THE EVOLUTION OF THE WEEP-HOLE

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ABSTRACT

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Uncontrolled water intrusion through the envelope is perhaps the most common and insidious threat to success of a building's performance and its structural integrity. Introducing weep-holes into wall construction is one method meant to mitigate issues associated with dampness, by providing an outlet for drainage at the base of the wall cavity. The use of these small, interstitial elements is crucial to the long-term welfare of our building stock and also indirectly, to the health and well-being of building inhabitants. A major campaign to prevent dampness, stimulated by public health concerns in America and abroad during the 19th century, led to widespread development and use of the brick cavity wall in building construction. The hollow space within these double-wythe walls acted as an additional layer of weather protection and as a thermal barrier, but was also a new location where water could collect. This research traces the development of early cavity wall construction methods and theories employed in response to dampness problems during the late 19th century, and investigates concepts behind the rise in application of the weep-hole during the early 20th century.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

INTRODUCTION

Weep-holes, interstitial drainage elements within the building envelope fabric, and their effectiveness emerge as a frequent topic of discussion within the field of construction defects consulting regarding appropriate drainage methods used to prevent moisture build-up within the building envelope. These small, obscure voids are often seen in various types of wall and window systems. Several technical sources that include the International Building Code, Association for Preservation Technology International (APT) bulletins, and construction drawings recommend or require the integration of weep-holes during construction, but rarely do these sources elaborate beyond simply stating that weep-holes should be used. These mysterious, terse references appeared to be fragments of a much grander idea that begged to be put into context.

The initial goal of this thesis was to trace the application of through-wall channels used in different types of envelope construction for the purpose of drainage. This proved to be more complex than originally anticipated. After much preliminary research, weep-holes incorporated into the wall for drainage were found to be a relatively recent 20th century development. Delving further into the study of weep-holes necessitated a closer examination of the concepts of drainage and dampness, the removal of which is the catalyst for a number of construction remedies at the envelope. These remedies include the introduction of the cavity wall and, ultimately, weep-holes.

The development of the cavity wall can be traced to the evolution of social thought and scientific progress that emerged during the latter half of the 19th century. The proliferation of building construction literature, the development of the sanitation movement, and increased scientific progress in engineering and architecture identify the late 19th and early 20th centuries as the key period when many of the ideas related to wall drainage began to take shape.

The amount of literature published from approximately 1850 to 1950 on methods to remediate dampness in wall construction suggests that although some of these ideas may have been used in earlier traditional building methods, they began to be codified at a time when large scale technical and public health developments were also taking place. Undoubtedly, these factors influenced the field of building construction. Increasingly widespread publication of construction manuals and advertisements also allowed for a greater dissemination of information during this period than had been seen in previous years.

A major campaign to prevent dampness, driven by public health concerns in America and abroad, led to the development and use of the brick cavity wall. Physicians demanded rational principles in architecture, attempting to distinguish professional builders from those who operated by trial and error.[1] Encouraged by developing theories in the medical profession, public thought held that proper ventilation could prevent or even cure the spread of disease. With limited understanding of the sources causing dampness and mechanisms of moisture movement, builders primarily focused on construction methods that were intended to increase ventilation and evaporation throughout the wall.

In order to help keep the interior of a building dry, a second wall layer was added. The hollow air space within these double-wythe walls acted as an additional layer of weather protection and as a thermal barrier. However, it was also a new location where water could collect. Wind-driven rain could seep through the exterior wythe and separately, condensation could form in this new hollow air space between the interior and exterior walls. Builders were then confronted with the need to drain the hollow wall space. At present, this concept has been largely unexplored within the history of American building technology. It remains a particularly pressing and only partially resolved issue in today's construction of increasingly complex, moisture-proof building envelopes.

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[1] Annmarie Adams, *Architecture in the Family Way: Doctors, Houses, and Women, 1870-1900* (Montreal: McGill-Queen's University Press, 1996), 43.

Early attempts to rid the cavity of excess moisture involved various strategies to increase air ventilation within that space. However, due to the realities of the built world and complex unforeseen conditions within the as-built envelope, waiting for evaporation to fully remove moisture within a wall cavity cannot be relied upon. The installation of weep-holes, seen at the base of the exterior wall or over lintels and shelf angles, represents a crucial shift that occurred from approximately 1920 through the 1940s in effectively addressing the issue of moisture intrusion by providing an outlet for drainage. Weep-holes provide a pathway for water to escape without compromising the strength, stability, and insulative properties of the cavity wall. Without weep-holes, moisture can remain within the wall indefinitely, causing material damage and fostering an environment for the growth of organisms and insects potentially harmful to human health. The purpose of this thesis is to examine the introduction and evolution of the weep-hole within the building envelope, based upon prevailing notions of dampness in buildings during the late 19th and early 20th centuries.

The shift from employing drainage instead of ventilation in order to remove moisture from walls did not immediately occur in cavity walls, as they experienced a decline in use immediately following the turn of the 20th century. Instead, this understanding of drainage as a necessary component in wall construction first occurred in engineered retaining walls, windows, and terra-cotta cladding systems. Advancements in material testing and the simultaneous growth of the insulation and brick veneer industry helped facilitate the translation of weep-holes used in wall cladding and window systems to cavity walls, as they again gained popularity in America during the 1930s.

In the years following World War II, America's construction industry experienced significant changes with the advent of new building methods and materials, stimulated by technology and production methods developed during the war. The application of weep-holes and the concept of wall drainage continued to evolve during the middle and later part of the century, but it did so in an atmosphere of rapidly changing technology and building systems. Though the popularity of the traditional brick cavity wall has since been replaced by that of veneer, steel frame and curtain wall cladding, and exterior insulated finish systems, among others, the weep-hole and the concept of wall drainage remains a fixture of these modern day envelope systems, as do our intentions to prevent damage to interior finishes and to promote healthy indoor environments within our buildings.

CHAPTER 1.

Dampness And Its Effects Upon Building Construction

1.1 What is Dampness?

Dampness is moisture caused by the presence of water in the atmosphere and/or environment. The issue of controlling dampness is of great importance in building construction due to material concerns of structural degradation, as well as the personal health of building inhabitants. Factors that affect the amount of dampness in a material include: rate of moisture ingress throughout the wall, rate of evaporation, humidity, size of capillary vessels in a porous material, height of the water table, and the rate of water vapor transmission through the wall.[2] The severity of building component deterioration and our perceptions of the issues associated with it largely depend on the capacity of these masonry materials to transmit, retain, or dispel moisture.

1.2 Sources of Dampness

Dampness may result from exposure to one or more of the following primary sources of water intrusion into buildings.

1) *Rising damp*: Rising damp refers to the upward movement of water through a material. In building construction, moisture present in the ground may be drawn up into porous materials through capillary action, in a uniform or non-uniform manner.

2) *Wind-driven rain*: Wind-driven rain is rain falling with a horizontal velocity onto the exterior surfaces of a building. Winds with strong horizontal pressure may contribute to rain penetration through the envelope by driving moisture into masonry pores, joints, and cracks. Additionally, upward pressures produced by wind encourage water

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[2] M. Lieff and Heinz R. Treschel, eds., *Moisture Migration in Buildings*, "An Evaluation of Methods of Treating Rising Damp," by J. L. Heiman (Philadelphia: American Society for Testing and Materials, 1982), 122.

already collected at these areas of weakness to breach the envelope through a suction effect, thereby permitting further penetration into materials through capillary action.[3]

3) *Condensation*: When warm, moisture-laden air comes into contact with a cooler surface, the water vapor present in the air precipitates into a liquid against the cooler surface. The amount of saturation in the air is often referred to as relative humidity; and the temperature at which fully saturated water vapor precipitates is called the dew point.[4] The term "condensation" describes this phenomenon of precipitation, which often occurs within cavity walls where the airspace forms a barrier between the cooler outside atmosphere and a warmer, more humid indoor atmosphere.

4) *Leaks*: Deficiencies in roof cover, improper flashing, lack of drainage due to blocked gutters, and open mortar joints are examples of poor construction and maintenance methods that can result in leaks. Moisture, acted upon by the force of gravity, will continue to move in a downward pattern, wetting materials beneath the point of origin.

Once moisture comes into contact with, and is absorbed by, building materials, it moves from wetter to drier areas through capillary action. Capillary action, or the ability of liquid to flow through the narrow tube-like spaces of a material, is the result of inter-molecular attractive forces and surface tension within the walls of the tube. It is stronger within narrower spaces, and may occur in opposition to gravity.[5]

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[3] R. T. Gratwick, *Dampness in Buildings*, 2d ed. (London: Granada Publishing Limited, 1974), 282-284.

[4] Denison Olmsted, *A Compendium of Natural Philosophy*, ed. E.S. Snell (New York: Clark & Maynard, 1864), 152.

[5] Gratwick provides a detailed and thorough description of capillary action and the mechanisms of moisture movement through materials. See R. T. Gratwick, *Dampness in Buildings*, Chapter 4.

1.3 Effects of Dampness on Buildings

Given the ability of moisture to breach the building envelope and travel through materials, the appearance of dampness in a building can manifest in a number of ways that can affect the durability of materials and may lead to conditions that affect both the physical and mental well-being of building inhabitants. The complexity of building systems and their varied exposure to weather elements and user patterns often make identifying the origin of moisture intrusion a very difficult, confusing, and lengthy process. Possible combinations produced by different sources of moisture intrusion, mechanisms of movement, and material reactions in different environments around the world create a unique scientific case study for each individual structure.

The following short and by no means inclusive list identifies a few conditions that may indicate the presence of dampness and moisture.

- Stains
- Damage to interior finishes
- Spalled or eroded masonry
- Crumbling mortar
- Efflorescence and frost attack
- Biological growth (sometimes accompanied by a musty odor)

1.4 Dampness as a Health Risk

People rely on buildings for safety and shelter, and often take for granted the controlled comforts of modern building structures as they spend an increasing amount of time within their walls. Over time, people have come to expect a certain degree of comfort, warmth, and dryness as inherent qualities in buildings. Today, these qualities are still not ensured as a result of the construction process and allergy concerns often prompt discussions about the need for "healthy" buildings.

Historically, afflictions ranging from general ill health to tuberculosis, rheumatism, and death were often associated with dampness in buildings.[6] Sanitary engineering developed as a professional discipline in Great Britain during the 1860s and 1870s.[7] Schools and institutes began to offer courses in rationalizing the science of architecture. Early "building doctors" and sanitary inspectors, who were tasked with investigating residential buildings in an attempt to diagnose and treat architectural problems, often criticized the lack of scientific basis in building construction as a primary reason that enabled the spread of various diseases despite medical efforts to cure them.[8]

R. Scott Burn, editor of *The New Guide to Masonry, Bricklaying and Plastering: Theoretical and Practical,* wrote in 1870, "When experienced medical officers see rows of houses springing up

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[6] Annmarie Adams attributes this connection to Edwin Chadwick's 1842 *Report on the Sanitary Condition of the Labouring Population of Great Britain*, a seminal text identifying housing and environmental conditions as primary factors that led to, and even encouraged, the spread of disease. By 1870, the fear that houses could cause sickness was widespread. See Adams, *Architecture in the Family Way: Doctors, Houses, and Women, 1870-1900*, 29.

[7] In 1883, a British surgeon named T. Pridgin Teale published *Dangers to Health: A Pictorial Guide to Domestic Sanitary Defects*, a book which focuses on the dangers of poor drainage conditions and the spread of illness through poor ventilation. The book attempts to educate the public on sanitary conditions within their own homes, and to inform the architect, "who may learn how by every sanitary detail which he designs amiss, or by oversight allows to be badly carried out, [that] he is opening a door for illness to the future occupant of the house." See Adams, *Architecture in the Family Way: Doctors, Houses, and Women, 1870-1900*, 11; T. Pridgin Teale, preface to *Dangers to Health: A Pictorial Guide to Domestic Sanitary Defects*, 4th ed. (New York: D. Appleton & Company, 1883), xiv.

[8] Adams, *Architecture in the Family Way: Doctors, Houses, and Women, 1870-1900*, 42.

on a foundation of deep retentive clay, inefficiently drained, they foretell the certain appearance among the inhabitants of catarrh, rheumatism, scrofula, and other diseases, the consequence of an excess of damp, which break out more extensively and in severer forms in the cottages of the poor..."[9] Construction manuals published just before and after the turn of the century similarly identify poor health as a result of injurious conditions manifest from unregulated moisture and decay.[10]

One common theory regarding the spread of disease held that miasmas transmitted the evils of dampness and decay from the ground environment to the house and subsequently, to the body through the presence of adulterated air, particularly within a contained space. Circa 1870, Burn pointed to fog as an ideal vehicle to convey decomposing matter within damp soil into the confines of the home, adversely affecting the mental and physical efforts of inhabitants.[11] Similarly, George Powell, author of *Foundations and Foundation Walls,* wrote in 1884, "A dry cellar is one of the requisites to a healthy house. A moist or damp cellar acts as a constant reservoir of damp, chilly and impure air... Many fatal cases of sickness can be traced to this cause, and, doubtless, if our cellars were looked after more carefully, there would be less complaint of malaria and kindred ailments."[12]

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[9] Robert Scott Burn, ed., *The New Guide to Masonry, Bricklaying and Plastering: Theoretical and Practical* (Edinburgh: A. Fullarton & Co., 1868-72), 149.

[10] For further reference, see Baird Smith's discussion on historic attitudes to dampness. The language associating dampness with sickness is prevalent in construction manuals and echoes that seen in contemporary sanitary engineering literature. See Baird M. Smith, *Dampness in Historic Buildings: Methods of Diagnosis and Treatment* (dissertation, University of York, 1979), 16-17; George T. Powell, *Foundations and Foundation Walls* (New York: William T. Comstock, 1884), 67-68; *Advanced Building Construction: A Manual for Students* (London: Longmans, Green & Co., 1896), 59; Henry Adams, *Cassell's Building Construction: Comprising Notes on Materials, Processes, Principles, and Practice* (London: Cassell and Company, Limited, 1913), 75; Walter R. Jaggard and Francis E. Drury, *Architectural Building Construction: A Text Book for the Architectural and Building Student*, Vol. 2 (Cambridge: University Press, 1936), 21.

[11] Burn, *The New Guide to Masonry*, 149.

[12] Powell, *Foundations and Foundation Walls*, 68.

In recent years, scientists have found consistent, although not conclusive, associations between bio-organic growth and adverse effects on the respiratory health of building inhabitants.[13] A 2004 study by the Institute of Medicine of the National Academy of Sciences concluded that "excessive indoor dampness is a public health problem" and recommended corrective action.[14] A subsequent quantitative study performed by the Lawrence Berkeley National Laboratory in 2006 concluded that building dampness and mold are associated with a 30% - 80% increase in upper respiratory tract symptoms, but the causal relationship has not been defined to date.[15] Strong correlations were found between exposure to dampness and health issues. As noted in the report, it is unlikely that dampness itself will cause adverse health effects. However, it may be argued that dampness fosters conditions that allow organisms such as mold, mildew, and pests to flourish. These, in turn, may directly impact the health of inhabitants, as previously feared during the 19th century. Research on this issue, however, remains ongoing.

1.5 The Search for a Solution to Dampness

Dampness in buildings was so prevalent in masonry structures and accounts varied so wildly as to its exact causes that a seemingly infinite number of attempts toward a solution were tried from the turn of the 19th century onwards. Emerging medical theories regarding the origins of disease significantly influenced the development of brick construction methods, which remained largely

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[13] A quantitative study of the effects of bio-organic growth on health are discussed in a research paper published by the Environmental Energy Technologies Division of the Lawrence Berkeley National Laboratory. See William J. Fisk, Quanhong Lei-Gomez, and Mark J. Mendell, *Meta-Analyses of the Associations of Respiratory Health Effects with Dampness and Mold in Homes (*Berkeley: Lawrence Berkeley National Laboratory, Environmental Energy Technologies Division, Indoor Environment Department, 2006).

[14] Fisk et al., *Respiratory Health Effects*, 2.

[15] Ibid., 7.

unstandardized until after the turn of the 20th century.[16] Spurred by public concern, wall ventilation was increasingly promoted as a way to eliminate dampness. Application and development of these measures were primarily based on trial and error. A review of literature published during the late 19th and early 20th centuries indicates that some methods of addressing dampness were relatively similar, while others, in retrospect, appear to be unique exercises in preventing moisture intrusion. Some methods may never have entered into common building practice. Builders recognized the need to mitigate moisture intrusion into the building, but their lack of expertise in identifying and isolating the various sources precluded their ability to effectively do so.

Besides wall ventilation, contemporary published literature also focused on damp-proofing and water-proofing solutions at the foundation and grade levels. This suggests that builders, as well as the public, generally associated illness with conditions that were primarily thought to originate from ground conditions but could be solved through evaporation at the wall level.[17] As quoted in Baird Smith's dissertation, *Building News Magazine* noted in 1880, "...There is, perhaps, no source of mischief so pernicious to health and so destructive to the comfort of a house, as a damp wall, and certainly there is nothing so difficult to cure, save by having to resort to radical measures of an expensive kind."[18]

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[16] Standardization presumably occurred sometime after the tenth edition of Ira Baker's *A Treatise on Masonry Construction* was published in 1909. He stated, "There is not even a remote approach to uniformity in the specifications for the brick-work of buildings. Ordinarily the specifications for the brick masonry are very brief and incomplete." See Ira O. Baker, *A Treatise on Masonry Construction*, 10th ed. (New York: John Wiley and Sons, 1909), 178.

[17] Baird Smith notes in his dissertation that some builders surmised that only those structures which had been built on soil exhibiting a moist condition at the time of construction would be affected by capillary action. Another theory posited by Joseph Gwilt in the *Encyclopedia of Architecture*, published in 1842, states dampness in buildings is a result of damp materials used during construction, which then continue to draw dampness from the soil. See Smith, *Dampness in Historic Buildings: Methods of Diagnosis and Treatment*, 16-17; Joseph Gwilt, *An Encyclopaedia of Architecture, Historical, Theoretical, and Practical* (London: Longman, Brown, Green, and Longmans, 1842), 962.

[18] Smith, *Dampness in Historic Buildings: Methods of Diagnosis and Treatment*, 24.

Promoting ventilation and evaporation by incorporating air spaces into wall construction was a method used to address damp walls that stemmed from long-held beliefs connecting sickness and dampness that existed prior to the development of professional sanitary engineering. Builders commonly stated that increased ventilation and air circulation through confined spaces was an effective means of preventing damp and promoting dryness of walls, though details and further explanation were vague or non-existent.[19] Within the broader discussion of public health in the years before and after the turn of the 20th century, architects and engineers responded to the call for increased ventilation and daylight by modifying various aspects of the building envelope in an effort to ensure that the buildings they constructed would prove more conducive to health. An 1873 report titled "Sanitary Relations to Health Principles in Architecture" stated, "after medicine, 'as professions most concerned in the preservation of public health rank those of the Architect and Engineer.'"[20] The idea that increased ventilation in buildings, particularly in houses, could help to prevent and even potentially cure illness reinforced early notions that incorporating a means of ventilation within wall construction was necessary, thus encouraging further development of cavity wall construction.

