Volume Changes - Analysis and Effects of Movement

Abstract: This *Technical Note* describes the various movements that occur within buildings. Movements induced by changes in temperature, moisture, elastic deformations, creep, and other factors develop stresses if the brickwork is restrained. Restraint of these movements may result in cracking of the masonry. Typical crack patterns are shown and their causes identified.

Key Words: corrosion, cracks, creep, differential movement, elastic deformation, expansion.

SUMMARY OF RECOMMENDATIONS:

- Use the following coefficients to calculate movements of brick veneer:
  - Thermal expansion: 4 x 10^{-6} in./in./°F (7.2 x 10^{-6} mm/mm/°C)
  - Moisture expansion: 5 x 10^{-4} in./in. (mm/mm)
  - Creep: 0.7 x 10^{-7} in./in. per psi (0.1 x 10^{-4} mm/mm per MPa)
- Consider coefficients of movements for other materials in contact with brickwork
- Consider elastic deformation and movement of structural elements supporting and connected to brickwork

INTRODUCTION

All building materials change in volume in response to changes in temperature or moisture. Changes in volume, elastic deformations due to loads, creep and other factors result in movement. Restraint of these movements may cause stresses within building elements that result in cracks.

To avoid cracks, masonry elements should be designed to minimize movement or accommodate differential movement between materials and assemblies. A system of movement joints can reduce the potential for cracks and the problems they cause. Movement joints can be designed by estimating the magnitude of the different movements that occur in masonry and other building materials.

This *Technical Note* describes volume changes in brick masonry and other building materials. It also describes the effects of volume change when materials are restrained. *Technical Note* 18A discusses the design and detailing of movement joints and the types of anchorage that permit movement.

MOVEMENTS OF CONSTRUCTION MATERIALS

Most buildings do not allow exact prediction of building element movements. Volume changes are dependent on material properties and are highly variable. The age of the material and temperature at installation also influence expected movement. When mean values of material properties are used in design, the actual movement may be underestimated or overestimated. The designer should use discretion when selecting the applicable values. The types of movement experienced by various building materials are indicated in Table 1.

Brickwork will generally increase in size over its service life. This is the net effect of a variety of conditions that causes the size of brickwork to change, but is influenced primarily by irreversible moisture expansion. Unrestrained elements or sections of brickwork will expand vertically from their support and horizontally from the center as shown in Figure 1.

Table 1
Types of Movement of Building Materials

Building Material	Thermal	Reversible Moisture	Irreversible Moisture	Elastic Deformation	Creep
Brick Masonry	✓	---	✓	✓	✓
Concrete Masonry	✓	✓	---	✓	✓
Concrete	✓	✓	---	✓	✓
Steel	✓	---	---	✓	---
Wood	✓	✓	---	✓	✓

