As such, the owner desired to replace the 990 windows consisting of overall area of approximately 115,000 sq. ft.

The original windows largely remained place prior to the start of the window replacement project, consisting of steel-framed industrial sashes with single-pane glass. The window jambs and heads were originally encased in a pocket formed within the reinforced concrete structure and set in mortar. This condition was problematic because corrosion of the steel resulted in concrete distress and subsequent leakage around the perimeters of the windows.

Based on the requirements of the historic district, aluminum-framed windows with simulated muntins applied to the exterior were selected. Of the most common opening size (16 ft. wide by 10 ft. tall), six fixed sashes were used together with two operable sashes to closely replicate the existing window profile.

The quality management system of the manufacturer was accredited by a multi-national company and included the requirements for incoming materials, in-process inspections, final inspections, and containment of non-conforming materials. During a visit to the plant, work instructions that are part of the manufacturer's process control were provided and quality processes were demonstrated. These included checklists for visual inspections for critical dimensions. Low-E detectors were used to confirm the orientations of the surface coatings. Air and water infiltration testing of sashes was demonstrated and one of the sashes was observed to leak when tested at the design pressure of 12 pounds per square foot (psf).

Subsequent to the plant visit, additional test reports documenting the results of air and water infiltration testing were requested. The provided results included tests of approximately seventy sashes performed at the plant. Many of the tests were performed to a pressure that was 25 percent higher than the specified pressure. However, the reports also showed that 20 percent did not pass the test. Sashes that did not pass the test were deglazed, re-sealed, and retested. Causes of window leaks included inadequate gasket compression, incomplete sealing of the interior wedge gaskets, incomplete sealing at metal-to-metal joinery, and orientation of the pressure equalization gaskets for the adaptor grid. These issues were believed to be corrected when initial lot of windows were sent to the project.

[6] Slaton, Deborah and David S. Patterson. "Avoiding Fenestration Failure with Quality Control Testing". The Construction Specifier, Construction Specifications Institute, February 2009, p.66.

The field-testing requirements for the project included multiple tests at 5, 50, and 90 percent of the project completion. For every failed test, that window was required to be repaired and retested, and one additional window selected by the architect was to be tested. The field tests performed initially found issues similar to what had occurred at the plant. These failures were due to the manufacturer not recognizing the significance of problems observed during the fabrication process and failing to realizes the process deficiencies were resulting in additional problems that were not contained prior to shipment.

To correct the known issues, the manufacturer performed on-site testing of 100 percent of the operable and non-operable sashes that were on-site and not yet installed using a mobile testing unit. Additionally, remediation of the small number of sashes that were already installed was also performed. For sashes that had not yet been fabricated, several process improvements were made together with the incorporation of a "ten for ten" testing plan at the plant. The first ten sashes were tested for air and water infiltration. If ten consecutive tests passed, the line was considered to be controlled and subsequently tested at a frequency of 10 percent. If a failure was noted all of the sashes produced that shift would be tested. Provided test results showed that the number of failed sashes was greatly reduced, though an additional failure mode that was not originally observed was also identified.

This failure mode was determined to be the result of improper location of the fasteners used for the attachment of the operable arms. The position of the holes for fasteners used to attach the arm hardware was dependent on the person performing the fabrication to locate the holes correctly. The result of improper location of the holes for the fasteners was that the gasket for the operable sash could be inadequately compressed. The manufacturer responded by modifying the jig used to locate the holes so that it could only fit the sash in the correct location, preventing a reoccurrence - poka-yoke. Application of the poka-yoke procedure together with other improvements in the containment process resulted in improved results for tests performed at the plant and successful field-testing.

6. Conclusions

Poka-yoke concepts can be applied during the manufacture of window products. Use of these concepts requires an understanding of processes involved. Some processes may not lend themselves to error-proofing methods and it is also important for manufacturers to recognize the significance of quality control failures and contain products that are known to be deficient. Containment will generally include not only the deficient tested product but some number of units manufactured before the deficient unit was determined. Until processes are corrected, the frequency of testing should be greatly increased until the problems are corrected to within the desired level. Confirming the results of manufacturing tests is critical in the field, since the mock-up and field tests will typically include additional adjacent conditions. Assessing problems early is best. Correspondingly, problems at the plant should be addressed at the plant. Problems in the field should be ideally addressed prior to the start of construction. Waiting until the end of a project to discover a problem will result in significant cost, delay, and owner dissatisfaction.