XII DBMC
International Conference on Durability of Building Materials and Components
PORTO - PORTUGAL, April 12th-15th, 2011

Movement Provisions in Exterior Cladding Systems: History and Evolution of Details and Materials

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ABSTRACT

All building cladding materials expand and contract as a result of environmental variations and material properties. Fired clay products, such as brick and terra cotta, expand as they absorb atmospheric moisture in the first years of service. Concrete products, such as concrete block, cast stone, and reinforced concrete, shrink as they cure. Thermal movements are proportional to the coefficients of thermal expansion of the materials and can vary dramatically. Structural systems, particularly reinforced concrete, also shrink or shorten over time as a result of sustained loading. Cladding systems are a complex assemblage of various components, systems and materials which are all subjected to various movements resulting from material properties, thermal cycles and structural behavior. These factors result in a complex multi-dimensional interaction, which if not properly accommodated can cause significant distress and deterioration in exterior cladding systems. These movements have historically been addressed both passively through subtleties in the details and actively with the incorporation of expansion joints. However, the materials used and the details themselves often lacked adequate movement capabilities and had limited long term effectiveness.

This paper will review the historical development of expansion provisions in cladding systems in the United States and will be divided between detailing considerations and materials. Various specific case studies will be included to demonstrate the historical evolution of movement detailing, materials, and specific detailing and design of movement provisions.

KEYWORDS

Expansion joints, Movement joints, Movement provisions.

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1 INTRODUCTION

All buildings are exposed to natural environmental forces including wind, moisture in various forms and temperature variations. Over time, these forces begin to reduce the durability of building systems and materials. While building materials and typologies vary based on region, historical precedent, culture and function, building systems must interact and respond to these forces. Buildings have also become larger and more complex. Technologies and tastes change and evolve, yet at their basic essence, a building provides enclosure and protection from environmental forces. As building technologies have advanced, materials and systems have been combined in new and different combinations with increased complexity. A major ramification of this evolution of technologies and materials is a lag in the understanding of how various materials and systems can be combined to perform effectively and remain durable. Different material and physical properties introduce the need to allow the materials and systems to remain serviceable. Expansion joints are one of the methods which are incorporated into building systems to accommodate differential and anticipated and unanticipated movements. This paper will present a brief overview of the need for and development of expansion joints. Case studies will be introduced which exemplify atypical situations.

2 WALL ASSEMBLY MATERIALS AND SYSTEM MOVEMENTS

2.1 Expansion/Contraction Due to Thermal Changes

All materials increase in volume when heated, and decrease in volume when cooled; in summer months a typical wall will be greater in length and height than in winter months. All materials are susceptible to seasonal changes as well as daily changes in temperature from night to day. The amount of volume change that occurs is a function of the temperature change, and the material's coefficient of thermal expansion. Masonry has a unique and less understood property which is the irreversible nature of this process overtime. When a masonry system consisting of masonry units and mortar in between undergoes contraction, the individual masonry units contract as well, creating minute separations between the masonry units and the mortar binder. Fine debris collects in these separations, preventing the units from fully re-engaging with the mortar during an expansion cycle, wedging the materials apart. These small displacements accumulate over the length of the masonry section, resulting in net expansion of the masonry system over time.

2.2. Expansion/Contraction Due to Moisture Absorption

Another unique characteristic of clay-based masonry units is that they are the smallest they will ever be when leaving the kiln after the firing process due to the virtual absence of moisture in the units. As the units are exposed to the normal in-service environment, they absorb atmospheric moisture and expand in volume. Once the masonry unit's moisture content reaches equilibrium with the environment, the unit volume stabilizes, with only minor increases over time and some cyclic changes in volume due to seasonal fluctuations in environmental moisture.

2.3 Differential Volume Changes in Construction Materials

Variations in thermal coefficients result in adjacent materials expanding and contracting different amounts. Other physical properties such as reaction to moisture can create differential volume changes. If materials in contact expand or contract at different rates, then stresses can develop between the two as the material with a smaller volume changes restrains the one with a larger volume change. If these distinctly different materials were rigidly connected the expanding material develops compression forces because it is restrained by the shrinking material. Conversely, the shrinking material tends to crack or pull apart due to tensile stresses that result as it is "dragged" by the expanding material.