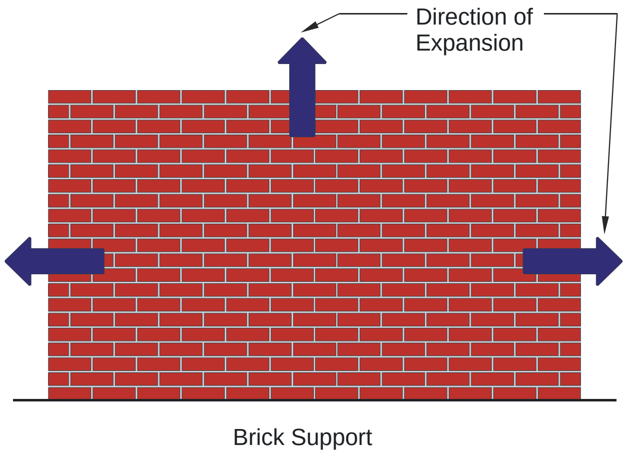

Figure 1
Direction of Brick Expansion

Table 2
Thermal Expansion

Material	Design Coefficients of Linear Thermal Expansion	
	x 10^{-6} in./in. per °F	x 10^{-6} in./in per °C
Brickwork	4.0	7.2
Concrete Masonry	4.5	8.1
Stone		
Granite	4.4	7.9
Limestone	4.4	7.9
Marble	7.3	13.1
Concrete	5.5	9.9
Metal		
Aluminum	12.8	23.1
Bronze	10.1	18.1
Stainless Steel	9.9	17.8
Structural Steel	6.5	11.7
Wood, Parallel to Fiber		
Fir	2.1	3.7
Oak	2.7	4.9
Pine	3.0	5.4
Wood, Perpendicular to Fiber		
Fir	32	58
Oak	30	54
Pine	19	34
Autoclaved Aerated Concrete	4.5	8.1

Temperature Movement

All building materials expand and contract with variations in temperature. For unrestrained conditions, these movements are theoretically reversible. Table 2 indicates the coefficients of thermal expansion for brick and other common building materials.

Unrestrained thermal movement is the product of temperature change multiplied by the coefficient of thermal expansion and the length of the element.

The stresses developed by restrained thermal movements are equal to the change in temperature multiplied by the coefficient of thermal expansion and by the modulus of elasticity of the material.

The temperature change used for estimating thermal movements should be based on mean temperatures in the component. For solid masonry walls, temperatures at the center of the wall should be used. In cavity walls and veneers, the temperature at the center of each wythe or component should be used. In discontinuous construction, the wythes will have different temperatures due to the separation of the wythes by an air space and perhaps insulation.

Surface temperatures of brick walls may be much higher than the ambient air temperature. Wall orientation, color, brick wall type and presence and location of insulation are governing factors. It is possible for a dark, south facing wall to reach surface temperatures as high as 140 ºF (60 ºC), while the ambient air temperature is well below 100 ºF (38 ºC). The mean temperature of a 4 in. (102 mm) thick insulated brick veneer is very close to the surface temperature of the brick. A thicker or uninsulated wall may have a lower mean temperature than the outside surface. The temperature range experienced by brickwork is the difference of the high and low mean temperatures of the brickwork. In practice, this range is usually taken as 100 ºF (38 ºC) and is based on the annual high and low temperature of the exterior ambient air.

Other building materials expand and contract at rates different from that of brick masonry. These differences are important when elements such as window frames, railings, or copings are attached to brick masonry. Distress may occur in either material. Bowing may occur in composite walls that have concrete masonry interior wythes.

Moisture Movement

With the exception of metals, many building materials tend to expand with an increase in moisture content and contract with a loss of moisture. For some building materials these movements are reversible; while for others they are irreversible or only partially reversible.

Brick. Brick expand slowly over time upon exposure to water or humid air. This expansion is not reversible by drying at normal temperatures. A brick is smallest in size when it cools after exiting the kiln. The brick will draw moisture from its environment and increase in size from that time. Most of the expansion takes place over the first few weeks, but will continue at a much lower rate for several years (see Figure 2). The amount of moisture expansion depends primarily on the raw materials and to a lesser extent on the firing temperatures. Brick made from the same raw materials that are fired at lower temperatures will expand more than those fired at higher temperatures.

In brickwork, moisture expansion of the brick is somewhat offset by drying shrinkage of the mortar. As brick with larger face dimensions cover more wall area, the brickwork will experience more moisture expansion.

Predicting the total moisture expansion of brickwork is difficult; however, it can be estimated by multiplying the coefficient of moisture expansion by the length of the wall. The *Building Code Requirements for Masonry Structures* (ACI 530/ASCE 5/TMS 402) [Ref. 3] design coefficient of linear moisture expansion for brickwork is 3 x 10^{-4} in./in. (mm/mm). For brick veneer, a design coefficient of linear expansion of 5 x 10^{-4} in./in. (mm/mm) is recommended.

