THE DESIGN OF MOVEMENT JOINTS IN ADHERED CERAMIC TILE FACADES

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INTRODUCTION

Recent developments in ceramic tile and adhesive mortar technology have created an entirely new market for the direct adhesive application of ceramic tile on exterior building facades. However, the demand for these types of systems have occurred at such a rapid pace, that there has been little time devoted to the development of design and construction standards. The ceramic tile industry is now at a critical juncture to exploit the market potential of ceramic tile facades because there is now sufficient empirical evidence to substantiate what was once considered controversial theory on the long-term performance of exterior ceramic tile using direct adhered methods.

This paper will focus on what is arguably the most critical and least understood aspects of direct adhered ceramic tile facade systems; the mechanisms and effects of movement in buildings, and the use of movement joints to control stress induced by movement. Current standards for the design of movement joints and related detailing in adhered ceramic tile facades are based loosely on a combination of traditional standards for mechanically anchored masonry and stone walls, together with general standards for movement in ceramic tile floors. However, these standards do not address conditions and concerns specific to movement in exterior, multi-story ceramic tile facades. The purpose of this paper is to promote a better understanding of building movement, and to begin the process of promulgating mandatory standards for the design of movement joints in adhered ceramic tile facades.

BUILDING MOVEMENT FUNDAMENTALS

All buildings and building materials move to varying degrees, and it is essential to accommodate that movement, and the accompanying dimensional changes. Ceramic tile installed on an exterior building facade is considered a veneer or finish, and not a structural component. The back-up wall assembly and structural frame must be designed to control and isolate all building movement. The ceramic tile, being directly adhered and fixed in position, must be designed and installed to move with the underlying frame and wall assembly. This concept is extremely critical, because it is a common misconception that thermal movement of the ceramic tile itself is the only movement mechanism that could cause problems or adhesive failure of an exterior ceramic tile wall system.

There are a variety of types of dynamic movements that occur in the exterior wall of a building. Most of these movements are quantifiable through mathematical calculations. However, building movements are dynamic, that is, they are constantly changing and not necessarily simultaneous. As a result, the exact magnitude of resulting stresses from building movement can be difficult to predict, if not indeterminate. Fortunately, structural theory dictates that movements be considered cumulative and simultaneous in order to provide a safety factor for the most extreme conditions. While this approach appears overly conservative, it provides the design architect and engineer with a way to quantify movement in a ceramic tile facade.

The following is a simple example of why all building movements must be considered cumulative: a ceramic tile wall surface may reach a temperature of 70 C under sustained hot sun. A sudden rainstorm will cool the surface of the tile, causing rapid contraction, but the the underlying support wall may remain hot and continue to expand. During the rainstorm, there is significant wind, causing the building to sway or drift. The result is an unpredictable, but common, combination of movement events causing differential thermal and live load (wind) movement.

TYPES OF BUILDING MOVEMENT

This paper will use buildings with concrete structural frames and masonry infill/ back-up walls as a model for analysis. This type of structure is not only more common around the world, but is also a better model for studying the mechanisms of building movement. The following types of building movement must be considered in a concrete framed building:

Live loads (wind, seismic) and dead loads (gravity)
hermal movement
Drying shrinkage
Moisture expansion
Elastic deformation under initial loads
Creep of concrete under sustained loads
Differential settlement

Live loads - Lateral forces due to anticipated gravity, wind or seismic loads must be analyzed to determine 1) the required tensile and shear bond strength of adhesive mortars to resist these forces and, 2) the amount lateral building movement, also known as building *drift*, that must be accommodated in movement joints.

The design and selection of adhesive mortars is not the subject of this paper, but this subject merits a brief discussion to understand the difference between the role of adhesive mortars and the role of movement joints in controlling building movement in ceramic tile facades. Adhesive mortars must be selected and designed to resist gravity, wind, seismic forces, and shearing stress caused by other types of building movement, whichever is greatest. In most cases, the weight of ceramic tile due to gravity is not a significant factor in design. The negative (suction) and positive (pressure) forces imposed by wind or the shearing forces of seismic activity or thermal movement are typically far greater than gravity (weight of tile) loads.