[19] Ventilation was a predominant topic in the discussion of how to rid hollow, hollow-brick, and cavity walls of dampness. Sources frequently recommended ventilation without a clear explanation of how it actually worked, which contributes to an overall lack of clarity in the historical discussion of effective damp-resisting construction methods. See J. C. Loudon, *The Architectural Magazine and Journal of Improvement in Architecture, Building, and Furnishing and in the Various Arts and Trades Connected Therewith*, vol. 1, "On A Method of Preventing Damp From Rising in the Walls of Buildings on Clay and Other Moist Soils," by William J. Short (London: Longman, Rees, Orme, Brown, Green, and Longman, 1834), 233; J. C. Loudon, *An Encyclopaedia of Cottage, Farm, and Villa Architecture and Furniture* (London: Longman, Orme, Brown, Green & Longmans, 1839), 172; "Lessons in Brickwork - V: Hollow or Cavity Walls," *The National Builder* 47, no. 5 (November 1908), 30; F. W. Haglock, "Concrete Block Walls Act as Ventilators," *The National Builder* 47, no. 4 (1908), 28; Carl Pfeiffer, "Sanitary Relations to Health Principles in Architecture" (presentation, Annual Meeting of the American Public Health Association, New York, NY, 1873); Adams, *Cassell's Building Construction*, 75; Jaggard and Drury, *Architectural Building Construction*, 20, 42, 53; *Advanced Building Construction: A Manual for Students*, 59.

[20] Pfeiffer, "Sanitary Relations to Health Principles in Architecture," 3.

Builders explored various methods of preventing building contact with ground air, moisture, water, and drainage during the late 19th and early 20th centuries. These methods included, but are not limited to, the following:

- Damp-proof coursing at foundations[21]
- Foundation areaways[22]
- Water-proof coating processes[23]
- Hollow walls
- Hollow-block walls
- Cavity walls

In their search for a solution to dampness, builders were forced to confront a number of complex variables and developments that lacked the benefit of scientific and time-tested application. In general, hollow, hollow-brick, and cavity walls were thought to prevent dampness in walls by maximizing surface exposure to air, thereby increasing the possibility for ventilation, and thus,

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[21] Various damp-proofing techniques were documented during the 19th century. Although methods of installation vary widely, common types of damp-proof coursing involved application of stones of low porosity (typically slate), high fired or glazed brick, sheet lead, or a layer of concrete or asphalt. Not all were efficacious. See Smith, *Dampness in Historic Buildings: Methods of Diagnosis and Treatment*, 18; *Advanced Building Construction: A Manual for Students*, 61.

[22] Foundation areaways, also known as air drains, were narrow, dry areas constructed along the perimeter of foundation walls to prevent damp walls caused by rising damp. *Advanced Building Construction* states, "...The width of the area is... sometimes is so reduced that the arrangement simply amounts to providing a hollow wall." Gratwick attributes the origin of the hollow wall to foundation areaways. Giovanni and Ippolito Massari's *Damp Buildings, Old and New* discounts the general effectiveness of this method of damp prevention by the early 1990s. See *Advanced Building Construction: A Manual for Students*, 59-60; Gratwick, *Dampness in Buildings*, 51; Giovanni and Ippolito Massari, *Damp Buildings, Old and New*, trans. Cynthia Rockwell (Rome: International Centre for the Study of the Preservation and Restoration of Cultural Property, 1993), 89-91.

[23] Asphalt and tar, as well as hydraulic cement and insoluble compounds, were common methods recommended by 19th century builders to render the interior or exterior of basement walls dry. Builders recognized, however, that these "expensive external coverings" did not mitigate rising damp on the interior. See *Advanced Building Construction*, 58 - 59.; Smith, *Dampness in Historic Buildings*, 16.

evaporation. The plethora of these hollow wall systems invented from roughly 1830 to 1930 attests to the prevalence of dampness and public concerns as to the effects of dampness on health. Other innovations in building construction also occurred in the areas of damp-proofing, waterproofing, and site drainage. Despite various experiments and proposed "solutions," perhaps Ira Baker, in *A Treatise on Masonry Construction*, was the most accurate when he observed, "It sometimes becomes necessary to prevent the percolation of water through brick walls. A cheap and effective process has not yet been discovered, and many expensive trials have proved failures."[24]

Driven by the fundamental desire to construct healthful indoor environments, successful mitigation of moisture at the envelope occurred through a lengthy trial and error process that progressed during the late 19th century and well into the 20th century, through a process that paralleled technological developments and changing concepts of building envelope construction. Solid wall construction was generally recognized as a system that inevitably resulted in dampness due to the ability of materials to retain moisture. Cavity wall construction, on the other hand, provided an extra layer of protection against moisture because the outer wythe provided increased weather protection for the inner wall. The cavity air space itself helped to prevent direct transmission of moisture from one wall to the next. This system was not waterproof, but the continuous air space between the two wythes was thought to increase air circulation and stimulate evaporation, theoretically ridding any moisture from porous wall materials. The ability of the outer wythe to act as a functional outer skin that shed the majority of rain and inclement weather before they reached interior spaces and the principles behind maintaining a dry wall system is described in the following chapter.

[24] Ira O. Baker, *A Treatise on Masonry Construction*, 7th ed. (New York: John Wiley and Sons, 1889), 178.

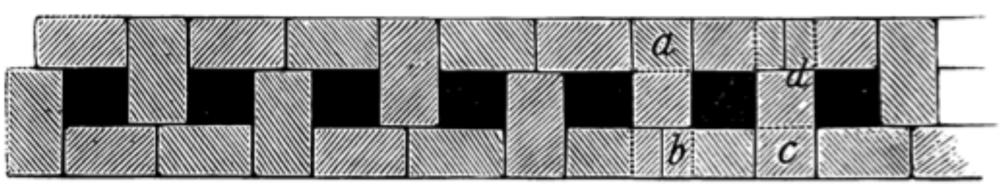
CHAPTER 2.

Cavity Wall Construction and the Rain Screen Principle

2.1 The Cavity Wall Defined

Part of the complexity in understanding the historical development of the cavity wall and related concepts stems from a general confusion of terminology used in building construction manuals and journals during the late 19th and early 20th centuries. Although terms such as “hollow wall,” “hollow brick wall,” and “cavity wall” had various meanings and were used somewhat interchangeably in historic literature, a brief look at these terms is required here to clarify and define the manner in which they are used in this particular text.

A *hollow wall* shall refer to a wall, composed of an inner and an outer wythe, in which standard bricks are laid in various configurations so as to form multiple individual hollow spaces.[25] These spaces typically measure 2 to 3 inches thick in between wythes and run in a continuous vertical, but not horizontal, pattern. The hollow wall was typically constructed for the purpose of material savings, thermal insulation, and dampness prevention. (See *Figure 2.1*.)



[Fig. 3. Hollow 12 inch wall.]

Figure 2.1: Typical 12” hollow wall construction, plan view. Hatched areas represent bricks; solid black areas are hollow voids.

[25] “Hollow wall” is a very general term seen in 19th and early 20th century literature that builders often used to refer to various configurations of hollow-block walls, cavity walls, and hollow walls as defined here.

A *hollow-brick wall*, also known as a *hollow-block* or *hollow-tile wall* shall refer to a wall constructed of specially molded fired-clay units that are perforated with open spaces.[26] They are used in wall construction for the purpose of constructing thermally-insulated and, in theory, well-ventilated walls. (See *Figure 2.2*.)

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Figure 2.2: Typical hollow-brick construction, section view. Note the open cells in the "tile."

[26] The term "hollow brick wall" is often used in construction manuals, and typically refers to the type of wall construction seen in Figure 2.1, which shall heretofore be referred to as a "hollow wall." A hyphen has been added to this term for clarification throughout this text, so that "hollow-brick wall," "hollow-block wall," and "hollow-tile wall" denote only those masonry units molded with voids prior to firing, as seen in Figure 2.2.

The term *cavity wall* shall refer to a wall composed of an inner and an outer wythe, in which standard bricks are laid in two distinct parts that are separated from each other by a horizontally and vertically continuous air space, measuring approximately 2 to 3 inches wide. The inner and outer wythes are tied together with metal connections.[27] Total wall thickness may range from 8 to 24 inches thick, with the thin outer wall typically built in Flemish, English, or stretcher bond.[28] Buildings constructed with cavity walls typically benefit from improved thermal performance and less likelihood of damp penetration at finished interior spaces. (See *Figure 2.3*.)

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Figure 2.3: Typical cavity wall construction, section view. Note the 2" cavity space and weep holes at the wall base. These elements comprised standard recommendation in Architectural Graphic Standards*, 1941.*

[27] James Stevens Curl, *Encyclopaedia of Architectural Terms* (London: Don Head Publishing, 1992), 73.

[28] *Advanced Building Construction*, 62.

A survey of brick and masonry construction manuals supports the notion that providing a dry interior space was the primary concern in the minds of builders. Hollow walls were widely associated with successful mitigation of dampness both in America and abroad.[29] The popularity of 19th and early 20th century construction methods that incorporated various hollow spaces in walls was primarily tied to efforts to produce a healthy and dry living atmosphere. References to "cavity walls," "hollow-brick walls," and "hollow walls" consistently appear in the larger discussion of preventing dampness at foundations and cellars, repelling moisture, applying damp-proof coursing, and providing dry interiors. The hollow spaces created within these walls primarily attempted to address dampness issues caused by rising damp or wind-driven rains.

Although cavity, hollow-brick, and hollow walls were used concurrently, it is the cavity wall that stands out because of its role as a precursor to modern day veneer systems and curtain wall cladding. Its construction reflects the beginnings of an effective concept for preventing water penetration known as the rain screen principle, a crucial component of these modern wall systems.

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[29] Some discussion is necessary regarding the initial purpose of hollow wall construction, which is seen earlier and with more prevalence than cavity wall construction. Many early builders seemed to equate warmth or thermal insulation with dryness, although they are not exactly the same thing. In 1850, Andrew Jackson Downing stated that leaving a hollow space between brick fill and weather-boarding results in a "dry, warm, and substantial house." He lists among the advantages of hollow walls "the prevention of dampness, which always strikes through a solid wall." The majority of 19th century sources describe prevention of dampness in buildings as an immediate concern, and increased thermal insulation as an added benefit. *An Encyclopaedia of Cottage, Farm, and Villa Architecture* noted that hollow walls provided dryness and were less easily penetrable by exterior temperatures. A popular method known as Dearn's Hollows Walls also claimed that "the hollows in the walls will prove an antidote to damp." Robert C. Burn's *The New Guide to Masonry, Bricklaying and Plastering* and George Powell's *Foundations and Foundation Walls* identify dampness as the primary reason why hollow walls are recommended for construction. Powell states, "... [hollow walls] make a dry and damp-proof structure," and that it is general practice to set grooved, fire-proof blocks against the inside of exterior walls in order to leave an air space at walls "exposed on the exterior to weather and where there is a tendency for moisture to drive through." It is unclear if early builders believed warm spaces encouraged dryness at walls, or if by keeping the walls dry, they could create warm spaces. See Andrew Jackson Downing, *Architecture of Country Houses: Including Designs for Cottages, Farm-Houses, and Villas, with Remarks on Interiors, Furniture, and The Best Modes of Warming and Ventilating* (New York: D. Appleton & Co., 1850), 54, 58; Loudon, *Cottage, Farm, and Villa Architecture*, 14, 172-173; Burn, *The New Guide to Masonry*, 147; Powell, *Foundations and Foundation Walls*, 83-84.

2.2 The Rain Screen Principle

A number of early damp-proofing and water-proofing techniques were intended to prevent any and all water from entering the building envelope. This would prove next to impossible to achieve. A wall system with surfaces and joints impervious to water is difficult to create. Moreover, these elements would need to remain perfectly impervious to water for an indefinite period of time, despite the tendency of materials to degrade and comprehensive systems to decrease in water-tightness over time. The acceptance and recognition that water will inevitably penetrate a building's exterior is the first step towards a successful solution to maintaining dry walls.

To leak into a building, water requires an opening and a pressure differential, which provides the force required to move the water through the opening. The characteristics that comprise a wall's ability to effectively provide a controlled interior environment also create a large pressure differential, which makes it susceptible to water penetration. Wind and air currents that exist outside of the building can create higher pressure at the exterior. Because of the tendency of air and water to move from areas of higher pressure to lower pressure, these conditions effectively push lingering moisture through the wall towards the interior of a building. A 1962 publication by the Norwegian Building Research Institute stated, "The only practical solution [to preventing water leakage] is to design the exterior rain-proof finishing so open that no super-pressure can be created over the joints or seams in the finishing. This effect is achieved by providing an air space behind the exterior finishing, but with connection to the outside air. The surges of air pressure created by the gusts of wind will then be equalized on both sides of the exterior finishing."[30]

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[30] *The Rain Screen Principle and Pressure-Equalized Wall Design*, AAMA Aluminum Curtain Wall Series, CW-RS-1-04 (Chicago: Architectural Aluminum Manufacturers Association, 2004), 4.

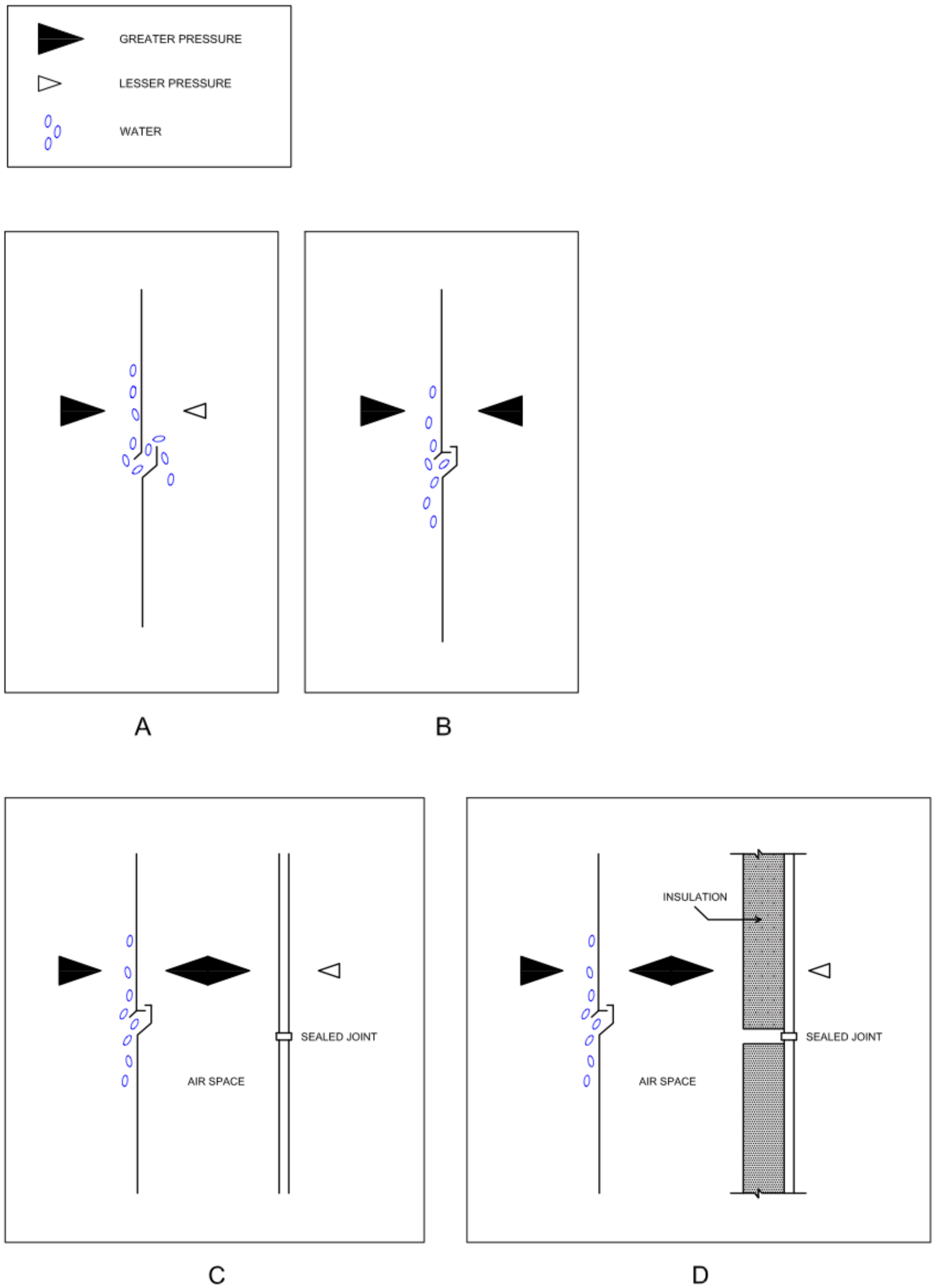

Figure 2.4: Images (A) through (D) depict movement of moisture at typical wall systems with differential air pressure. Image (D) illustrates a complete wall system constructed with the rain screen principle. Surface joints are left open, and pressure is equalized at the exterior and the air space. The inner wall, tightly sealed, is protected from the majority of rain because of the rain screen and pressure equalization.

The rain screen principle, identified in approximately 1960, refers to this type of wall system whereby pressure equalization occurs at both sides of the exterior wythe, or the “screen,” which purposefully is not tightly sealed in order to connect outside air to the cavity space between the two walls (See *Figure 2.4*).[31] The air space behind the facing ensures that air pressure is equal to or higher than that of the outdoor air pressure at all times (See *Figure 2.4-C*). The Architectural Aluminum Manufacturers Association (AAMA) notes that this is not simply a ventilated space.[32] Water can more freely penetrate the cavity, but the wall is so designed that water can also escape more freely as well. Sufficient openings in the wall guarantee a free flow of air, preventing pressure buildup on only one side of the wall. Thus, the wall is made water-resistant specifically by eliminating the pressure differential between inboard and outboard surfaces of the exterior wythe. This also eliminates the dependence on joints at the facing to keep out both air and water. The inner wythe, which contains properly sealed joints that can then be protected from the majority of inclement weather and kept dry, provides the structural load-bearing capacity of the wall while the exterior wythe acts as the skin (See *Figure 2.4-D*).

