Balancing Preservation and Energy Efficiency in Building Retrofits

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ABSTRACT

Energy conservation has become one of the primary goals of architecture and engineering design today, especially when retrofitting existing buildings. The desire to improve the energy efficiency of an existing building must be balanced with the need to preserve the existing structure and architectural features, as changes to the thermal and moisture properties of the building enclosure can have serious negative impacts, such as degradation of the existing masonry walls or interior finishes along with interior air quality and other moisture related issues. Prior to implementation of any retrofit option, the existing conditions must be evaluated, and the project goals must be understood. Each retrofit project is unique and must be evaluated as such. The impact of the proposed repairs on the existing building behaviors must be understood, and the value of the energy improvements must be considered. Common retrofit strategies are found throughout the industry that lend themselves to improving the energy performance of an existing building. Such strategies include adding a continuous air barrier, improving the thermal performance of roof and wall assemblies, improving the performance of fenestration, and addressing bulk water infiltration. Each of these strategies aims to meet requirements of industry codes and standards, but must be balanced with the preservation of the existing building, specifically when the building has historical significance. For each of these retrofit strategies, different parameters should be considered to ensure the project goals are met while ensuring the repairs provide positive impacts to the building performance.

INTRODUCTION

There is a significant movement towards energy conservation in the built environment. Not only does this movement provide a sense of environmental stewardship, but also can be beneficial from an economic standpoint with reduced operating costs. Based on data collected from the U.S. Energy Information Administration (EIA) in 2012, buildings are responsible for almost half of all U.S. energy consumption (CBECS 2016). There is a focused effort through national initiatives to reduce this number and promote energy efficient buildings, such as the U.S. Department of Energy's "Better Buildings" Initiative and Architecture 2030. While these initiatives focus on the overall performance of the building, the Commercial Buildings Energy Consumption Survey conducted by the EIA in 2012 shows that heating, cooling, and ventilation account for 44% of energy use in a building (CBECS 2016). These activities are directly related to the HVAC performance, which is directly impacted by the performance of the building envelope. Even with the most efficient HVAC design, if the building envelope has significant air leakage or is not insulated properly, the systems will not operate as intended. For renovation projects intending to upgrade energy performance, retrofit strategies for building envelope components must be carefully evaluated to ensure the preservation of the existing building components. Figure 1 graphically depicts many of the key factors that must be considered when balancing the desire to preserve the existing performance of building materials and components while increasing the energy efficiency of the building.

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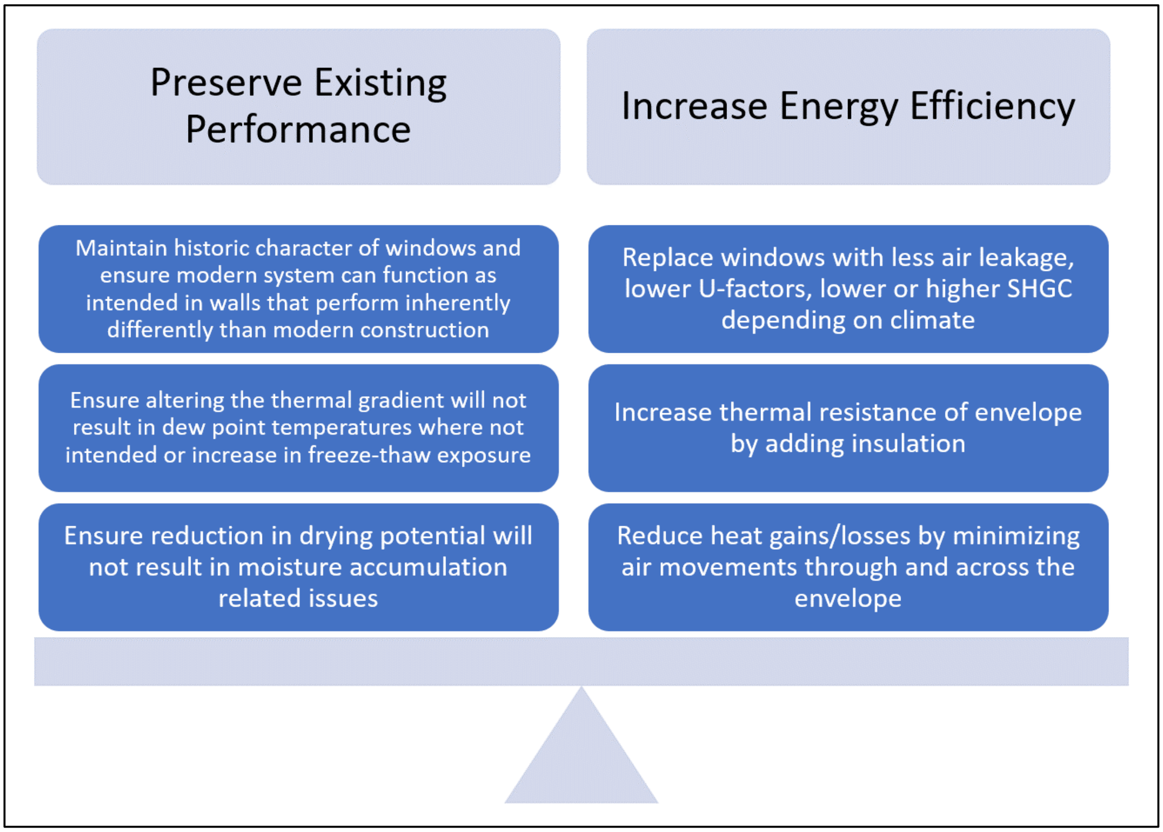

Figure 1. Considerations for balancing the preservation of existing performance of building materials while increasing the energy efficiency of the building.

Code & Project Requirements

Design codes and standards are evolving to incorporate measures that improve the performance of the building envelope. While there are other design guidelines and standards available, the International Building Code references the use of the International Energy Conservation Code (IECC) as buildings relate to energy efficiency. In addition to code requirements, an understanding of project goals should also be discussed before any design is undertaken so the design can progress in a manner that can achieve these desired outcomes. Within the IECC, there are several ways that designs can be developed that comply with the building envelope requirements. A project team must determine which of these compliance paths will be used to meet code requirements.

