IV–34. Analysis of Nonstructural Volume Changes in Masonry Construction

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ABSTRACT

Vertical exterior walls or horizontal paving surfaces are subject to diurnal or seasonal temperature changes. When the temperature gradients are nonlinear, bending stresses are introduced due to curling towards the heat. If bonded to foundation walls or slabs on grade, bond shearing and tensile stresses are generated at base boundaries. Moisture changes either in the form of drying, shrinkage, or hydroscopic expansion are generally higher than temperature effects and usually uniform throughout the mass. Hence, boundary stresses generated by moisture changes can be more critical than those due to temperature.

This paper reviews the order of magnitude of these volume changes and offers methods of stress calculation. Periodic heat flow is examined analytically. As ordinary strength of material approaches fail at boundary locations, finite analysis methods have been employed to provide useful theoretical insights. It is apparent from this work that stresses from nonstructural volume changes can cause ordinary structural calculations to be substantially low estimates of actual stresses.

INTRODUCTION

In recent years, with the emphasis on load-bearing masonry construction, several rational engineering design methods have been developed and have had code acceptance. These methods primarily deal with structural resistance to vertical gravity loads and to horizontal lateral loads such as wind or earthquake. In addition, the science of soil mechanics has led to the development of foundation engineering in recent design history; this reduces the hazard of damage from earth settlement or heaving. In contrast to this sophisticated analysis for structural loading of masonry, nonstructural volume changes due to temperature and moisture have received much less attention. While it may be argued that failure due to these mechanisms is less likely to endanger public safety, nevertheless, such failures frequently have significant, economic consequences as well as questionable aesthetics. Many times brittle masonry surrounding steel or concrete framing experiences distress from movements of the frame due to thermal or moisture changes in the frame itself. In this case, masonry is blamed by the owner or lay observer because it experiences the failure though it may not be the cause.

This paper will primarily deal with potential masonry distress from volume changes due to heat or moisture. Thermal changes deal essentially with diurnal and seasonal cyclic amplitudes of air temperature and solar radiation. Very high fire or very low cryogenic temperatures are not considered. Moisture changes are those resulting in shrinkage or swelling from vapor or liquid water. Disruptive effects of ice, either in spalling the material body, or in displacing walls as at shelf angles, is not considered. Volume increases due to chemical changes are not dealt with here; this might include expansion from rusting steel or from magnesium compounds in mortar. The masonry materials are limited to clay and concrete bonded by cementitious mortar. The use of these materials in combination with steel and concrete frames is also examined, especially the latter due to their shrinkage and creep characteristics.

Designers are encouraged to rationally consider the effects of volume changes considered here. No new structural engineering principles are involved. Some familiarity with thermal stresses, finite differences methods, and statistics is presumed. Too often the structural engineer, the professional best qualified, either neglects such volume changes, or regards them of secondary importance. Unfortunately, ordinary safety factors do not accommodate their effects. Even where he does consider them, poor architectural detailing or indifferent field execution can cause trouble. Masonry systems are brittle materials, weak in tension; they are especially sensitive to restrained volume contractions.

MATERIAL PROPERTIES

Thermal coefficients of linear expansion of some common building materials are shown in Table 1. This tabulation includes clay and concrete masonry. To be noted is that the coefficient of thermal expansion of the two materials is significantly different, the concrete block being about 50% higher than clay masonry. When used together in a composite wall, this may have adverse consequences. In general, ceramic building materials range from 3.0 to 9.0×10^{-6} in./in. °F with clay masonry at the lower range and gypsum products at the upper. Metals range from 7.0 to 13.0×10^{-6} in./in. °F with steel at the lower range and aluminum at the upper. Organic materials range well above aluminum from 15.0 to 45.0×10^{-6} in./in. °F. While masonry materials have low thermal expansion of the common building materials, their relatively high modulus (stiffness) and low tensile strength make them vulnerable to cracking from even moderate temperature gradients or changes. Since thermal stress in a fully restrained body is the product of the elastic modulus, thermal coefficient, and temperature change, as noted below, a high expanding organic of low modulus can receive no greater stress than a low expanding inorganic of high modulus. Consider a comparison between a plastic product and unit masonry as shown in Table 2.