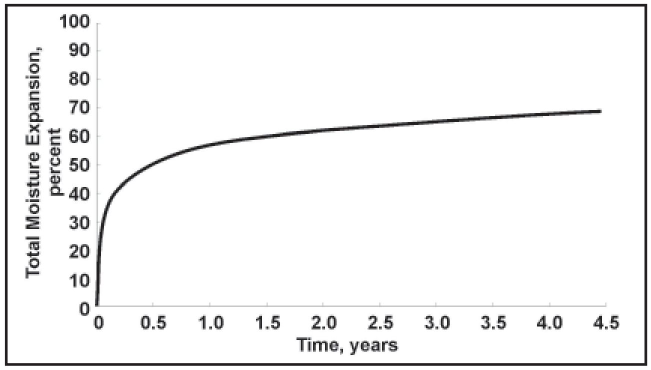

Figure 2
Projected Moisture Expansion of Fired Brick vs. Time

Masonry materials expand due to freezing when saturated. Freezing expansion, when it occurs, has a small effect on total expansion of masonry. Although limited, available data indicates that the coefficient of freezing expansion for brick ranges from 0 to 10.3 x 10^{-4} in./in. (mm/mm). A design value for brick masonry of 2 x 10^{-4} in./in. (mm/mm) is recommended. Freezing expansion is typically negligible, as it only occurs when fully saturated brick are subjected to temperatures at or below 14 ºF (-10 ºC).

Concrete Masonry. Concrete masonry units experience shrinkage as a result of moisture loss and carbonation and will expand as moisture content increases. These combined movements typically result in a net shrinkage of concrete masonry that is also affected by the method of curing, aggregate type, change in moisture content, cement content, temperature changes and wetting and drying cycles. The total potential linear drying shrinkage due to changes in moisture content is determined using ASTM C 426, Test Method for Linear Drying Shrinkage of Concrete Masonry Units [Ref. 2], which measures unit shrinkage from a saturated condition to a condition of equilibrium at a relative humidity of 17 percent. Typical linear shrinkage values for concrete masonry units range from 2 x 10^{-4} to 4.5 x 10^{-4} in./in. (mm/mm). The coefficient of shrinkage for concrete masonry is assumed to be half of the total linear shrinkage determined by ASTM C 426.

Carbonation is the chemical combination of hydrated portland cement with carbon dioxide present in air. Although there is currently no standard test method to measure carbonation shrinkage, the National Concrete Masonry Association recommends a value of 2.5 x 10^{-4} in./in. (mm/mm) be used to estimate carbonation shrinkage in concrete masonry walls [Ref. 5].

Concrete. Concrete shrinks as it cures or dries and swells when it is wet. Shrinkage of concrete is influenced by the water-cement ratio, composition of the cement, type of aggregate, size of concrete member, curing conditions, and amount and distribution of reinforcing steel. Shrinkage values for ordinary concretes are generally range from 2 x 10^{-4} to 7 x 10^{-4} in./in. (mm/mm) depending on the factors listed.

Wood. Wood shrinks during the natural seasoning process as the moisture content drops from the fiber saturation point (28 to 30 percent) until it reaches equilibrium with the environment. Shrinkage occurs differently in the radial, tangential, and longitudinal directions of the wood. The American Softwood Lumber Standard PS 20 [Ref. 1] suggests an average shrinkage value of one percent per each four percent drop in moisture content (a coefficient of 0.0025 in./in. (mm/mm) per percent change in moisture content) for typical softwoods. Longitudinal shrinkage (0.5 x 10^{-4} in./in. (mm/mm) per percent change) is usually small enough to be neglected in design. Moisture expansion and contraction continues with changes in moisture content of the wood.

Elastic Deformation

Elastic deformation is a reversible change in length, volume or shape produced by stress in a material. In the structural design of a building, the designer must consider all forces imposed on the structure. These include dead and live loads and such external lateral forces as wind, soil, snow loads, earthquake and blast. Each of these forces creates stresses in the building materials which can result in deformations and deflections of the building elements. If a material remains within its elastic range, it will return to its original shape once the applied forces are removed.

There are several types of deformation to consider. Horizontal elements such as beams and lintels deflect vertically due to their own weight and dead and live loads. Lateral deflections of walls and columns and reductions in lengths of axially loaded structural elements due to design loads must be considered. Walls, beams, columns and building frames move horizontally from lateral loads such as wind and seismic events. Columns and bearing walls are shortened in length due to vertical dead and live loads.