Prescriptive Compliance Path. The prescriptive compliance path provides basic guidance to meet code where design requirements can generally be selected from tables based on the type of construction. In addition to requirements specific to the mechanical design, service water heating, electrical power and lighting, the requirements for building envelope focus on insulation of roof and wall assemblies, thermal performance of fenestration assemblies, and air leakage. While the provisions for insulation and fenestration are prescriptive, the air leakage requirements are mandatory, meaning that regardless of the compliance path selected, provisions must be in place to limit air leakage through the building envelope. Beginning with the 2012 version of the IECC, a continuous air barrier must be provided throughout the building thermal envelope, with the exception of certain climate zones, or whole building air leakage testing in accordance with ASTM E 779 (ASTM 2014) must be conducted to demonstrate that the leakage is less than 0.4 cfm/ft^2 when tested at 0.3 inches of water pressure differential.

Total Building Performance Compliance Path. The total building performance compliance path allows energy modeling to be performed that compares the energy consumption of a "standard reference design" building to the "proposed" building. The standard reference building generally meets the prescriptive requirements outlined within the code, so the proposed building must perform equal to or better than the prescriptive requirements collectively. In addition to the energy comparison, certain requirements for each system remain mandatory, such as the air leakage requirements for the building envelope. It should also be noted that for existing buildings, the use of the total building performance compliance path is not a permitted compliance path, but depending on the scope of the repairs, alterations or additions, compliance may not be required provided it can be demonstrated that such modifications do not increase the energy consumption of the building.

ASHRAE 90.1 Compliance Path. ASHRAE 90.1 "Energy Standard for Buildings Except Low-Rise Residential Buildings" (ASHRAE 2016) can be used as an alternate to the requirements of the IECC. ASHRAE 90.1 outlines three compliance paths that are similar to those of the IECC as it relates to the building envelope. These include the Prescriptive Building Envelope Option, Building Envelope Trade-Off Option, or the Energy Cost Budget Method. For the Prescriptive Building Envelope Option, similar tables are used to determine the thermal performance requirements for roof, wall, and fenestration assemblies. The incorporation of a continuous air barrier is a mandatory requirement regardless of the compliance path. The Building Envelope Trade-Off Option and Energy Cost Budget Method allow for various calculations and modeling techniques to be used to determine the required thermal performance of roof, wall, and fenestration assemblies to meet code.

Historic Building Exceptions. Both the IECC and ASHRAE 90.1 have specific provisions that exempt from meeting code requirements any building that is listed in the State or National Register of Historic Places or designated as a historically significant building. This exception is critical for restorations or alterations to historical buildings, as these buildings have typically withstood the test of time and changes to the building construction could have detrimental impacts on the existing materials and building components. However, many retrofit projects are undertaken on buildings that do not fall under these exceptions, but the long-term performance of the building is still a major concern to the Owner. Especially in these cases, understanding the project goals and desired outcomes in these situations are key to balancing any energy upgrades with the preservation of the existing building. Depending on the scope of the retrofit, different exceptions may be applicable so the retrofit meets the intent of the code requirements without having to meet prescriptive requirements.

Beyond Code. There are countless other guides and standards that often apply and require performance above the IECC levels. These include LEED certifications, ASHRAE 189.1 (ASHRAE 2014), International Green Construction Code, Energy Star, statewide or local regulations, and even project or Owner specific goals or requirements. Regardless of where the energy upgrade requirements are rooted, each requirement must be evaluated based on the impact to the long-term building performance using a similar assessment.

BUILDING ENVELOPE PERFORMANCE OVERVIEW

Generally speaking, energy efficiency upgrades to the building envelope fall under two main mechanisms of energy transport: air leakage and thermal performance. Each of these mechanisms impacts heat gains and losses through the building envelope and are applicable to both opaque assemblies (i.e. walls and roofs) and fenestration systems (i.e. windows, curtain walls, storefronts, and skylights). For opaque assemblies, a hygrothermal analysis can be performed to evaluate the long-term performance of the assembly based on the thermal performance and moisture transport of the assembly. In the case of retrofit, renovation, and preservation projects, the existing hygrothermal performance of the envelope must be fully understood so that the impacts of any proposed changes to the envelope assemblies can be weighed against the relative energy costs. After all, there is no value in saving money on heating or cooling costs if the added insulation creates conditions in the existing walls that will promote the corrosion of steel structural elements and degrade the useful service life of masonry that had previously survived 100 plus years and will now cost additional money to repair properly.

Air Leakage Overview

Addressing air leakage is considered a mandatory code requirement when it comes to energy efficiency because the movement of air through the building envelope can be a costly defect in the performance of the building. Convection is the fastest way to move heat or moisture from one space to another. This can induce moisture in areas not designed to resist it or move hot or cold air into spaces that reduce occupant comfort. The mechanical system must then resolve these issues through dehumidification or additional heating and cooling that will increase energy consumption. Finding ways to reduce air leakage in the building envelope will reduce this heat and moisture transport which inherently reduces energy costs. Furthermore, it can increase occupant comfort by eliminating the drafts created from air movement.

While an increased amount of air leakage can make it difficult to maintain constant and uniform temperatures throughout an existing building, there are several benefits with respect to the performance of such buildings, which tend to function inherently different from modern or new construction. Air leakage provides natural ventilation to the building which can increase the indoor air quality in certain instances. Additionally, air movement can also provide a mechanism for drying out moisture within building walls and roof assemblies. If too much moisture becomes trapped within these assemblies, there is the potential for moisture related issues such as biological growth, corrosion of metal elements, or decay of wood elements, which can lead to issues for building occupants and structural failures.

Older buildings generally do not have a continuous air barrier plane or designated air barrier membrane such as what is found in modern construction. However, many older envelope assemblies contain materials which can constitute an air barrier material or could be incorporated into the building's air barrier assembly. For example, multiwythe brick walls can function like an air barrier material provided all penetrations, terminations, and interruptions of the masonry are detailed to maintain continuity of the air barrier. This may be difficult to achieve depending on adjacent construction. If isolated modifications are made to an existing building component to comply with the continuous air barrier requirement, these changes should be evaluated to ensure the reduction in natural air movement does not eliminate a drying source that is integral to the overall walls' performance.

