DYNAMIC EXTERIOR WALL SYSTEMS FOR SOLID MASONRY WALLS IN HUMIDIFIED BUILDINGS

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ABSTRACT

The challenges of "modernizing" solid masonry buildings are fairly well understood for typical buildings, but less so for humidified buildings, especially those in cold climates. The conversion of existing, often historically-significant buildings into climate controlled museum spaces is a fairly common theme in renovation projects. Unfortunately, failures in these types of buildings due to inappropriate treatment of the exterior walls is also common, and can have severe consequences for the operation of the building as well as its long-term durability.

While "bare" masonry walls may be sufficient for non-humidified spaces such as offices and residential buildings, additional measures are necessary to control both heat and moisture migration through masonry walls in humidified buildings. In museum spaces, the treatment of exterior walls must also take into account their use as hanging walls for artwork, displays and other exhibits. Without adequate thermal and moisture control, wall hangings may experience significant localized temperature and moisture gradients even though the ambient interior conditions are held stable. From a preservation standpoint, it is these gradients, rather than specific temperature and relative humidity settings, that contribute to degradation of artwork and artifacts.

This paper discusses the unique challenges of renovating masonry walls for humidified buildings, including considerations for controlling condensation and preventing fluctuating conditions on the wall surface, without leading to accelerated freeze-thaw damage or deterioration in the existing masonry. Specialized "dynamic wall systems" that couple the building enclosure with the mechanical system as a means of thermal and moisture control will be discussed, and practical examples of the implementation of these systems will be presented.

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INTRODUCTION

Museums and archives/art storage facilities are unique buildings for many reasons, the most notable being that the value of the building contents and collections often exceeds the value of the building itself. Consequently, these buildings require extreme care in both their design and construction, especially with respect to the control of heat, air, and moisture migration.

Moisture-related problems in high humidity buildings tend to be much more severe than those in more typical buildings such as offices and residential spaces (O'Brien and Patel, 2010). The most common problems associated with museums include condensation on interior surfaces, condensation in concealed locations within walls/roofs, and inability to maintain desired interior set points (either in terms of failure to meet target levels or failure to maintain those levels consistently). These problems are more severe in colder climates, such as the northeastern United States, but the typical humidity levels in museum buildings make the moisture-related problems plausible in any climate where exterior temperatures fall below 10ºC (50ºF) – the majority of North America.

Designing a new museum building is challenging, but an even greater challenge lies in converting an existing building into a museum space. Existing constraints in renovation projects often complicate wall design and detailing conditions that could otherwise be simply resolved in new building design. The special case of converting a solid masonry-walled structure into a museum brings further challenges, as simply adding insulation and vapor control layers can actually lead to more problems than they solve. This paper reviews the challenges of maintaining museum environments in solid masonry buildings and presents effective solutions based on the authors' experience.

THE MUSEUM ENVIRONMENT

Museums and archives generally have strict requirements for interior temperature and relative humidity (RH) control. A museum environment of 21.1ºC (70°F) / 50% RH is a commonly-accepted standard, but these set point recommendations being based more on anecdotes than on rigorous testing or evaluation. Museum conservators in England found that paintings hidden in slate quarry caves during World War II experienced much slower degradation than when on display in the British Museum. The conditions in those caves, approximately 17.2ºC (63°F) and 58% RH and nearly constant, were loosely rounded to 15.5ºC (60°F) and 60% RH and subsequently considered the optimum museum environment for paintings. To account for occupant comfort and variability in collections, conservators established the ideal range for museums and libraries at 15.5 to 23.9ºC (60 to 75˚F) and 50 to 65% RH. Subsequently, in 1978, Garry Thomson stated in *The Museum Environment* (Thomson 1978) that "modern-day mechanical systems are capable of maintaining a year-round environment of 21.1º±1.1ºC (70˚±2˚F), 50% ±5% RH". Although Thomson does not state that these are ideal storage conditions for artwork, etc., those numbers and that publication have for years been considered the "museum standard". While some individuals (Wood, 2006) and institutions (Mecklenburg, et. al., 2004) have put considerable effort into redefining the museum environment based on scientific research, they are working against considerable inertia given that "21.1/50" has been so widely accepted for so long.

Despite the emphasis on specific set points, for the majority of common collections, consistency in the interior conditions is often more important than specific set points. Although all materials have different ideal storage conditions, limiting fluctuations in temperature and relative humidity helps to reduce mechanical stresses in the materials due to thermal- and moisture-related expansion and contraction (Mecklenburg and Tumosa, 1999). Natural materials such as paper, leather, and wood expand and contract as their temperature and moisture contents change. Large or sudden swings in these levels can induce stresses in the materials, leading to premature degradation. Although in theory it may be possible to maintain a museum in a cold climate at a constant 30% RH to reduce condensation potential, such low humidity levels would require highly specialized equipment to maintain during summer months. Despite its impact on condensation risk, maintaining year-round 50% RH in museum environments often ends up being a good balance between the need to humidify during the winter and dehumidify during the summer. In some instances, depending on the collection in question as well as the approval of the curator(s), some seasonal variation in humidity levels may be introduced to reduce the risk of moisture-related damage to the building. Often referred to as "ramping", this strategy involves a gradual shift from a reduced winter set point to the more typical 50% level during the summer. Changes in RH are often carried out over a period of weeks or months to avoid "shocking" the collection with an abrupt change in moisture conditions.

