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Accommodating Movement in Building Envelope Materials

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If expansion joints are not provided, the building will make its own.

We may think of the building envelope as an inanimate object, but, really, its components can be quite mobile. Building materials grow, shrink, shift, bulge, deform, and elongate in response to stresses and fluctuations in the environment, and these dimensional changes often impose strain on adjacent elements.

Where the forces of movement are not foreseen during design and construction, evidence of the struggle will emerge, in the form of cracks, spalls, displacement, broken glass, warped metal, and, eventually, breakdown of the assembly.

Failure to anticipate and allow for movement in building materials compels imparted stresses to find their own path to release, which is nearly always an undesirable one. Not only are cracks unsightly, they also open pathways for moisture penetration into the building enclosure, which compounds the problem as materials swell or corrode, placing further outward pressure on adjoining components.

To design for movement in the building envelope is to identify the properties of the materials used in construction, as well as the environmental and siting conditions of the building, and to develop a design that either minimizes or allows for such movement. For instance, where dimensional changes are anticipated, the design should accommodate each material's propensity for expansion and contraction, and the building enclosure must allow for differing – and, often, opposing – movement of adjoining materials.

Calculations and detailing for seemingly small movements in the building envelope may seem cumbersome and time-consuming, however the forces that develop from these deformations can be immense. Neglecting to include adequate expansion joints, control joints, bond breaks, flexible anchorage, slip planes, and other means to allow for changes in dimension will ultimately expend more time and money in remediation than a prudent approach would require at the outset. Where a building owner is faced with the unfortunate discovery that such practices were not employed at the time of construction, all is not lost. There are rehabilitative measures that can be taken after the fact, but unless the underlying issue of restrained movement is addressed, cosmetic fixes to cracked masonry or displaced stone will do little to keep ahead of the problem.

With attention to the causes of movement, including fluctuations in ambient temperature and moisture, applied loads, chemical interactions, and materials' propensity to expand or shrink over time, the general behavior

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of each element in relation to others can be predicted. To allow for factors that might impact as-built conditions, a conservative approach to incorporating fluidity in the building envelope design should limit movement if possible and accommodate material movement, without imposing restraint.

Types of Movement

When designing for movement of building enclosure materials, architects and engineers must consider dimensional changes that can arise from the effects of the environment, including temperature and moisture variations, as well as elastic and inelastic deformation from applied loads and volume changes due to chemical interaction. Designers should also take into account the tendency of a given material to shrink or expand over its service life, and the ways in which neighboring materials with opposing volume changes might pull or push against each other.

Temperature Movement

Changes in temperature cause most building materials to expand and contract. Unless the movement is restrained, the changes are generally reversible. As the temperature rises, materials tend to expand, then contract again as the temperature drops. How great these volume changes are depends on the type of material and may be expressed in terms of ***coefficient of thermal expansion*** *(see table).*

Projected thermal movement is the product of the coefficient of thermal expansion, the overall temperature change, and the length of the component. As an example, take a 10-foot sheet of copper roofing at a building site with a temperature swing of up to 100°F, for which the panel would increase in length 0.0000098 in./in./°F × 120 in. × 100°F, which is 0.1176 in., or just under 1/8 in. Although this number might seem small enough to be negligible, restraining the copper sheet by hard fastening it at both ends would lead to bowing and buckling as the temperature rises and the copper expands, and, as the temperature drops, the shrinking metal would strain at the fastening points, potentially tearing itself apart.

COEFFICIENTS OF LINEAR THERMAL EXPANSION

MATERIAL	AVERAGE COEFFICIENT OF LINEAR EXPANSION ($\times 10^{-6}$ IN./IN./°F)
BRICK	4.0
CONCRETE (STRUCTURAL)	5.5
CONCRETE (NORMAL POURED)	8.0
STAINLESS STEEL	5.5 TO 9.6
TYPICAL STEEL	7.3
COPPER	9.8
ALUMINUM	12.8
GLASS (PLATE)	5.0
GLASS (HARDENED)	3.3

Moisture Movement

Porous building materials such as brick and concrete expand as they absorb water and contract as they dry. Like temperature movement, moisture deformation is generally reversible, except in the case of the initial shrinkage or expansion that takes place with some building materials. Often considerably greater than subsequent reversible moisture-related dimension changes, expansion or contraction due to natural aging can yield significant internal stresses that may manifest as cracks, spalls, open joints, and leaks as restrained elements struggle to release built-up pressure.