Thermal Performance Overview

In addition to convective heat flow caused by air movement, heat can be transferred through conduction and radiation. Conduction is the transfer of heat through direct contact of materials. Conduction is evaluated in the building envelope as thermal resistance, or R-value, of components comprising wall and roof assemblies. The greater the thermal resistance of the materials, the less conductive heat flow will occur, thus reducing the energy consumption of the building. Radiation is most commonly evaluated in the fenestration assemblies by the amount of solar heat that is permitted to radiate through the glazing, which is quantified by the Solar Heat Gain Coefficient (SHGC). This can provide a positive impact in colder climates that use solar radiation as a passive heat source, or a negative impact in warmer climates where additional heating loads would require increased use of cooling systems. Positive impacts of radiation can also be realized in a thermal mass, which store heat from the sun that can be utilized in different ways to offset heating costs.

Changes to the thermal performance of an existing assembly must be balanced with the long-term performance of the existing materials. For example, the thermal performance for wall assemblies is generally increased by adding insulation to the interior of the existing assembly. With the addition of insulation, the existing walls are no longer exposed to as much interior heat during winter months. For wall types such as mass masonry walls, this causes the potential for an increased number of freeze/thaw cycles that could cause damage to the outer surfaces of the masonry. Depending on the type of insulation installed, the drying potential of the wall assembly could be reduced. Before adding insulation, any moisture stored in the wall assembly was permitted to dry to both the interior and exterior. If an impermeable insulation is installed, this eliminates the interior drying potential and could cause excessive moisture to be stored in the existing building materials that could lead to moisture related issues. Alternatively, if insulation is installed in an area prone to high moisture loads, the long-term performance of the insulation itself could be compromised depending on the material properties of the insulation and the ability to resist moisture.

Hygrothermal Analysis Overview

For any changes to the opaque assemblies of the building envelope, a hygrothermal analysis should be performed to understand the potential for any moisture accumulation within the assembly. A hygrothermal analysis considers the movement of heat and moisture simultaneously across an assembly. The goal of this analysis is to design an assembly that does not create conditions where condensation may occur in locations where it cannot be managed or conditions with prolonged exposure to high levels of relative humidity and moisture that could degrade the materials.

To prevent condensation, the placement and thickness of insulating materials should be such that surface temperatures within the assembly do not drop below the dew point temperature at a given point in time. The dew point is a function of both temperature and humidity. The temperature at different points in the assembly can be altered through insulation placement and interior temperature settings. The humidity at different points in the assembly is dependent on vapor diffusion through the materials comprising the assembly.

The relationship between temperature and humidity is governed by the Ideal Gas Law. At a constant temperature and constant volume, a difference in the concentration of vapor molecules across a material creates a vapor pressure difference. The vapor pressure difference forces the vapor molecules from the area of high concentration to the area of low concentration through the material, inducing vapor diffusion, until a point in time where the concentration of vapor molecules has equalized. Depending on the material properties and the hygrothermal loads, the rate of vapor diffusion will vary. Materials with a low vapor permeance will limit the amount of vapor passing through. Conversely, materials with a high vapor permeance will readily allow water vapor to pass through. If enough vapor molecules accumulate in one location due to limited vapor permeance of materials, the relative humidity can increase at a given temperature and may create a condition where the dew point temperature is realized, precipitating the occurrence of condensation.

To analyze these conditions, a steady state analysis or a transient analysis can be performed. Steady state analysis evaluates a wall assembly during specific interior and exterior conditions, but does not consider the impact of preceding or subsequent conditions. Steady state analysis also does not take into account many parameters and variables that transient analysis includes, such as impacts of material properties including sorption, desorption, and initial moisture content. A transient analysis will evaluate the assembly over time, which considers different conditions the assembly is exposed to, and is the most accurate type of analysis currently available in the industry.

In addition to evaluating an assembly for condensation potential, other factors should be considered. Limitations on the assumed interior conditions for the analysis are required to ensure the building occupants are comfortable. If certain materials are exposed to high levels of relative humidity for extended periods of time, the potential for biological growth, corrosion, or structural decay of wood increase. Biological growth jeopardizes human health, while corrosion and decay of wood elements can compromise the structural integrity of the building materials. Transient hygrothermal analysis can be used to predict the moisture levels and temperature at different depths within the envelope assembly so that these additional failure criteria can be assessed.

Incorporation of hygrothermal analysis for wall and roof assemblies into the design is part of best design practice. As building construction becomes more air tight, such an analysis is more important as convective air movement no longer provides a mechanism for drying out any incidental moisture accumulation within the assembly. For retrofit applications, performing a hygrothermal analysis of the existing assemblies as well as the proposed assemblies will ensure that alterations do not have a negative impact on the existing materials and building components.

EVALUATION OF RETROFIT STRATEGIES

Before implementing any retrofit to an existing building, the proposed alteration should be evaluated to ensure it adds value to the project and does not have adverse effects on the building performance. Any proposed changes should align with the overall project goals while meeting applicable code requirements. The existing conditions must also be fully understood so that improvements are effective and align with the desired outcome for the project. Common retrofit strategies include the addition of a continuous air barrier, improvements to the thermal performance of opaque assemblies, improvements to the thermal performance of fenestration assemblies, and addressing bulk water infiltration.

Addition of Continuous Air Barrier

Code Compliance and Project Goals. If compliance with IECC is part of the project goals and requirements, meaning that the project does not qualify for an historical exception or the scope does not fall under one of the exceptions offered for existing buildings, then minimizing the building's air leakage will be one of the few mandatory code requirements. There are three general approaches available to accomplish this, each with their own benefits and drawbacks:

1. Demonstrate compliance through whole building air leakage testing.
2. Rely upon existing building materials to comprise the continuous air barrier through transition detailing.
3. Add a designated air barrier membrane to the existing building.

Demonstrating compliance through whole building air leakage testing is rarely the option chosen as this can be a complicated and costly endeavor, especially if the building is occupied and will remain so during the renovations. It is also somewhat of a gamble because the results can't be known ahead of time, meaning much effort and money can be spent just to conclude that more money must be invested to reduce the air leakage.