Elastic deformation is most important when considering elements that support brickwork. The design of longer lintels and shelf angles are typically controlled by deflection. Such deflection should be limited or accommodated by the veneer design or cracking of the veneer may result.

Lateral Drift. The drift or side-sway of a structural frame may cause distress to brick masonry used as in-fill walls or exterior cladding. Lateral loads from wind or earthquakes are transferred to brickwork if it is attached rigidly to the frame. The same is true for deflection of floor slabs or spandrel beams. Masonry built in contact with these elements will be loaded due to the movement of the member. Masonry intended to be non-loadbearing may become loadbearing.

Creep

Creep, or plastic flow, is the continuing, irreversible deformation of materials under load or stress. The magnitude of movement due to creep in masonry and concrete depends on the stress level, material age, duration of stress, material quality, and environmental factors.

In frame structures, especially concrete frame buildings, vertical shortening due to creep or shrinkage of the structural frame may impose high stresses on the masonry. These stresses develop at window heads, shelf angles, and other points where stresses are concentrated.

Brick. Creep in brick masonry primarily occurs in the mortar joints and is negligible. ACI 530/ASCE 5/TMS 402 stipulates a design coefficient of creep for clay masonry of 0.7×10^{-7} in./in. per psi (0.1×10^{-4} mm/mm per MPa).

Concrete Masonry. Concrete masonry exhibits more creep than brick masonry because of the cement content in the units. ACI 530/ASCE 5/TMS 402 stipulates a value of 2.5×10^{-7} in./in. per psi (0.36×10^{-4} mm/mm per MPa).

Concrete. Creep is most significant in concrete frame structures. Creep in concrete begins after load is applied and proceeds at a decreasing rate. High-strength concrete experiences less creep than low-strength concrete. Creep is slightly greater in lightweight aggregate concretes than normal weight concretes. In high-rise buildings, the total elastic and inelastic shortening of columns and walls due to gravity loads and shrinkage may be as high as 1 in. (25 mm) for every 80 ft (24 m) of height.

Estimating Combined Movements

Equation 1 below, combines the effects of movements above that affect brickwork, and can be used estimate the amount of expansion that would be experienced by an unrestrained brick wythe. Although typically neglible, local conditions must be considered to determine if freezing expansion will occur.

$$m_u = (k_e + k_f + k_t \Delta T)\, L \qquad \textit{Eq. 1}$$

where:

m_u = total unrestrained movement of the brickwork, in. (mm)

k_e = coefficient of moisture expansion, in./in. (mm/mm)

k_f = coefficient of freezing expansion, in./in./°F (mm/mm/°C)

k_t = coefficient of thermal expansion, in./in./°F (mm/mm/°C)

ΔT = temperature range experienced by brickwork, °F (°C)

L = length of wall, in. (mm)

Using the recommended values given previously for coefficients of expansion and temperature range experienced by brickwork, the equation becomes:

$$m_u = (0.0005 + 0 + (0.000004 \times 100))L$$

$$m_u = 0.0009L$$

In addition to the expansion of brickwork, other movements of building materials decribed herein, restraint conditions, construction tolerances and wall orientation may affect the size and spacing of expansion joints.

Other Causes of Movement

Other causes of movement in building elements that may occur under given conditions include corrosion of steel, drift of the building frame, and the action of unstable soils. It is beyond the scope of this *Technical Note* to discuss these items in detail. However, they are briefly described below.

Corrosion of Steel. Excessive corrosion of steel embedded in masonry can cause cracking or spalling of masonry. The volume of rust is greater than that of the steel from which it is formed. This increase causes pressure on the surrounding masonry and may result in movement and cracking.