The rain screen principle relies on equalization of pressure, not direct drainage, to prevent water penetration to interior spaces. Thus, it should be noted that a wall system which applies the rain screen principle is different than one which employs drainage for moisture control. However, a properly constructed cavity wall “if adequately vented and properly flashed at its base” effectively forms a rain screen and allows water to drain out at the base of the wall if pressure within the cavity is equalized with that of the exterior atmosphere.[33] AAMA notes that minor

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[31] A 1996 specification by the Architectural Aluminum Manufacturers Association (AAMA) notes that the rain screen concept used to prevent water intrusion was recognized approximately 35 years prior to the publication, although the physical principles upon which it is based are fundamental. Historical use of these principles in construction was most likely used instinctively rather than scientifically. See *The Rain Screen Principle and Pressure-Equalized Wall Design*, AAMA, 6.

[32] This contradicts earlier theories, prevalent during the 19th and early 20th centuries, which stated that providing means for increased ventilation could overcome the dampness problem in walls.

[33] *The Rain Screen Principle and Pressure-Equalized Wall Design*, AAMA, 8.

leakage may occur through the rain screen. Thus, it is imperative that the air space always be drained to the outside.[34] By creating a relatively contained pressure-equalized atmosphere within the wall, any water that does find its way past the rain screen will be released outwards from the building and prevented from seeping into the building through the sealed inner wythe.

2.3 Moisture Problems Associated with Cavity Walls

Although the rain screen principle had not yet been articulated or developed during the late 19th century, some basic concepts of the rain screen were seen in the construction of the cavity wall. By providing an exterior skin, cavity walls were more effective than solid and other hollow wall types in preventing water intrusion, particularly from wind-driven rain; but their construction did not guarantee dry building interiors. Water that penetrated the outer wythe was often not drained quickly enough, or at all. Lingering moisture within the cavity space could easily find its way to the inner wall via surface absorption and capillary action, while stagnant air encapsulated within the wall cavity did little to promote evaporation or drying.

In fact, builders now had to contend with additional complexities within the wall system, such as cold-bridging created by wall connections, as well as moisture accumulation and condensation within the cavity. Cold-bridging describes a condition where heat flows through a material "bridge" that is the path of least resistance in a layer of insulation. In the case of a cavity wall, heat flows through metal or brick header connections, which bond the interior and exterior wythes for increased stability and distribution of lateral load. Historically, these connections presented a significant concern for the transmission of dampness to interior walls. Due to

[34] Ibid., 6.

temperature differentials, condensation occurred when areas adjacent to metal or brick ties reached dew point conditions and resulted in unsightly patches of damp at interior finishes.[35]

In contrast to relatively large cold-bridges formed by brick headers, metal ties were small in section, cheaper to utilize, and due to their lack of porosity, presented less potential for moisture to penetrate; thus, they were recommended over brick or stone for bonding purposes. Cold-bridging concerns were also exacerbated by the tendency of mortar to fall into the wall cavity and lodge on top of the ties. Formation of a mortar bridge could potentially draw moisture from the outer wall and along the connection, via capillary action, towards the inner wall.

Additionally, the effectiveness of the cavity wall at insulating the building created an increased temperature differential between the interior and exterior spaces, causing condensation to occur directly inside the cavity. Furthermore, the cavity space was completely inaccessible to builders, owners, and inhabitants and rendered future problems, such as vermin or mold growth, difficult to remedy.

While cavity wall construction also provided improvements in material economy and insulation, the issue of removing moisture from within the cavity severely limited the benefits created by its construction. As a result, cavity walls experienced a significant decline in use by the turn of the

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[35] The idea that materials within the cavity promote moisture travel between walls is later explored during the 19th and 20th centuries in the discussion of cold-bridging and in various attempts to prevent moisture from traveling along bonding ties. See *Advanced Building Construction*, 62; Gratwick, *Dampness in Buildings*, 252; Jaggard and Drury, *Architectural Building Construction*, 22; Giovanni and Ippolito Massari, "Damp Buildings, Old and New," *Bulletin of the Association for Preservation Technology* 17, no. 1 (1985), 21; William B. Lowndes, *Brick, Stone, and Plaster* (Scranton: International Textbook Company, 1924), 43; John A. Mulligan, *Handbook of Brick Masonry Construction* (New York: McGraw-Hill Book Company, Inc., 1942), 355-356; Harry C. Plummer and Leslie J. Reardon, *Principles of Brick Engineering: Handbook of Design* (Washington, D.C.: Structural Clay Products Institute, 1943), 147-148; Powell, *Foundations and Foundation Walls,* 86.

20th century and did not gain popularity in America again until after 1930.[36] Along the way, significant technical developments such as large scale public works projects and engineered cladding materials in the fields of architecture and engineering would provide the tools necessary for a revival of the cavity wall in a technologically superior form.

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[36] A 1960 publication by the Building Research Institute observes that cavity walls were constructed in the United States prior to the turn of the 20th century, but notes that they were typically not used in construction from approximately 1900-1930. *Brick, Stone, and Plaster* confirmed this in 1924, stating, "Difficulties that largely offset their advantages are met with in construction, however, so that hollow walls [or more properly, double walls] are not often used in the United States." In 1943, *Principles of Brick Engineering* recorded a renewed interest in and an increased popularity of cavity walls. See *Insulated Masonry Cavity Walls* (Washington, D.C.: National Academy of Sciences, National Research Council, 1960), 1-2; Lowndes, *Brick, Stone, and Plaster*, 25-26, 43; Plummer and Reardon, *Principles of Brick Engineering*, 1.

CHAPTER 3.

The Evolution of the Weep-Hole

3.1 A Discourse on Dampness: Ventilation versus Drainage

Construction of the cavity wall was a tremendous step along the path of progress towards creating a water-resistant wall. It helped to alleviate the problems of cold, damp interiors associated with solid wall construction by minimizing the possibility of direct penetration of dampness.[37] Many builders continued to devote efforts towards finding the most effective construction of the cavity wall. Numerous variations in design and construction to reduce dampness were tried. Still, water often collected in the cavity itself, requiring further remediation. Initially, methods to address the moisture problem included alterations to the cavity wall that incorporated means of ventilation and evaporation, instead of direct drainage.

A retrospective look at *The Ten Books on Architecture*, written during the first century B.C., shows that the idea of using ventilation to promote dry building walls was not a new concept unique to 19th century development of the cavity wall. Vitruvius writes, "But if a wall is in a state of dampness all over, construct a second thin wall a little way from it on the inside, at a distance suited to circumstances, and in the space between these two walls run a channel, at a lower level than that of the apartment, with vents to the open air. Similarly, when the wall is brought up to the top, leave airholes [*sic*] there. For if the moisture has no means of getting out by vents at the bottom and at the top, it will not fail to spread all over the new wall."[38] Thus, an extra layer of weather protection was created, and as Vitruvius suggests, a space between the two wythes would theoretically allow air to circulate within and subsequently, help dry the wall.

In 1886, *American Architect and Building News* references this exact passage from Vitruvius while noting, "It is strange that, with all our boasted progress in engineering and practical

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[37] Ancient Greek wall construction with its hollow air space may be the earliest documented cavity wall. Similar to 19th century construction methods, stones were laid level to create two parallel walls, with additional stones laid at intervals across the unfilled cavity space and run through the entire wall thickness for bonding. See Vitruvius, *The Ten Books on Architecture*, trans. Morris Hicky Morgan (New York: Dover Publications, Inc., 1960), 51-53.

[38] Vitruvius, *The Ten Books on Architecture*, 209.

architecture, we are really little better off than the Romans were in the construction of basement walls that shall resist moisture."[39] The article also bemoans, "How few builders of such walls take care to make the cavity extend below the level of the floor, or to see that openings are left."[40] With the exception of a few scattered references such as Palladio, who likewise built upon the works of Vitruvius and declared, "It is very commendable in great fabricks [*sic*], to make some cavities in the thickness of the wall from the foundation to the roof, because they give vent to the winds and vapours, and cause them to do less damage to the building," it appears that the height of development in brick cavity wall construction occurred after 1880.[41]

Although Vitruvius included air-holes in the wall for evaporative purposes, it is unclear if he also intended to prescribe direct drainage of the wall through these features. However, this early documented example of cavity wall construction expresses important ideas that pertain to later development of the concept of wall drainage at the building envelope. Firstly, a vertically and horizontally continuous cavity separating the inner wall and outer wall is shown as necessary to prevent the transfer of moisture to the interior of a building. Secondly, he introduces the practice of implementing voids through the base of the wall to help promote and direct water movement outwards from the building.

At least as early as 1834, the early 19th century saw the reintroduction of channels perforating cavity walls that were specifically intended to relieve dampness. One purpose of including these channels was to ventilate damp basement areas and to keep timber floor joists dry.[42] It is clear from texts and manuals of this time period that in order to remediate dampness at the basement,

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[39] "Foundation Walls," *The American Architect and Building News*, March 13, 1886: 129.

[40] Ibid.

[41] Andrea Palladio, *The Four Books of Architecture* (London: Isaac Ware, 1738; reprint, New York: Dover Publications, Inc., 1965), 7.

[42] See Haglock, "Concrete Block Walls Act as Ventilators," *The National Builder*, 2; Loudon, *The Architectural Magazine and Journal*, "On A Method of Preventing Damp From Rising in the Walls of Buildings on Clay and Other Moist Soils," by William J. Short, 233; Gratwick, *Dampness in Buildings*, 182.

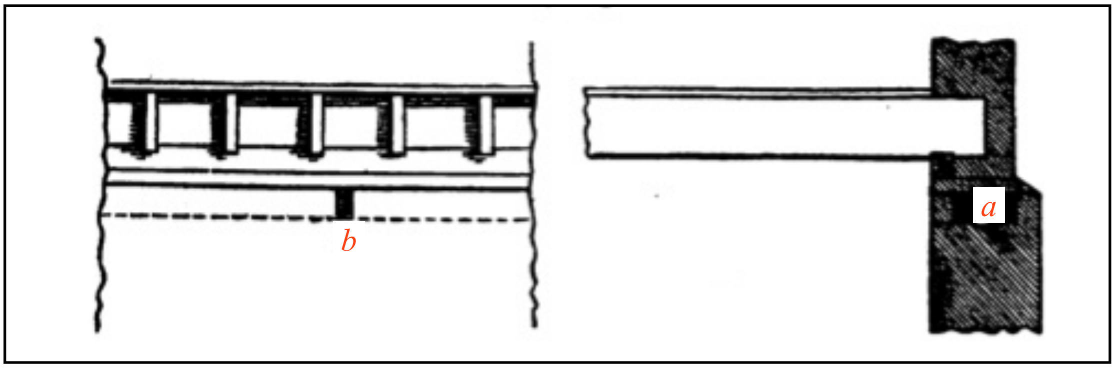

Figure 3.1: A diagram of an early ventilated cellar space exhibiting openings (b) at the interior wythe that connect to a channel (a) within a solid wall.

builders utilized these channels with the intent to ventilate and evaporate damp air, not to drain any moisture that had accumulated, within the wall space. These through-wall channels were placed at intervals along the wall and connected a hollow air space within the wall to air at interior building spaces. One early building design by surveyor William J. Short in the 1834 *Architectural and Magazine Journal* illustrates a hollow channel in the center of a solid wall, located just below a damp-proof course of "cheap stone or slate" (See *Figure 3.1*).[43] In order to ventilate the cellar space, Short proposes that "at various intervals... small openings communicating between this channel and the interior of the building should be made; so that a current of air from the exterior may be driven through the channel and openings under the floors, in order to sufficiently ventilate the same."[44] Without calling for additional openings at the outer wythe and with only a small channel in a solid wall, it is unlikely that Short's method for ventilation, and thus evaporation, was effective.

[43] Loudon, *The Architectural Magazine and Journal*, "On A Method of Preventing Damp," 233.

[44] Ibid.

Later adaptations of the through-wall channel commonly utilized "air-bricks" at intervals along the base of the inner wythe and the top of the exterior wythe (See *Figure 3.2*). An air-brick, as defined in *A Dictionary of Architecture and Building* in 1905, is a hollow or pierced brick

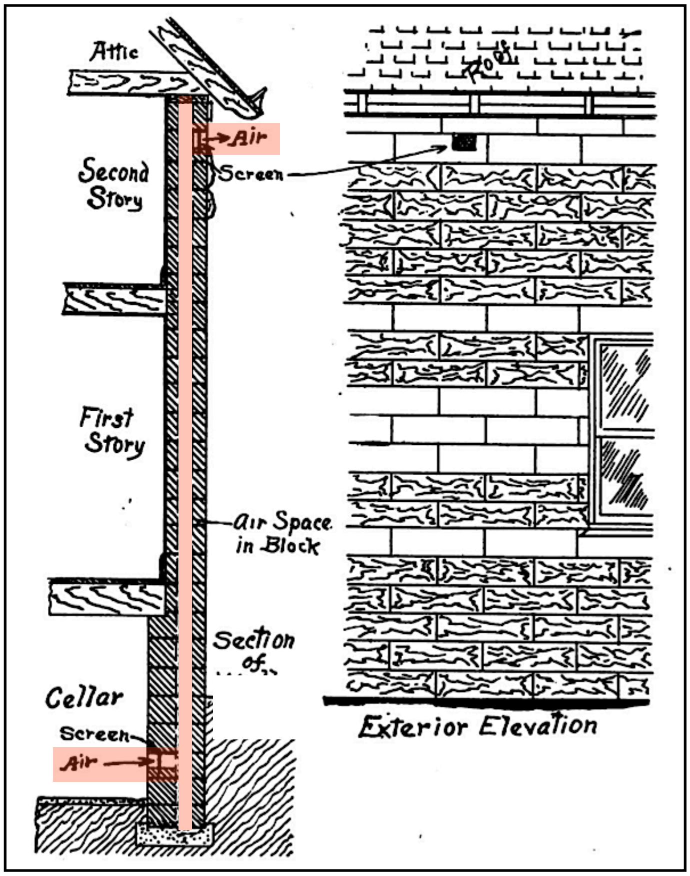

Figure 3.2: Air-bricks are utilized at the base of the interior wythe and the top of the exterior wythe to ventilate a damp cellar space. Although this particular image depicts the use of air-bricks in concrete block walls, it illustrates the popular idea that the use of air-bricks could promote ventilation through the wall if configured in the manner illustrated.

or piece of hard material, about the size of a brick, that is built into a wall with ordinary bricks to allow the passage of air.[45] It seems that builders thought dampness could be drawn out from the basement, into and up through the wall cavity by convection, finally exiting through air-bricks at

[45] Russell Sturgis, *A Dictionary of Architecture and Building*, vol. 1 (New York: The Macmillan Company, 1905), 355.

the top of the exterior wall.[46] In theory, this system could promote the health of inhabitants by expelling adulterated air, which could otherwise spread insidiously throughout the rooms of the house. It is unclear if this was scientifically proven at the time, but the proliferation of similar thought published in contemporary building literature indicates its popular acceptance.[47]

One thing is clear, however; drainage is not addressed in construction of these particular wall systems. In fact, the placement of interstitial wall channels at the base of interior wythes directly contrasts the fact that weep-holes must necessarily be placed along the exterior wythe in order to function properly. A look at the terminology used in early building literature supports this theory. Terms such as “air-brick” and “venting” imply an evaporative function at the cavity wall, whereas the term “weep-hole” (which does not readily appear in envelope construction until after 1910 in window systems and 1920 in wall cladding systems) inherently implies a primary function of drainage. Common sense dictates that draining water from within the wall should be directed outwards, instead of towards an interior space that builders hoped to keep dry. However, variations of this ventilation system continued to be used into the beginning of the 20th century.[48]

Following the turn of the century, a distinct shift in the application of air-bricks occurred. Instead of connecting space within the cavity to interior spaces, air-bricks were placed at the base of the outer leaf, thereby connecting the hollow space to exterior fresh air. Still, based on descriptions of such configurations, application of air-bricks through the exterior wall was intended for the purpose of ventilation, not drainage. An article published in 1908 by *The National Builder*

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[46] For additional information on air-bricks and ventilation, see Gratwick, *Dampness in Buildings*, Chapter 10.

[47] See Haglock, “Concrete Block Walls Act as Ventilators,” *The National Builder*, 2; Loudon, *The Architectural Magazine and Journal*, “On A Method of Preventing Damp From Rising in the Walls of Buildings on Clay and Other Moist Soils,” by William J. Short, 233; Gratwick, *Dampness in Buildings*, 182; Teale, *Dangers to Health: A Pictorial Guide to Domestic Sanitary Defects*.

[48] For additional discussion, see Adams, *Cassell’s Building Construction*, 75; Gratwick, *Dampness in Buildings*, Chapters 10-11; Haglock, “Concrete Block Walls Act as Ventilators,” *The National Builder*, 28; Giovanni and Ippolito Massari, “Damp Buildings, Old and New,” *APT*, 20-24; William A. Radford, *Architectural Details for Every Type of Building* (Chicago: The Radford Architectural Company, 1921), 17.

describes “customary” practices of hollow wall building and notes, “The bottom course of the outer wall is not less than one course below the damp-proof course of the inner wall, and has air bricks in it at intervals of 4 ft. to 6 ft., to allow a constant upward current of air to dry out any moisture; similar air-bricks are put at the top if the hollow space is covered.”[49] Similarly, *Cassell's Building Construction*, published five years after *The National Builder* article, maintains that it is “absolutely essential to have air-bricks or ventilating grids in the outer face of a cavity wall. They should be placed about 6 ft. or 8 ft. apart in the lowest course of the face-work wall, that is, at the bottom of the cavity... [and] similar air-bricks must be placed at the top of the cavity to allow of [*sic*] continuous ventilation” (See *Figure 3.3*).[50]

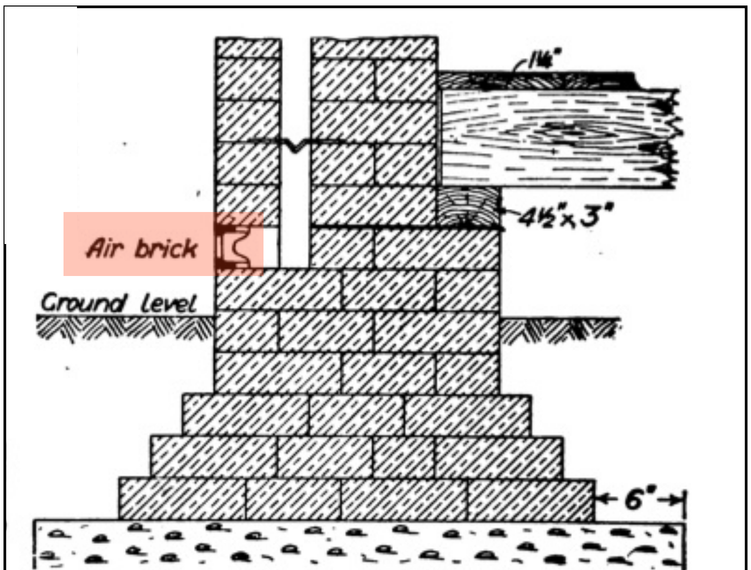

Fig. 72.—Foundation of Cavity Wall.