Most existing wall assemblies include at least one material that will have the ability to function as an air barrier material. For example, code considers the following, among other things, to function as air barriers provided all joints and penetrations are properly sealed: 1/2" interior gypsum board, 1/2" exterior gypsum sheathing, 5/8" or thicker Portland cement or gypsum plaster, fully grouted CMU, cast in place or precast concrete, and solid or hollow clay or shale masonry. If these materials are to be relied upon to perform as an air barrier material, all integrations with adjacent materials, penetrations, and terminations of these existing materials would need to be properly detailed to ensure a continuous air barrier. The difficulty with this approach is ensuring that an appropriate material within each unique assembly has been designated as the air barrier and then identifying all conditions which will require details to maintain the continuity of the building's designated air barrier materials. Additionally, the existing materials which are intended to function as the air barrier are not always located at the correct depth within an envelope assembly where needed to properly or adequately control air infiltration and exfiltration. For example, an existing stud framed wall may feature interior gypsum board which can function as an interior air barrier, but based on the project's climate and exposure, the building may also require an exterior air barrier to prevent migration of exterior air into the stud cavity. The placement of the air barrier and the impacts on the hygrothermal performance are discussed in greater detail below.

For the reasons mentioned, most designers decide to install a new membrane intended to function as the air barrier. The benefit of this approach is having an identified plane of air management to which adjacent systems like windows, doors, other fenestration, and roofs can be integrated. This approach can make the transition details more straightforward. However, there are many parameters that should be evaluated when a new air barrier membrane is added to an existing building as discussed further below. As such, the other two approaches should not be written off.

Evaluating Existing Conditions. Generally, the scope of the retrofit project and the condition of the existing building will be the driving force behind determining which approach for minimizing air leakage is most appropriate for the project. Early in the project planning phase, the condition of the existing materials, including the integrity and usable service life of concealed materials, should be thoroughly assessed to identify what materials will remain, which materials will be repaired, and which materials will require replacement. In preservation projects, the scope is commonly limited to interior alterations only, and the existing exterior walls remain in place. Especially in the cases of buildings with existing mass masonry walls, it is typical to add interior air barriers, insulation, furring, and finishes to accommodate new electrical and plumbing systems. However, in some instances, especially if there are latent defects or deficiencies within the envelope assembly, exterior work is unavoidable. Repairs to the exterior of the building should focus on preserving the existing materials and building components to the greatest extent possible, and ensuring repair materials are compatible with the existing construction and, for historical buildings, consistent with materials from that construction era. In cases when comprehensive repairs or replacement are required that involve removal of exterior cladding, additional scope of work such as incorporation of modern air and weather barriers or insulation could be evaluated provided they add value to the project. Determining the necessary scope of the retrofit project as early as possible will help to direct the most appropriate method of minimizing air leakage.

Regardless of what approach is eventually taken, a thorough understanding of the building's air infiltration and exfiltration patterns is needed. ASTM E1186 (ASTM 2017) outlines field procedures that can help identify the conditions which are leading to excessive air infiltration or exfiltration. Using the methods described in this standard, specific areas or conditions can be identified as the primary targets for reductions in air leakage, either by adding a new air barrier or modifying existing details at those conditions. This standard outlines how infrared surveys, smoke pencils, tracer gas, and visual observations can be used, ideally in combination with each other, to focus on conditions that are leading to excessive air leakage. Conditions most commonly leading to excessive air leakage include: fenestration perimeters; roof to wall integrations; penetrations for structural supports for canopies, awnings, shade devices, and other overhangs; unsealed electrical, mechanical, or plumbing penetrations; changes in cladding or wall types especially where barrier type walls meet drainage type walls; and discontinuities in back up construction at columns, floor lines, and other structural interruptions. These field survey methods will help qualitatively locate the detail which can be revised to result in the maximum reductions in air leakage with the minimum amount of effort. In addition to identifying air infiltration or exfiltration, that is air moving to and from the interior or exterior across the entire wall assembly, any considerable air migration within the wall assembly should also be noted. For example, through smoke pencil testing or visual and tactile observations, it may be possible to note that the stud cavity is drafty, with lots of air movement between the studs. This air may be originating from the exterior or the interior and may be offering the existing wall considerable drying potential which should be accounted for when assessing the implications of adding a new air barrier or modifying the air barrier transition details.

Understanding the air flow patterns of the existing building is important when weighing the need for an air barrier and developing air barrier transition details. It is also important to qualitatively recognize the air permeance of the remaining materials so that any anticipated air flow within a wall assembly can be represented in the hygrothermal modeling described below. For example, unsealed joints in existing exterior sheathing may negate the sheathing's ability to function as an air barrier, and as such, ventilation of the stud cavity with exterior air should be accounted for in the hygrothermal models when examining the behavior of the existing wall assembly. It is equally as important to understand the water vapor permeance for new and existing materials that are to remain, so they also can be accounted for within the hygrothermal analysis. For generic materials, such as gypsum wall board and certain types of insulation and sheathing, it is not necessary to conduct any testing of samples as published data can be used with relative certainty. However, if unidentified coating or materials are contained within the existing assembly, samples should be taken and the vapor permeance should be determined using methods outlined in ASTM E 96 (ASTM 2016) or ASTM E 398 (ASTM 2013).

Evaluation of Retrofit Strategies. When a new membrane air barrier is to be added to an existing envelope assembly, several parameters must be evaluated and explored. Determination of many of the parameters will require transient hygrothermal analysis as discussed below. The parameters that must be addressed include the following:

- Air barrier placement: Can a membrane added to the interior of the existing assembly be effectively installed? Can the membrane be properly integrated with and transitioned to other assemblies such as windows when installed at the proposed plane within the wall?
- Air barrier type: Will a sheet membrane or fluid applied membrane be installed? For sheet membranes, will it be self-adhered or mechanically attached? Are there existing materials present that are incompatible with the air barrier?
- Air barrier vapor permeance: What is the appropriate vapor permeance of the air barrier? Should the air barrier also function as a vapor retarder?
- Air barrier constructability: Will continued occupancy, access, construction sequencing, limits to the scope of work, abatement of hazardous materials, or other project limitation drive the installation of the air barrier?
- Historical impact: Will the installation of the air barrier impact the historical nature of the existing building components in a way that the repairs will be irreversible? Does the installation of the air barrier follow best practices for historical preservation?