EXAMPLE:

A 30 x 30 cm ceramic tile, weighing approximately 20 kg/m^2 and fully bonded, wouldrequire an adhesive with a shear bond strength of .002 kg/cm^2; a high quality adhesive mortar shear bond strength would be 30 kg/cm^2, and tensile bond strength of 10 kg/cm^2 . However, a 10 story high building exposed to a 115 km/hour wind speed could be exposed to a potential negative (suction) wind pressure of 308 kg/m^2. This wind speed requires an adhesive mortar with a tensile bond strength of .03kg/cm^2. As you can see this strength still provides a significant safety factor to resist wind suction. While the analysis of seismic or extreme thermal shear forces is considerably more complex, these forces can approach the design shear bond strength of adhesive mortars.

Wind and seismic forces can also cause lateral building movement called *drift*. This type of movement is characterized by the swaying of a building from wind or seismic activity, and is the type of movement that can be controlled and isolated with movement joints. While seismic and wind movement joints are typically a structural engineering function of the underlying structure and wall, it is critical that this movement capability extend through to the leveling and adhesive mortars, as well as the ceramic tile surface.

Building codes in some countries limit drift or displacement of a story relative to the adjacent story to .005 times the story height. For example, a 4 meter single story height could have maximum allowable drift due to design wind load of .005 x 4m x 1000mm = 20mm between stories (movement is not cumulative, but relative only between eachfloor level). This is significant movement, albeit under worst case conditions, but placement of movement joints horizontally at each floor level, and vertically at strategic locations such as along column or window edges every 4 - 5 meters maximum is mandatory to eliminate restraint of drift. In addition, a common design concept to accommodate severe wind or seismic drift in a ceramic tile facade is to isolate the underlying leveling mortar / plaster / wall render with a cleavage membrane and utilize galvanized steel or plastic reinforcing grid which is attached with flexible connections to the underlying support wall or structure. The combination of movement joints and a floating leveling bed will control the effects of extreme building movement on the ceramic tile wall assembly.

Thermal movement - All building materials expand and contract when exposed to changes in temperature. There are two factors to consider in analyzing thermal movement; 1) the rates of expansion of different materials (also known as the linear coefficient of thermal expansion), and 2) the anticipated temperature range exposure for the components of the wall assembly. The primary goal in analyzing thermal movement is to determine the amount of total, as well as differential movement, that occurs between components of the ceramic tile wall assembly.

EXAMPLE:

A porcelain ceramic tile has an average coefficient of linear expansion of between 4 - 8 times 10 minus 6 mm/°C/mm of length. Concrete has an expansion rate of 10 x 10 minus 6 mm/°C/mm. The surface temperature of a dark tile may reach as high as 60 °C in hot sun, and the lowest ambient temperature in a moderately cold climate may be minus 10 °C, resulting in a temperature range of 70 °C for the tile. The temperature range of the concrete structure, not exposed directly to the sun and insulated from temperature extremes by the tile, and leveling/ adhesive mortars as well as length of time exposure, may only be 30 °C. For a 50 meter wide building, the differential movement is as follows: Concrete .000010 x 50m x 1000mm x 30 °C = 15 mm Tile .000006 x 50 m x 1000mm x 70 °C = 21 mm

Because the tile thermal expansion is greater, this figure is used. The general rule for the width of a movement joint is 2-3 times the anticipated movement, or 3 x 21 = 63 mm. Minimum recommended width of any individual joint is 10 mm, therefore, a minimum of 6 vertical joints (inclusive of corners) across a 50 meter wide ceramic tile facade, each 10 mm in width , are required *just to control thermal* movement under the most extreme conditions. Similarly, there is an approximate differential movement of 6 mm over 50 m between the tile and underlying concrete structure that must be accommodated by the flexibility of the adhesive and leveling mortars.

Thermal induced deflection or bending of the buildingís structural frame is another often overlooked cause of stress on a direct adhered ceramic tile facade. This phenomena can occur when there is a significant temperature differential between the exterior and interior of the structural frame, causing the frame to bend and exert force on the exterior wall assembly. An engineering analysis to determine movement joint requirements is mandatory, because, unlike a mechanically anchored wall finish with flexible connections, the frame transmits movement directly to a fixed, direct adhered tile finish. This problem is more acute in steel framed buildings.