Figure 3.3: An air-brick is utilized at the base of brick face-work, intended for the purpose of ventilation.

[49] “Lessons in Brickwork - V: Hollow or Cavity Walls,” *The National Builder*, 30.

[50] Adams, *Cassell's Building Construction*, 42.

Based on a survey of literature pertaining to wall construction, there appear to be four general configurations of through-wall channels used in cavity wall construction, with varying results of effectiveness in keeping building walls dry.

1) Voids only at the base of the interior wythe.

2) Voids at multiple locations at the interior wythe.

3) Voids at the base of the interior wythe and top of the exterior wythe.

4) Voids at the base of the exterior wythe and top of the exterior wythe.

A clear distinction emerges between through-wall channels used for ventilation and those used for drainage. Perforations at the inner wythe were routinely used to increase ventilation of the cavity itself or within individual rooms of a building. In certain cases, these voids in the wall fabric were used in combination with voids at the exterior wythe. On the other hand, perforations used for drainage are located only at the base of the exterior wall. Outlets incorporated into the envelope to promote air circulation cannot be considered true weep-holes, although they may inadvertently act as such given the right conditions. Air-bricks installed at the base of the exterior wall, although primarily intended for the purpose of ventilation, also provided outlets for water to potentially exit the wall. This seemingly small change from incorporating air-bricks at the base of the inner wythe instead to the base of the outer wythe in brick wall construction may have unintentionally provided a blueprint for a more effective and direct means of draining damp walls.

3.2 Engineering Developments in Drainage During the Late 19th Century

Evidence of building methods specifically intended to provide drainage of the building envelope are quite scarce prior to the 20th century. However, wall drainage was commonly employed in engineering projects such as dams, revetments, and retaining walls. The means to address the extreme soil and hydrostatic pressure conditions present in large-scale, sub-grade construction necessitated advanced technical research and understanding in the field of civil engineering. Thus, related terms “weeper,” “weeping-hole,” “weeps,” and “weep-hole” originate from civil engineering and are seen in British literature beginning in the 1870s and 1880s. By the 1890s, references to weep-holes used for drainage of retaining walls was common in engineering journals and literature.

Weep-holes were open spaces incorporated at certain pre-determined intervals along the wall that provided a simple and efficient means of drainage. At 9 inches high by 2 inches wide, the early weep-holes described by Selim Hobart Peabody and Charles Francis Richardson in *The International Cyclopedia* in 1899 were much larger than their modern day cavity wall counterparts and were recommended at a distance of every 36 square feet of wall.[51] An engineering publication from 1898 titled *Railway Construction* notes, “Suitable arrangements must be made to take away the drainage water which will collect at the back of the walls, and weeping holes or outlets must be left in the lower part of the walls to convey the water into the water-tables on the line.”[52] Also in 1898, *The International Cyclopedia: A Compendium of Human Knowledge* noted that if water was allowed to remain behind the retaining wall, it increased pressure build-up on the wall by turning the earth into a semi-fluid state.[53] Wet soil fill

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[51] Ibid.

[52] William Hemingway Mills, *Railway Construction* (London: Longmans, Green & Co., 1898), 63.

[53] Selim Hobart Peabody, and Charles Francis Richardson, “Retaining Wall,” *The International Cyclopedia: A Compendium of Human Knowledge*, ed. H. T. Peck, vol. 12 (New York: Dodd, Mead and Company, 1899), 584-585.

behind this barrier could create significant hydrostatic pressures, which would subsequently weaken the strength and stability of the wall. Thus, early weep-holes helped to release and balance the pressure of moisture build-up at sub-grade and retaining walls.

In cold climates, major concerns about water penetrating masonry structures were heightened because of the potential for moisture remaining in the masonry to freeze. Upon freezing, the moisture would expand within the pores of the material, frequently causing it to crack or burst. A means of removing excess moisture that typically collected at the reverse side of the wall structure and at foundations was required.

The International Library of Technology, published in 1905, described the need for soil drainage at the back of a retaining wall at a sloped site, in one instance, to prevent "any surface water from running down the slope of the surcharge [embankment] and thence down the back of the wall, causing a change in the nature of the filling and probably damaging the masonry by freezing."[54] Because of this issue, weep-holes, typically formed of terra-cotta, lead, or copper pipe, were used for drainage at the retaining wall. It was recommended that builders place these "weepers" at intervals of one for each 5 to 6 yards of surface area. Additional open drains running along the length of the wall were placed at the rear side of retaining walls in order to help promote drainage directly to weep-holes.[55]

Weep-holes were also recommended in the repair of the Chanda Fort, a fortified wall that measures approximately six miles in circumference and surrounds the city of Chanda, helping to hold back seasonal flood waters from the Erai River. The British Superintendent reported in an archaeological survey conducted in India from 1914-1915 that the Chanda Fort, constructed during the middle of the 15th century and "still of great utility to the municipality" even after

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[54] *International Library of Technology* (Scranton: International Textbook Company, 1905), 30.

[55] Ibid., 30-31.

five centuries, was in need of minor conservation repairs at the time.[56] He describes the wall as follows:

> The walls have been constructed in two parts — (i) the outer part, on which the battlements stand, which is built of rubble-in-mud with dressed stone in mortar on the outside and coursed stone-in-mud on the inside, and (ii) the rampart wall, built against the former; it is also constructed of rubble-in-mud with dressed stone on the inside and random stone paving on the top. *Water gets in between these two walls*... and either causes the mud to swell or has to force its way outwards and thus splits the face of the wall and causes collapse [emphasis added]. Had the walls been provided with *weep-holes to permit of the water finding its way out*, very little damage from this cause would have occurred [emphasis added]. The bastions have collapsed for the same reason, water having got in through cracks in the floor or where the paving has come away from the wall. To preserve the wall properly this percolation of water must be stopped... All cracks must be filled, missing paving replaced, and where walls appear weak, weep-holes provided.[57]

Despite the recommended use of weep-holes for repair of a double-wall-type system to counteract the cyclical expansion and contraction of fill between inner and outer walls, this description is not meant to imply that the walls at Chanda Fort are early cavity walls. This description is simply used as one of many examples of the benefits gained from and necessity of functional drainage in a variety of different wall types.

Wall drains were also utilized during construction of New York City's underground rail tunnels during the late 19th century. As documented in 1874 by *Scientific American Magazine*, masonry tunnels comprising four tracks within three parallel passageways were built in phases along the

[56] *Annual Report of the Archaeological Survey of India, Eastern Circle, For 1914-1915: Superintendent's Report, Part II* (Calcutta: Bengal Secretariat Book Depot, 1915), 74-75.

[57] *Annual Report of the Archaeological Survey of India*, 74-75.

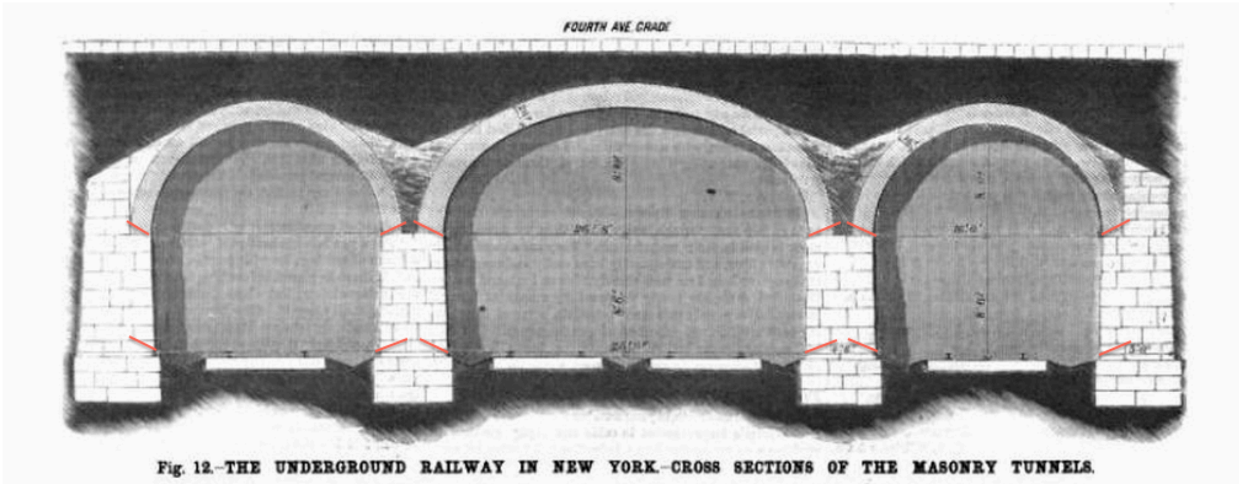

Figure 3.4: Red lines indicate general configuration of wall drains constructed at the base of walls and spandrel arches in masonry tunnels of the New York City underground railway.

west side of Manhattan, from 49th Street to 133rd Street. Six-foot thick walls were constructed beginning at three feet below railroad grade. These walls rose approximately 15 to 20 feet high and tapered in thickness as the wall extended upwards until reaching street grade. Depending on existing topography, the face of retaining walls at open cut sections would transition to the interior face of masonry tunnels, where ground headway increased and the railway continued completely below grade (See *Figure 3.4*). Some sub-grade passageways were finished with stone facings, others lined with brick masonry. Both types used holes at the wall base for drainage.[58]

During construction of an open cut section from 49th to 79th Streets, drain openings measuring 4 inches by 6 inches were set into the base of masonry retaining walls at 50 foot intervals.[59] Similar construction was undertaken at 116th to 133rd Streets.[60] Increased headway due to a high ridge between 66th to 71st Streets necessitated modified construction of the tunnels. Brick arches

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[58] "The Underground Railway, New York City," *Scientific American* 31, no. 21 (November 21, 1874), 323.

[59] Ibid.

[60] Ibid.

resting on stone abutments were constructed, with rubble masonry fill at spandrels. Clay pipe drains, measuring six inches in diameter, ran through the thickness of the arch at its base and were placed every 50 feet to properly drain rubble fill.[61]

Significant construction efforts and money were invested in building transportation infrastructure during the late 19th century. Within these subterranean transportation tunnels, weep-holes helped to balance hydrostatic pressure by allowing moisture to drain from the soil backfill towards the interior of the tunnel. Although seemingly unrelated to the cavity wall, retaining wall construction and technical advancements during the late 19th century promoted an understanding of the necessity of drainage in order to prevent structural damage to walls. The transfer of ideas from engineering to architecture foreshadows the increasingly scientific movement towards materials testing and a more comprehensive understanding of building systems performance that would support later development in the field of architecture particularly during the beginning and middle of the 20th century. This progression occurred gradually, as water penetration was only addressed for individual envelope components for many years.

3.3 Weep-Holes and Condensation Gutters in Window Construction

The use of weep-holes in building envelope construction first appears during the 19th century in windows, particularly in the construction of casement windows in order to remove excess water that resulted from condensation and rain penetration. In 1880, *The Architectural Magazine* published a review of architect C.W. Trendall's 1833 book *Examples for Interior Finishings*, in which Trendall illustrates in two plates, "Another French casement window, with the parts of the full size, showing the meeting styles, hanging styles, window frame, meeting bar, [and] metal bar

[61] "The Underground Railway, New York City," *Scientific American* 31, no. 24 (December 12, 1874), 371.

to insert in the window sill, perforated with holes for the escape of rain water, & c. [*sic*]"[62] The reviewer's indication that "there is nothing new or remarkable in [this book]" suggests that the use of drainage holes in window construction was relatively common knowledge by the late 19th century.[63] Several additional sources also indicate that some principles of water drainage at the envelope were understood and employed more readily in window construction prior to the application of weep-holes in cavity wall construction.

Rivington's *Notes on Building Construction*, published in 1875, describes the use of drainage holes in French doors. The author states, "When a casement window extends down to the floor it becomes in fact a glass door, and is often made to open inwards; in such a case it is very difficult to keep water from entering between the foot of the door and the sill... Any wet that may penetrate between [the throated weather board and the metal water bar fixed in the oak sill] is caught in the groove formed in the sill at the back of the water bar, and conveyed away through a hole bored in the oak sill as dotted" (See *Figure 3.5*).[64] Channels that ran behind the frame, along the sides of the sash, likewise helped to direct excess water to the grooved sill formation, where it was then directed outwards from the building.[65]

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[62] J. C. Loudon, *The Architectural Magazine and Journal of Improvement in Architecture, Building, and Furnishing and in the Various Arts and Trades Connected Therewith*, vol. 1, "Reviews: Examples for Interior Finishings, by C. W. Trendall, Architect," (London: Longman, Rees, Orme, Brown, Green, and Longman, 1834), 136-137.

[63] Ibid.

[64] A later publication in 1921 titled "Construction of the Small House" described similar channels as a means of ventilation instead of drainage at the window, stating that "all well-designed trim has a gouged-out space at the back to permit circulation of air around it." See H. Vandervoort Walsh, "Construction of the Small House," *Architecture* 44, no. 2 (August 1921), 254; *Notes on Building Construction: Arranged to Meet the Requirements of the Syllabus of the Science and Art Department of the Committee of Council on Education, South Kensington*, Part 1 (London: Rivingtons, 1875), 205.

[65] *Notes on Building Construction*, 206.

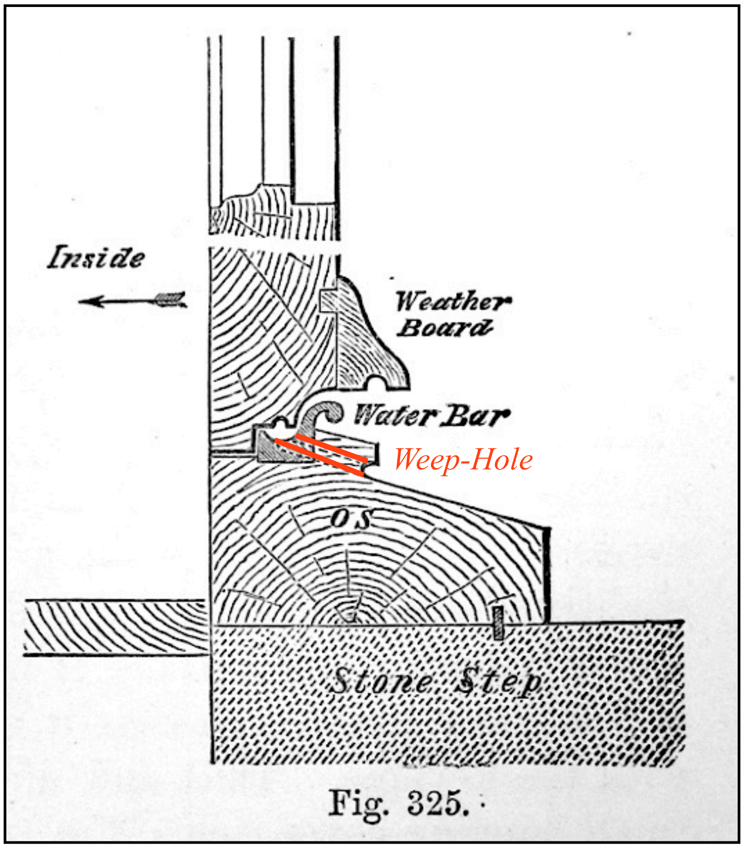

Figure 3.5: A drainage hole conveys water that collects in the water bar away from the base of the French door and the building.

Similarly, the 1921 publication of *Architecture* features an article on window trim titled "Construction of the Small House" by H. Vandervoort Walsh. This article helps to crystallize an idea pertinent to water drainage at the envelope that would later be applied not only to cavity walls, but to all manners of modern wall and window construction. Discussing casement windows, Walsh states, "...The difficulty of weathering can be overcome to a large extent by not attempting to keep out the rain but lead it down and around the sides, draining it off at the sill. This is accomplished by cutting a 1/4-inch half-round groove around the sides and in the sill to act as a canal for collecting the water which has seeped in. A few 1/4-inch round weep holes from the groove in this sill outward will drain this collection of water off."[66]

[66] H. Vandervoort Walsh, "Construction of the Small House," *Architecture* 44, no. 2 (August 1921), 256.

As mentioned in Chapter 2, many earlier efforts in keeping a building dry focused on preventing moisture altogether which, as seen by the number of construction remedies and vigorous attempts over several centuries, proved next to impossible. Understanding and addressing moisture as an inevitability in casement window construction subsequently allowed builders to formulate an effective method of removing collected moisture from the assembly.

Construction of casement windows illustrated yet another concept in envelope construction that had not yet been fully realized in wall construction by the early 20th century. Rivington's *Notes on Building Construction* states, "In exposed places [French or casement windows] should be made to open outwards, as then the wind pressing upon them from the outside only makes them close more tightly."[67] This statement indicates a recognition of the differential pressures that exist between indoor and outdoor environments. As described in the rain screen principle in Chapter 2, the same force that causes wind to close a window more tightly in this instance must be countered in some manner to prevent water from also being driven into vulnerable joints at windows and walls. Weep-holes not only provide an outlet for the release of water but, in combination with other means used to prevent pressure build-up at enclosed spaces, can help balance atmospheric pressure differential between these spaces, depending on the relative sizes of the weep-hole and cavity. Although there does not appear to be any 19th century scientific literature in regards to proving how this principle worked in window construction, and ideas may have been driven by instinct or experience and handed down through traditional building practices, the use of weep-holes in windows is a concept and a method of addressing water penetration in one building sector that may have helped influence its later use in terra cotta cladding and cavity walls.

[67] *Notes on Building Construction*, 204.

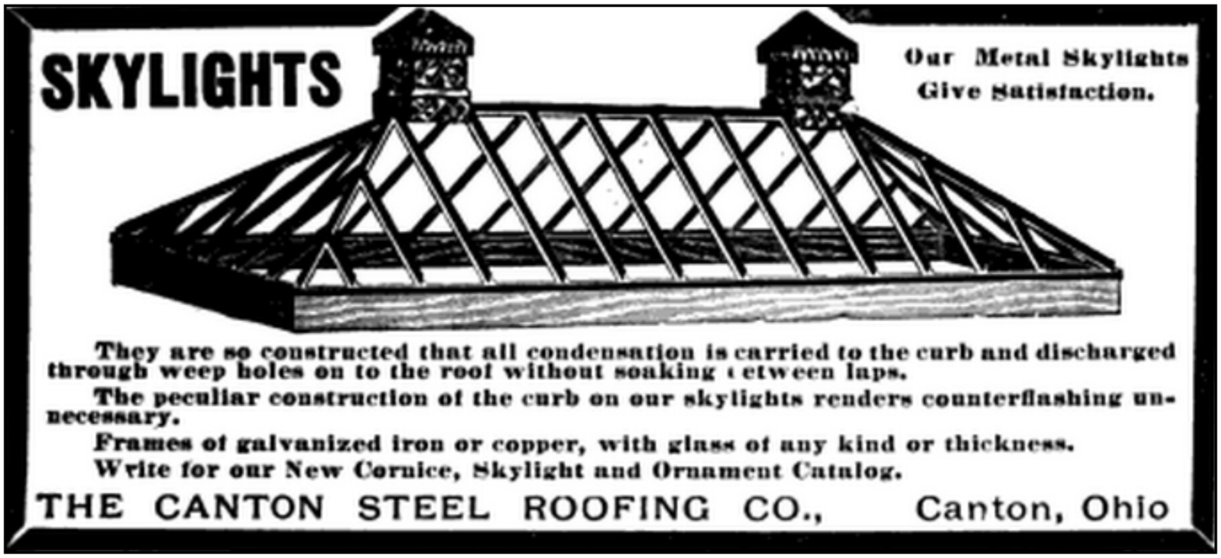

Figure 3.6: A 1908 advertisement for metal skylights manufactured by The Canton Steel Roofing Company touts the benefit of using weep-holes.