Even if a new full-scale air barrier will not be added as part of the scope of work in lieu of utilizing existing materials that function as the air barrier, the impacts of reducing the convective air flow through and around the assembly will need to be carefully evaluated. This would require a more targeted approach to address excessive air leakage at specific conditions and integration details. For renovations, retrofits, and preservation projects, it is critical to compare the past performance of an envelope assembly to the proposed performance of an envelope assembly. Hygrothermal analysis is needed to ensure that the addition of an air barrier or the alteration of how an assembly manages air flow will not result in unintended moisture accumulation within the assembly. The procedures described in ASTM E 3069 (ASTM 2017), "Standard Guide for Evaluation and Rehabilitation of Mass Masonry Walls for Changes to Thermal and Moisture Properties of the Wall," can be applied to the existing wall assembly. Although the standard is focused on mass masonry walls, the concepts and overall approach, specifically for the hygrothermal analysis, can be carried out and modified as needed on many existing wall assemblies.

To assess the changes for any existing wall assembly, a series of transient hygrothermal analyses should be conducted in accordance with ASHRAE 160, "Criteria for Moisture-Control Design Analysis in Buildings" (ASHRAE 2016). For the analysis, the standard assumptions which are outlined in ASHRAE 160 should be modified to be representative of what was found in the evaluation of the existing conditions, including values for initial moisture content and ventilation rate through and across the wall assembly. The hygrothermal performance of the existing wall, including any air movement, should be carefully compared to the performance of the proposed assembly accounting for reductions in air movement.

Evaluation of the hygrothermal models should generally include impacts of drying potential due to limiting air movement or vapor diffusion due to the permeance of the proposed air barrier. Often the addition of an interior air barrier will reduce the drying potential of existing walls, resulting in increased moisture content within the assembly. The impact of the reduction in air migration should be evaluated to identify any potential increases in the overall moisture content within the existing wall assembly. Any increases should be balanced to ensure moisture levels do not approach levels that create a potential for condensation where it cannot be controlled, formation of biological growth, or environments that cause corrosion of embedded metal elements. For mass masonry walls in particular, consideration should be given to the potential for an increase in the freeze-thaw cycles to which the existing masonry would be exposed. Simultaneously, an interior air barrier aims to limit convective heat losses, which reduces heating costs but can result in colder temperatures within the masonry. The moisture sensitivity of the proposed assembly due to moisture sources or rain penetration through the assembly must also be evaluated. Measures to mitigate the level of exposure to moisture may be required as part of the project. For example, if the addition of an interior air barrier and insulation will result in a reduction of the drying potential to the interior, the mortar joints for a masonry wall may need to be repointed to limit the water penetration through the assembly.

Improving Thermal Performance of Wall Assemblies

Code Compliance and Project Goals. Based on the project scope and goals, it is likely that an increase of the thermal performance of the existing walls will be desired or required. The minimum prescriptive thermal requirements of the IECC and ASHRAE 90.1 can be met by using the minimum insulation requirement or the U-factor alternative. Especially in the cases of preservation projects, insulation can typically only be added to the interior. This will inherently impact the temperature and relative humidity within the existing walls. The more insulation that is added, the greater impact there will be on the performance of the existing walls. As such, it is important to only add as much interior insulation as needed to meet the project goals and requirements. With this in mind, it is typically more prudent to use the U-factor alternative to demonstrate compliance with the IECC because this allows for the thermal resistance of the existing materials to be accounted for, thereby reducing the amount of insulation required by code. Additionally, in the case of existing mass masonry walls, the thermal performance goes beyond just the thermal resistance of the wall. Mass masonry walls add to energy efficiency due to their thermal mass. They can temporarily store and subsequently release heat due to their specific heat and overall weight which provides a higher heat capacity than framed walls. This phenomenon is known as the thermal lag effect and can help reduce heating and cooling costs especially in the spring, summer, and fall. The IECC indirectly accounts for this by allowing for a higher U-factor for mass walls as compared to framed walls. However, as insulation is added to the interior, the benefit of the daily thermal buffering resulting from the thermal lag effect is diminished as a thermal break is created between the interior space and the masonry wall.

Evaluating Existing Conditions. One of the first steps in evaluating improvements in thermal performance is determining the thermal performance of the existing wall as the baseline. The existing U-factor should be determined either through calculations or field measurements. ASHRAE Fundamentals (ASHRAE 2005) and ASHRAE 90.1 Normative Appendix A (ASHRAE 2016) offer procedures for theoretically calculating U-factors of envelope assemblies based on published data. To calculate the U-factor, the existing material types and thicknesses will need to be determined in the field. When the components of the wall assembly cannot be verified, the approximate in-situ U-factor of an existing wall can be determined using ASTM C1155 (ASTM 2013) and requires the installation of heat flux sensors and thermocouples. For this procedure, the building elevation and exposures, ambient conditions, and time of year should be taken into consideration when installing the sensors and analyzing the data, specifically the impacts of solar radiation should be minimized while the temperature difference between the interior and exterior should be maximized. Once the existing U-factor is known, the need for additional insulation can be calculated

Evaluation of Retrofit Strategies. When evaluating the impacts of additional insulation, several parameters should be considered. As noted with respect to addressing air leakage, determining many of these parameters will require transient hygrothermal analysis. The parameters that must be addressed include the following:

- <u>Amount of insulation</u>: What is the assembly U-factor of the existing wall? What is the goal U-factor for the modified walls? Has this goal been coordinated with the mechanical design, energy model, code requirements, and any other project requirements? Based on the type of insulation, to what thickness does the required R-value equate?
- <u>Location of insulation</u>: Is exterior insulation an option? Is placing the insulation on the interior the best option when considering all project goals, including the long-term performance of the existing materials? If insulation is to be placed on the interior, will it be installed continuously behind new framing for new interior finishes or will space limitations require it to be installed within the framing? Should some insulation be installed at both locations?
- <u>Permeance of insulation</u>: Based on the hygrothermal analysis, would a more permeable insulation such as an unfaced mineral wool or fiberglass batts be required to mitigate the moisture within the existing wall? Can the existing wall function with an impermeable insulation such as extruded polystyrene (XPS), expanded polystyrene (EPS), or closed cell spray polyurethane foam? Does the insulation need a facer and should the facer be faced towards the interior or the exterior? What should the permeance of the facer be?