Thus, a high coefficient of linear expansion, if accompanied by a low modulus, does not necessarily generate high thermal stresses. Generally, thermal changes are completely reversible if cycled.

On the other hand, moisture changes are not always reversible. Moisture expansion of clay masonry is not believed to be reversible at ordinary ambient temperatures. Moisture shrinkage of clay masonry is minor, being largely due to the cementitious mortar it contains. On the other hand, both shrinkage and swelling of concrete masonry is a sizeable phenomenon. Repeated cycles of wetting and drying of concrete masonry can result in some decreased magnitudes of movement.

As less is well known about moisture changes in clay masonry, some special discussion is now made. Since some original work by McBurney on three structural tile causing field cracking, it has been recognized that clay bodies can expand from moisture after leaving the kiln. McBurney's work based on reheating to 400°C and autoclaving as per ASTM C151 showed a potential moisture expansion of 0.001 to 0.002 in./in., a sizeable quantity that he believed to be irreversible at ordinary temperature; i.e., no corresponding shrinkage existed. Subsequent work by Brownell and Young has indicated that this moisture expansion taking place at ordinary ambient condition of temperature and humidity is probably less than 0.001 in./in. Their work on 27 brick sources gave expansion ranging from 0.002 in./in. to 0.00089 in./in. after 84 months exposed to 50% RH at atmosphere temperature. Hosking and Hueker have built full-scale walls subject to outdoor exposure. Using Australian brick, they autoclaved to dimensional stability 220 specimens, yielding the following moisture expansion:

High	0.00850 in./in.
Mean	0.00350 in./in.
Low	0.00140 in./in.

Accompanying this laboratory measurement on bricks, a series of walls was built (nine walls 11′-8″ long and two walls 63′-3″ long). Bricks were placed in the wall under three conditions: (1) "kiln fresh" from the manufacturer; (2) "as delivered" about two weeks after manufacture; and (3) "soaked" about five weeks after manufacture and thoroughly wetted prior to placing in the wall. Since realistic wall measurements are less than 0.001 in./in., the value of the autoclave brick test as an indicator of absolute wall expansion is very questionable. This wall work shows that the amount of resultant expansion is highly dependent upon the amount of expansion of the clay units that has taken place after kiln firing but prior to their being placed in the wall. More recently, Smith has quantitized this by showing that this expansion is proportional to the logarithm of time. Thus in one month, 34% has taken place; in one year, 59%; in ten years, 82%.

The work of these three investigations suggests that this clay masonry moisture expansion has an order of magnitude that is 0.001 in./in. Young has shown that this moisture expansion of fired clay bodies is probably due to chemical absorption of water vapor and is irreversible at ordinary temperatures. As 0.001 in./in. is three times that expected from thermal volume change, experienced observation must assume a mechanism of accommodating for adsorbed moisture expansion. Walls generally do not exceed thermal volume changes theoretically possible. It is hypothesized that three mechanisms of accommodation exist:

1. Low-modulus mortar joints accommodate local expansion in the neighborhood of the unit.
2. Experimental work has been primarily upon unrestrained specimens. Real walls are restrained at their boundaries by built-in construction conditions.
3. Substantial expansion can take place between the kiln-fresh condition and placement in the wall.

Based on historical field performance, it is judged that 0.002 in./in. should be used to provide for some allowance of clay masonry moisture expansion.

MASONRY VOLUME CHANGES

Thermal Movements

Thermal changes are of two kinds: diurnal or daily and seasonal or annual. It is not fully recognized that diurnal gradients may be more severe than seasonal. This is due to at least three factors:

1. Diurnal changes are associated with fluctuation of surface temperatures whereas seasonal with mean wall temperatures. In the summer, the latter may be one-third to one-half the latter. In winter, these differences are still pronounced due to daytime surface heating, even when the ambient air temperature is below zero.
2. Diurnal changes being relatively rapid afford short time periods for volume change adjustment. Seasonal changes being relatively slow, allow long time periods for masonry adjustment. Relatively, the diurnal is a "shock-like" phenomenon compared to the seasonal.
3. The dynamic nonlinear character of diurnal gradients can result in critical tensile stresses, even when the wall is free of boundary restraints. Thus, a freely curling or bowing wall subject to a steep nonlinear heat gradient (diurnal effect) can theoretically develop critical tension whereas a linear steady-state gradient (seasonal effect) is theoretically stressless.