Although weep-holes already appear to be in general existence during the last quarter of the 19th century, a leading American manufacturer of windows, Henry Hope & Sons, claims to have popularized their use in 1894 with the introduction of condensation gutters with weep-holes in their manufactured windows.[68] By the early decades of the 20th century, the terminology used to describe drainage holes in a number of different architectural and engineering applications (although not yet in construction of the cavity wall) and the term "weep-hole" appears to be relatively commonplace and the use of weep-holes continued to appear in literature regarding the construction of casement windows and increasingly, skylights. An advertisement for metal

[68] *Hope's Casements and Leaded Glass*, published in 1919, notes that after the company introduced condensation gutters in 1894, they were "copied so largely [by others] as to have become almost a standard feature in casement construction." After inquiring with building owners as to the effectiveness of such window types and conducting their own investigations of window performance in casement installations, Henry Hope & Sons noted that "complaints of leakage and draught through weep-holes are not at all uncommon." Working under the incorrect assumption that "condensation only occurs during the first few months of occupation of a new building, while the walls are loaded with moisture," the company recalled the use of condensation gutters and associated weep-holes in favor of a wide, shallow channel at the interior sill that would allow condensation to evaporate freely or be wiped up as necessary. They stated that the condensation gutters were "quite useless on account of their small capacity" and that in actuality, the weep holes "only serve as inlet holes for rain and wind during cold and stormy weather." Despite this anomaly, it appears that weep-holes continued to be used in windows made by other manufacturers. See Henry Hope & Sons, Introduction to *Hope's Casements and Leaded Glass* (New York: Henry Hope & Sons, 1919).

skylights placed in *Carpentry and Building* magazine was accompanied by a brief description stating, "[The skylights] are so constructed that all condensation is carried to the curb and discharged through weep-holes on to the roof without soaking between laps. The peculiar construction of the curb on our skylights renders counterflashing unnecessary" (See *Figure 3.6*).[69] While the lack of roof counterflashing may have proven detrimental in the long term, the weep-hole concept in this advertisement echoes the language seen in similar skylight and window advertisements in *Sweet's Catalogue* and other magazines from this period (See *Figure 3.7*).[70]

Today, the construction of many modern curtain wall buildings, in which glazing forms the majority of envelope material, lends itself to our perspective of windows as a crucial component that requires extensive detailing and attention as a wall material. However, during the 19th and early 20th centuries, the transfer of ideas between window and wall construction and related attempts to release moisture that had collected within spaces in the constructed assembly systems still had yet to occur.

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[69] Canton Art Metal Company, "Skylights," Advertisement in *Carpentry and Building* 30, no. 2 (February 1908), 10.

[70] In the 1911 publication of *Sweet's Catalogue*, the G. Drouvé Company advertised the "Anti-Pluvius" Puttyless Skylight with the claim that "[The skylight] is perfectly impervious against rain and dust, even in the severest storms." A drip hole was illustrated at the base of the glass assembly. The Thomas W. Irwin Manufacturing Company also noted the use of condensation gutters which would help "carry away the water condensed from the atmosphere to the roof by means of port-holes." The Universal Skylight Company is the only manufacturer in this edition of the catalogue that identified the drainage components specifically as "weep-holes" in a detail drawing. Vaile & Young also provided an illustrated advertisement showing outlets at the condensation gutter bars, although no explanation is provided. In a departure from the other manufacturers, the New York Bridge and Iron Company, manufacturers of the "Paradigm-Duxbac" Ventilating Skylight, however, featured a different conceptual application of perforation at the metal frame, stating that the "1/4-inch ventilating holes every three inches apart, and the same in the top of the caps" helped the assembly to "[shed] water like a duck's back and [ventilate] at the same time." Consistent use of weep-holes in skylight construction is not seen at this time, and advertisements show various combinations of condensation gutters with or without weep-holes identified as such. See *Sweet's Catalogue of Building Construction* (New York: The Architectural Record Company, 1911), 512, 514-515, 519, 524-526.

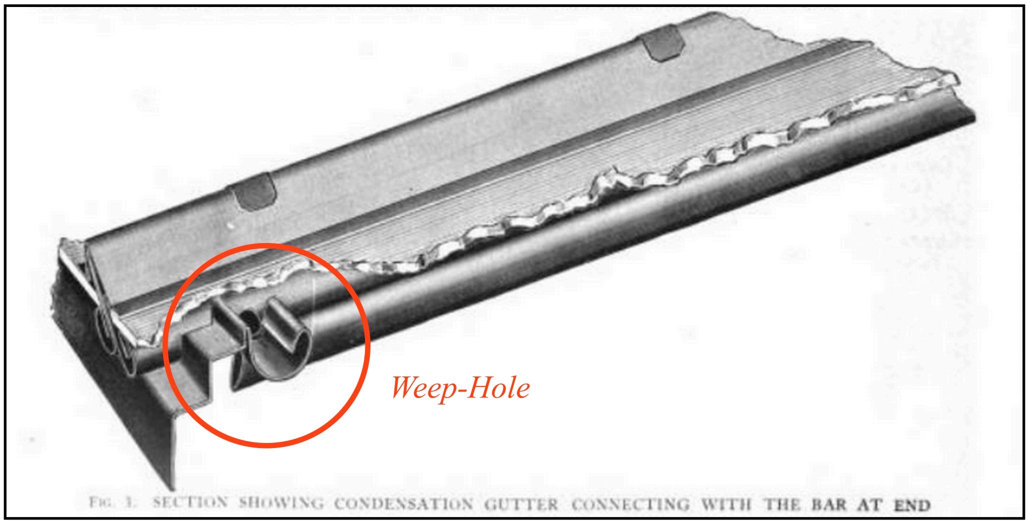

Figure 3.7: A condensation gutter with weep-hole, shown in a 1911 Sweet's Catalogue advertisement for "Vaile & Young's Patent Metallic Skylight."

3.4 Building Wall Drainage Prior to the 20th Century

Presumably because drainage was not used as a primary method of removing water from a wall, the term weep-hole was not used in relation to cavity or hollow-block wall construction during the 19th century. Rare references to related drainage components, termed "drain bricks," were vaguely described indicating negative space or vacuities within the wall.[71] Towards the end of the 19th century, a relatively rare call for drainage of the cavity wall is seen, by providing voids at the exterior wall base. In 1896, an excerpt titled "Horizontal Damp-Proof Coursing" stated,

[71] One obscure reference from 1839 illustrates the use of drain bricks in Dearn's Hollow Walls, a hollow-block wall system. Drain bricks were set in cement at the base of the hollow-block wall system, three courses above the footing. Installation was recommended "on a level with the supposed floor of the house. The use of this course of draining bricks is to carry off any water that might at any time find its way into the vacuity, when this mode of building is used in walls under the level of the ground." It is unclear how the drain-bricks functioned in reality. Because references to Dearn's Hollow Walls in other sources do not mention drain bricks, these elements may have been a very minor or inconsequential component of the proposed system. Alternatively, drain bricks may have been thought to be ineffective and thus, their use bore neither repetition nor elaboration. While the description and illustration of Dearn's Hollow Wall system indicate an understanding that water penetration through the exterior wythe could occur, it remains unclear whether an actual outlet for collected water was provided, or how this system was incorporated into the envelope. See Loudon, *Cottage, Farm, and Villa Architecture*, 172.

"In hollow walls, to prevent wet which comes into the hollow space, through the outer portion of the wall, from finding its way along the top of the damp-proof course to the interior of the wall, a cement fillet may be run along the angle at the bottom of the hollow space between the top of the damp-proof course and the inner portion of the wall, and an exit should be afforded - in any case temporarily - for the water at various points by leaving openings in the brickwork. If these are left permanently they should be protected by gratings."[72] The cement fillet acted as early wall-base flashing, directing water on the face of the inner wythe through to the exterior of the envelope. Construction of these temporary drainage voids would have helped to relieve dampness only during construction or the early phase of a building's life cycle. If these channels were filled soon after, long term mitigation of dampness and wall drainage would be less easily achieved.

The specific form of this particular example of incorporating voids through the building wall matrix is not recorded in any further detail. Open spaces through the wall, which would have been large enough to require protective gratings, may have consisted of air bricks or gaps within the mortar. Installation of gratings would have helped to protect vermin from entering the cavity, while allowing unhindered passage of water exiting through wall channels.[73] The general lack of information on wall drainage from contemporary sources also suggests that weep-holes in cavity wall construction were either rarely used or very poorly documented in literature. Thus, a great deal of this research depends on interpreting the somewhat vague and scattered pieces of information on the concept of cavity wall drainage during the 19th and early 20th centuries.

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[72] *Advanced Building Construction*, 60.

[73] Jaggard and Drury are among the few authors to state the disadvantages of cavity walls. One potential drawback of the cavity wall is that "it may harbour vermin if these can gain access, and thus produce an insanitary [*sic*] condition which is difficult to remedy since the cavity cannot be inspected." See Jaggard and Drury, *Architectural Building Construction*, 21.

The aforementioned description of voids in the building envelope, employed in combination with the cement fillet, diverges from other contemporary references by making no mention of evaporation and ventilation through the proposed channel. The through-wall voids, as described in *Advanced Building Construction*, appear to be stand-alone drainage elements at the exterior wall base. The latter description of open interstices covered by protective gratings at the cavity wall base is one of the earliest known descriptions of a weep-hole precedent in cavity walls.

3.5 Drainage of Terra Cotta Cladding

The rise of steel frame construction and growth of the terra cotta industry towards the end of the 19th century and early 20th century paralleled the temporary decline of cavity wall construction. The ability of terra cotta to withstand fire and to take an infinite number of finishes and amount of ornamentation contributed to its popularity as a high-performing, cost-efficient, and lightweight cladding material for large scale steel frame buildings. Terra cotta was molded into relatively thin forms, requiring webbing at the back of individual units in order to provide structural stability to the forms. This method of manufacturing produced significantly lighter-weight forms and at the same time created hollow spaces within the terra cotta units. These hollow spaces were packed with concrete or masonry backfill during construction of the building, or left partially hollow. Alkalinity of the concrete provided corrosion protection for encased metal anchors that were commonly used to attach terra cotta units to the building. In some cases, only the metal anchors were encased in concrete and the front portion of the terra cotta unit was left hollow for economic reasons and to reduce overhanging load at projecting roof elements.[74]

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[74] Herbert M. Greene Architects, Ralph H. Cameron, and Edward W. T. Lorey. "Atlantic Terra Cotta in Combination," *Atlantic Terra Cotta* 6, no. 8 (January 1924), Sheet No. 1.

Standardization was not formalized within the terra cotta industry during the early 20th century. With the exception of work conducted by the in-house engineering standards branch of the Atlantic Terra Cotta Company, very little scientific research on terra cotta materials, construction methods, or performance once installed in the field was conducted during the years prior to World War II. Thus, architects and builders relied heavily on methods of trial and error.[75]

Various problems related to moisture intrusion were observed in terra cotta. Water penetration through mortar joints, porous clay units, and leaking roof elements often occurred behind the face of terra cotta units. In many instances, repetitive wetting over a period of time resulted in insidious damage to the cladding system and metal anchor support systems. In general, the gradual deterioration of terra cotta components was hidden from view, often making it difficult to identify, and patterns continue to be uniquely dependent on variations in manufacture, original installation, component parts, and attempted repairs.[76]

Glazed architectural terra cotta was perceived as an impervious, "weatherproof" surface and initially, architects and builders designed these systems without flashing, drips, or weep-holes.[77] Moisture intrusion was often attributed to faulty mortar joints, which were observed to "crack and disintegrate to some extent under the action of the elements."[78] Water migrated past joints and surfaces and collected in the wall area behind the face of terra cotta units, typically in open pores of concrete back-fill or any areas that were left unfilled by builders. By the early 1920s, it

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[75] Theodore H.M. Prudon, "Architectural Terra Cotta and Ceramic Veneer in the United States Prior to World War II: A History of Its Development and An Analysis of Its Deterioration Problems and Possible Repair Methodologies," (doctoral dissertation, Columbia University, 1981), abstract.

[76] de Teel Patterson Tiller, "The Preservation of Historic Architectural Glazed Terra-Cotta," *Preservation Brief* 7 (Washington, D.C.: National Park Service, 1979).

[77] Tiller, "The Preservation of Historic Architectural Glazed Terra-Cotta."

[78] Herbert M. Greene Architects, Ralph H. Cameron, and Edward W. T. Lorey. "Atlantic Terra Cotta in Combination," *Atlantic Terra Cotta* 6, no. 8 (January 1924), Sheet No. 2.

was apparent that many of these buildings were not water-tight, despite original intentions, and that more attention to flashing, exposed architectural features, and joints was needed.

Conducted by the Atlantic Terra Cotta Company, an examination of buildings constructed from approximately 1880 to 1920 revealed a number of saturated terra cotta cornices and parapets, as well as cracked and deteriorated mortar.[79] An article titled "Keeping Buildings Dry" in the monthly *Atlantic Terra Cotta* series observed, "At first glance, ... it should not be very difficult to make [cornices, parapets, and balconies] water-tight, but the present condition of a great many of these features proves that for one reason or another, water-tight joints are not being obtained."[80] Lack of moisture control often resulted in aesthetic deterioration of the facade, damage to interior plaster ceilings and walls, and rapid corrosion of steel members anchoring architectural terra cotta ornament, which created significant safety concerns.[81]

These early observations of terra cotta deterioration stimulated discussion within the industry to determine the source of, and possible solutions to, water-related deterioration. By the early 1920s, the question of whether or not to fill terra cotta units was a significant concern that remained up for debate. Although there is a lack of information on contemporary thought regarding water infiltration through the integral masonry backup of terra cotta cladding, it is possible that, by completely filling the void, builders thought there would be no opportunity for moisture to permeate the building. Others, however, believed that moisture penetrating the cladding system could easily saturate fill, causing it to expand and burst through the face of the terra cotta unit due to cyclical freeze/thaw action.[82]

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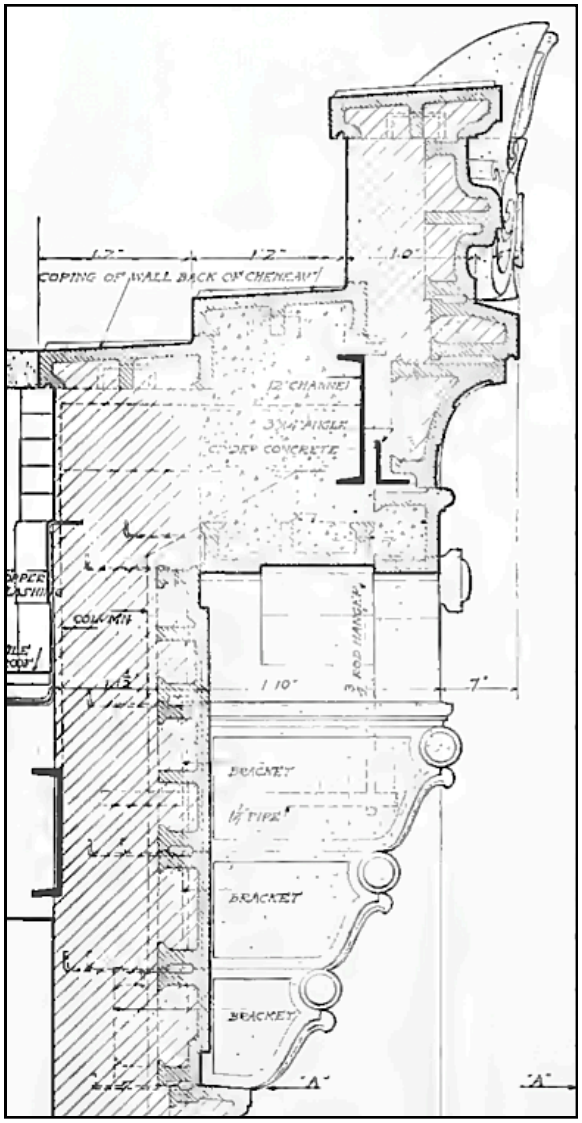
[79] Engineer of Standards, "Keeping Buildings Dry," *Atlantic Terra Cotta* 7, no. 1 (1924).

[80] Ibid.

[81] Ibid.

[82] George A. Hool, and Nathan C. Johnson, eds., *Handbook of Building Construction: Data for Architects, Designing and Constructing Engineers, and Contractors*, vol. 2 (New York: McGraw-Hill Book Company, Inc., 1920), 996.



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1914

1927

Figures 3.8 (left) & 3.9 (right): A standard construction detail for a "Heavy Bracketed Cornice with Ornamented Cheneau Showing Method of Support and Anchorage," published by the National Terra Cotta Society, shows complete masonry backfill at terra cotta units in the original 1914 drawing. A revised drawing of the same detail was published in 1927, illustrating partial fill and hollow voids (highlighted in red) behind terra cotta units, as well as weep-holes (highlighted in blue) indicated in the drawing as "W. H."

A review of published terra cotta literature reveals that prior to 1920, terra cotta cladding was typically back-filled with concrete. Many of the buildings constructed in this manner and examined by Atlantic Terra Cotta exhibited deterioration.[83] Between 1920-1930, an increasing number of terra cotta details illustrated partial masonry fill backup with voids left immediately behind cladding, particularly at cornice and parapet locations (See *Figures 3.8 and 3.9*).[84] Atlantic Terra Cotta's article "Keeping Buildings Dry" observed that "damage... is caused by the freezing of water that collects in pockets and open spaces in the interior of walls and structural features. The expansion of ice repeated through a number of cycles may finally rupture the masonry."[85]

Growing awareness that buildings were inherently not water-tight represents a tremendous conceptual breakthrough in the development of wall construction and the ability of 20th century architects and builders to understand building performance. With this new recognition that water penetration was inevitable, architects began illustrating provisions for terra cotta drainage in construction details.