Brick is smallest in size after exiting the kiln, when it is the driest it will ever be. From then on, it expands as it absorbs moisture from the atmosphere and precipitation. Drying the brick at normal temperatures will not reverse this expansion process, which is greatest in the first few weeks after firing but continues at a slower rate for years. Just how much a given brick will expand depends mainly on raw materials, but firing temperature is also a factor. A brick fired at lower temperatures will expand more than the same brick fired at higher temperatures.

Concrete shrinks as it cures, due to the natural moisture loss that occurs soon after the concrete is cast. As with brick, the initial dimensional change of concrete is irreversible and tends to be significantly greater than any ensuing moisture-related volume fluctuations. The degree to which concrete will shrink during curing depends on the properties of the concrete mix, including water-cement ratio, cement composition, and aggregate type, as well as size of the concrete unit, curing conditions, and size and placement of embedded reinforcing steel.

Wood is the building material most subject to dimensional changes due to moisture. As part of the commercial seasoning process, the wood shrinks as moisture content diminishes from the initial fiber saturation point, until reaching equilibrium with the environment. After this initial shrinkage, changing moisture content in the wood will continue to cause the wood to swell and shrink. The degree of shrinkage differs in the radial, tangential, and longitudinal directions, with the latter typically so small as to be considered negligible from a design standpoint. This swelling and shrinkage can ultimately cause the lumber to crack.

Chemical Action

In the presence of moisture, chemical reactions can take place within or between building materials that impact the volume and integrity of the component.

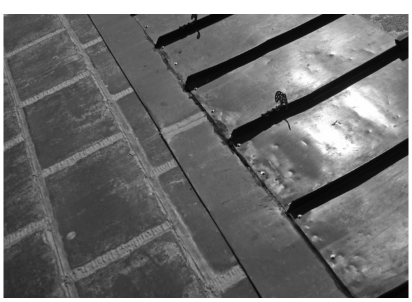
Corrosion occurs when ferrous metals are exposed to moisture, whether through direct contact with liquid water or via the condensation of ambient humidity. As steel corrodes, it expands; the volume of rust is greater than that of the original steel from which it formed. The pressure of the swelling steel is then transferred to the surrounding concrete, brick masonry, glazing, or other material, causing movement and cracking.

Carbonation takes place when hydrated Portland cement in concrete reacts with carbon dioxide in the air. Although the reaction leads to an increase in the mass of the concrete, it also causes a reduction in volume. Not only does carbonation lead to concrete shrinkage, it also reduces the alkalinity of concrete, making the embedded reinforcing more susceptible to corrosion.

Alkali Silica Reaction (ASR), characterized by fine patterns of cracking in concrete, is an expansive reaction between minerals in some aggregates and alkali hydroxides in the cement. The reaction forms a gel that absorbs water and expands, exerting tremendous outward pressure on the concrete.

Shear cracks riddle the exterior wall of this urban parking structure.

At this garage, movement-related cracking worsened as embedded steel corroded.



Solutions for copper roofs: lapping cleats that allow sheets to slide *(standing seam, right)* or small sheet sections *(flat seam, left)*.

A variety of other chemical reactions can also cause dimensional changes and deformation in building materials, which place sufficient strain on the components to cause cracking and threaten the structural integrity of the assembly.

Structural Deflection

In response to the variety of forces acting on the building envelope, the components will undergo deformation and movement. In addition to the ***dead loads*** (forces that remain relatively constant, i.e. the self-weight of the building envelope) and ***live loads*** (changing forces related to building usage) that should be considered as part of the design of a building, environmental forces that can cause structural deflection include wind, soil settlement, snow loads, and the seismic forces of earthquakes. Vertical dead and live loads, including the weight of the building element itself, cause horizontal members like beams and lintels to deflect vertically, while columns, bearing walls, and building frames tend to shift horizontally from the lateral forces of wind and seismic events. The building envelope needs to be adaptable to these changing forces.

Sustained, excessive loading may lead to irreversible deformation known as ***creep*** or ***plastic flow,*** from which the material does not fully recover even if the load is removed. Once a load is applied during erection of the structure, wood and concrete members begin to sag permanently by a small amount, eventually stabilizing after the first several years of the life of the building. Concrete, a seemingly solid mass, has some fluid properties, which cause deck slabs to thin and expand in length. Other building materials, like brick, exhibit only negligible creep in response to applied loads. However, if attached rigidly to a wood or concrete frame, masonry may sustain stresses from movement of the adjoining member.