An additional feature of most museums that complicates building enclosure design is that they are often maintained at a positive interior air pressure with respect to the exterior. The reason for this is simple contaminant– positive pressure prevents outside air from entering museum spaces, whether through the enclosure itself or through doors and other openings. While effective in this regard, the undesirable aspect of positive pressure is that warm, humid interior air is being constantly forced out through the enclosure where it poses a significant condensation risk. In addition to carrying moisture, moving air (in the form of air leakage through the enclosure) also carries heat. If air leakage is severe enough, heat and moisture flows to or from the interior can cause variations in the interior temperature and RH. Although a daily swing of 10% RH due to cold, dry air infiltration may not be problematic in an office building, such a swing could be damaging to the museum contents and can compromise the museum's reputation – the ability to maintain interior environmental conditions within tight tolerances is often a prerequisite to borrowing collections from other museums.

SOLID MASONRY CHALLENGES

Controlling heat, air, and moisture in modern lightweight construction is accomplished through the use of dedicated control layers – insulation, air barriers, vapor retarders and weather barriers. These layers control the elements, preventing the flow of heat, air, vapor and water through walls, roofs, and other exterior components. By arranging these materials in the proper sequence across a wall section, good separation can be achieved between the interior and exterior components in the walls – more specifically, moisture sensitive components can be kept in the "dry" zone while cladding and other more durable materials are kept in the "wet" zone.

With traditional solid masonry construction, the walls themselves from both the structure and the enclosure of the building, with no true separation between “dry” and “wet” zones. Rather than acting as barriers to heat, air, and moisture, masonry walls act more like buffers, allowing for slow heating, cooling, wetting, and drying in response to changing environmental conditions (Figure 1).

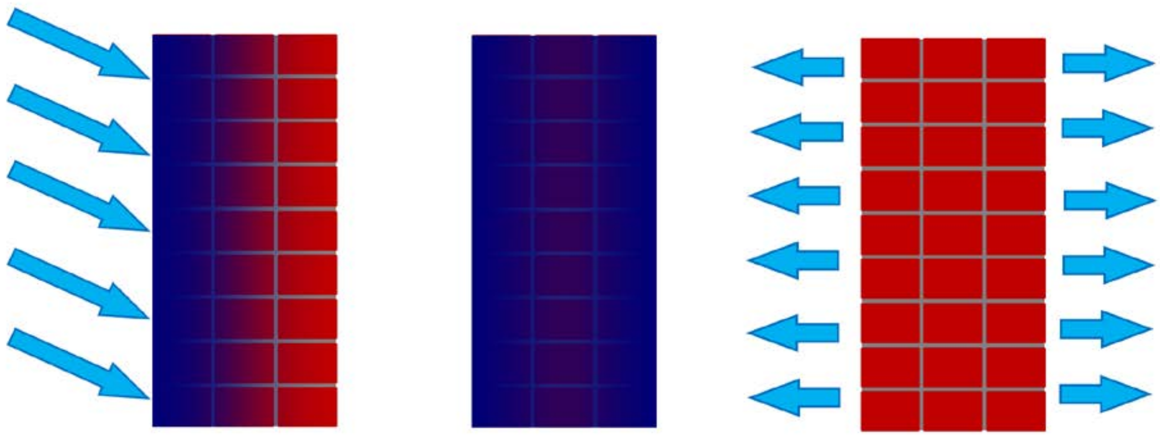

Figure 1 – Wetting, redistribution of moisture, and drying of a solid masonry wall system.

While uninsulated solid masonry buildings have been in use for centuries and have clearly passed the test of time in most respects, subjecting these walls to high interior humidity levels can result in a range of problems, including condensation on interior surfaces, concealed moisture damage within the masonry, or visible damage or efflorescence/staining on exterior surfaces. The risk of wall damage depends on the type and condition of the masonry. Hard-fired, exterior brick that can withstand direct exposure to rain and freezing temperatures is unlikely to be affected by increased interior humidity levels. Conversely, relatively weak materials such as face-bedded sandstone (which is prone to failure even in non-humidified buildings; Photo 1) can be significantly affected by increased interior moisture levels.