- Moisture Sensitivity: Based on the location and exposure of the insulation, does the insulation need to be moisture resistant? If so, will the moisture resistance need to be with respect to dimensional stability, biological growth resistance, decreased thermal performance, or all three? What are the impacts if the insulation takes on moisture and changes dimension or suffers a reduction in the R-value?
- Fire Safety: Does the insulation need to be non-combustible or have a specific flame spread or smoke index? If the insulation is a foam plastic, will NFPA 285 requirements apply? Will a thermal separation between the insulation and the interior space be required?
- Added Value: What will be the cost to install the insulation and is that offset by the anticipated energy cost savings based on the addition of the insulation? Is there a negative impact on the long-term durability of the existing materials that would reduce the useful service life of the building or individual systems within the building envelope? Is value lost as a result of the decrease in usable interior space due to added insulation?

Just as with the addition of an air barrier, it is critical to compare the hygrothermal performance of the existing wall assembly to the hygrothermal performance of the newly insulated wall assembly. A series of transient hygrothermal models will be required for this assessment. For mass masonry walls, ASTM E 3069 (ASTM 2017) methods should be used for the assessment. Modified versions of these methods can be used with engineering judgement for other wall types. The approach described previously for evaluating the impacts of reducing the air leakage should be simultaneously used to evaluate the impacts of adding insulation. The hygrothermal performance of the existing wall should be carefully compared to the performance of the proposed assembly accounting for any additional insulation.

The results of the hygrothermal analysis should be evaluated for various performance factors. The addition of insulation on the interior will decrease the temperatures of exterior cladding or finishes, which could be problematic. For masonry walls, the addition of interior insulation will reduce the winter-time temperatures of the existing masonry, which increases the risk for additional freeze-thaw cycles. The addition of insulation, particularly when installed on the interior, may result in portions of the existing wall approaching the dew point temperature. Depending on the permeance of the insulation, the added insulation may cause additional moisture to accumulate within the existing wall materials. If this occurs, the humidity may approach levels that create a potential for condensation where it cannot be controlled or create conditions for biological growth and corrosion of embedded metal elements. The moisture sensitivity of the insulation should also be considered, and measures may be required to mitigate water infiltration or vapor diffusion through the exterior cladding.

Improving Thermal Performance of Roof Assemblies

Code Compliance and Project Goals. Similar to the walls, both IECC and ASHRAE 90.1 (ASHRAE 2016) allow for the prescriptive minimum thermal performance to be met for roof assemblies using either the minimum insulation requirements or the U-factor alternative. Both also specify the requirements based upon if there is an attic (typical of steep slope roofs) or if the insulation is entirely above the roof deck (typical of low-slope roofs). Aside from the thermal performance, it is important to note that Section 1203 of the International Building Code (IBC) requires ventilation for attics and enclosed rafter spaces. This requirement is founded in hygrothermal performance, and ventilation is typically required at the underside of the roof deck for the performance of the roof.

In addition to bringing the attics and roofs up to code, it is common for project programing requirements to result in the attic or portions of the attic becoming conditioned or partially conditioned space. Often mechanical equipment will be located within the attic, or the retrofit will include wet sprinkler systems which may require partial conditioning of the previously nonconditioned attic space. Moving the boundary of the building’s conditioned versus nonconditioned space means that the line of the building envelope and thermal insulation must move to include the newly conditioned space. This will often require adding insulation at the roof line, which creates enclosed rafter spaces, and knee walls constructed within the attic in lieu of insulation that was previously installed at the attic floor. Such alterations often impact the ventilation provisions for the attic space.

Evaluating Existing Conditions. Just as with improving the thermal performance of the walls, the U-factor or minimum insulation of the roof assembly, including the attic if present, needs to be determined. To do this, all the existing materials must be identified, and their thicknesses documented. Also, the existing ventilation and convective airflow patterns will need to be qualitatively determined. Ridge and soffit vents should be documented, and infrared, smoke pencils, and visual observations should be used to garner an understanding of the existing ventilation provisions of the attic and roof assembly. This step is critical as ventilation is typically designed into the existing attic space for a steep sloped roof, so any alterations will impact the original design intent and behavior of the space. ASTM Work Item WK54379, "Standard Guide for Evaluation, Rehabilitation, and Retrofit of Existing Steep Sloped Roof Assemblies," (ASTM 2017) outlines the procedures for assessing the exiting roof and attic assemblies, including an annex on the importance and role of ventilation.

The scope of the roof repairs and renovations will need to be determined early in the project planning phase as this will drive where insulation and air barrier are necessary and appropriate. A condition assessment of the roof covering, underlayment, insulation, deck, structural supports and drainage provisions should be conducted as the conditions of these elements can drive the ultimate scope of the roof and attic renovation. For low-slope roofs, the vertical clearance at the edges and extreme locations away from drains should be documented along with roof drain locations.

Evaluation of Retrofit Strategies. ASTM WK54379 (ASTM 2017) outlines the strategies needed for the initial field evaluation and hygrothermal modeling of steep slope roofs. Whenever the ambient interior conditions, air barrier, vapor retarders, or insulation schemes are altered, it is necessary to consider a wide range of parameters. Many of these parameters will need to be determined through comparing hygrothermal models of the existing assembly to the options for the proposed assembly. The following parameters will need to be considered:

- <u>Amount of Insulation</u>: The appropriate amount of insulation should be determined based upon the existing U-factor or insulation materials to remain as compared to the requirements of the applicable code, mechanical design, or other project requirements.
- <u>Type of Insulation</u>: Based upon the required additional R-value needed, the space available for added insulation, and the hygrothermal models, the appropriate type of insulation will need to be determined. Blown cellulous and fiberglass batts are typical for attic floor applications while XPS or polyisocyanurate would be typical for above deck applications.
- <u>Location of Insulation</u>: Considering the boundaries of conditioned versus non-conditioned or semi-conditioned space will dictate the line of the building's thermal envelope and continuous air barrier. The insulation may need to be located at the attic floor if the attic is to remain unconditioned. However, if the attic space will become conditioned or semi-conditioned space, the insulation will need to be located at the roof line, either above the roof deck or below the roof deck or a combination of the two locations. When insulation is added to the underside of the roof deck or underside of the rafters, provisions for ventilating the enclosed rafter spaces or otherwise mitigating moisture accumulation within the rafter spaces is critical in maintaining the integrity of the roof deck, especially in the cases of wood roof decks. As a caution, incorporation of insulation at the underside of the roof deck is most likely to lead to long-term issues when not detailed or constructed properly. In cases where soffit and ridge vents are not incorporated into the existing building design, or may be incorporated but in locations that are not ideal for ventilating between each roof rafter, insulating the underside of the roof deck may not be a feasible option without significant alterations to the overall roof system. If only portions of the attic space are to become conditioned or semi-conditioned space, knee walls will need to be constructed and the buildings thermal envelope will need to follow the attic floor, the knee walls, and the roof line.
- <u>Air Barrier Location and Type</u>: If the roof and attic was previously uninsulated or minimally insulated or unconditioned and it will become conditioned or fully insulated, the critical concern is related to the roof deck approaching dew point temperature. When heat losses are minimized through the addition of insulation at the attic floor, which is ideal from an energy consumption standpoint, the temperature of the roof deck