One such detail is provided of a stepped roof and pedestals at the Scottish Rite Cathedral in San Antonio, Texas. Designed by Herbert M. Greene Company Architects, the detail illustrates a "modern, open type of construction, [which] is far superior to the old method."[86] Construction details show a typical section through the terra cotta roof, with hollow units jointed together along the profile of the stepped roof (See *Figure 3.10*). Along the beds of terra cotta roof slabs,

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[83] Engineer of Standards, "Keeping Buildings Dry."

[84] This is particularly evident in a comparison of the first and second editions of *Architectural Terra Cotta: Standard Construction*, in which the National Terra Cotta Society published detailed plates and specifications for the installation of terra cotta. See *Architectural Terra Cotta: Standard Construction* (New York: National Terra Cotta Society, 1914); *Architectural Terra Cotta: Standard Construction*, 2d ed. (New York: National Terra Cotta Society, 1927).

[85] Engineer of Standards, "Keeping Buildings Dry."

[86] Greene Architects, Cameron, and Lorey, "Atlantic Terra Cotta in Combination," Sheet No. 2.

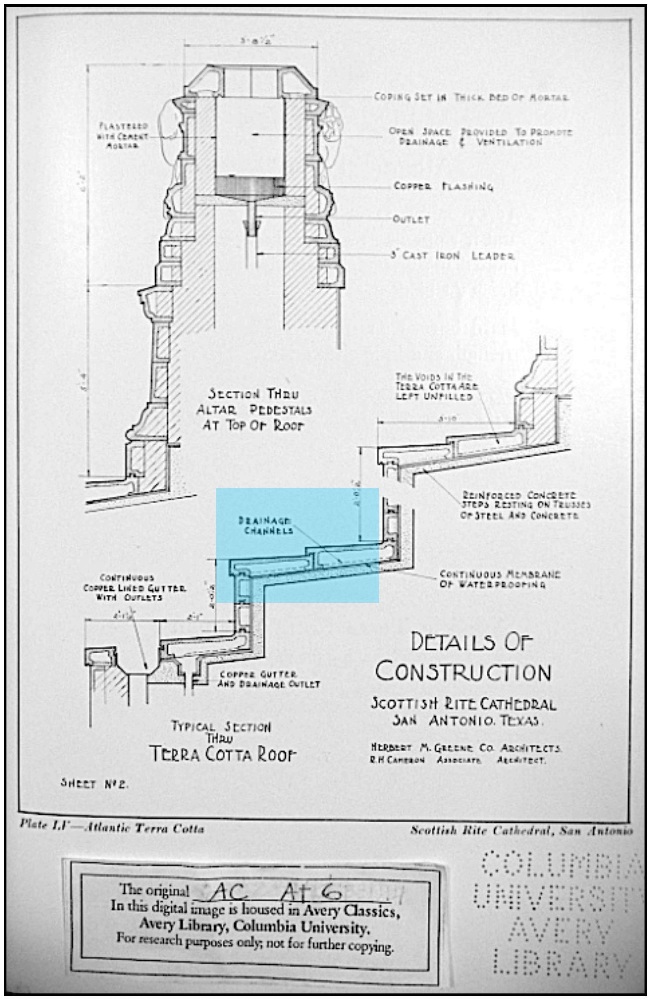

Figure 3.10: Drainage channels facilitate moisture drainage over the top of waterproofing towards a copper gutter and drainage outlet at the Scottish Rite Cathedral in San Antonio, Texas. Detailed by the Atlantic Terra Cotta Company (1924).

drainage channels were implemented so as "to facilitate easy flow of moisture" on top of the recommended waterproofing membrane and towards a copper-flashed gutter with a drainage outlet intended to remove potential water seepage that was expected to occur through mortar joints.[87] A note on the detail drawing states, "The voids in the terra cotta are left unfilled," in

[87] Ibid.

order to promote drainage.[88] Construction of the altar pedestals also appears unfilled in contrast to previously built solid forms, which the company noted typically resulted in heavily saturated masonry.[89]

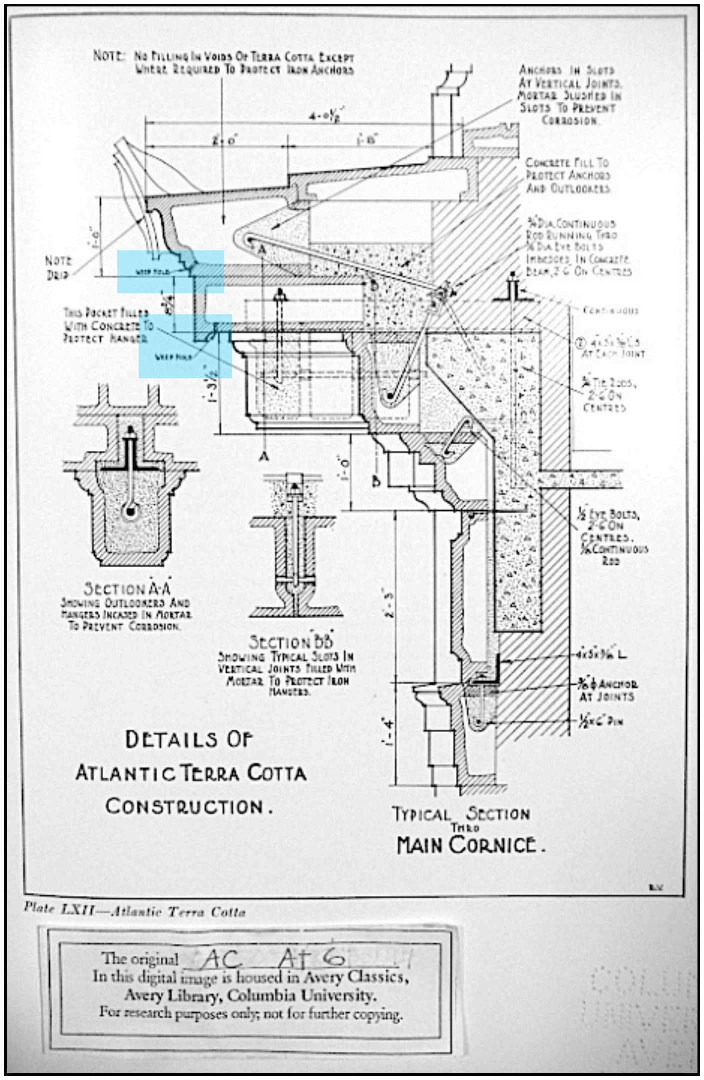

Figure 3.11: Typical section detail of a terra cotta cornice, Atlantic Terra Cotta Company (1924). Weep-holes (highlighted in blue) are specified at the base of overhanging, unfilled terra-cotta cornice units.

[88] Herbert M. Greene Co. Architects, "Details of Construction: Scottish Rite Cathedral, San Antonio, Texas," architectural drawing, *Atlantic Terra Cotta* 6, no. 8 (1924), Plate LV.

[89] Greene Architects, Cameron, and Lorey, "Atlantic Terra Cotta in Combination," Sheet No. 2.

Supplemental construction drawings of a terra cotta cornice at the Scottish Rite Cathedral do not show any provisions for drainage in the January 1924 publication. However, details for a typical cornice in the February issue, and all subsequent issues thereafter, illustrate weep-holes at the base of terra cotta units, which are recommended to remain hollow except where required for protection of anchors (See *Figure 3.11*).

An advertisement produced by the Atlantic Terra Cotta Company, one of the day's leading manufacturers of terra cotta, indicates that their inclusion of weep-holes in cladding drainage stems from contemporary archaeological excavations conducted on an ancient Mesopotamian structure, which reveals the early use of weep-holes in brick structures.

> By introducing weep-holes in Atlantic Terra Cotta Construction we follow a practice that has stood a test of sixty centuries. Recent excavations in Mesopotamia conducted by the Museum of the University of Pennsylvania have cleared a great brick tower erected 6000 years ago, known to be similar in appearance, size and construction to the Tower of Babel... We quote his report in part: "The quality of the brick and of bricklaying is astonishingly good and much of the wall face is as clean and new looking as when built. The surface is relieved by shallow buttresses; a further variety is afforded by the numerous 'weeper holes' running through the thickness of the burnt brick wall for a drainage of the filling, which without this precaution would have swelled with the infiltration of the winter rains and burst the casing."[90]

Looking to this ancient precedent and observation of conditions at existing structures that utilized terra cotta at the facade, the company recommended that although encasement of metal components in concrete was required to prevent corrosion, voids in terra cotta units should generally be left unfilled to minimize damage from water. Noting that fill often became saturated, which increased the potential for rupturing cladding in freezing conditions, the company specified that "the Terra Cotta [*sic*] should be provided with weep-holes to promote drainage and ventilation."[91] This convergence of drainage and ventilation represents somewhat

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[90] "Weep-Holes 6000 Years Ago." *Atlantic Terra Cotta* 7, no. 1 (June 1924).

[91] "Atlantic Terra Cotta Construction: Domed Roof, Finial and Lamp Standards on Tower," *Atlantic Terra Cotta* 6, no. 12 (May 1924), Plates 4 and 5.

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Figure 3.12: A detail titled "Dome Construction with Moulded Ribs" shows weep-holes indicated with the notation"W.H." at the topmost section of the dome. Individual terra cotta units are unfilled.

of a contradiction in understanding the true function of weep-holes, but indicates the progression of thought from ventilation to drainage as a primary means of addressing dampness in walls that was beginning to materialize as a result of ongoing technical examinations of terra cotta.

Throughout the mid-1920s, new details that incorporated weep-holes, flashing, and soft joints appeared in published literature. Weep-holes were often recommended in conjunction with a waterproofing membrane, to provide additional protection against leaks beyond the contractor's control. "In the event of slight leakage, the water cannot penetrate beyond the membrane, and finds its way out through the nearest weep-hole. Thus, saturation is prevented."[92] These changes were recorded in *Good Practice in Construction* by author Philip Knobloch, whose 1927 book showed weep-holes at cornice detailing. This detail was modified from the original publication just four years earlier where weep-holes were not included. The revised 1927 edition of *Standard Construction* published by the National Terra Cotta Society did likewise, including weep-holes in a domed roof construction and a specification that stated "Projecting courses, cornices and heavy ornamental detail may have washes, drips and weep-holes, where shown on the approved shop drawings" (See *Figure 3.12*).[93] The Atlantic Terra Cotta Company acknowledged that refinements such as weep-holes, drip mouldings, and protection of metal were likely to result in increased cost of manufacturing and drafting, but noted that the fundamental importance of including these water-shedding features should become standard industry practice.[94]

Although terra cotta continued to be manufactured through the middle of the 20th century, the popularity of the industry began to decline towards the end of the 1920s and early 1930s as machine-made ceramic veneer, a cost-effective and aesthetically popular material, was introduced.[95] Regardless, the prevalence of early engineering efforts in terra cotta cladding systems would have a profound impact on the way the construction industry began to examine wall performance and building design in a more scientific and more holistic manner. The pioneering efforts from terra cotta manufacturers in the field of wall drainage would later transcend not only terra cotta cladding as the merits of cavity wall construction led to their renewed popularity and use in high-rise buildings during the 1930s and 1940s, but also in the

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92 "Atlantic Terra Cotta Construction: Domed Roof, Finial and Lamp Standards on Tower," Plates 4 and 5.

93 "Standard Specification for the Manufacture, Furnishing and Setting of Terra Cotta, Adopted by National Terra Cotta Society," *Architectural Terra Cotta: Standard Construction*, 2d ed. (New York: National Terra Cotta Society, 1927), Plate 59.

94 "Atlantic Terra Cotta Construction," *Atlantic Terra Cotta* 6, no. 9 (1924).

95 Prudon, "Architectural Terra Cotta and Ceramic Veneer in the United States Prior to World War II," 46-47.

multitude of different wall systems which were to follow during the remainder of the 20th century.

3.6 Development of Weep-Holes in Cavity Wall Construction

It remains unclear exactly how use of the weep-hole transitioned from terra cotta cladding to the cavity wall during the first half of the 20th century. The use of weep-holes in terra cotta cladding, commonly employed by 1930, appears to precede their popular use in cavity wall construction by approximately a decade. By the early 1940s, a general awareness among builders regarding the necessity for wall drainage had developed, along with the recognition that a completely water-tight building was difficult, if not impossible, to achieve. The confluence of a number of factors appear to have aided the development of this realization and the subsequent use of weep-holes in cavity wall construction. First, terra cotta as an industry was so prevalent in its heyday that it is entirely probable that contemporary ideas and techniques from this particular system were effectively transferred into masonry construction as well (i.e. the cavity wall) and became part of standardized thinking within the construction industry. The presence of inherent hollow spaces in both envelope systems, as well as similar concerns about corrosion of metal components within the wall and the difficulty of obtaining tight mortar joints may have contributed to the translation of weep-hole use in brick cavity walls.

Weep-holes were commonly recommended, if not already commonly utilized, in cavity walls by the time the second edition of Ramsey and Sleeper's *Architectural Graphic Standards* was published in 1941. The book illustrates open voids incorporated into the base of load-bearing and panel brick cavity wall construction. This is a marked change from the original 1932 publication, in which only very basic methods for solid and hollow brick wall construction were illustrated.[96] Open vertical joints that functioned as weep-holes were recommended in multiple other sources as well, although use of the term "weep-hole" appears inconsistent, having not yet become part of the standardized lexicon within the industry. In 1942, Mulligan's *Handbook of Brick Masonry Construction* stated, "In a cavity wall with an exterior section only the thickness of one brick (3-3/4 in.), it is expected that in very wet weather water will penetrate through the brick and trickle down the inner face. Some means should be provided to conduct this water to the outside of the wall... Open vertical joints will provide a means of egress for moisture collected on the damp-proof course."[97] Evolving concepts for drainage of the continuous cavity space appear similar to early ideas employed for wall drainage at discontinuous cavity spaces in terra cotta cladding, and contemporary architects and builders may have drawn upon this earlier building wall precedent.

Secondly, condensation became a significant concern among architects and building owners during the 1930s. Although people were already familiar with the idea of condensation, L.V. Teesdale, a senior engineer at the Forest Products Laboratory observed in 1937, "only recently has it become a general problem, particularly in the better class of construction."[98] Teesdale attributed rising concerns about condensation to recent design changes intended to improve the thermal comfort of occupants, and building efforts to decrease heat loss and wind infiltration.[99] These improvements included the use of insulation and weather stripping in cavity and brick

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[96] See Charles George Ramsey and Harold Reeve Sleeper, *Architectural Standards for Architects, Engineers, Decorators, Builders and Draftsmen* (New York: J. Wiley & Sons, Inc., 1932), 16; Charles George Ramsey and Harold Reeve Sleeper, *Architectural Standards for Architects, Engineers, Decorators, Builders and Draftsmen*, 3rd ed. (New York: J. Wiley & Sons, Inc., 1941), 9-10.

[97] Mulligan, *Handbook of Brick Masonry Construction*, 357.

[98] L.V. Teesdale, *Condensation in Walls and Attics* (Washington, D. C.: U.S. Department of Agriculture, Forest Products Laboratory in cooperation with the University of Wisconsin, 1937), 1.

[99] Teesdale, *Condensation in Walls and Attics*, 1.

veneered walls, resulting in overall tighter construction.[100] Thus, wall drainage became an even more pressing issue as temperature differentials were exacerbated in newly constructed wall systems. It is possible that with increased potential for condensation in walls, builders began to look towards their counterparts in the window industry, which had earlier found a means to address the same basic issue.

Finally, the fundamental recognition that water would most likely enter the wall provided the impetus for further scientific research and technical development of wall construction. The principle that the way in which a wall functions relies on performance of the building as a whole, instead of individual component parts, likely prompted architects and builders to treat the detailing of design and construction from a new perspective that involved a holistic view of the structure. It appears that this was on the mind of several building-conscious individuals, as the popularity of weep-holes used in cavity walls can be seen in the array of construction patents filed on the subject of wall drainage, beginning in the late 1930s.

A flurry of sometimes conflicting and convoluted theories of wall drainage emerge from these proposals. Patented weep-hole systems from 1938 to the present day suggest integration of drainage channels into a variety of cavity wall, solid brick wall, brick veneer wall with stud framing, and solid wall configurations of brick facing and concrete masonry unit back-up. Proposed methods of forming weep-holes were varied — lubricated rubber tubing removed from the mortar prior to completely setting; string which was expected to wick water out of the cavity and, upon disintegration, leave voids at joints; and pre-fabricated components that could be

[100] Ibid.

inserted in the mortar joint at appropriate, pre-determined intervals.[101] The lack of cohesion between patented systems indicates some level of confusion surrounding the concept of building wall drainage during the middle of the century. Yet, each system provides an invaluable glimpse into contemporary thought on the subject.

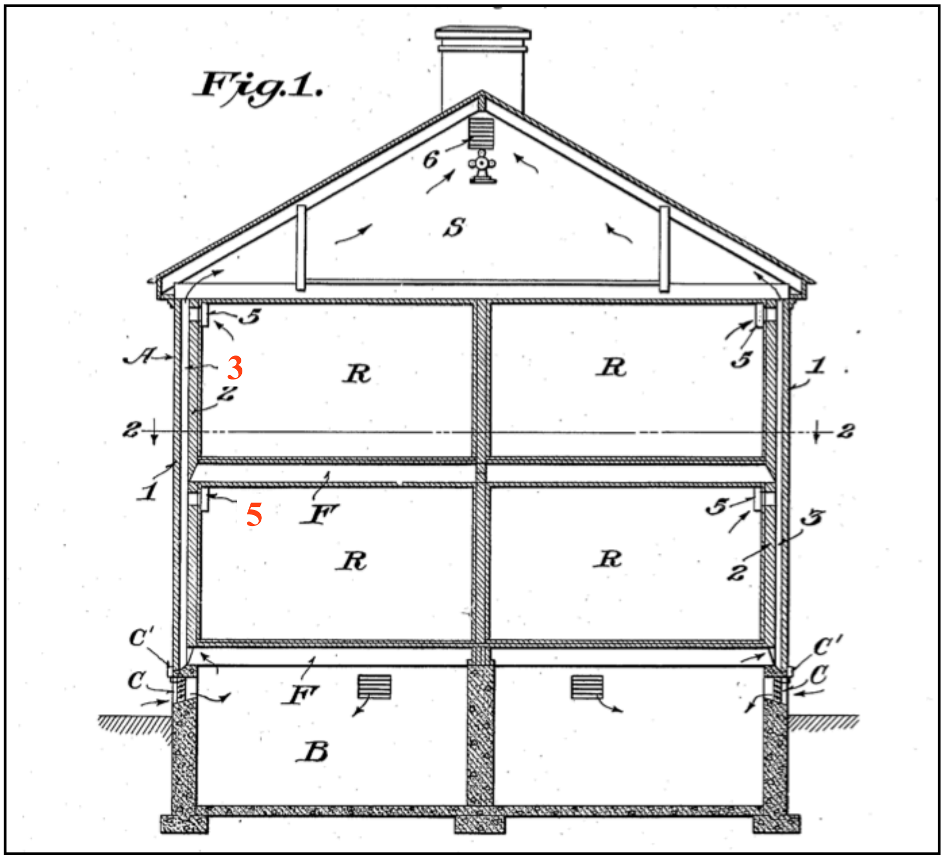

Figure 3.13: A cavity wall assembly with airspace (3), patented by Paul Wood in 1938, incorporates methods of ventilation and drainage with vents (5) connecting interior spaces within the building.