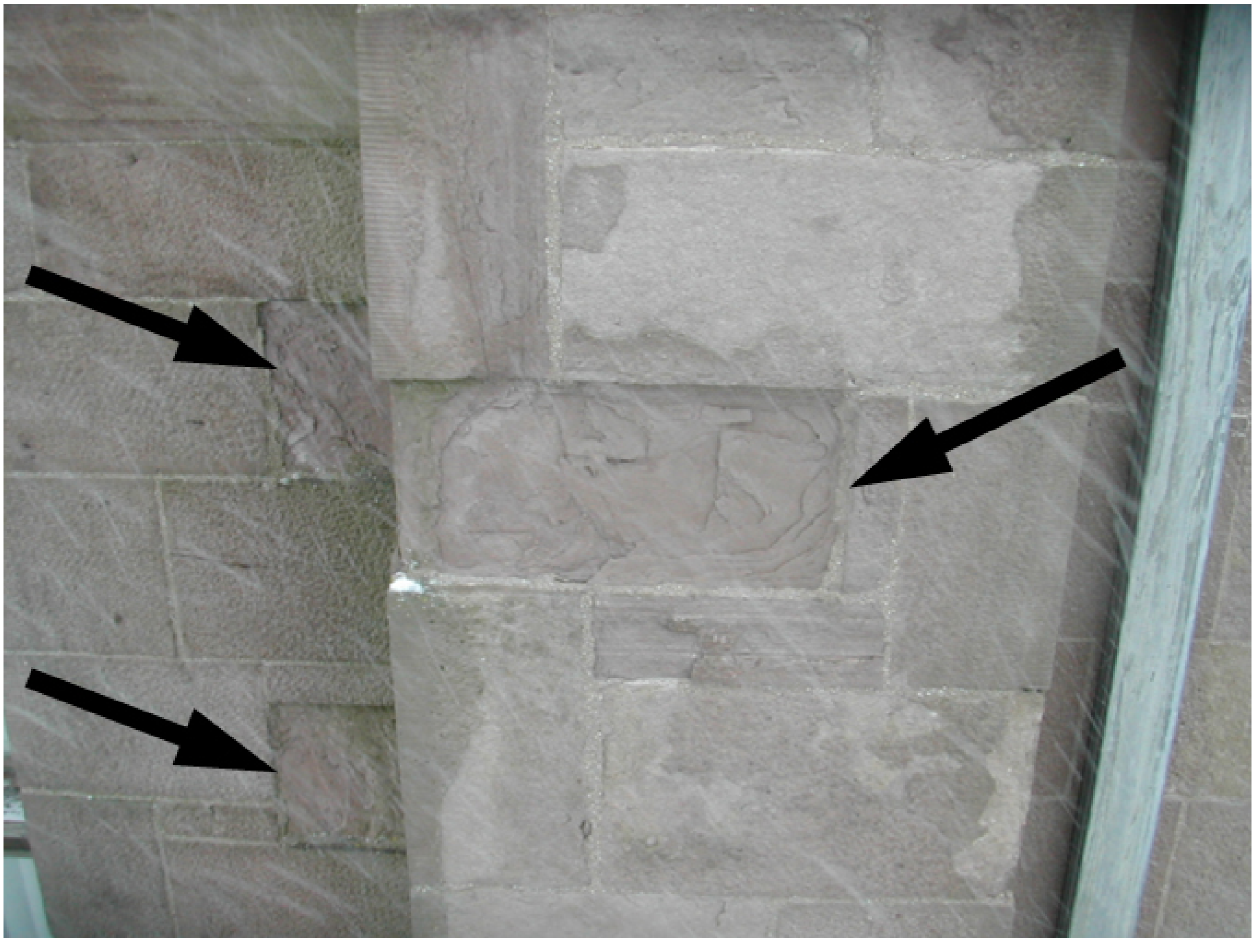

Photo 1 – Typical deterioration pattern for face-bedded sandstone.

While the seemingly obvious strategy of adding insulation and air/vapor barriers to solid masonry walls to accommodate higher interior humidity levels is simple in concept, in practice those materials can end up causing more problems than they solve. Interfering with the ability of masonry walls to "breathe" and dry to the interior can lead to moisture retention within the masonry as well as interior finish materials (Photo 2). Adding interior insulation reduces heat flow into the masonry wall and subjects the interior portion of the wall to temperatures it has never been subjected to. With enough insulation, the interior portion of the masonry will experience freeze/thaw conditions.

Older (i.e., pre-1900) solid masonry walls used durable stone or more thoroughly fired brick as the exterior wythe due to the need for weathering resistance, and weaker, "common brick" for interior/backup wythes. "Common brick" had sufficient strength to support the wall but was less resistant to weathering. The use of common brick diminished as extruded terracotta block and concrete masonry units – both of which were more durable than common brick - became more popular as backup materials. The reduced durability of common brick was generally not a problem because the inner wythes were protected from extreme events by the outer wythes, and were warmed from the interior during cold weather due to the lack of interior insulation (i.e., inner wythes were exposed directly to the interior). With the addition of insulation and a vapor retarder, the retained moisture and freeze-thaw cycling discussed above can lead to accelerated freeze-thaw damage to wall materials, particularly materials like common brick that were never intended for exposure (Photo 3). Even if breathable insulations are used and vapor retarders omitted, some risk still exists since the elevated interior moisture levels in a museum space will eventually result in higher moisture contents in the masonry wall materials. In most cases, adding air/vapor-permeable insulation, such as fiberglass or mineral wool, to the interior of a masonry wall increases the risk of condensation on the back of the masonry, which is now kept colder by the insulation but may not be fully isolated from moist interior air.