during winter months will be colder than the non-insulated scenario. This can create condensation on the underside of the roof deck or moisture accumulation that leads to structural decay of wood roof decks if the migration of interior conditioned air and water vapor are not properly managed through the inclusion of an air and/or vapor barrier and adequate attic ventilation. The insulations typically used at the attic floors are highly air and vapor permeable. The hygrothermal analysis should account for anticipated air movements based on the field evaluation. The models should be used to determine the appropriate location and vapor permeance of any necessary air barriers.

- Ventilation Provisions: For steep slope roofs, whatever ventilation provisions were included in the hygrothermal models should be provided in the field. If the natural ventilation patterns from the soffits to the ridge vents are interrupted, mechanical ventilation provisions may need to be included in the renovations.
- Drainage Provisions: For steep sloped roofs, the existing gutters and downspouts should be inspected to ensure they are in good working order and are not exposing the attic or the walls to excessive bulk water. For low slope roofs, it should be ensured that both primary and secondary drainage provisions are provided. When additional insulation is added above the roof deck this may require scuppers to be raised or even additional roof drains to be added if the vertical clearance away from the existing drains cannot accommodate the added thickness of the total roof overburden.

Improving Thermal Performance of Fenestration Assemblies

Code Compliance and Project Goals. When replacing fenestration assemblies, the new assemblies must meet the requirements of the IECC. Alterations or repairs to existing fenestration assemblies may be exempt from meeting code provided the changes to the existing assemblies do not increase the overall energy consumption of the building. Determining which fenestration assemblies require improvements, along with the scope of those improvements, should be developed to meet the project goals. An understanding of the existing conditions should also be evaluated when determining the scope of work to ensure the improvement effort addresses the goals of the project. For example, if an existing window is performing poorly due to convective air movement within a wall cavity, simply installing a new window will not mitigate the original concern. Other alterations, such as installation of cavity closures to prevent air movement, may also be required to satisfy the project goals. The aesthetics of the repairs or replacement should also factor into the repair approach to ensure any changes fit the architectural intent of the building design.

Following the prescriptive compliance path, the U-factor, SHGC, and air leakage requirements are the key elements to meeting code requirements. The U-factor and SHGC consider thermal performance via conduction and radiation, while minimizing air leakage will improve thermal performance via convection. The U-factor and SHGC are determined based on the framing elements and glazing components. The U-factor is a measure of the heat flow through the fenestration assembly, so the lower the U-factor, the greater the thermal performance of the assembly. The SHGC is a ratio of the solar radiation passing through the assembly versus the incident solar radiation. Depending on the climate zone, a higher or lower SHGC may be beneficial for the overall building design. Maximum air leakage rates for various types of fenestration must also be met in order to meet code requirements.

Evaluating Existing Conditions. As previously noted, evaluating the existing conditions is a critical component to developing a plan to improve the thermal performance of fenestration assemblies. There are standardized tests and computer modeling and simulation tools that can be used to evaluate the thermal performance and air leakage of existing fenestration assemblies. Once the baseline performance is known, repair strategies can be developed that will provide the most value to the project. To meet thermal performance requirements, only the glazing may need to be replaced. To meet air leakage requirements, only the re-sealing and re-gasketing the existing framing and glazing components may be necessary. Without this initial evaluation, repair strategies may be more costly and intrusive than is needed to meet the project goals or code requirements.

Determination of the existing U-factor and SHGC can be done through testing or computer simulation. For the most accurate results, testing would require the fenestration component to be removed and delivered to an accredited testing laboratory that can perform testing in accordance with NFRC 102 or ASTM C1199 (U-factors) and NFRC 201 (SHGC). There are a limited number of laboratories within the United States that can perform these tests. Alternately, the fenestration can be modeled using NFRC approved software. In order for these models to be accurate, detailed shop drawings, including the geometry and configuration of the framing components and material properties as well as the glazing components, must be known. There are also simplified calculations to determine the approximate U-factor using an area weighted method and published data from ASHRAE Fundamentals (ASHRAE 2005).

Existing air leakage can only be determined through field testing. ASTM Standard E783 (ASTM 2010) provides the procedures for testing air leakage through doors and windows. The applied pressure differential and corresponding allowable air leakage rates are dependent on the fenestration type. The IECC provides the maximum allowable air leakage rates, but references various AAMA and NFRC standards for determination of the applicable pressure differential during testing.

While not specifically required by code, the presence of condensation on the interior surfaces of fenestration assemblies, or within glazing units, can create an aesthetically unpleasing sight, cause damage to interior finishes and diminish the thermal performance of the assembly. Condensation can be identified through visual observation, but more detailed analysis can be performed based on knowledge of the interior and exterior climates and surface temperatures of the fenestration frame. Utilization of data logging instrumentation and performing a dew point analysis can determine whether condensation is likely to occur, and under what conditions, on a window frame. The condensation potential of sealed insulated glazing units can also be determined with ASTM E576 (ASTM 2010).

Evaluation of Retrofit Strategies. There are many creative solutions that can be implemented to improve the thermal performance of fenestration assemblies. Generally, replacing the unit in its entirety can provide the most energy efficient solution, but may not add the most value to the project or maintain the historical nature of the building. When evaluating new fenestration frames, consideration should be given to the framing material and configuration, the frame's placement within the existing wall assembly, and the integration of the frame with the adjacent air barrier system. Different material types have inherently different thermal resistance, and the frame geometry can also reduce heat transfer, especially with the incorporation of a thermal break. Whether replacing the entire unit or just the glazing, the type and number of glass layers, type and placement of coatings or films, and incorporation of gas fills into an insulated glazing system should be evaluated to provide a glazing assembly that meets the project needs. Should the glazing and framing remain in place, films and coatings can be applied to the exposed surfaces of the glass that can reduce heat transfer of the glass, but would not improve the performance of the surrounding framing. Such coatings may alter the appearance of the glass and should be evaluated to determine their long-term durability. Shading devices could be used to provide some thermal resistance to the assembly or block solar heat gain in warmer climates. Consideration could also be given to installing storm windows interior or exterior of the existing windows, although it may be difficult to integrate the storm windows with existing building components. If the intent of the storm windows is to preserve the existing windows, this alteration will change the aesthetics of the window, which should also be considered against the project goals. Storm windows should also be carefully designed so that condensation does not form between the existing window and storm window, or provisions should be included to properly manage such condensation.