Settlement

When the soil beneath a building shifts, expands, or contracts, foundation settlement can cause displacement and cracking of the facade, especially where settlement is nonuniform and one portion of the building settles more than another. Proper site preparation and appropriate foundation design can prevent differential movement and limit uniform settlement to within an acceptable range.

Other Causes of Movement

Displacement and deformation of building elements is a complex topic, and much remains to be researched regarding the inter-relationship among the dimensional stability characteristics of materials, the external forces impingent on a built structure, and the interaction between dissimilar components. Therefore, precise prediction of building element movements is not usually achievable. Factors such as temperature at installation, age of materials, ambient humidity, and individual variation in composition even among relatively uniform materials, as well as a range of other variables, make exact calculations impossible.

Fortunately, enough is known about the most common mechanisms of building movement that conservative estimates can guide design in accommodating typical anticipated dimensional changes. To avoid over- or underestimating movement, design professionals should use the discretion born of experience to select appropriate tolerances.

Strategies for Accommodating Movement

The principal cause of movement-related cracking and displacement of building materials may be thought of as a failure of imagination. Accustomed to thinking of our world in terms of the mobile (people, vehicles, animals) and the stationary (earth, rock, buildings), it is easy to forget that these categories are imprecise at best and often inaccurate. This classification system is the reason earthquakes are so deeply unsettling (earth = stationary) and broken-down cars so infuriating (cars = mobile). It is also why buildings tend to be under-designed as relates to provision for movement. Imagining that a brick facade could expand by several inches flies in the face of object permanence, the idea that objects remain constant over time. Despite evidence to the contrary, it may be reassuring to persist in thinking that the concrete poured today will remain dimensionally stable a year from now, as opposed to facing the discomforting fact that a solid material can shrink, distort, and, even, flow.

The tendency to disregard changes in building materials notwithstanding, it is advantageous to avoid inadvertently constraining forces of movement, which can become so great under restraint that they rip the building apart. To prevent the adverse effects of restrained movement, the design professional has two main strategies: strengthen building materials to resist stress and limit movement, and incorporate movement joints to provide flexibility for buildings to move according to their natural tendencies.

Material Strengthening

To enable materials to better resist the stress of anticipated movement, strengthening is common practice in building design and construction. For example, manufacturers aim to limit shrinkage in concrete by using the smallest amount of water that still affords the requisite strength and workability, along with adequate moist curing.

However, despite these precautions, some shrinkage will still occur. Weak in tension, concrete that is rigidly fixed to other parts of the structure will crack when subjected to the tensile stress from shrinkage or temperature-induced contraction. Incorporating temperature reinforcement, typically steel bars or welded-wire fabric, into the slab provides resistance to compressive forces and reduces shrinkage cracking. This practice is commonly employed for parking garage decks, which are subject to large temperature swings, as well as for building floor slabs.

Design professionals can manipulate those characteristics of materials that contribute to movement. Specifying light colors or shading devices reduces temperature range at the building exterior. Allowing materials with high irreversible initial shrinkage, like concrete or cast stone, to mature before use cuts down on movement after installation. Seasoning of wood limits moisture-related expansion and contraction.

Movement Joints

Despite construction practices that limit shrinkage, expansion, bowing, and heaving, buildings will still move. Under restraint, the stress of tension or compression builds until it is released in the form of cracks, displacement, or breakage. Provisions should be made that allow the building to readily adapt to dimensional changes and the effects

Brick expansion leads to vertical and step cracking as forces seek pathways to relief.

Bowing and displacement in brick masonry are symptoms of restrained movement.

Relieving angles and horizontal joints support masonry and allow for expansion.

of variable environmental conditions.

Movement joints divide the building into discrete segments and allow each section to move relatively independently. Used in combination across the exterior envelope, the various types of movement joints include construction joints, control joints, expansion joints, isolation joints, and sliding joints. Especially for large buildings or those with a complex geometry, joints are critical to creating simpler units that can respond to tensile or compressive forces without placing stress on adjacent building areas.