Anchors, ties and joint reinforcement are embedded in mortar and may be exposed in an air space or cavity. Thus they may be susceptible to corrosion. Metals embedded in grout, such as reinforcing bars, are less susceptible to corrosion since they are protected by the grout and not exposed. Other items in masonry susceptible to corrosion are steel lintels, steel shelf angles, anchor bolts and other metal fasteners in masonry. To minimize corrosion, do not use additives in mortar that accelerate corrosion, such as calcium chloride, and minimize the amount of water within masonry through proper design, detailing and installation. See *Technical Note* 44B for more on corrosion resistance of metal ties and anchors.

Unstable Soils. Unstable or expansive soils often cause movement or differential settlement in foundations that support brick masonry. Proper foundation design will help ensure stable support and allow uniform settlement within acceptable limits.

IDENTIFYING EFFECTS OF MOVEMENT

Changes in building materials and technology have affected the design and behavior of many building components, including masonry walls. The increased use of thinner walls and the tendency to specify high compressive strength mortars have become common. Although stronger units and mortars increase the compressive strength of the masonry, they do so at the expense of other important properties. Thus, masonry walls today tend to be thinner and more brittle than their massive ancestors. These thinner walls are more susceptible to cracking and spalling if differential movement is not addressed in design. *Technical Note* 18A includes recommendations for accommodating differential movement in new construction. Proper design and construction of brickwork can help prevent the detrimental effects of movements. The following section demonstrates specific conditions in brickwork and their underlying causes.

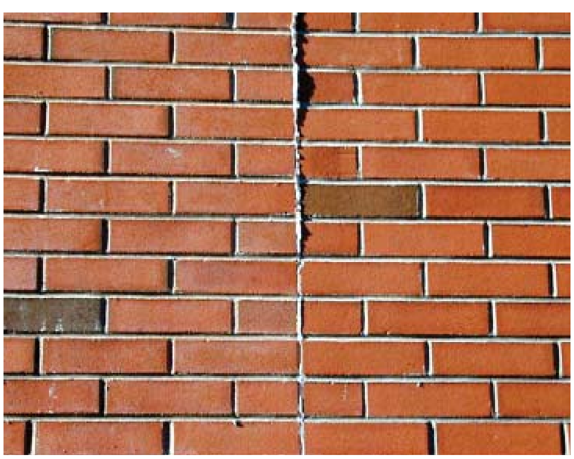

Photo 1
Sealant Forced Out of Expansion Joint Due to Expansion of Long Wall

Cracking is perhaps the most frequent type of distress that affects masonry walls. The shape, location and magnitude of cracking will often indicate the cause. Conditions that occur when movement is not accommodated are illustrated in the following photographs. *Technical Note* 18A recommends details that help prevent these conditions.

Long Walls. When expansion joints are too narrow or spaced too far apart, the expansion of the brickwork may not be adequately accommodated. This may force sealant material out of an expansion joint as shown in Photo 1. If expansion continues, then cracking occurs at other locations. In walls with openings, diagonal cracks may occur in brickwork between windows or doors. Such cracks usually extend from the head or sill at the jamb of the opening, depending upon the direction of movement and the path of least resistance. Because the effects of expansion are cumulative, dividing long walls into smaller segments reduces the amount of movement that the expansion joint has to accommodate.

Corners. Brickwork will expand in the plane of the wall. At a corner, the brickwork on each side will expand toward the corner. Absence of an expansion joint near a corner or an insufficient number of expansion joints in the wall can result in cracking at the corner as shown in Photo 2. This typically occurs at the first head joint on one side of the corner.

Offsets and Setbacks. When parallel walls expand toward an offset without an expansion joint, the movement may produce rotation of the offset and vertical cracks as shown in Photos 3 and 4.

Structural Frame Concerns. The brick veneer in Photo 5 is supported by a steel shelf angle on a concrete frame. Over time, creep and shrinkage of the concrete frame along with expansion of the brickwork has caused the steel shelf angle to bear on the masonry below. Brickwork between floors can bow if it is not adequately attached to the backing, or the backing is not sufficiently rigid.

Steel frames typically have larger drifts and deflections than concrete frames. This movement generally becomes evident at shelf angles and may result in spalling if not accommodated. An expansion joint below each shelf angle alleviates this concern.