Typical summer values of maximum surface temperatures, when the maximum ambient air is 95°F, are shown in Table 3

At night, due to nocturnal radiation, the building surfaces cool to temperatures well below the air-conditioned interior. In the winter season when ambient air is below zero, building surfaces can be above freezing, giving rise to temperature differences of 50°F to 75°F at the surface, while the middle of the wall remains at the level to which it descended during the early morning (a level approaching zero, in a heavily insulated wall).

Fig. 1 establishes the heat flow mathematics for periodic building surface heating. Note the time lag effects which give rise to initial sharp, dynamic gradients.

Fig. 2 summarizes the maximum tensile stress associated with two boundary conditions: (1) restrained at the boundaries (fully or partially), and (2) free to deform unre-

strained. Approximating the temperature gradients by an n-degree parabola for analytical convenience, the formulae for the maximum tensile stress for two limiting boundary conditions are:

Partial restrained:

$$t_{max} = (E\alpha\Delta T)/(n + 1) \text{ at the inside surface} \quad (1)$$

Full unrestrained:

$$t_{max} = (E\alpha\Delta T)\ [2(n - ..1)(3\Theta_n - 1]/[(n + 1)(n + 2)] \quad (2a)$$

$$\text{where } \Theta_n = [6/(n + 1)(n + 2)]^{\frac{1}{n-1}} \text{ at the wall middle} \quad (2b)$$

If fully restrained, the wall is entirely under compression; but as walls are usually built, partial restraint is more likely because the joints at wall tops are filled only at the outside surface. The inside, particularly if of block, is frequently a void under a spandrel beam. For one-story buildings, or multistory curtain walls with "soft" joints under shelf angles, it may be more accurate to assume the top hinged with bottom restrained. Precise boundary conditions are unfortunately difficult to evaluate. The two cases considered represent limiting conditions of practical interest. If fully unrestrained, the walls will of course bow or curl toward the heat. Theoretically, deflections are approximated by the formula:

$$\Delta = (\alpha\Delta T L^2)/(8d) \quad (3)$$

The above formulae are for homogenous walls; those for composite walls are extremely complex. By using average α and E values, composite cases can be roughly evaluated.

Moisture Movements

Wall movements due to moisture changes are dealt with as a composite model (see Fig. 3). Consider a brick-block wall wherein the brick of clay masonry expands and the block of concrete masonry shrinks. Fundamentally, the case is similar to the thermal gradient effects studied above. Theoretically, if fully restrained, the block is in uniform tension and the brick in uniform compression with the former magnitude being $E_c\epsilon$. Real behavior in the field generally reduces the moisture change case to the fully unrestrained case in which the tension in the block is:

$$t_{max} = (E_c\epsilon)/[(1/m\rho) + 1] \quad (4)$$

The curling or bowing that the unrestrained case experiences has the following theoretical magnitude:

$$\Delta = \left[(3L^2\epsilon)/(4c)\right]/\left[(m\rho + m\rho^2)/(7 + 4m\rho - 6m\rho^2 + 4\,m\rho^3 + 7\,m^2\rho^4)\right] \quad (5)$$

In composite wall construction (brick-block), the moisture expansion of clay masonry is additive to the moisture shrinkage of the concrete masonry with the critical tension occurring in the block. The curling or bowing, if unrestrained, even without clay masonry expansion, is much greater than the effects of thermal gradient.

SUMMARY

In conventional brick-block construction, the use of usual interest is the unrestrained boundaries. In this case, thermal tension will occur in the clay brick. Its magnitude can be estimated by Equations (2a) and (2b) using n = 6. It can be shown that the maximum thermal tension is associated with that nonlinear temperature gradient corresponding to a 6th degree parabola. Thermal deflections can be estimated by Equation (3). For composite construction, use average material property values; the thermal formulae are for homogenous materials only. For moisture changes, ϵ is usually the magnitude of concrete block shrinkage; if clay brick moisture expansion exists, it is simply added to the shrinkage magnitude. Equations (4) and (5) yield tensile stress and deflection values based on the composite modular ratio m and the composite dimensional ratio ρ. For moisture changes, critical tension occurs in the block.