Moisture Shrinkage / Expansion - Underlying structures or infill walls constructed of concrete or concrete masonry will undergo permanent shrinkage from cement hydration and loss of water after initial installation. The amount of shrinkage is dependent on several variables; water/cement ratio of concrete, relative humidity/rainfall, thickness of concrete, and percentage of steel reinforcement. While an average of 50 % of ultimate shrinkage occurs within the first 3-6 months (depending on weather conditions), the remainder can occur over a period of 2 or more years. In a wet, humid environment, the period of high initial shrinkage is difficult to predict. If possible, it is recommended to sequence or delay the direct application of ceramic tile and leveling mortars until after the majority of shrinkage of a concrete structure has occurred, which under ideal conditions may be about 6 months.

EXAMPLE:

Reinforced concrete walls will ultimately shrink between .00025 to .00045 times the length, depending on a number of variables such as concrete water / cement ratio , amount of steel reinforcing, etc. A concret framed building which is 40 meters high will shrink up to 18 mm vertically. Ceramic tile does not shrink, and in some cases will undergo moisture expansion. As a result, there must be provision in the movement joints to absorb at least 18 mm of contraction (joint width must be approximately 2-3 times the anticipated movement, or 54 mm total. Assuming 10 stories at 4 m height each, shrinkage could add approximately 5.5 mm in width to the horizontal movement joint at each floor level, depending on how much of the ultimate shrinkage has occurred at the time of installation of either leveling mortars or ceramic tile.

Conversely, ceramic tile, or more commonly, underlying clay brick masonry walls, can undergo long term, permanent expansion from moisture absorption. Dimensional changes in ceramic tile can be virtually eliminated by use of an impervious or semi-vitreous tile. However, clay brick masonry back-up walls must be detailed to accommodate moisture expansion.

Structural deformation - As a building is constructed, the weight of materials increase, and permanent movement, known as elastic deformation, occurs in heavily stressed components of the structure. For example, the spandrel beam or lintel over the windows is allowed to move or deflect up to 1/500 of the span. Therefore a beam spanning 5 meters between columns is allowed to move 10 mm vertically from initial position under full load. The spandrel beam is typically the optimum location for a horizontal movement joint at each floor level of a building. The joint should continue from the surface of the ceramic tile and through the adhesive and leveling mortars. Similarly, it is also critical to leave a space between the bottom of the spandrel beam and the top of the backup masonry wall to allow for this movement. The backup wall is not designed as a load bearing wall, and may crack or bulge when directly exposed to loads from the floor above. This space is typically filled with a compressible filler to allow for movement, flashed to prevent water penetration, and braced laterally to the columns with masonry anchors and reinforcing.

Long term deformation movement in concrete structures, also known as *creep*, occurs more slowly and can increase initial deflections by 2-3 times. Allowance for this type of long term movement must be considered in the design of movement joints. Creep is typically of greater concern in taller, reinforced concrete frame buildings, especially those that do not incorporate compressive reinforcing steel in the structural design.

EXAMPLE:

A typical 10 story building is 40 meters tall. Creep, or long term deformation may be as high as .065 percent of the height. Creep would be calculated as follows: 40 m x 1000mm x .00065 = 26 mm potential reduction in the height of the concrete structure.

Differential settlement - Buildings structures are typically designed to allow for a certain tolerance of movement in the foundation known as differential settlement. In most buildings, the effect of normal differential settlement movement on the exterior wall assembly is considered insignificant, because significant dead loading and allowable settlement has occurred long before application of ceramic tile. Differential settlement of a buildingís foundation that occurs beyond acceptable tolerances is considered a structural defect, with significant consequences to a direct adhered ceramic tile facade.

MOVEMENT JOINT DESIGN FUNDAMENTALS

One of the primary means of controlling stresses induced by building movement in a direct adhered ceramic tile facade is with movement joints (also known as expansion, dilatation, or control joints). As demonstrated above, all buildings and materials move to varying degrees, and therefore the importance of movement joints can not be understated. At some point in the life cycle of an adhered ceramic tile facade, there will be a confluence of events or conditions that will rely on movement joints to maintain the integrity of the wall system. Maintaining integrity of the wall system can be as simple as preventing cracks in grout joints, to preventing complete adhesive bond failure of the ceramic tiles (which is the primary concern in direct adhered ceramic tile systems). Proper design and construction of movement joints requires careful consideration of the following factors:

Location
Frequency
Size (width/depth ratio)
Type and detailing of sealant & accessory materials

Location - The main function of movement joints are to isolate ceramic tile surfaces from other fixed components of the building, and to subdivide the tile and the underlying wall assembly into smaller areas to compensate for the cumulative effects of building movement. While each building is unique, there are some universal rules for location of movement joints that apply to any direct adhered ceramic tile facade:

1) Existing structural movement joints - movement joints may already be incorporated in the underlying structure to accommodate thermal, seismic or wind loading. These joints must extend through to the surface of the ceramic tile, and , equally important, the width of the underlying joint must be maintained to the surface of the tile.