Photo 2 – Moisture trapped on the outboard face of an interior vapor retarder installed over a solid masonry wall.

Photo 3 – insulation combined with a vapor retarder led to accelerated freeze-thaw damage to interior wythe of masonry in a solid brick wall.

In non-humidified buildings, with relatively durable wall materials, it may be possible to add some level of vapor permeable insulation without adverse effects. However, in museums the interior environment requires that a vapor retarder be installed in the exterior walls for condensation control, making the addition of any insulation potentially detrimental.

When considering the performance of solid masonry walls in museums, designers must keep in mind that due to the relatively low insulating value of the walls (a typical, 3-wythe brick masonry wall has an RSI-value of approximately RSI-0.5 (R-2.8)), anything hung on the exterior walls essentially becomes “coupled” to the wall performance. Since temperature drop across a layer in a wall assembly is proportional to the total thermal resistance of the layer compared to the total assembly resistance, adding a wood framed painting with a resistance of RSI-0.2 (R-1.1) means that over 25% of the temperature drop in the system will occur across the painting. This produces an effective drop in the surface temperature of the wall behind and around the painting (Figure 2).

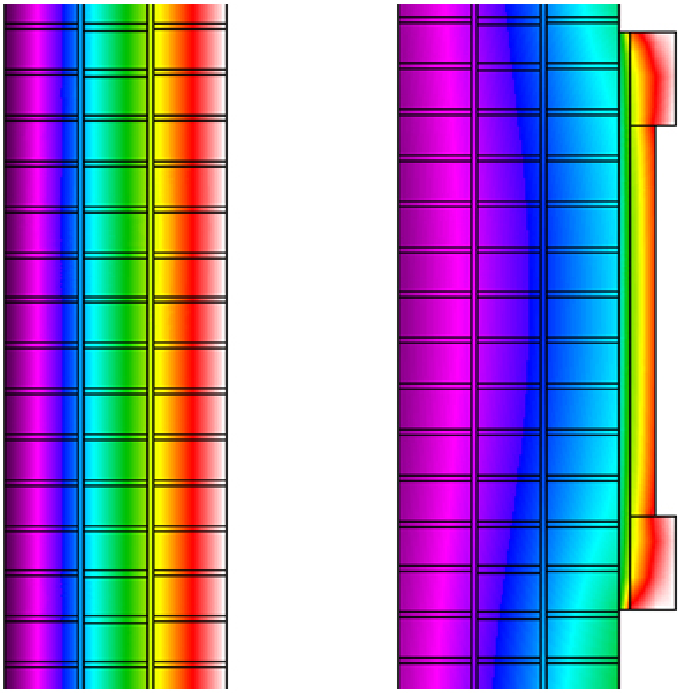

Figure 2 – Adding an interior hanging to a 3-wythe masonry wall produces a drop in the wall surface temperature behind and around the painting.

While the drop in temperature around wall hangings can be enough to cause condensation by itself (since the wall surfaces drop below the interior dew point), hangings such as thick oil paintings or anything with a plastic or glass facing also act as strong vapor retarders, increasing the risk of condensation and moisture accumulation on the walls regardless of their surface temperature (Photo 4). Even in the absence of condensation, the temperature drop across and moisture flows can produce localized fluctuations in temperature and RH levels that are not acceptable for the artwork being displayed. Shelving containing artifacts or other forms of storage or display will be subjected to similar conditions - they effectively become the wall's insulation and vapor retarder, creating temperature and vapor gradients across their thickness.