[101] See Abram B. Friedberg, "Flashing," U.S. Patent 1,935,116, filed September 19, 1931, issued November 14, 1933; Paul A. Wood, "Building Construction," U. S. Patent 2,116,859, filed May 10, 1938, issued September 6, 1938; Allison G. Munro, "Brick Wall Construction," U.S. Patent 2,163,286, filed March 18, 1938, issued June 20, 1939; Edwin L. Johnson, "Weep-Hole Form," U.S. Patent 2,934,931, filed November 22, 1954, issued May 3, 1960; William C. Kortvely, "Weephole Ventilator," U.S. Patent 3,257,929, filed March 2, 1964, issued June 28, 1966; Monroe J. Cox and William J. Steier, "Combination Wall Tie, Draft Stop, and Drainage Means for Wall Constructions," U.S. Patent 3,293,810, filed May 22, 1964, issued December 27, 1966; Ben Brewer, "Insect-Proof Weep-Hole," U.S. Patent 3,429, 084, filed July 10, 1967, issued February 25, 1969; David G. Risdon, "Weep-Hole Device," U.S. Patent 4,282,691, filed September 26, 1979, issued August 11, 1981; Ciro Alvarado, "Weep-Hole Cover," U.S. Patent 5,167,104, filed July 8, 1991, issued December 1, 1992; Stephen Paulle, "Wall Drainage Assembly," U.S. Patent 6,105,323, filed May 18, 1998, issued August 22, 2000.

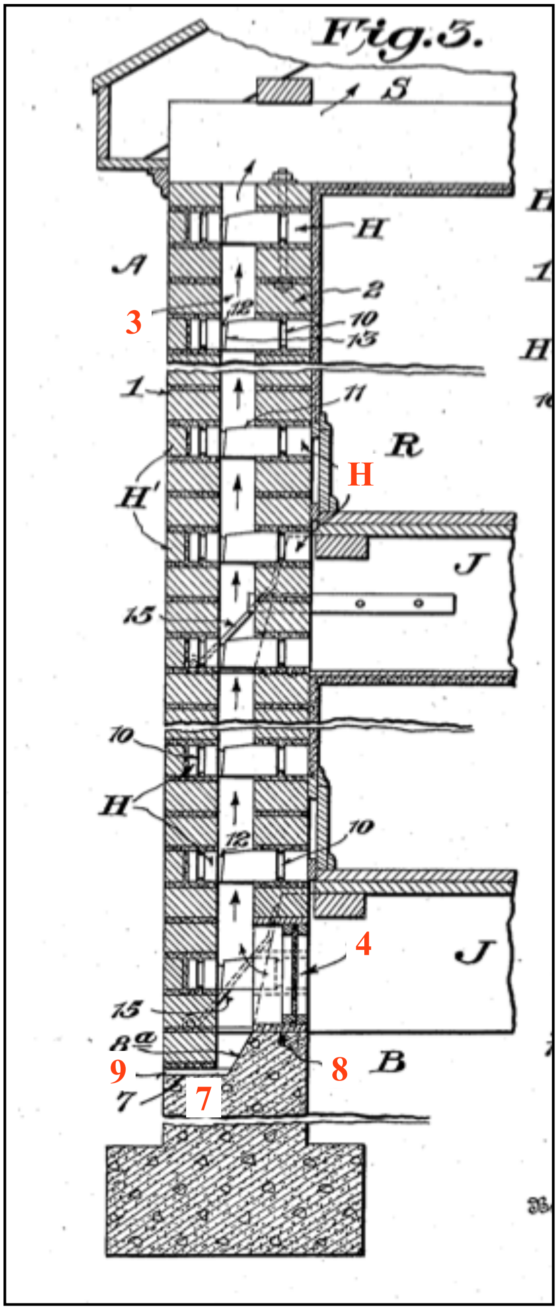

Figure 3.14: Detail of Wood's 1938 patented cavity wall assembly. Grooved brick headers (H) tie the double wythe wall across the cavity air space (3) and are designed to direct water down through the cavity towards the stepped concrete shoulder (7, 8). The inclined shelf is intended to facilitate drainage away from the wall, through weep holes (9) at the base of brick facing. Interior air is connected through vents (4) at the basement space and near the ceiling of individual rooms (seen at 5 in Figure 3.12).

In 1938, Paul A. Wood of Roanoke, Virginia submitted one of the earliest patented wall drainage system that incorporated weep-holes. This patent describes a hollow wall masonry system incorporating both drainage and evaporation intended to render a building "damp-proof or water-proof while at the same time obtaining air conditioning and insulating effects through adequate ventilation" (See *Figures 3.13 & 3.14*).[102] The interior wythe of the proposed cavity wall is equipped with vents at the top of the foundation wall (labeled 4) and ventilators (labeled 5) located near the ceiling of each room. Enclosed foundation spaces and inhabitable room spaces are connected through the horizontally and vertically continuous 2" cavity (labeled 3), which the inventor claims will provide automatic air conditioning by way of convection currents.

Wood proposes other damp-proofing methods at sub-grade walls including an air space that "[serves] as a drain for water and which communicates with a plurality of separate relatively narrow flues in the wall of the building," as well as flashing and drain openings intended to deflect water from the walls to render them damp-proof from the effects of wind-driven rain.[103] As illustrated in Figure 3.14, the stepped concrete shoulder (labeled 8) at the top of the footing forms a lower shelf (labeled 7) seen at the base of the hollow wall. This inclined shelf performs as inherent flashing and directs water "which may make its way through the completed outer wall section outwardly of the building through suitable weep-holes (labeled 9) formed beneath the lower face of the first course of brick on the outer wall section."[104] Special header tiles (labeled H), specified for tying the wythes together, provide grooved surfaces that promote drainage throughout the wall space and direct water to the concrete shoulder and weep-holes below.

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[102] Paul A. Wood, 1938. Building Construction. U. S. Patent 2,116,859, filed May 10, 1938, issued September 6, 1938, 1.

[103] Ibid.

[104] Ibid., 2.

Relying on patents alone certainly does not provide an accurate reflection of the continuing evolution of the weep-hole during the mid and late 20th century. Instead, patents reflect an aspect of contemporary thought, though the extent to which these innovations were used is unknown through patent research alone. Efforts to understand issues of dampness continued well into the middle of the 20th century, with renewed focus on wall drainage in addition to ventilation of the cavity. Although one cannot assume that all individuals who filed patents relating to building construction were necessarily practicing builders, it is reasonable to suspect that they were relatively familiar with building construction. Many were appropriately versed in architectural terms, materials, and contemporary construction problems.

By the end of World War II, the concept of wall drainage appears to be common within various fields of the building industry. However, patents and literature progressing towards the middle of the century exhibit a certain amount of confusion in understanding proper and effective use of weep-holes. The concept of controlling moisture migration through the wall was still largely tied to ideas involving evaporation and ventilation, creating misunderstandings about how moisture could be eliminated from the wall. Trends in technology and materials continued to change at the same time, presumably making it difficult to keep up with understanding how these systems and concepts effectively worked.

The prevalence of wall drainage systems implemented in brick cavity wall systems is unknown. Nor do we know if they were installed, what regions they were used in, how frequently they were installed, or the long term effects of their construction. It is difficult to accurately assess the popularity or effectiveness of their use, but conducting surveys and additional building research may help to determine when and/or where cavity wall drainage was implemented. Case studies with access to interior wall cavities would be further necessary to complete the picture of wall drainage systems and their effectiveness around the United States. The feasibility of such a study may be a prohibitive undertaking for any present day individual or group, especially considering that many of these very early cavity wall design concepts may only have been constructed on individual vernacular or residential buildings, if at all, making access and identification extremely difficult.

Based on information provided in literature from roughly 1900 to 1950, the plethora of wall systems designed to remove moisture from the wall indicates some lack of early success, and it would be fair to speculate that many of these early drainage systems did not work effectively to rid the wall cavity of moisture. However, these seemingly simple voids in the wall membrane are significant not only because they illustrate the transition from ventilation to drainage as the primary means of addressing moisture intrusion, but because they help to keep cavity wall systems dry and aid in our ability to understand performance of the building system as a whole.

The trajectory of the use of weep-hole comprises only a small part of overall efforts to comprehend and improve moisture control in building construction. As noted, wall assembly systems have changed dramatically over the course of the 20th century, including developments in brick veneer, thin-shell masonry cladding methods, and glass curtain wall systems, just to name a few. Although materials and methods have changed, weep-holes continue to be used as a part of all of these systems. Charting the overall course of weep-hole development in these other systems throughout the remainder of the 20th century still has yet to be explored.

CONCLUSION

The effects of dampness on buildings and inhabitants are wide-ranging, and addressing symptoms in each case is made more complex by the difficulties in identifying the cause of moisture, which may originate from multiple sources. Such complexities are reflected in the plethora of sanitary engineering literature from 1870 to 1900. Popular opinion of medical professionals and the public held that disease stemmed from unsanitary ground level conditions that could travel and permeate the air within a confined building space. As a result, primary efforts were directed towards increasing ventilation within the home and within exterior walls. Driven by the need to create healthy living environments, builders engaged in a lengthy trial and error process to create dry interior spaces by mitigating and preventing moisture migration through the envelope during the late 19th and early 20th centuries.

During this period, weep-holes developed in separate building components. First, large scale municipal engineering works necessitated construction of retaining walls for public works projects that involved building dams, water supply systems, and transportation infrastructure beginning in 1870. Weep-holes integrated at the base of sub-grade and retaining walls helped to relieve hydrostatic pressure within the soil that could critically damage structural stability of the wall.

Secondly, weep-holes were frequently used in casement window and skylight construction, particularly after the turn of the 20th century. At the building envelope, the acknowledgment that water penetration was inevitable and efforts to direct water away from the building first appears within glazing systems. Incorporated into the design of the framework, condensation gutters and outlets allowed collected water to drain outwards of the window or skylight system. Additionally, builders recognized the existence of differential pressures between indoor and outdoor spaces, and used this condition advantageously by constructing outwardly-opening casement windows in order to minimize water penetration at these components.

Thirdly, widespread use and increased development of terra cotta cladding led to a more informed understanding of building wall performance during the early 20th century. Recognition that terra cotta did not provide a water-tight surface, despite its perception as an impervious glazed surface, and concerns about saturated masonry fill compelled architects and engineers to address water penetration of integral terra cotta cladding. Beginning after 1920, leading companies such as the Atlantic Terra Cotta Company and the National Terra Cotta Society depicted weep-holes in standard construction details as one means to address widespread deterioration of joints, steel anchor supports, and exterior wall cladding, and damage to interior finishes by providing drainage of partially-filled or unfilled terra cotta units.

Following the decline in popularity of terra cotta, weep-holes used in cavity walls began to appear in standard brick construction manuals after 1940. Although through-wall channels have been used in masonry walls for several centuries, perforations within the cavity wall fabric were typically used for wall ventilation instead of drainage prior to 1940. Wall drainage as a means of maintaining a dry wall is a relatively recent 20th century concept. Based on patents filed from 1938 to the present day, builders continued to experiment with wall drainage in both solid wall and cavity wall systems for some time. Modern developments in construction include increased use of weep-holes at brick cavity walls, drainage of envelope components, and advanced scientific understanding of the rain screen principle, which developed after 1950.

Weep-holes are only a small part of the overall effort to comprehend and improve building performance. Through construction of the cavity wall, many early builders initially desired to create a completely dry wall and early efforts focused on trying to increase ventilation within the wall. Driven by advancements in materials engineering and scientific testing, a progressive understanding that building envelopes were not water-tight led to the recognition that water needed to be removed from the wall by means other than ventilation. By the middle of the 20th century, the necessity for wall drainage was clear. This understanding informed builders that, contrary to instinct, providing open joints at the exterior wythe could in fact lessen water penetration at dry interior spaces and better enable the wall to shed any water that breached the protective outer wythe.

Implementation of water drainage systems in walls was a complex endeavor during the early 20th century and remains so today. While advancements in construction technology continue to be made, moisture intrusion through the envelope remains a problem. Cross-pollination of related ideas that has occurred throughout history in separate building elements stresses the need for continued communication across a variety of different architectural, engineering, and construction disciplines. With continued research, understanding the transition from ventilation and evaporation of the wall to the evolution of wall drainage can serve as a foundation for ongoing and future technical dialogue, one that reflects the delicate balance of material condition, thermal insulation, and future building performance. With this understanding comes a hope for improved maintenance practices for the increased longevity and protection of a wide range of our collective historic built fabric.

RECOMMENDATIONS FOR FURTHER RESEARCH

It is the author's hope that this thesis may provide a foundation for additional research on the subject of building wall drainage and weep-holes. Areas for further study may include, but is certainly not limited to, the following:

- Development of weep-holes used in masonry civil engineering for public works projects.

- Development of weep-holes used in window systems.

- The use of weep-holes in wall systems after 1930. Areas of study may include cast stone, stone veneer, brick veneer, cavity walls, curtain walls, and exterior insulated finished systems, among others.

- Growth of the insulation industry and related development of moisture control practices during the late 1930s and early 1940s.

- Development of weep-hole forms, i.e., voids in mortar, voids formed by removal of string, manufactured weep-hole products.

- A technical evaluation of freeze-thaw expansion and contraction conditions at saturated masonry fill.

- A technical conservation investigation on the effectiveness of weep-holes.

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APPENDIX A

TIMELINE OF KEY WEEP-HOLE-RELATED EVENTS

A general timeline of information pertaining to the evolution of wall drainage is provided here, to help situate the reader's understanding of weep-holes within broader contextual events during the 19th and first half of the 20th centuries.

1st Century B.C.

Vitruvius writes *The Ten Books on Architecture* and proposes the cavity wall as a solution to dampness. In his text, he introduces the cavity wall to address primary building concerns of structural stability and protection of interior finishes. First, by removing rubble fill within the wall, builders could help prevent loss of mortar strength and wall deterioration by leaving the wall space hollow.[105] Secondly, he advises builders to construct vents through the cavity wall in order to promote communication between fresh air and air within the cavity. "For if the moisture has no means of getting out by vents at the bottom and at the top, it will not fail to spread all over the new wall."[106] Ventilation, and thus evaporation, is viewed as a primary means by which to mitigate the presence of dampness.

1738

Palladio states, "It is very commendable in great fabricks [*sic*], to make some cavities in the thickness of the wall from the foundation to the roof, because they give vent to the winds and

[105] Vitruvius, *The Ten Books on Architecture*, trans. Morris Hicky Morgan (New York: Dover Publications, Inc., 1960), 51.

[106] Vitruvius, *The Ten Books on Architecture*, trans. Morris Hicky Morgan (New York: Dover Publications, Inc., 1960), 209.

vapours, and cause them to do less damage to the building."[107] No mention is made of wall drainage.

1821

One of the earliest known 19th century descriptions of a hollow wall is given in *Hints on an Improved Method of Building*, by Thomas Dearn. As noted in T. Ritchie's "Notes on the History of Hollow Masonry Walls," Dearn's description of the cavity wall consists of two walls, each 4-1/2" thick, with a 2" thick air space in between.[108]

1830s

Conductor of *The Architectural Magazine* and author of *An Encyclopaedia of Cottage, Farm, and Villa Architecture*, J. C. Loudon publishes multiple methods of constructing walls of stock brick in configurations that form individual, hollow spaces. The general reasoning is, voids "will prove an antidote to damp" by allowing air circulation and ventilation.[109] The primary intent of these methods is to address issues of rising damp at the foundation and at basement/cellar spaces.

1850s

Domestic architecture continues to be the context for further development of the hollow-brick wall concept. The popularity of hollow-brick walls also results in several patented molds for creating fired clay units with voids.

Andrew Jackson Downing's *Architecture of Country Houses* is published in 1850. Downing identifies the following four advantages of hollow brick wall construction: 1) Savings of brick

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107 Palladio, *The Four Books of Architecture*, 7.

108 T. Ritchie, "Notes on the History of Hollow Masonry Walls." *Bulletin of the Association for Preservation Technology* 5, no. 4 (1973): 40-49.

109 Loudon, *Cottage, Farm, and Villa Architecture*, 172.

and mortar, 2) Prevention of dampness, 3) Savings of lathing and studding at interior walls, and 4) Security from fire. He illustrates walls comprised of multiple individual hollow spaces (i.e., not a continuous cavity) and credits introduction of the hollow wall in America to his colleague Ithiel Town.[110]

1856 - 1874

Construction of an 82-mile long sewage system takes place in London. Headed by chief engineer Sir Joseph Bazalgette, the new system is devised to discharge sewage below the level of the Thames River, to prevent stagnant sewage from intermixing with the city's drinking water, and to remove it from within city boundaries.[111]

1860s

In part stimulated by public health concerns and the desire to provide fresh water to citizens, municipalities throughout the world begin to invest in public works projects such as dams and drainage sewers, particularly during the latter half of the 19th century. Additionally, large scale railway transportation systems are constructed in major cities such as New York and London. These projects, which require significant amounts of excavation and construction of new infrastructure, necessitate the use of well-engineered retaining walls and revetments.

1870s

Sanitation becomes a major public health concern. The fields of architecture and medicine are intertwined, as doctors attempt to rationalize the spread of disease by addressing defects within the built environment. A paper presented at the Annual Meeting of the American Public Health

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[110] Downing, *Architecture of Country Houses*, 59.

[111] William J. Healy, *Public Utility Galleries and Sewerage Systems of Europe* (Chicago: 1914), 13.

Association states, "after medicine, 'as professions most concerned in the preservation of public health rank those of the Architect and Engineer.'"[112]

Architect Carl Pfeiffer further states that the "Science of Ventilation" and subsequently, sanitation, "is a question which affects not merely the personal comfort of individuals, but according to the opinion of the ablest pathologists, it influences the health and affects the duration of life."[113] Attempts to provide means for ventilation and evaporation, which are believed to be key components to promoting a healthy and dry building, are common in the construction of cavity walls. However, these attempts do not necessarily result in effective prevention of dampness.