To mitigate air leakage, the source of the air leakage must be determined to ensure it can be properly addressed. Air leakage through the fenestration assembly itself could be solved by simply resealing and re-gasketing the assembly. An understanding of the design of the fenestration is required to ensure internal drainage provisions are not inadvertently sealed during this process. Air leakage around the fenestration assembly could be addressed by installing cavity closures and properly integrating the fenestration with the adjacent air barrier. While the existing fenestration components remain in place for this repair approach, selective demolition would be required around the fenestration to uncover the perimeter integrations. New integrations should be carefully designed, as in older buildings a material specifically designed as an air barrier may not be present. Furthermore, many older buildings rely on convective air movement for natural ventilation and drying potential so incidental moisture does not accumulate within the assembly. Sealing off air movement around the fenestration may limit this drying and cause moisture related issues that can have negative impacts on building materials and occupant comfort. The incorporation of storm windows could also be evaluated, provided the considerations discussed previously are vetted.

As condensation formation is a result of surface temperatures dropping below the dew point, without replacing the fenestration completely, retrofit strategies should aim to increase the interior surface temperature of the fenestration frame. This can be done by adding a mechanical wash that applies heated air over the surface of the frame, incorporating electrical heating elements that directly heat the frame, or by altering interior temperature settings. Each of these approaches should be evaluated to determine if the increase in energy consumption balances the cost of simply replacing the fenestration. There would also be aesthetic considerations for adding additional components to and around the fenestration. In altering the interior controls, occupant comfort should be held paramount when determining the set points for the mechanical system. Some spaces may have special requirements for temperature or relative humidity that cannot be adjusted. Making a space too warm or too dry to prevent condensation could also make the space uncomfortable for building occupants.

Addressing Bulk Water Infiltration

Code Compliance and Project Goals. While bulk water infiltration is not specifically mentioned in the IECC, many retrofit and repair projects need to address water infiltration as part of the scope, and water infiltration can have a direct impact on the hygrothermal performance and the energy efficiency of the building. Excessive water infiltration can introduce additional moisture loads on the interior of the building that must be managed by the mechanical system and can reduce the thermal resistance of materials comprising the building envelope. Most importantly, damage and deterioration of building materials can compromise the structural integrity of the building and lead to biological growth that is hazardous for building occupants. Bulk water management should always be included in the project goals for any retrofit project.

Evaluating Existing Conditions. Unless the source of bulk water infiltration is obvious, evaluation of the existing conditions to determine the source of water infiltration should be undertaken prior to proposing potential repair options. Guidance for such an evaluation is provided in ASTM E2128 (ASTM 2017) for wall assemblies, ASTM E1105 (ASTM 2015) for fenestration subjected to air pressure differentials, and AAMA 501.2 (AAMA 2015) for fenestration without an air pressure differential. Low-slope roof assemblies can be evaluated using ASTM D7053 (ASTM 2017). Non-standardized diagnostic testing can also be performed in order to isolate areas and determine pathways for water infiltration.

Evaluation of Retrofit Strategies. Based on the findings of the initial evaluation, retrofit strategies should aim to mitigate the root cause of the bulk water infiltration. Ideally, the repairs would perform over the life of the building and would not require continual maintenance, which only adds cost to the operating budget for the building. Repair strategies should be considered simultaneously with proposed energy efficient upgrades. Depending on the repair, the incremental value added to the project for increasing building performance could be coupled with addressing bulk water issue. For example, repair strategies for systematic failures of weatherproofing membranes could include incorporation of additional cavity insulation and new cladding elements that improve the thermal and hygrothermal performance of the wall, if done properly.

For each unique building envelope component, repairs should be considered based on the existing conditions and preservation of the existing component. For wall assemblies, this would include understanding the method of water management to ensure alterations to the existing conditions do not impact the intended behavior. Repair approaches will vary based on whether the wall manages water through internal drainage systems, barrier systems, or mass masonry walls. For fenestration assemblies, existing integral drainage channels and perimeter flashings should be understood so that repairs do not trap water within existing assemblies that are intended to have free drainage.

CONCLUSION

Each existing building is unique, and retrofit strategies should be evaluated as such. Beyond the observable differences such as location, construction type, and material properties, the program requirements for buildings will vary based on the Owner's needs. The desired energy improvements should be clearly defined before any design is undertaken such that all design decisions can be made with the end goal in mind. Applicable code requirements and compliance paths, as well as supplemental standards and guidelines, should be outlined for the project team. Understanding the project goals may guide the compliance path to ensure the retrofit meets both code and project requirements. An evaluation of the existing conditions is critical to ensuring any modifications do not have negative impacts on the building performance and create issues that were non-existent prior to any repairs.

The retrofit strategies should also be evaluated to ensure they add value to the project. The definition of "value" will differ depending on the project goals and Owner's desires for the building, which is why it is important for designers and Owners to discuss these topics before any design work is undertaken. Added value is typically a function of associated cost, but depending on the project, more value may be placed on historic preservation techniques or other factors.

The impact of the repairs must also be considered when evaluating retrofit strategies. Repairs that alter the thermal and moisture behavior of the wall or roof assembly must be evaluated from a hygrothermal standpoint to verify there is not a negative impact on existing building components. Visual changes to the building should aim to be seamless with the architectural intent of the building to limit the aesthetic impact of the repairs. For historical structures, any alterations should be consistent with the historic nature of the building; input from local or state historic preservation offices may be required to approve proposed retrofits. The impact of the retrofit project on the building occupants must also be considered during the construction phase and post-occupancy. Repairs may need to be executed in a phased approach to limit disruptions. The design should also be developed with occupant comfort in mind, to ensure the retrofit addresses the end users' needs for the building space.

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