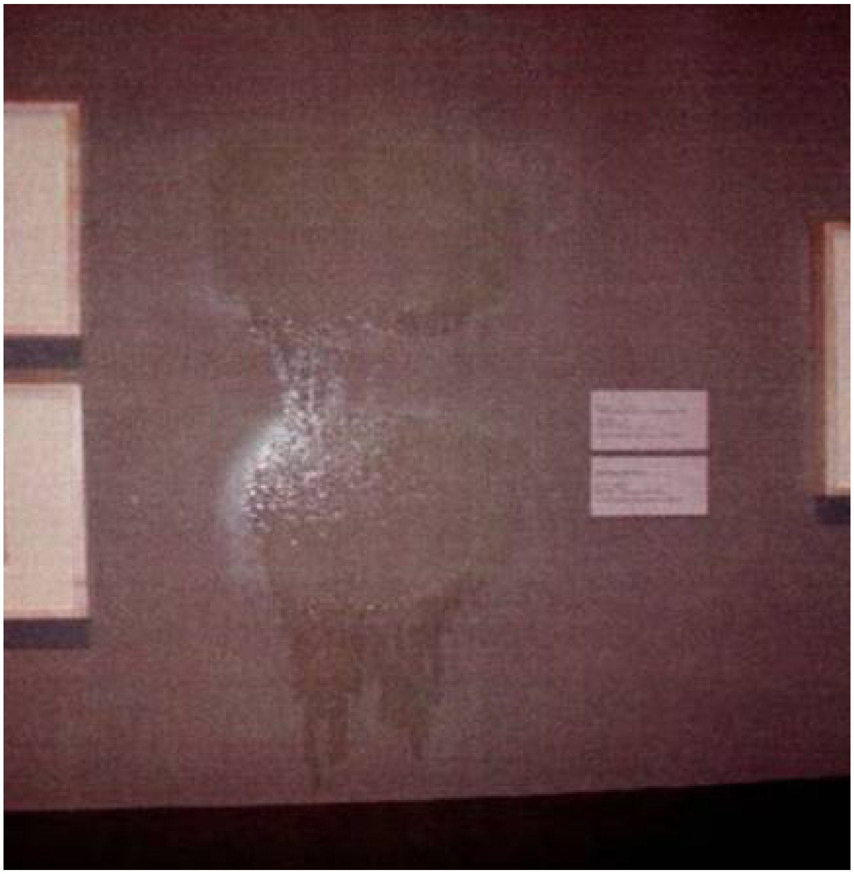

Photo 4 – Moisture accumulation on an exterior wall (plaster installed over 3-wythe brick masonry) behind hung artwork. Artwork has been removed in this photograph.

DYNAMIC WALL SYSTEMS

An ideal design for a masonry wall system in a museum should prevent condensation and moisture accumulation within the masonry while providing a stable environment for collections placed against the wall. This requires that the design control airflow and prevent moist air exfiltration, keep the interior masonry warm (both above the interior dew point and above freezing), and prevent damage to, or localized temperature and moisture gradients around, artwork that may be hung on the exterior walls. To accomplish all of these goals, an active system is necessary.

Design

The intent of a dynamic wall system for museums is to maintain temperature and moisture conditions in the masonry walls as close as possible to their previous states while allowing for the addition of interior humidification and positive air pressure. A wall system design that we have used successfully on multiple projects essentially turns the exterior walls into return air plenums that are integrated with the mechanical systems. The system is shown schematically in Figure 3.