Construction joints are used where construction work must be interrupted, primarily in concrete construction. Positioned where they are least likely to impair structural strength, construction joints must allow some displacement caused by thermal and shrinkage movement, while transferring flexural stresses from external loads across the joint.

Control joints (also called **contraction joints**) create a plane of weakness in concrete or other brittle materials that tend to shrink, allowing cracks to form at predetermined locations, rather than randomly throughout the material. Typically, control joints are gaps or grooves that are designed to open as the concrete shrinks. As with construction joints, these must be located such that the structural integrity of the concrete is not adversely affected.

Expansion joints separate large surfaces of materials, such as brick masonry facades, glazed curtain walls, or plaza terraces, into discrete segments, releasing stresses from changes in temperature, elastic deformation, moisture expansion, settlement, chemical action, creep, and other forces. Expansion and shrinkage are cumulative, so regularly spaced expansion joints reduce the amount of movement that any one

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Design of Movement Joints

Movement joints must not only allow for dimensional changes, but also act integrally with the building enclosure to support necessary floor loads, maintain fire separations, protect against noise, thermal transfer, and air and moisture infiltration, and, in the case of plazas and garages, minimize tripping hazards and carry traffic. Joints must do all this and be durable and maintainable, withstanding season after season of use without premature degradation or wear.

Some joints function only in a push-and-pull manner, along one plane, while others accommodate shear motion. Joints must be of sufficient size to handle movement, without being so large they are difficult to weatherproof or compromise the building aesthetic. The anticipated direction and extent of movement will guide joint design, as will climate, location, and building geometry.

Placement. Typically, building movement joints are located:

- At periodic intervals along a continuous wall;
- At changes in wall direction, including building corners and setbacks;
- At wall openings, such as windows and doors;
- At changes in building height;
- At junctions between areas subjected to differing climactic conditions;
- Between adjoining buildings;
- Between dissimilar materials;
- At penetrations;
- Below shelf angles;
- Between panels in a veneer assembly;
- At structural slab intersections in a concrete parking garage; and
- Between sheets of metal roofing.

At the exterior side of movement joints, sealants typically provide protection from air and water infiltration. For longevity, it is important to select only sealants with high expansion and compression capabilities, taking into consideration adhesion to the substrate and resistance to weathering.

Vertical Joints. To allow for horizontal expansion and contraction along an exterior wall, vertical expansion joints should be positioned to break the wall area into sections that share the same support conditions, exposure, and construction. Joint spacing should take into consideration the amount of expected movement, compressibility of joint materials, and the size of the joint. While no single recommendation can apply to all structures, a general rule of thumb for brick masonry cavity walls suggests placing vertical expansion joints at approximately 20-foot intervals along a horizontal run of brick.

Horizontal Joints. Throughout the height of a wall, brick expands and contracts vertically. If the masonry were supported only at the bottom of the wall, not only would the multi-story stack crush the brick at the bottom, the top of the wall would rise and fall during thermal cycles, ultimately increasing in height as the brick absorbs moisture. To account for expansion and prevent cracking, brick masonry is typically supported by horizontal ***relieving angles*** (***shelf angles***) at regular intervals. These steel, L-shaped members are attached to the floor slab or structural frame, typically at each floor. Horizontal expansion joints below relieving angles provide space for vertical expansion of the brick and allow for deformation of the metal on which the brick bears. ■

Shattered glass and displaced concrete block due to building enclosure movement.

Metal cladding displacement and exposure of underlying structural steel.

joint must accommodate. At corners, offsets, and setbacks in the facade, cladding materials like brick masonry will expand horizontally toward the corner, forming long, vertical cracks and displacement if expansion joints are not provided.

Building expansion joints are to the whole building what expansion joints are to a single building element: they divide the building into sections, so that stresses from one portion do not compromise the integrity of the entire structure. These wide, flexible joints extend through the building to create smaller units that move autonomously.

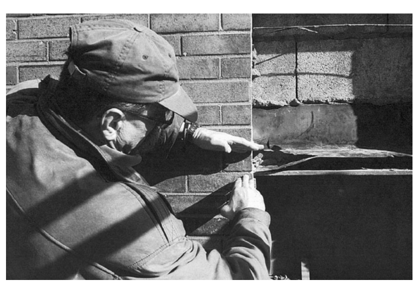
Isolation joints allow for movement between dissimilar materials or between old and new construction. For example, building frames constructed of concrete or steel will move differently than will brick veneer, leading to spalling and bowing if not accommodated. Similarly, concrete slabs adjoining walls, columns, or pipes will crack under restraint unless isolation joints are provided at the material interface.