When both thermal and moisture changes occur together, noticeable bowing or curling can be observed, frequently accompanied by many shrinkage cracks in the block and cracked headers (if used) or thin webs in the brick. The older masonry header construction is particularly vulnerable to these effects, resulting in total collapse of exterior brick skins. The thin web construction of solar screen has failed for similar reasons. Jamming of operative doors and windows in deforming walls has happened. Bowing or curling walls cause disruption of roof and foundation levels, especially the tilting of parapets and the separation of masonry outward at door and window jambs. Designers will do well to accommodate these movements by some rational analysis as suggested here.

TABLE 1

Material	Thermal Coefficient ($\times 10^{-6}$in./in.°F)
Clay Masonry	
Clay or shale brick	3.6
Fire clay brick or tile	2.5
Clay or shale tile	3.3
Concrete Masonry	
Dense aggregate	5.2
Cinder aggregate	3.1
Expanded-shale aggregate	4.3
Expanded-slag aggregate	4.6
Pumice or cinder aggregate	4.1

TABLE 1—cont'd.

Material	Thermal Coefficient ($\times 10^{-6}$in./in.°F)
Stone	
Granite	4.7
Limestone	4.4
Marble	7.3
Concrete	
Gravel aggregate	6.0
Lightweight, structural	4.5
Metal	
Aluminum	12.8
Bronze	10.1
Stainless steel	9.6
Structural steel	6.7
Wood, Parallel to Fiber	
Fir	2.1
Maple	3.6
Oak	2.7
Pine	3.6
Wood, Perpendicular to Fiber	
Fir	32.0
Maple	27.0
Oak	30.0
Pine	19.0
Plaster	
Gypsum aggregate	7.6
Perlite aggregate	5.2
Vermiculite aggregate	5.9

TABLE 2

Material	Thermal Coefficient	Elastic Modulus	Thermal Change	Thermal Stress
Plastic Product	30×10^{-6} in./in. °F	0.3×10^{6} psi	100°F	900 psi
Unit Masonry	3×10^{-6} in./in. °F	3.0×10^{6} psi	100°F	900 psi

TABLE 3

Surface Orientation	Air Temp °F	Surface Temp °F	Time to Maximum
East, vertical wall	77	151	8:00 am
South, vertical wall	93	135	1:00 pm
West, vertical wall	93	168	4:00 pm
North, vertical wall	93	108	5:00 pm
Roof, horizontal deck	93	172	Noon