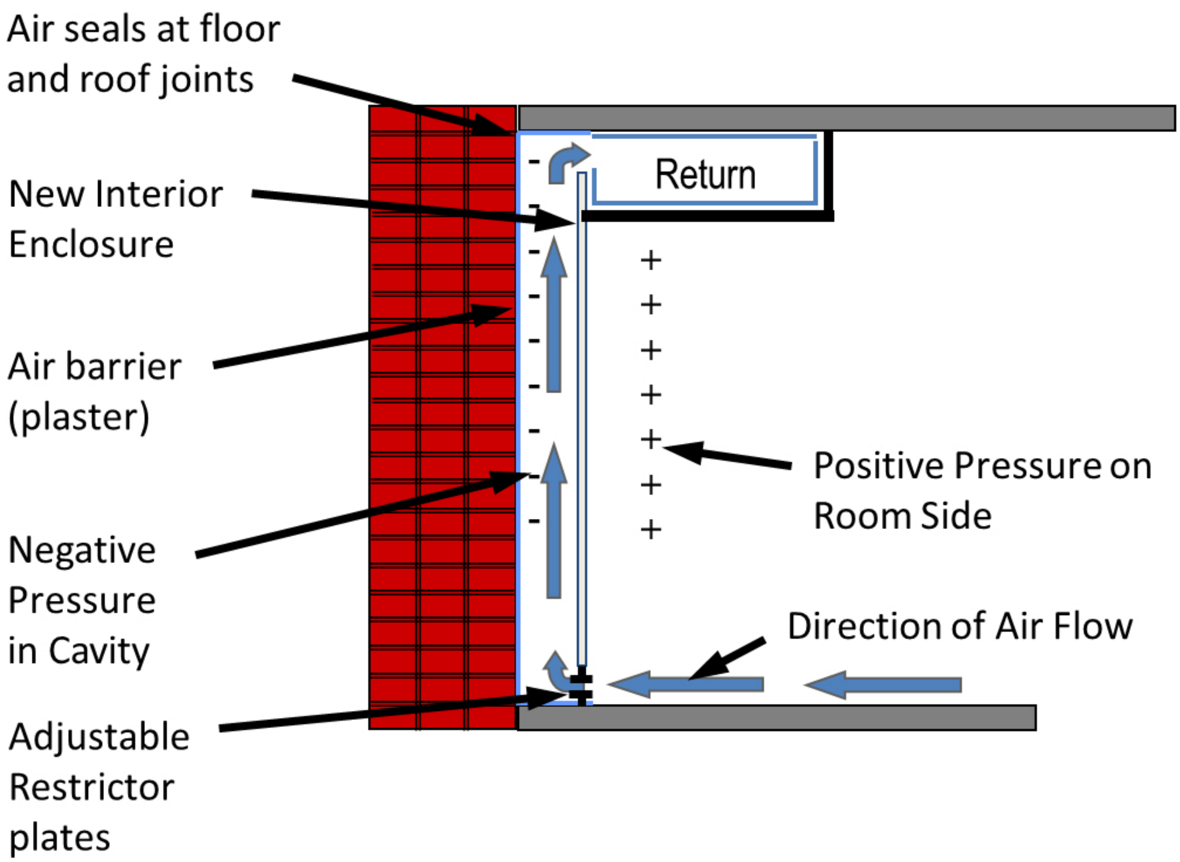

Figure 3 – Schematic of dynamic / ventilated wall system

The first component of the system is an air barrier installed over the existing masonry. The air barrier, which must be a vapor permeable material, limits airflow through the masonry wall and consequently limits air exchange between the exterior and interior. For masonry walls, a coat of cement plaster is often sufficient to improve the airtightness of the wall. Depending on the applicable code, plaster, as a noncombustible material, may be the only option since the vent space may qualify as a return air plenum, precluding the use of liquid applied air barriers or similar materials without the required flame spread/smoke development ratings. A vented space is then constructed inboard of the wall, with interior finishes facing the room/space. The entire vented space is connected to a return air plenum which feeds back to the mechanical system. The key component of the system is a calibrated or adjustable restrictor plate at the base of the wall which allows for negative pressure to be maintained in the interstitial wall cavity.

In typical operation, the mechanical system delivers conditioned air to the room space, maintaining the space at a positive pressure to prevent outside contaminants from entering.

Room air is drawn through the restrictor plates (as shown in Figure 3) which create a pressure drop. The plates are calibrated so that the pressure in the vent space is lower than the exterior ambient air pressure. In this arrangement, the room operates under positive pressure to prevent bulk air entry at doors, etc., but the vented wall cavity operated under negative pressure to prevent humid air exfiltration through the walls. This is the primary defense against moisture-related damage to the walls; the air barrier is installed to prevent air from leaving, but also to limit the amount of exterior air that enters the wall cavity that would need to be treated/conditioned. Air that does enter through the exterior walls is immediately drawn through the vent space and returned to the mechanical system, where it is treated and filtered before being delivered back to the space (eliminating any potential contaminants which may have entered the space via the airstream).

The movement of air across the interior of the masonry wall has the benefit of delivering more heat to the masonry than still air, thereby raising interior surface temperatures of the masonry. This can be critical in extremely cold climates where condensation on the masonry itself is a risk. The system design must take into account the velocity of the airstream as well as the height of the wall so that temperatures on the masonry are maintained above the dew point for the full height of the walls. Similarly, the moving airstream will evaporate moisture from the masonry walls and return it to the mechanical system for removal, providing redundancy in the event of excessive wetting of the masonry or incidental water leakage through the walls.

By removing heat and moisture loads from the exterior walls directly, before those loads can affect the space, the dynamic wall provides the additional benefit of maintaining relatively constant conditions on the interior finish wall. This wall can be used to hang paintings or other artwork since temperature and moisture conditions are nearly the same on both sides of the wall regardless of the temperature and moisture conditions in the masonry. To this end, a continuous sheet of plywood installed over the studs is useful for providing flexibility to the Owner for artwork display (i.e., they are not limited to hanging at stud locations only). The dynamic wall essentially de-couples the interior finishes and hangings from the masonry wall, allowing museums greater flexibility in planning their displays and providing a more stable microclimate around the artwork.

In cases where the existing masonry walls are constructed of suitably durable materials, it may be possible to add insulation to those walls and increase the overall thermal performance of the system. Due to the extreme variability in masonry properties, physical testing of masonry samples should always be performed as part of an insulation study to determine the properties of the actual materials in the wall. Hygrothermal analysis of the system needs to be performed to identify the appropriate insulation material and optimal thickness. In most cases, analysis will demonstrate that the insulation should be vapor permeable to prevent moisture accumulation in the masonry. Where insulation cannot be added without damaging the masonry, the thermal performance of the system is relatively poor compared to typical building code requirements for exterior walls. This inefficiency is, unfortunately, a necessary cost of utilizing a solid masonry building for a museum space.

Construction

The construction of dynamic wall systems can be relatively simple, in the case of an archive space with minimal detail, or extremely complex for larger buildings with varying wall constructions, wall heights, and window details.

The simplest case is that of an archive space with no windows and minimal aesthetic requirements. In this case, restrictor plates at the base of the wall can be left exposed (Photo 5) and ductwork at the top of the wall does not need to be concealed (Photo 6).

Photo 5 – Calibrated restrictor plate exposed at base of vented wall.

Photo 6 – Return air ductwork at top of wall system. Discrete duct "taps" connect top of wall return plenum to main return air ductwork.