2.4 Structural Frame Shrinkage

A condition unique to some structures is the impact of irreversible shrinkage and creep over time on materials such as concrete and wood. As the structural frame loses moisture it reduces in volume, resulting in a shortening effect on the structure. Typically the large majority of shrinkage occurs in the first few years of service but can continue for several years after, depending upon the exposure of the materials to environmental conditions, until it reaches equilibrium with the surrounding atmosphere. This type of volume change results in a vertical shortening of the structural frame that is in conflict with materials that remain constant or increase in volume over time.

2.5 Structural Frame Creep

When load is applied to structure and sustained, it will initially deflect but then continue to deform over time. This long-term change in volume due to application of load or stress is referred to as creep. Creep typically results in a continual vertical shortening of the structural frame due to the sustained application of dead load. Similarly to shrinkage, the majority of creep will impact a structure shortly after loading, but can continue to have a modest effect throughout the life of the structure.

2.6 Movement due to Lateral, Seismic and Gravity Loads

Whenever load is applied to a structural element, it undergoes displacement. The amount of displacement is dependent on the magnitude of the load, the direction of the load, and the physical properties of the structural element. All wall systems are exposed to lateral loads from either wind or seismic events, as well as gravity loads in the form of both dead (self weight, and permanent applied loads) and live loads (transient, occupancy-based loads). These loads can either affect the wall system directly, or cause deflections of the back-up structure supporting the materials that is then translated to the cladding material through the connections or supports securing it to the structure. The deflections resulting from the application of these loads need to be accommodated to limit cracking and damage where the stresses exceed the tensile capacity of the material.

3 WALL SYSTEM EVOLUTION

Wall systems undergo movements for many reasons. As our understanding of construction materials increased, so did the recognition that these movements need to be accommodated to prevent damage to the wall structure. This accommodation was accomplished by the introduction of expansion joints.

To understand the development of expansion joints into building construction, it is necessary to understand how building construction has evolved. For purposes of discussion, the evolution of building construction can be divided into four general time periods: the period before the Industrial Revolution (before 1870), the period of the Industrial Revolution through the beginning of 20th Century, the period between 1900 and World War II and the period beginning around 1950 through today.

3.1 Pre-Industrial Revolution (before 1870)

Buildings constructed prior to the Industrial Revolution were generally smaller, simple structures built from local materials, based on historical precedent, and of vernacular style. Structural systems were usually simple consisting of bearing walls and timber roofs. The walls served the dual purpose of providing weather protection and structural support. Mass monolithic masonry walls function by absorbing moisture and holding the moisture within the masonry until it evaporates. Expansion joints were not explicitly included in these buildings. Building movements were accommodated by the materials and construction systems which had sufficient ductility and flexibility to accommodate such movements. Even masonry structures, normally considered rigid and brittle, were constructed with lime putty mortars which allowed for some movement without compromising the integrity of the structure.

Personal comfort and expectations prior to the Industrial Revolution were also much different than today. Non-uniform and varied temperatures were expected since the primary source of heat was fire places. Cross ventilation and air circulation were the only methods available for cooling. Thus, building movements which were unaccomodated and resulted in breaches in the envelope systems were often not considered a significant issue or were resolved on an as-needed basis through routine repair and maintenance. Building typologies were heavily influenced by the weather, available materials and historically proven precedents.

It should be noted that during this period, and even dating back to the previous century, the need to accommodate expansion and differential movement in bridges and other large civil structures was well understood and incorporated into designs. For masonry and concrete structures, the approach was to control cracking and distress since moisture infiltration was not as significant an issue for such structures. The introduction of metal in bridge construction and the much higher coefficient of thermal expansion of cast iron (double) and steel further necessitated the need for expansion joints.