Movement of structural elements rigidly attached to masonry is transferred to the masonry and may cause cracks. These movements may be due to drift of the building frame or lateral expansion from creep. These cracks may occur on the exterior as well as the interior of the building. Space between the structural member and the brickwork and use of flexible anchors will reduce the likelihood of such cracking.

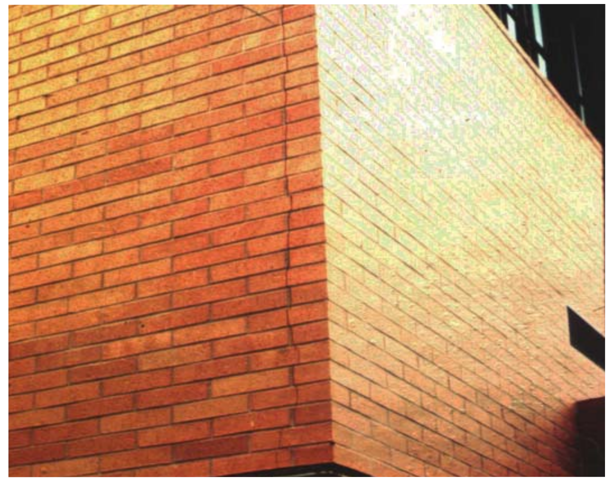

Photo 2
Crack at Corner Without Expansion Joint

Photo 3
Crack at Offset Without Expansion Joint

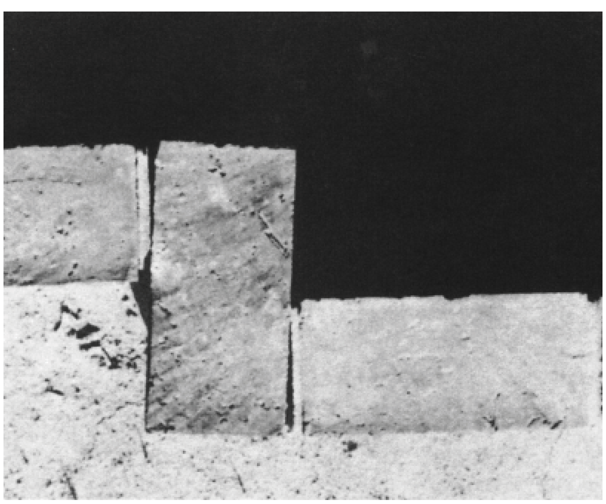

Photo 4
Rotation at Offset Without Expansion Joint

Photo 5
Spalling in Brickwork Without Horizontal Expansion Joint Due to Shortening of Structural Frame

Photo 6
Movement of Parapet Away from Corner

Photo 7
Crack at Foundation Due to Lack of Bond Break Between Brickwork and Concrete