In finished spaces with more focus on aesthetics, the same system is used but the primary components must be concealed behind finishes. Photo 7 shows an example of a finished gallery space in a solid masonry wall museum that utilizes the dynamic wall design. The close-up image shows all that is visible of the vented wall inlet - a narrow slot at the base of the wall below a piece of trim. The trim is removable for cleaning and maintenance purposes. In the same gallery, the return air ductwork for the vented walls, which comprise the vertical portions of the walls only, was concealed above the curved ceiling in a non-humidified attic space (Photo 8).

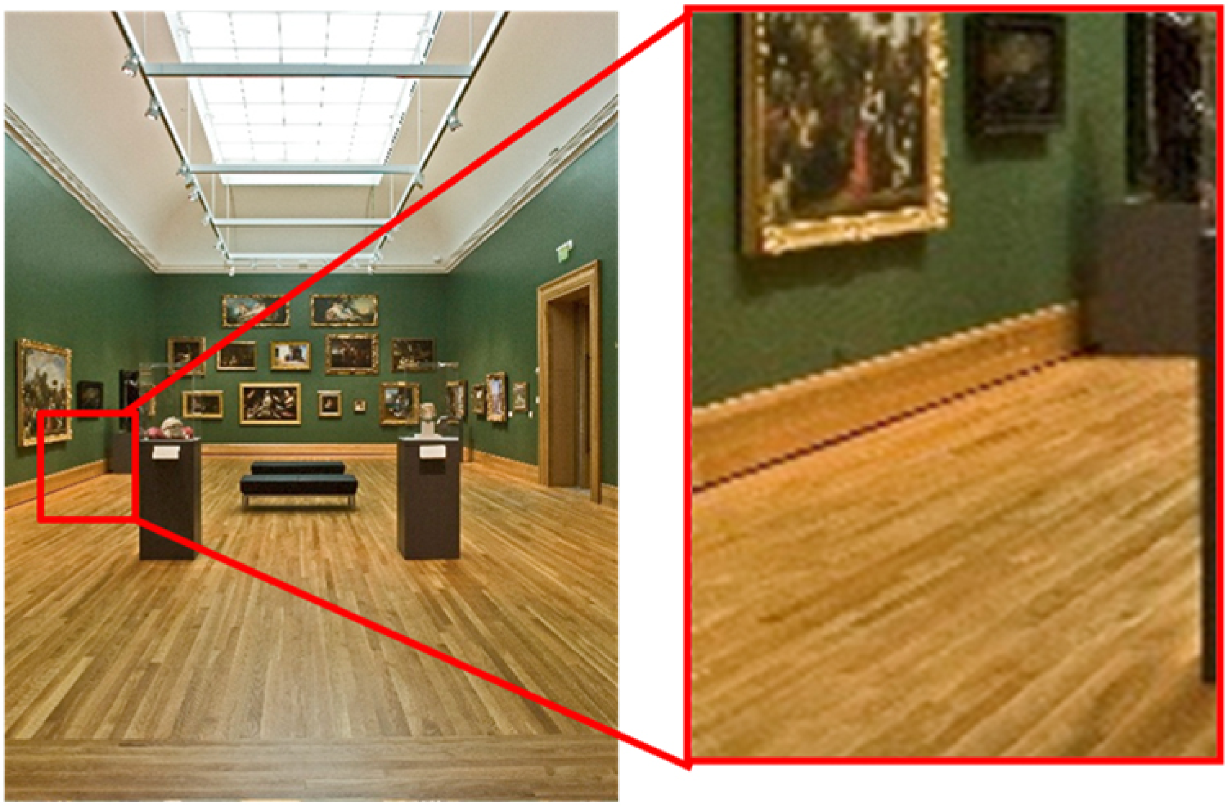

Photo 7 – Vented wall system installed in finished gallery space.

Photo 8 – Return air ductwork concealed in attic above curved ceiling.

Finished spaces with windows present an additional challenge for vented wall designs, as the windows create significant interruptions in the flow of air across the masonry walls. Failure to properly direct airflow around windows can lead to "dead spots" within the walls where condensation can develop, especially in colder climates where wall surface temperatures are critical. While computational fluid dynamics simulations can be used as a design tool, testing and evaluation of field-constructed mock-ups are essential as they provide a clear indication of performance.

Photo 9 shows the construction of a mockup window on a large museum project. The walls have been covered with a layer of cement plaster to act as the air barrier. In this example, two separate airflow paths are established so that flow around the window can be carefully balanced to maintain consistent air velocity and negative pressure in the vent space, and to eliminate "dead spots" where condensation may form during cold weather. Due to the complexity of the system and the difficulty (or potential inaccuracy) associated with computer modeling this type of condition, a field mockup proved more valuable and allowed the design and construction teams to evaluate, adjust, and finalize the window details in a relatively short amount of time.