3.2 Hybrid Curtain Wall Period (1870 to 1900)

The Industrial Revolution marked a dramatic shift both culturally and technologically. Cities were growing rapidly. The combination of economics and demand made the development of larger and taller buildings inevitable. High-rise buildings would not have been possible without the invention of the elevator and the development of the skeleton steel frame structural system. Elevators allowed building occupants to easily access upper floors of taller buildings which prior to that time actually had the lowest rents. Development of the skeleton frame structural system enabled the exterior walls of buildings to no longer be a part of the main structural system. Thus, window openings could be larger and the exterior skin of the buildings only had to provide enclosure. This type of wall system began to be referred to as a ‘curtain wall’ because the cladding system could be relative light and independent of the building’s structural system. While supported at each floor, these wall systems were more of a hybrid wall system since the mass of the wall remained the primary means of resisting environmental forces. Larger and taller building walls were now comprised of multiple materials, resulting in challenges from the more the complex interactions.

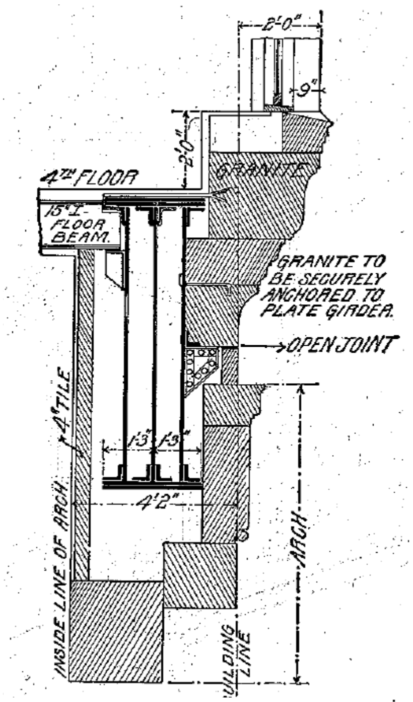

Figure 1. *Traditional detailing of masonry clad curtain wall systems.*

Some of these issues were understood from the beginning of this period and others were only understood after the early buildings of this period had been in service for some years. Building movement, and accommodating these movements, is one of the most significant of these issues. A review of construction details [Frietag 1895], reference books and buildings from this period reveals that there was an understanding of the need to accommodate these movements but there was not a complete understanding of the extent and magnitude of the movements (Fig.1). Cracking was generally attributed to differential settlement or incorporation of wood members within the wall plane. Period literature suggests the use of a 'slip sill' [Kidder 1911] which does not extend into the adjacent pier as a method to reduce cracks at sills. The general approach of the detailing during this period for larger masonry units such as stone and terra cotta was to allow for individual units to move without binding against adjacent units thereby accommodating small movements related to thermal changes and expansion (Fig. 2). Joints below larger projecting units were often left open to allow the members to deflect or rotate slightly without coming into contact with the units below.

Vertical expansion joints were very rarely explicitly incorporated into building facades. Horizontal movements were often accommodated by the detailing of the wall cladding which would be created by layered planes of materials sliding parallel to each other without transferring load to the adjacent plane. Some technical literature of the time refers to these joints as 'slip joints' [Kidder 1911]. This practice was common below the roof areas, but less common at roof elements such as parapets, cornices and water tables. As a result, many of these elements frequently now exhibit movement and shifting consistent with unaccomodated expansion and contraction--particularly at corners [National Terra Cotta Society 1927].

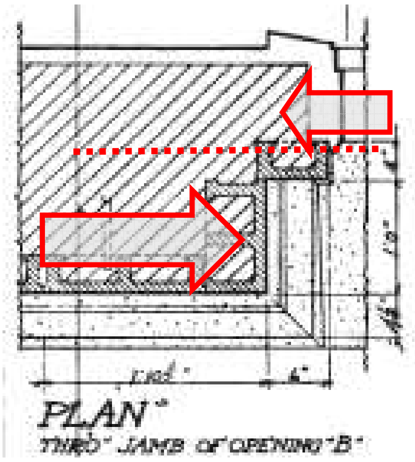

Figure 2. *Representative slip plane detail*

Horizontal expansion joints were rarely incorporated into hybrid cladding systems. This tends to indicate that the exterior walls, while supported at each floor were still being considered mass/bearing walls in many respects. While the outer wythe was typically supported at each floor, the backup wall system was typically set directly on the floor slab. The position and configuration of shelf angles which support the cladding are typically shown extending less than half the depth of the cladding material. The remaining portion of the unit, not bearing on the steel, was filled with mortar. This seems to be an indication that the load of the cladding between floors was not intended to be completely transferred at each floor. Rather, some compression may have been intended to be imparted on the cladding to minimize cracking by essentially preloading the masonry.