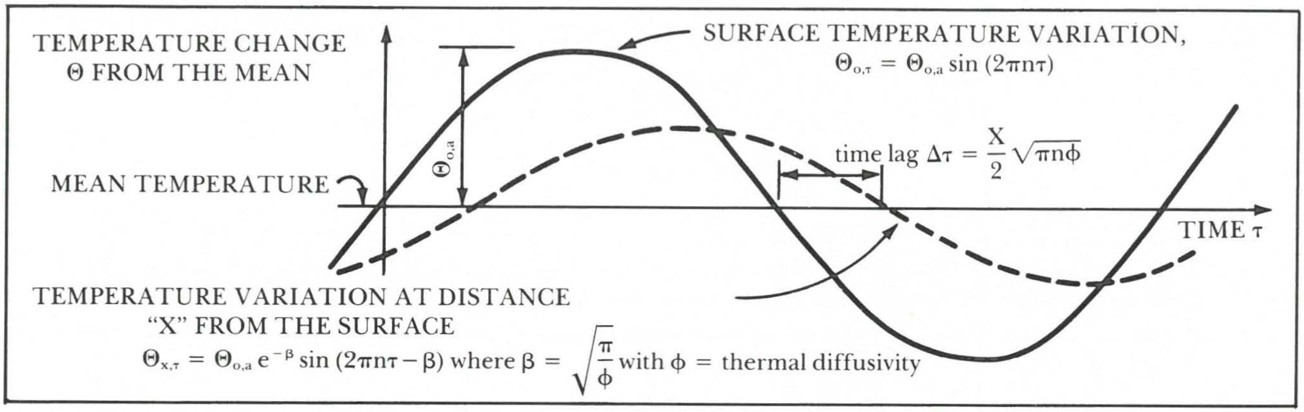

Figure 1. Time-Temperature Variation Within A Wall

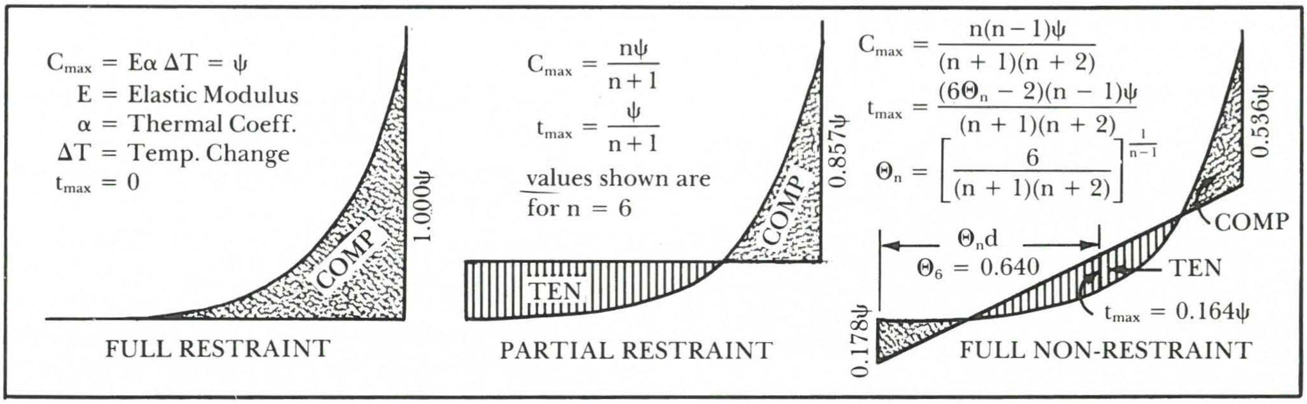

Figure 2. Stresses From Non-Linear Temperature Gradients.

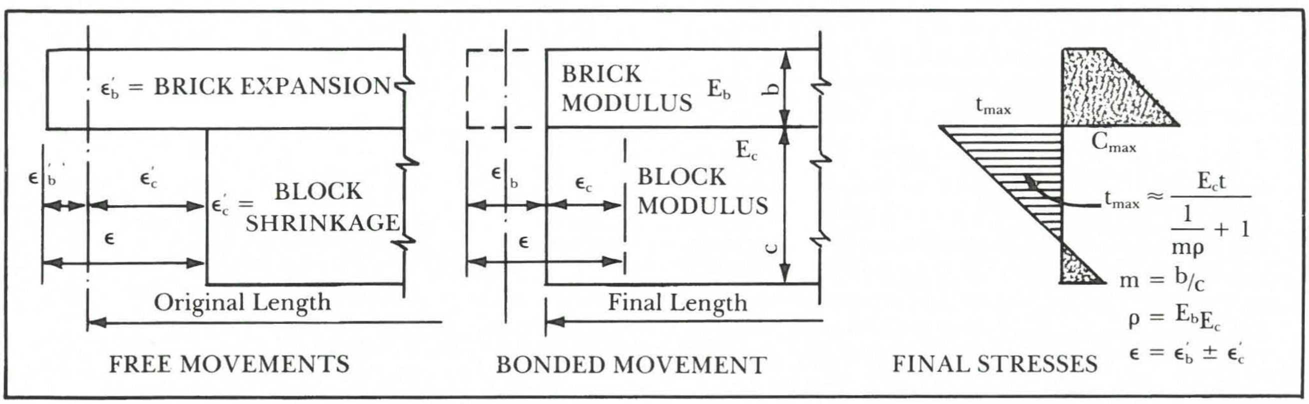

Figure 3. Stresses From Uniform Moisture Changes