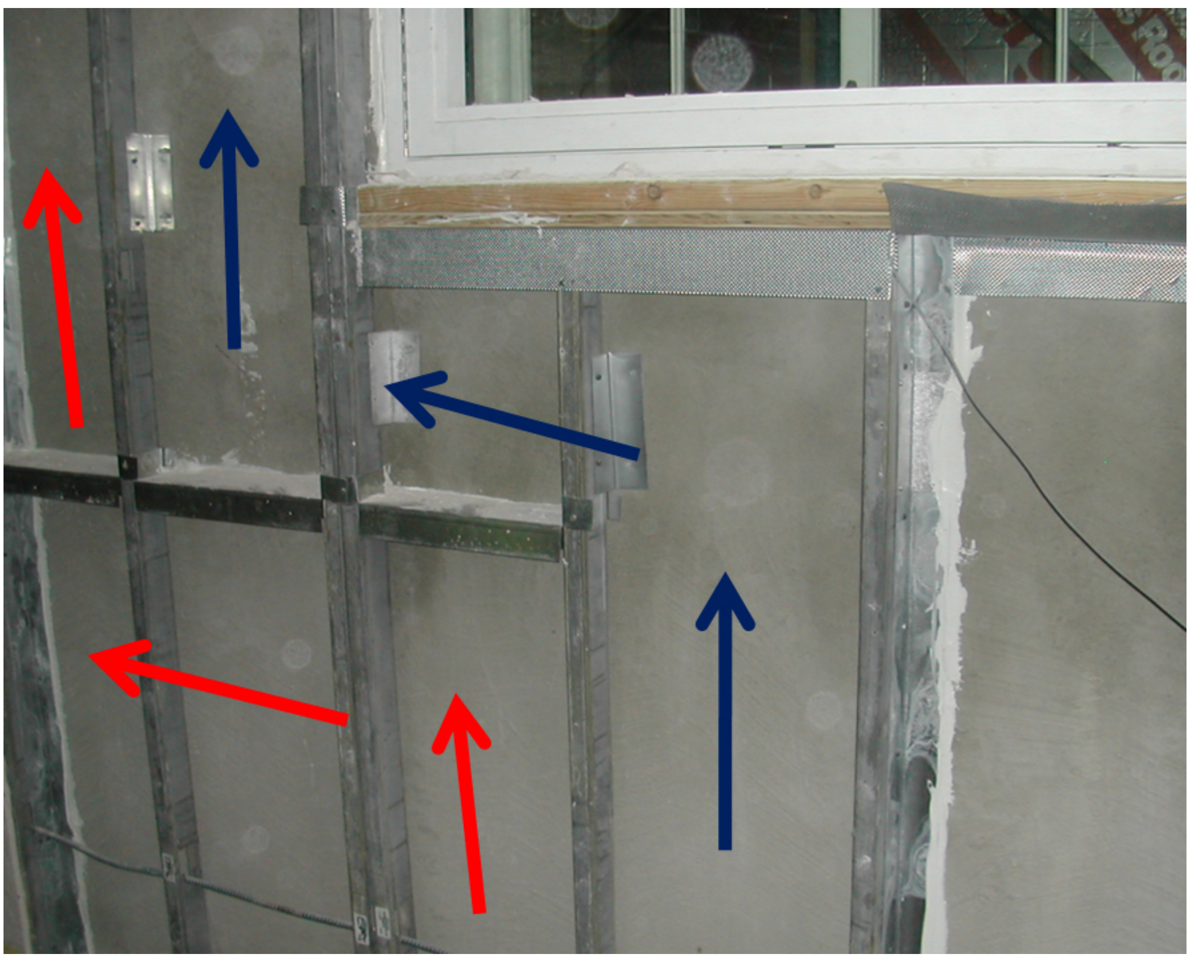

Photo 9 – Mockup of ventilation channels around a large window within a dynamic wall system.

Testing

As noted above, the complexity of ventilated wall systems often makes field testing a basic requirement for the project. Testing can range from simple airflow balancing to comprehensive pressure measurements and monitoring of temperature and RH levels within the system. Monitoring surface temperatures on the existing masonry during cold weather is one of the best indicators of performance since condensation risk can be directly evaluated. Monitoring of surface temperatures and ambient temperature/RH in the vented space can be useful in identifying “dead spots” in the system where additional airflow is needed, or where specific components to divert/deflect air within the vent space must be added.

CONCLUSIONS

Creating humidified environments within existing solid masonry buildings poses some unique design challenges, particularly when the building is intended for us as a museum or storage facility for art and artifacts. What would otherwise be an ideal environment for the masonry wall is inadequate for the preservation of artwork placed near or against the wall, and the ideal environment for a museum is conducive to accelerated deterioration of the masonry. A balance between the preservation of the building and its contents can be achieved with a dynamic wall system. This design approach essentially decouples the interior environment from the exterior wall by introducing a vented cavity that is coupled with the building’s mechanical system. This allows the wall to accommodate the stringent demands that humidification and pressurization places on the building enclosure while providing a safe, stable environment for the artwork in the building. When properly designed and implemented, dynamic walls serve the dual purpose of preserving and protecting the existing masonry and the building contents placed along its side.

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