The need to accommodate cracking and shrinkage in concrete was well understood during this period. Numerous references exist in the literature of the time regarding the need to accommodate the shrinkage of concrete as it cured to minimize and control cracking [Newman 1894].

Also understood at the time was the differential movement of the curtain wall relative to the structural frame. As stated by Viollet-le-Duc:

> *If, therefore, we undertake to encase an iron structure with a shell of masonry, that shell must be regarded only as an envelope, having no function other than supporting itself, without lending any support to the iron, or receiving any from it. Whenever an attempt has been made to mingle the two systems, mischief has resulted in the shape of dislocations and unequal settlements.*[Violette-le-Duc 1877]

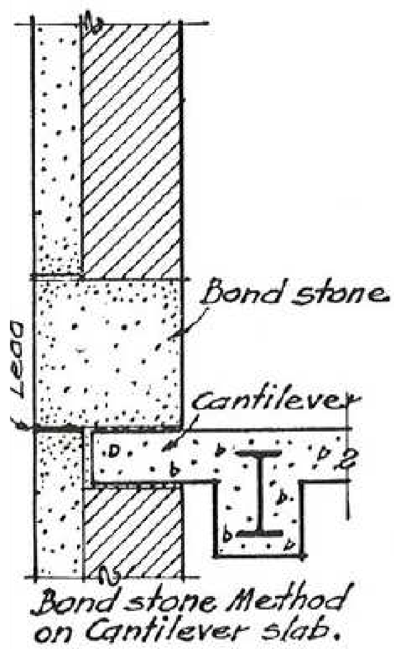

Figure 3. *Expansion provision in masonry curtain wall*

By 1894, lateral movement in curtain wall construction was actually being studied and analyzed. For example, lateral movements of steel-framed buildings in Chicago, including the seventeen-story Monadnock Building and the fourteen-story Pontiac Building, were documented under high wind loads [Stebbing 1894].

3.3. High Rise Masonry Curtain Walls Period (1900 to 1940)

The use of masonry bearing walls was pushed to its practical extreme by the early 1890s. Beginning around 1900, architects and engineers began to push the masonry curtain wall technology to its limits. Prior to 1900, high-rise curtain wall buildings were typically between 15 and 20 stories tall. Between 1900 and 1930 buildings in major cities throughout the United States gradually increased in height, routinely reaching more than 40 stories [Dupre 1996]. In 1900, the tallest building was roughly 122 m (400 ft). By 1930, the tallest building had exceeded 365 m (1200 ft) [Dupre 1996].

Horizontal expansion joints became more commonly incorporated, but were frequently undersized or inadequately spaced. Details of the period show a compressible material below support components. Commonly used materials included lead and various petroleum or linseed oil based materials (Fig. 3). Over time, these materials would age, become brittle and no longer accommodate movement. Taller buildings introduced a new behavior which, prior to this period, had not represented a significant issue--specifically, frame shrinkage. Moisture expansion, thermal expansion and differential coefficients of thermal expansion were known and understood, but frame shrinkage was a lesser understood phenomena and often knowledge of the issue did not bridge between the engineers and architect. The combination of expansion of the cladding system and shrinkage of the support frame could impart significant unintended loads and stresses into the cladding system. Later, additional stresses were imparted on the cladding as corrosion of the cladding support system occurred and the accumulation and confinement of corrosion scale occurred. Therefore, even if the various movements had originally been properly accommodated additional capacity for movement was required as the building aged but rarely provided.