2) Changes of plane - locate movement joints at all locations changes of plane, such as outside or inside corners.

3) Changes of materials - Different materials not only have different rates and characteristics of movement, but also act to restrain movement of the ceramic tile system. Movement joints must be located wherever the ceramic tile and underlying adhesive and leveling mortars meet a dissimilar material, such as metal window frames, penetrations, and any other type of exterior wall finish.

4) Each floor level (horizontal) - As discussed previously, a horizontal movement joint must be placed at each floor level (typically 3 - 4 meters) coinciding with the intersection of the back-up masonry wall and spandrel beam, or at the lintel over the windows. This location not only isolates movement at each floor level, but also provides the architect the opportunity to incorporate movement joints into the design of the building facade in an aesthetically pleasing, repetitive manner. Allowing for deflection movement between the spandrel beam or slab and the entire wall assembly (backup masonry, leveling /adhesive mortar, and ceramic tile) is one location that often does not receive adequate attention.

5) Parapets, freestanding / projecting walls - Care should be taken to insure adequate movement joints at these types of locations. These wall assemblies are exposed on both sides, resulting in greater movement stresses due to temperature extremes or wind.

As a general rule, if movement joints are located at all of the above typical locations, then the only remaining consideration is to locate additional vertical movement joints so that the field of a tiled area, including the adhesive and leveling mortar layers, is no greater than 4 - 5 meters wide (*see frequency below*). As with locating joints at each floor, the architect should take the opportunity and coordinate location of vertical joints with architectural features, such as aligning with vertical window frames, openings, columns, or other building features with a vertical alignment.

Frequency - A conservative general rule is to locate movement joints at a frequency of no less than every 4 -5 meters in each direction. With typical floor to floor heights less than 4 - 5 meters, a horizontal joint located at each floor level is sufficient to accommodate vertical movement. Vertical joints to control horizontal movement should be located every 4 - 5 meters, unless an actual mathematical calculation indicates either less frequency is allowable, or greater frequency is recommended, such as installing black tile in an extreme hot climate.

Size (width/depth ratio) - The proper width of a movement joint is based on several criteria. First and foremost, regardless of the width as determined by mathematical calculations, the minimum functional width of a movement joint should be no less than 10 mm; any joint narrower than 10 mm makes the proper placement of backer rods and sealant materials impractical, and creates an unacceptable depth (*see width/depth ratio below*).

The width of a movement joint filled with sealant material must be 2 to 3 times wider than the anticipated movement in order to allow proper elongation and compression of the sealant. Similarly, the depth of the sealant material must not be greater than 1/2 the width for proper function (width/depth ratio). For example, if 5 mm of cumulative movement is anticipated between floor levels, the movement joint should be 15 mm wide and 7.5 mm deep (a rounded backup rod is inserted in the joint to control depth; see *accessories* below).

Type and detailing of sealant & accessory materials - The first and most often ignored step in the design of a movement joint is *flashing or waterproofing the joint cavity.* Sealant materials, no matter how well installed, are not 100 percent effective as a barrier against water penetration. There are several techniques which rely on providing a second barrier to water , depending on the depth of the entire joint cavity. The most successful is the application of a thin, bondable waterproof membrane, approximately 15 cm wide, which is applied at the leveling mortar surface, and looped down into the joint to provide for movement. Once this material is installed, ceramic tile is installed using adhesive mortar, and then the backer rod and sealant is applied.