1872-1873

In "Notes on Retaining Walls," engineer J.H.E. Hart describes *weepers* as "rectangular holes about 2 inches wide, passing through the [retaining] wall from rear to front... so as to permit the escape of any water that might find its way to the back of the wall."[114] The terms *weeper* and *weeping hole* appear within additional literature on retaining walls, published by the Thomason Civil Engineering College at Roorkee, India.[115]

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[112] Carl Pfeiffer, "Sanitary Relations to Health Principles in Architecture" (presentation, Annual Meeting of the American Public Health Association, New York, NY, 1873), 3.

[113] Carl Pfeiffer, "Sanitary Relations to Health Principles in Architecture" (presentation, Annual Meeting of the American Public Health Association, New York, NY, 1873), 15.

[114] A.M. Lang, ed., *Professional Papers on Indian Engineering*, vol. 1, "Notes on Retaining Walls," by J.H.E. Hart (Roorkee: Thomason College Press, 1872), 146.

[115] A.M. Lang, ed. *The Roorkee Treatise on Civil Engineering in India*, vol. 1 (Roorkee: Thomason College Press, 1878), 431; J. H. C. Harrison, *The Roorkee Manual of Applied Mechanics; Stability of Structures and the Graphic Determination of Lines of Resistance*, vol. 2 (Roorkee: Thomason Civil Engineering College Press, 1900), 180.

1880s

Various means of drainage are commonly applied in the construction of retaining walls. The terminology, which includes *weepers*, *weeper holes*, *weeping holes*, and *weep-holes*, appears to be commonly understood and utilized within engineering journals by the 1890s.

Professional "sanitary inspectors" and "building doctors" commonly attempt to diagnose problems in architecture and examine the work of builders and plumbers, in particular, to ensure construction of a healthy building.[116] By raising consciousness about sanitation amongst the general population, the medical profession also stimulates public fear.

During the last two decades of the 19th century, as the work of architects and builders begins to take shape as a profession, information contained within building construction manuals is presented in a more sophisticated manner in terms of structure of content and scientific support of material. However, construction manuals frequently allude (without scientific evidence) to adverse health effects that result from inhabiting damp structures. At this time, cavity walls and walls made of hollow-bricks are used extensively.[117]

1884

London hosts the International Health Exhibition (IHE). Full-size sectional models of "Sanitary and Insanitary Dwellings" are created for exhibition. Turnout at the IHE exceeds the anticipated attendance of 4 million visitors.[118] Number of attendees and the exhibition itself are indicative of the extent to which public concern is focused on health and sanitation, particularly in cities.

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[116] Annmarie Adams, *Architecture in the Family Way: Doctors, Houses, and Women, 1870-1900* (Montreal: McGill-Queens University Press, 1996), 47.

[117] Powell, *Foundations*, 73.

[118] Annmarie Adams, *Architecture in the Family Way: Doctors, Houses, and Women, 1870-1900* (Montreal: McGill-Queens University Press, 1996), 13-14.

1890s

By the 1890s, metal wall ties, commonly used to bond inner and outer wythes, are preferred over brick headers because they help address the issue of cold-bridging. Ties are twisted in the middle to prevent moisture traveling along the bond from reaching the inner wythe, and direct moisture towards the base of the cavity.

1894

Window condensation gutters, presumably with "the so-called outlet holes which are necessary to complete the function of the lip or gutter," are introduced by window manufacturer Henry Hope & Sons in New York.[119] Over the course of the next 25 years, use of condensation gutters and weep-holes becomes relatively common in the manufacture of casement windows. By 1919, however, Henry Hope & Sons decides to abandon this system in favor of a sill channel at the interior of the room, claiming (incorrectly) that condensation "only occurs during the first few months of occupation of a new building" and that weep-holes "only serve as inlet holes for rain and wind during cold and stormy weather."[120]

1900s

Methods of constructing cavity walls are still commonly described in construction manuals during the early 20th century, even though the Building Research Institute remarks in 1960 that, based on evidence from demolition projects, the use of cavity walls significantly declined from approximately 1900-1930.[121] The use of hollow-brick and hollow-concrete walls is common,

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[119] Henry Hope & Sons, *Hope's Casements and Leaded Glass* (New York: No publisher listed, 1919), introduction.

[120] Henry Hope & Sons, *Hope's Casements and Leaded Glass* (New York: No publisher listed, 1919), introduction.

[121] *Insulated Masonry Cavity Walls*. Washington, D.C.: National Academy of Sciences, National Research Council, 1960.

while configurations such as Dearn's and Loudon's methods for hollow wall construction, seen almost a century earlier, also continue to be recommended for construction.[122]

Construction diagrams illustrate the introduction of air bricks at the base of the exterior wythe, thereby connecting the cavity space to exterior fresh air with the purpose of increased ventilation of the wall. However, use of air-bricks is inconsistent as they are also placed in various other configurations within the exterior and interior wythes of the wall.

1910s

The 10th edition of *A Treatise on Masonry Construction*, by Ira O. Baker, directly states, "There is not even a remote approach to uniformity in the specifications for the brick-work of buildings."[123] This admission helps to explain the general sense of confusion regarding terminology (interchangeable use of the terms *hollow wall*, *hollow-brick wall*, and *cavity wall*, for instance), as well as the variety of construction methods used to mitigate dampness.

Windows that employ weep-holes are seen in various magazine advertisements, as well as *Sweet's Catalogue of Building Construction*. Sometimes referred to as *drip holes*, *port holes*, or simply *outlets*, use of these drainage elements in combination with condensation gutters are primarily seen in casement windows and skylights. Variations in terminology and use indicate a general lack of standardization of this matter within the industry.[124]

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[122] T. Ritchie, "Notes on the History of Hollow Masonry Walls." *Bulletin of the Association for Preservation Technology* 5, no. 4 (1973): 45.

[123] Ira O. Baker, *A Treatise on Masonry Construction*, 10th ed. (New York: John Wiley and Sons, 1889), 178.

[124] See *Sweet's Catalogue of Building Construction* (1911), 512-526; *Sweet's Catalogue of Building Construction* (New York: The Architectural Record Company, 1915), 570-595, 736-743, 972; Canton Art Metal Company, "Skylights," 10.

1920s

Scientific studies on and closer examination of terra cotta, which is widely used as an exterior wall cladding material in North America, helps facilitate the realization that buildings are not water-tight. At this time, the practice of filling terra cotta units also changes, and builders begin to leave the voids in terra cotta unfilled in order to promote drainage, except where necessary to protect metal anchors.

1921

At the Seventeenth Annual Convention of the American Concrete Institute, the Committee on Nomenclature denotes several proposed changes in definitions from a preceding report issued in 1919. The weep-hole is defined as "A hole in a wall, floor or other structure made for the purpose of *providing* drainage."[125] (Italics denote change.)

1924

In their monthly series, Atlantic Terra Cotta publishes engineering findings and observations regarding deterioration of terra cotta in existing structures. The company recommends increased attention to and detailing of flashing and joints. Construction details show voids left unfilled during application, in order to encourage drainage across a waterproofing membrane. The designation "W.H." is commonly seen in drawings, indicating a weep-hole in terra cotta units.

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[125] "Report from the Committee on Nomenclature," in *Proceedings of the Seventeenth Annual Convention*, by the American Concrete Institute (Chicago: American Concrete Institute, 1921), 323.

1927

The National Terra Cotta Society publishes the second edition of *Standard Construction*, which now illustrates weep-holes in detail drawings. “Washes, drips and weep-holes” are included in a new standard specifications section for design and structure.

1930s

The popularity of terra cotta declines as machine-made ceramic veneer, a cost-effective and aesthetically popular material, is introduced.[126]

1940s

With cavity walls “becoming more and more popular in [the United States],” *Principles of Brick Engineering* provides the following information regarding their construction: “The air space or cavity is provided with weep-holes, formed by omitting mortar from vertical exterior joints at the bottom of the air space to permit the escape of any moisture that might accumulate.”[127] By this time, the cavity wall is primarily employed to provide insulation and to prevent moisture.

1941

In contrast to the original 1932 *Architectural Graphic Standards* by Ramsey and Sleeper, the revised edition of this influential and comprehensive resource contains an expanded section of cavity wall sections, depicting weep-holes at the base of cavity walls. Additionally, weep-holes are depicted in terra cotta units, used at soffits, copings, and balustrades, and above lintels.

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[126] Prudon, “Architectural Terra Cotta and Ceramic Veneer in the United States Prior to World War II,” 46-47.

[127] Plummer and Reardon, *Principles of Brick Engineering*, 147.

APPENDIX B

GLOSSARY

The list of following terminology has been compiled from various sources in an effort to help clarify terms used in this thesis.

Absorption: Absorption is the reception of gas, vapor, or liquid into a material by molecular or chemical attraction.[128]

Air-Brick: A hollow and pierced brick or piece of hard material, about the size of a brick, built into a wall with ordinary bricks to allow the passage of air.[129] A perforated brick built into a wall to allow air to enter a space.[130]

Air Drain: Air drains are cavities between the earth and the external, sub-grade walls of a building to prevent the penetration of damp through prolonged contact with the earth and to prevent transfer of moisture through capillary action. Air drains typically measure 9" thick or greater.[131]

Brick: A walling unit made of clay, sand and lime, or concrete, moulded into a rectangular shape while plastic, and capable of being picked up and laid with one hand.[132]

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[128] William Dwight Whitney, *The Century Dictionary and Cyclopedia*, vol. 1, "Absorption" (New York: The Century Company, 1906), 22-23.

[129] Sturgis, *A Dictionary of Architecture and Building*, 355.

[130] Curl, *Encyclopaedia of Architectural Terms*, 8.

[131] *Advanced Building Construction,* 60; Curl, *Encyclopaedia of Architectural Terms*, 8.

[132] Curl, *Encyclopaedia of Architectural Terms*, 55.

Brick Veneer: Brick facing material typically applied over wood framing and sheathing. It is non-load-bearing and is found principally in residential construction.[133]

Capillary Action: Capillary action is the ability of liquid to flow through the narrow tube-like spaces of a material, as a result of inter-molecular attractive forces and surface tension within the walls of the tube. It is stronger within narrower spaces, and may occur in opposition to gravity.[134]

Cavity Wall: A wall composed of two parts, where the inner and outer leaf are separated by a horizontally and vertically continuous space. The wythes are tied together with metal connections. The cavity wall provides improved thermal insulation and lessens the possibility of penetration by dampness.[135]

Cold-Bridging: Heat flows through a material "bridge" such as a metal or brick header connection that is the path of least resistance in a layer of insulation. Due to temperature differentials, condensation occurs when areas adjacent to metal or brick ties reach dew point conditions and result in unsightly patches of dampness at interior finishes.[136]

Condensation: When warm, moisture-laden air comes into contact with a cooler surface, the water vapor present in the air transforms into liquid. The amount of saturation is known as relative humidity, and the temperature at which fully saturated water vapor precipitates is known as the dew point.[137] The term "condensation" describes this phenomenon, which often occurs

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[133] Plummer and Reardon, *Principles of Brick Engineering*, 150.

[134] Gratwick, *Dampness in Buildings*, 27.

[135] Curl, *Encyclopaedia of Architectural Terms*, 73.

[136] See Gratwick, *Dampness in Buildings*, 252; Lowndes, *Brick, Stone, and Plaster*, 43; *Advanced Building Construction*, 62; Powell, *Foundations and Foundation Walls*, 86; Mulligan, *Handbook of Brick Masonry Construction*, 355-356; Jaggard and Drury, *Architectural Building Construction*, 22; Plummer and Reardon, *Principles of Brick Engineering*, 147-148; Giovanni and Ippolito Massari, "Damp Buildings, Old and New," *APT*, 21.

[137] Olmsted, *A Compendium of Natural Philosophy*, 152.

within cavity walls where the airspace forms a barrier between the cooler outside atmosphere and a warmer, more humid indoor atmosphere.

Damp-proof Coursing: Damp-proof coursing is the installation of a water barrier at the foundation level, designed to prevent or mitigate the spread of rising damp.

Foundation Areaway: See air-drain.

Header: A brick laid so that only its short face appears at the surface of the wall.[138]

Hollow Wall: A wall built in two thicknesses with a 2" to 3" thick continuous vertical, but not horizontal, cavity between the inner and outer shells of the wall for the purpose of saving material, thermal insulation, and prevention of dampness.[139]

Hollow-Block Wall: See hollow-brick wall. A hollow-block wall may also refer to a specially molded unit composed of cementitious material.

Hollow-Brick Wall: A wall constructed of specially molded fired-clay units that are perforated with open spaces. They are employed in wall construction for the purpose of constructing inherently thermal insulated and in theory, well-ventilated walls.

Rain Screen Principle: A theory governing the design of a building enclosure in such a way as to prevent water penetration due to rain by providing pressure equalization.[140]

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[138] Curl, *Encyclopaedia of Architectural Terms*, 55.

[139] Exact definitions vary between sources. See Burn, *The New Guide to Masonry*, 122; Gwilt, *An Encyclopaedia of Architecture, Historical, Theoretical, and Practical*, 986.

[140] *The Rain Screen Principle and Pressure-Equalized Wall Design*, AAMA, 1.

Retaining Wall: A wall built to retain a bank of earth: it is often battered, and sometimes battered and arched with concave arched walls behind the openings to resist the thrust of the earth behind. A revetment.[141]

Revetment: Retaining wall. Also any facing of stone on a construction not intended to be seen.[142]

Rising Damp: Rising damp refers to the upward movement of water through a material via capillary action.

Solid Wall: A brick wall, commonly used, that consists of a solid mass of brickwork with no hollow spaces in it. This type of wall is substantial, easy to construct, and economical.[143]

Veneered Wall: A wall with a facing fixed to a backing, but incapable itself of sustaining a load.[144]

Water-proofing: An impervious wall lining applied to prevent moisture from penetrating to the interior of the wall.

Weep-Hole: A small drainage hole for water to escape.[145] Voids formed by omitting mortar from vertical exterior joints at the bottom of the air space within a cavity wall in order to permit the escape of any moisture that might accumulate within.[146]

Wind-Driven Rain: Wind-driven rain is rain falling with a horizontal velocity onto the exterior surfaces of a building

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[141] Curl, *Encyclopaedia of Architectural Terms*, 264.

[142] Ibid.

[143] Lowndes, *Brick, Stone, and Plaster*, 25.

[144] Curl, *Encyclopaedia of Architectural Terms*, 336.

[145] Curl, *Encyclopaedia of Architectural Terms*, 342.

[146] Plummer and Reardon, *Principles of Brick Engineering*, 147.

APPENDIX C

LIST OF IMAGE SOURCES

<u>Chapter 2</u> <u>Source</u>

Figure 2.1 Downing, Andrew Jackson. *Architecture of Country Houses: Including Designs for Cottages, Farm-Houses, and Villas, with Remarks on Interiors, Furniture, and The Best Modes of Warming and Ventilating*. New York: D. Appleton & Co., 1850. Page 61.

Figure 2.2 Ramsey, Charles George, and Harold Reeve Sleeper. *Architectural Standards for Architects, Engineers, Decorators, Builders and Draftsmen*. New York: J. Wiley & Sons, Inc., 1932. Page 47.

Figure 2.3 Ramsey, Charles George, and Harold Reeve Sleeper. *Architectural Standards for Architects, Engineers, Decorators, Builders and Draftsmen*, 3rd ed. New York: J. Wiley & Sons, Inc., 1941. Page 10.

Figure 2.4 Author's illustration.

<u>Chapter 3</u>

Figure 3.1 Loudon, J. C. *The Architectural Magazine and Journal of Improvement in Architecture, Building, and Furnishing and in the Various Arts and Trades Connected Therewith*. Vol. 1. "On A Method of Preventing Damp From Rising in the Walls of Buildings on Clay and Other Moist Soils," by William J. Short. London: Longman, Rees, Orme, Brown, Green, and Longman, 1834. Page 233.

Figure 3.2 Haglock, F. W. "Concrete Block Walls Act as Ventilators." *The National Builder* 47, no. 4 (1908). Page 28.

Figure 3.3 Adams, Henry. *Cassell's Building Construction: Comprising Notes on Materials, Processes, Principles, and Practice*. London: Cassell and Company, Limited, 1913. Page 42.

Figure 3.4 "The Underground Railway, New York City." *Scientific American Magazine* 31, no. 24 (December 12, 1874). Page 371.

Chapter 3	Source
Figure 3.5	*Notes on Building Construction: Arranged to Meet the Requirements of the Syllabus of the Science and Art Department of the Committee of Council on Education, South Kensington*, Part 1. London: Rivingtons, 1875. Page 205.
Figure 3.6	Canton Steel Roofing Company. "Skylights." Advertisement in *Carpentry and Building* 30, no. 2 (February 1908). Page 10.
Figure 3.7	Vaile & Young. "Skylights and Architectural Sheet-Metal Work." *Sweet's Catalogue of Building Construction*. New York: The Architectural Record Company, 1911. Page 526.
Figure 3.8	"Heavy Bracketed Cornice with Ornamented Cheneau Showing Method of Support and Anchorage." *Architectural Terra Cotta: Standard Construction*. New York: National Terra Cotta Society, 1914. Plate 24.
Figure 3.9	"Heavy Bracketed Cornice with Ornamented Cheneau Showing Method of Support and Anchorage." *Architectural Terra Cotta: Standard Construction*. New York: National Terra Cotta Society, 1927. Plate 24.
Figure 3.10	Herbert M. Greene Architects, Ralph H. Cameron, and Edward W. T. Lorey. "Atlantic Terra Cotta in Combination," *Atlantic Terra Cotta* 6, no. 8 (January 1924). Plate LV.
Figure 3.11	Herbert M. Greene Architects, Ralph H. Cameron, and Edward W. T. Lorey. "Atlantic Terra Cotta in Combination," *Atlantic Terra Cotta* 6, no. 8 (January 1924). Plate LXII.
Figure 3.12	"Dome Construction with Moulded Ribs: Terra Cotta Covering Between and Skylight Curb." *Architectural Terra Cotta: Standard Construction*, 2d ed. New York: National Terra Cotta Society, 1927. Plate 59.
Figure 3.13	Wood, Paul A. "Building Construction." U.S. Patent 2,116,859. Filed May 10, 1938. Issued September 6, 1938. Sheet 1.
Figure 3.14	Wood, Paul A. "Building Construction." U.S. Patent 2,116,859. Filed May 10, 1938. Issued September 6, 1938. Sheet 3.

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"Atlantic Terra Cotta Construction: Construction and Flashing of Entrance Feature." Plate 8. *Atlantic Terra Cotta* 7, no. 1 (June 1924).

"Atlantic Terra Cotta Construction: Construction and Flashing of Main Cornice." Plates 6 and 7. *Atlantic Terra Cotta* 7, no. 1 (June 1924).

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