The exterior cladding is exposed to temperature changes and consequent temperature-related movements, while the embedded frame is protected. Structural frames shorten under dead load and material creep. Conversely, masonry curtain walls expand due to the intake of moisture. Early curtain walls were not built to accommodate these differential movements resulting in the introduction of unanticipated stresses into the curtain wall and frame. This problem came to be understood as evidenced by displacement measurements that were performed during construction of the Empire State building in 1931:

> *The horizontal deflection of the top of the Empire State Building was monitored by the American Institute of Steel Construction. Measurements were also made to determine exactly how much lower the various floors are than their theoretical position. These measurements showed that the 85th floor was 6 1/4 in. below its theoretical elevation during construction.* [Balcom 1931]

An example of distress from this displacement includes the bowing of the face masonry between shelf angles. To address this differential movement, a lead pressure-relieving joint ("cowing") was developed by the 1930s [Ross 1925]. Cowing was typically laid horizontally at mid-span in every story of the highrise masonry facade. This form of pressure relief was used in masonry envelopes until the 1960s. This type of joint has been superseded by soft joints beneath masonry shelf angles, as commonly used in construction today.

The change in style from Classicisms to Art Deco continued to make the notion of layered planes of materials desirable, and allowed the detailing of the wall cladding to continue to accommodate horizontal movements (by the incorporation of slip planes). However, the explicit incorporation of vertical expansion joints into building facades continued to be rare, though some references to placing vertical joints between 7.5 m and 15 m (25 and 50 feet) are made [Ross 1919]. Further, the wedding cake massing emblematic of Art Deco buildings both complicated and exacerbated accommodating horizontal movements with continuous vertical joints.

It was well understood that portions of buildings of different heights needed to be separated such that each section could move independently. The separation was achieved by creating slip planes between the building sections. During the construction process, the edge of a completed section of wall was treated with combinations of bitumens and felts to maintain a waterproof joint and allow for differential vertical movements.

3.4 Post War Period (1945 to 2000)

Following World War II building construction dramatically changed again. The desire for even taller buildings constructed rapidly and with standardized components resulted in a dramatic change in architectural expression and the development of the glass and metal curtain wall system. The curtain wall systems incorporated numerous building materials including various metals, stones, and clay masonry products, as well as cast-in-place and precast concrete. As buildings continued to increase in height, the desire to further reduce the weight of the exterior cladding and advancements in technologies resulted in gradual reduction of the thickness of the curtain wall systems. Wall systems prior to the 1940s were generally at least 300 mm (12 in) thick. In the decades following the 1940s the wall systems continued to get thinner culminating in claddings which were often less than 50 mm (2 in) supported by the stick framing of the metal curtain wall. By this period, the need to accommodate expansion and contraction in buildings was well understood and recognized within the construction industry.

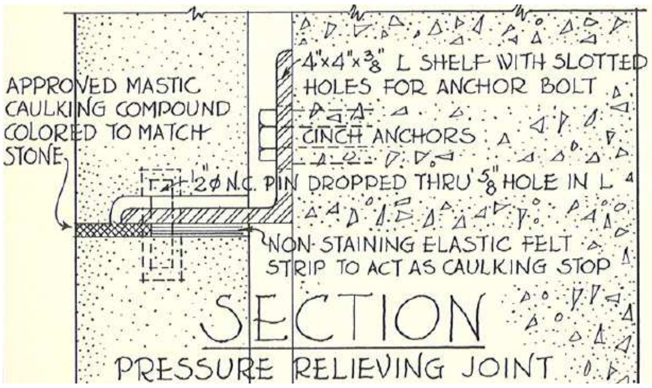

Figure 4. *Expansion joint detailing, circa 1949 exerted from Indiana Limestone Institute publication*