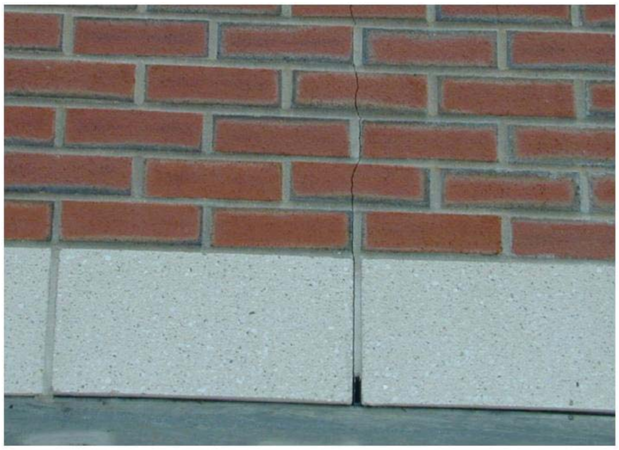

Photo 8
Crack Due to Deflection of Undersized Lintel

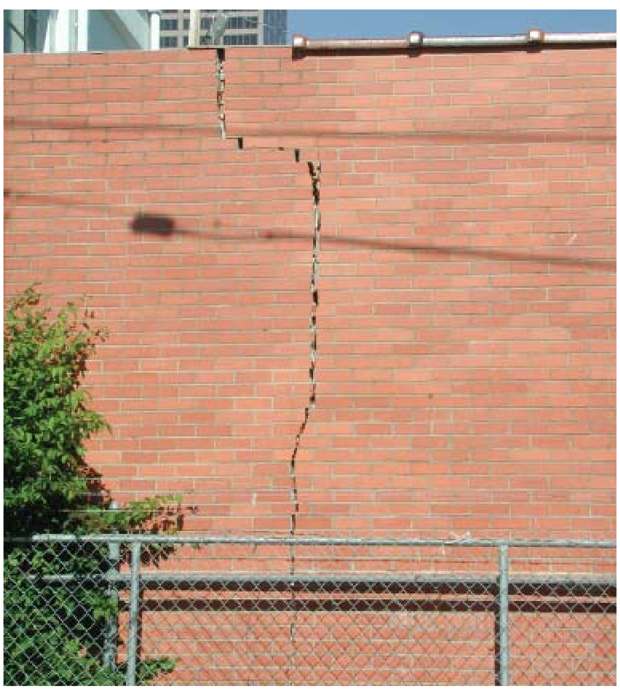

Photo 9
Crack Due to Differential Settlement

Parapet Walls. Parapets are exposed to the elements on three sides, as opposed to most walls which are exposed on only one side. As a result, parapet walls are subjected to extremes of moisture and temperature which may be substantially different from those in the wall below. Parapets also lack the dead load of overlying masonry to help resist movement. Expansion can cause parapets to bow if restrained at both corners and move away from corners if restrained only at one end as shown in Photo 6.

Foundations. Cracking of concrete foundations, as shown in Photo 7 or movement of above grade brickwork away from the foundation corner is often the result of shear stress at the interface between the brick and concrete. Because brick walls expand and concrete foundations shrink, differential movement will cause shearing stresses to develop when these materials are bonded together. A bond break or flashing placed between the concrete and brickwork will permit movement to occur.

Deflection and Settlement. Deflection and settlement cracks are identified by a tapering shape. Photo 8 shows a deflection crack caused by supporting brickwork on an undersized lintel. The crack is wider at the steel angle and tapers to nothing. *Technical Note* 31B details the proper design of steel lintels supporting masonry. Deflection cracks may also occur at steel shelf angles attached to spandrel beams that deflect.

Differential settlement may cause cracking when one portion of a structure settles more than an adjacent part, as shown in Photo 9.

Curling of Concrete. Masonry that is supported by or bonded to cast-in-place concrete slabs may crack if curling of the slab lifts the adjacent masonry. In some cases cracking of the brickwork can be prevented by separating it from the concrete slab with a bond break. Curling of concrete is most often the result of slab deflection and differences in moisture or temperature between the top and bottom of the slab. The American Concrete Institute or other concrete industry organizations should be consulted for recommended practices that minimize slab curling.

Embedded Items. Items embedded in or attached to masonry may cause spalling or cracking when they move or expand. Joint reinforcement should not bridge expansion joints. As the joint closes, the wire may buckle, pushing out adjacent mortar, as shown in Photo 10. Joint reinforcement may also transfer load across the expansion joint resulting in additional cracking.

Corrosion of metal elements within masonry may cause volume increases of such a magnitude as to crack or spall the masonry; however, mortar, masonry units and grout are considered to provide adequate protection when the minimum cover and clearance requirements of *Specification for Masonry Structures* (ACI 530.1/ASCE 6/TMS 602) [Ref. 13] are met. Proper corrosion resistant coatings on the steel item are also necessary.