After secondary flashing or waterproofing is complete, the movement joint must be fitted with a rounded backer rod, with a slightly larger diameter than the joint width for a snug fit. The backer rod must be a closed cell polyethylene material or similar material that will not bond to the sealant used to fill the joint. The backer rod serves two important purposes: 1) control of sealant depth for proper width/depth ratio, and 2) to act as a bond-breaker with the sealant so that the sealant adheres only to the edges of the tile. This allows the sealant material to elongate and compress freely, thereby preventing peeling stress at the tile edges (the primary cause of sealant joint maintenance problems and failure). If a joint does not have the depth to receive a backer rod, polyethylene bond breaker tape is available (commonly used for joints in thin-set floor applications)

The final step is *selection and installation of the sealant* joint material. There are many types of sealant products available on the market today, but only certain types are suitable for exterior ceramic tile facades. Sealants must meet the following basic functional criteria:

dynamic performance - must be high performance (also known as Class A or 25 rating), viscous liquid,curing type sealant capable of 12.5 - 25 percent movement over the life cycle (some silicon sealants have +50 percent movement, but there is no rating for this category). Pre-fabricated movement joints, which typically consist of two L-shaped metal angles connected by a cured flexible material typically do not meet the above movement capability criteria because they must be held under compression for an effective seal. Similarly, the selection of metal, such as stainless steel, is required to prevent corrosion or galvanic reactions; consult with manufacturers to insure compliance with these criteria.

rheological properties - must have sag-resistance equivalent to ASTM C920 Grade NS (non-sag for vertical joints)

mechanical properties - must have good elongation and compression, as well as tear resistance characteristics to respond to dynamic loads, thermal shock, and other rapid movement variations characteristic of an exterior ceramic tile facade.

weatherability- suitable for exposure to UV radiation (sun), water and temperature extremes; maintaining aesthetic appeal requires resistance to color fade, staining, and propensity for attracting contamination.

chemical resistance - must withstand cleaning chemicals, atmospheric pollution

adhesion - must have good tensile adhesion to non-porous or glazed surfaces of tile, ideally without special priming or surface preparation

color selection, ease of application, toxicity, odor, reparability, life expectancy and cost are some of the additional subjective criteria that do not affect performance, but require consideration.

Generically, high performance sealant are synthetic viscous liquid polymer compounds known as polymercaptans, polythioethers, polysulfides, polyurethanes, and silicones. Each type has advantages and disadvantages, and some may not meet all of the above criteria. As a general rule, polyurethane sealants meet all the criteria for exterior ceramic tile facades. Polyurethanes are available in either one-component cartridges, or two-component bulk packages, which require mixing and loading into a sealant applicator gun.

Installation of sealants and accessories into movement joints requires skilled labor familiar with sealant industry practices. The installation must start with a dry, dust free surface/ tile edges; some products require use of a priming agent as well; apply primers before installation of backer rods and protect underlying flashing or waterproofing to avoid deterioration by primer solvents. Any excess mortar, spacers, or other restraining materials must be removed to preserve freedom of movement. As explained above, use of a backer rod or bond breaker tape is necessary to regulate the depth of sealant, and prevent three-sided adhesion. Once sealant has been applied, it is necessary to tool or press the sealant with special tools to insure contact with the tile edges; the backer rod aids this process by transmitting the tooling force to the tile edges.Tooling also gives the sealant a slightly concave surface profile consistent to the interior surface against the rounded backer rod. This allows even compression/elongation, and prevents visually significant bulge of the sealant under maximum compression.

EXAMPLE:
Determine the width of horizontal movement joints required at each floor level in a 40 meter tall concrete frame building to control vertical movement only, with 4 meter floor to floor heights. Anticipated temperature range is 70 °C.
Thermal movement: 000006 x 40m x 1000mm x 70 = 17 mm
Shrinkage: 00035 x 40m x 1000mm = 14 mm
Creep: .00039 x 40m x 1000mm = 15.5 mm
Elastic deformation: .00020 x 40m x 1000mm = 8 mm

TOTAL MOVEMENT = 54.5 mm

Joint width aggregate (worst case) 3 x 54.5= 163.5 Total width
10 story building would have 11 horizontal joints, including the ground and roof levels 163.5/ 11= 15mm

CONCLUSION

This paper has presented an overview on the subject of building movement and the design fundamentals of movement joints in direct adhered ceramic tile facades. A ceramic tile facade is a complex, multi-layered system and requires careful architectural and engineering analysis of movement to to insure the safety and performance of what is probably the one of the most functional, versatile, and beautiful finishes in the world.