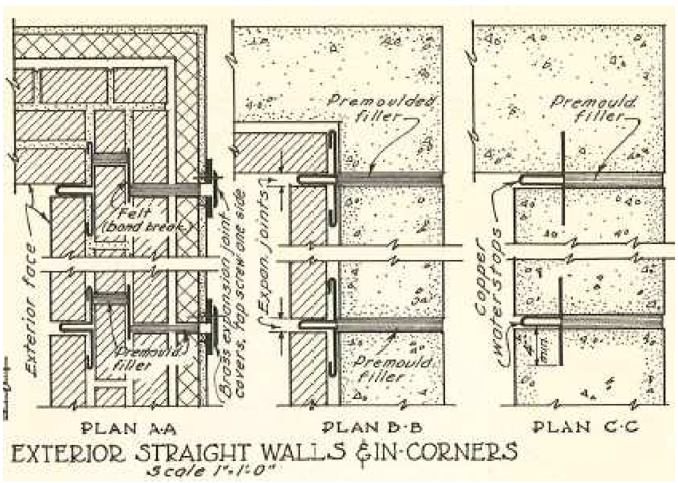

Figure 5. *Expansion joint detailing, circa 1950s*

A review of details from industry sources beginning in the 1940s reveals a greater emphasis on the incorporation of provisions to accommodate expansion and other building movements [ILI 1949]. Vertical and horizontal expansion joints are shown in typical details throughout the various publications being produced within the masonry and fenestration industries, Fig. 4.

A review of Architectural Graphic Standards, beginning with the first edition printed in 1932 and continuing through the fourth edition in 1951, revealed that a transition in recognition and design of expansion joints occurs between the third edition (1941) and fourth edition (1951) [Ramsey 1932, 1941 and 1951]. Virtually no mention of expansion joints relative to exterior cladding systems is made until the fourth edition, where the full implementation of expansion joints into exterior wall construction is

discussed (Fig. 5). It is also interesting to note that the need for expansion accommodation in concrete structures and roofing systems is acknowledged in these texts dating back to 1932, and in other references from previous decades.
Earlier references also identify the issue of both thermal and moisture expansion of masonry materials as well as the interaction of the embedded steel structure and the differential movement between the structural frame and the adjacent masonry. These conditions are acknowledged, but no suggestions are made for accommodating these phenomena. The larger issue seemed to be related to durability of the material due to moisture infiltration and subsequent freeze-thaw damage rather than the more global issues of cracking and macro movements of the wall systems.

A 1941 reference states '*expansion joints are expensive and in some cases difficult to maintain. They are, therefore, to be avoided if possible. In heated buildings joints can be spaced further apart than in unheated buildings. Also, where the outside walls are of brick or of stone ashlar backed with brick or where otherwise insulated, the joints can be farther apart than with exterior wall of lower insulting value.*' The reference goes on to state that in some instances buildings as long as 215 m (700 ft) long have been built without expansion joints. Joints were recommended at junctions in L-, T- and U-shaped building, at large openings in the floor construction. The joints were recommended to extend from the footing to the roof with doubled columns and girders [Huntington 1941].

Another significant development which began in the 1960s was the introduction of panelized and unitized cladding systems. This was an inevitable progression from hand setting of individual units: labor now represented a much greater percentage of the cost of construction and speed became an even greater necessity. Prefabrication of larger cladding components, which could be installed rapidly, was desirable to achieve greater quality control, consistency and productivity. Examples of these systems include clad and un-clad precast concrete panels, clad steel trusses and steel strong-back systems. Joints were critical to accommodate movement between larger facade components and to accommodate construction and structural tolerances (Fig. 6).

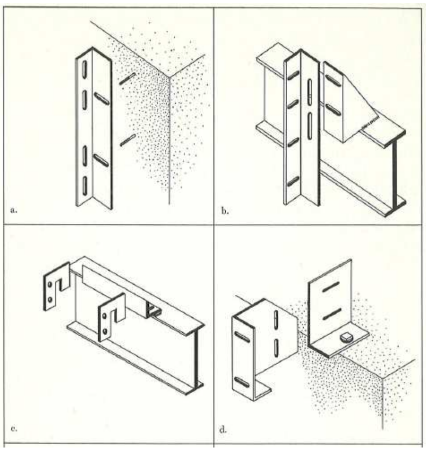

Figure 6. *Expansion/movement provision in anchorage for curtain wall*

4 CONCLUSION

Over the centuries, wall systems have became thinner, lighter, and less redundant. The effect of the environment and the inter-relationship of wall system components became more acute. All wall systems are dynamic in nature. A lack of understanding or recognition of actual wall system behavior, both historically and today, leads to physical damage, water leakage, and increased maintenance costs. In response to these concerns, there is and always been a constant effort to understand the physical properties of construction materials to better predict and accommodate the interaction between wall components. The introduction of expansion joints was a direct result of this desire to control and accommodate material movement due to material properties and exposure to the environment.

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