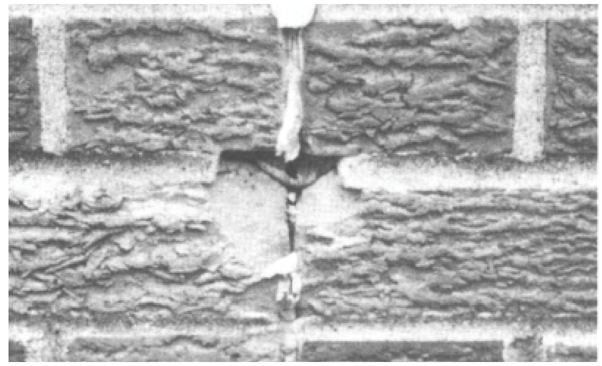

Photo 10
Spalling Due to Buckling of Joint Reinforcement Bridging an Expansion Joint

SUMMARY

This *Technical Note* describes the various movements that occur within common building materials and constructions. It also explains the effects of these movements. Cracking in brickwork can be minimized if all factors are taken into consideration and the anticipated movement is accommodated.

The information and suggestions contained in this Technical Note *are based on the available data and the combined experience of engineering staff and members of the Brick Industry Association. The information contained herein must be used in conjunction with good technical judgment and a basic understanding of the properties of brick masonry. Final decisions on the use of the information contained in this* Technical Note *are not within the purview of the Brick Industry Association and must rest with the project architect, engineer and owner.*

REFERENCES

1. American Softwood Lumber Standard, Voluntary Product Standard PS 20, National Institute of Standards and Technology, U.S. Department of Commerce, Washington, DC, 2005.
2. ASTM C 426, Test Method for Linear Drying Shrinkage of Concrete Masonry Units, *Annual Book of ASTM Standards,* Vol. 04.05, ASTM International, West Conshohocken, PA, 2006.
3. *Building Code Requirements for Masonry Structures* (ACI 530-05/ASCE 5-05/TMS 402-05), The Masonry Society, Boulder, CO, 2005.
4. “Building Movements and Joints,” Portland Cement Association, Skokie, IL, 1982.
5. Crack Control in Concrete Masonry Walls, NCMA TEK 10-1a, National Concrete Masonry Association, Herndon, VA, 2005.
6. Fintel, M., Ghosh, S.K. and Iyengar, H., “Column Shortening in Tall Structures-Prediction and Compensation,” Portland Cement Association, Skokie, IL, 1987.
7. Grimm, C.T., “Masonry Cracks: A Review of the Literature,” *Masonry: Materials, Design, Construction, and Maintenance*, ASTM STP 992, H.A. Harris, Ed., ASTM, Philadelphia, PA, 1988.
8. Grimm, C.T., “Probabilistic Design of Expansion Joints in Brick Cladding”, Proceedings of the 4th Canadian Masonry Symposium, University of New Brunswick, Canada, 1986.
9. *Load and Resistance Factor Design Manual of Steel Construction*, Third Edition, American Institute of Steel Construction, Inc., Chicago, IL, 2001.

10. Nilson, A.H., Darwin, D. and Dolan, C.W., *Design of Concrete Structures*, Thirteenth Edition, The McGraw-Hill Companies, New York, NY, 2003.

11. Robinson, G.C., “The Reversibility of Moisture Expansion”, *American Ceramic Society Bulletin*, Vol. 64, No. 5, 1985.

12. Scheffler, M.J., Chin, I.R. and Slaton, D., “Moisture Expansion of Fired Bricks,” *Proceedings of the Fifth North American Masonry Conference*, The Masonry Society, Boulder, CO, June 1990.

13. *Specification for Masonry Structures* (ACI 530.1-05/ASCE 6-05/TMS 602-05), The Masonry Society, Boulder, CO, 2005.

14. “Wood Handbook - Wood as an Engineering Material”, General Technical Report FPL-GTR-113, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, 1999.

15. Young, J.E. and Brownell, W.E., “Moisture Expansion of Clay Products,” *Journal of the American Ceramic Society*, Vol. 42, No. 12, 1959.

16. Davidson, J.I., "Linear Expansion Due to Freezing and Other Properties of Bricks," Proceedings of the Second Canadian Masonry Conference, Carleton University, Ottawa, Ontario, June 1980.