Sliding joints are typical of traditional wood detailing and allow components to slip past one another as they expand and contract. Standing seam copper roofs use this principle to allow the sheets to slide, while still being secure.

Each type of movement joint is intended to serve a specific function, so they may not be used interchangeably. Some, such as control joints, may be little more than score marks in the material, or they may be filled with an inelastic compound. Others, like expansion joints, contain flexible foam or pads. Selecting the appropriate type, size, spacing, and location of joints can make the difference between a building that weathers the seasons and one that succumbs to premature cracking and deterioration.

Differential Movement

Many brick masonry cavity walls use concrete block as back-up, a situation that leads to differential movement problems. After installation, brick tends to expand, while concrete shrinks. If the two are tied together rigidly, the wall will bow, deflect, and crack as brick and concrete pull against one another. Eventually, the ties binding face brick to concrete backup can break under strain, rendering the brick veneer structurally unsound and liable to fall from the building. Flexible anchors that can accommodate differential movement, in conjunction with sufficient cavity clearance, provide support while allowing for dimensional changes.



Inadequate space for the steel relieving angle has caused this wall to bow outward.

Where floor slabs and foundations adjoin cladding, or at intersections between banded wall materials, ***bond breaks,*** often in the form of building paper or flashing, allow independent movement of the different elements. Differences in temperature or moisture between the top and bottom of a concrete slab may cause deflection of the concrete called ***curling,*** which can crack facade materials directly supported by or bonded to the slab. In addition to construction practices that minimize concrete shrinkage, such as limiting water content and increasing the size and proportion of course aggregate, separating the structural slab from the exterior wall with a bond break can prevent the facade from cracking. Bond breaks may also prove useful to isolate bands of different cladding materials.

The main consideration for materials with different movement properties, whether they be exterior wall components, roofing materials, or plaza and terrace elements, is to provide structural support while allowing independent movement. Connectors that permit movement in one direction (e.g. along the plane of a wall) and resist movement in another (e.g. perpendicular to the wall) and flashings that create ***slip planes*** along lintels and angles are strategies that allow for certain types of movement while holding the envelope system stable.

Planning for Movement in Modern Construction

As advances in material technology have allowed for thinner and higher-strength building enclosure materials, the science of building movement has become central to the successful implementation of these new exterior assemblies. While innovations in extraction, fabrication, and structural

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representative projects

Material Movement

Building materials expand, contract, stretch, deform, creep, and swell. Hoffmann Architects designs solutions to building enclosure distress due to restrained movement and unforeseen dimensional changes, and we develop design strategies that allow building materials the flexibility to move according to their natural tendencies. Our projects involving movement-related rehabilitation include:

Washington Masonic Memorial, Alexandria, Virginia, *Earthquake Damage Evaluation.*

Prudential Plaza Building, Newark, New Jersey, *Marble Panel Facade Consultation.*

Southern CT State Univ., West Campus, New Haven, Connecticut, *Facade Consultation.*

Georgetown University, Ryan Hall and Isaac Hawkins Hall
Washington, District of Columbia
Exterior Restoration

Sikorsky Aircraft, Administration Building
Stratford, Connecticut
Facade Replacement

Columbia University, Mudd Hall
New York, New York
Parapet Repairs

Mandarin Oriental Hotel
Washington, District of Columbia
Earthquake Damage Assessment

Fairfield Warde High School
Fairfield, Connecticut
Masonry Wall Repairs

Countee Cullen Library
New York, New York
Exterior Rehabilitation

Smithsonian Institution, Donald W. Reynolds Center for American Art and Portraiture
Washington, District of Columbia
Copper Roof Replacement

NYC Health+Hospitals/Kings County
Brooklyn, New York
Building Envelope Rehabilitation

Travelers Tower
Hartford, Connecticut
Plaza Renovation

ARINC Headquarters
Annapolis, Maryland
Facade Investigation and Repair

Roberto Clemente and Riverbank State Parks
New York, New York
Masonry Facade Consultation

Pickwick Plaza
Greenwich, Connecticut
Facade Repair

Parking Authority of Baltimore City
Baltimore, Maryland
Assessment and Repair of Eight Garages

The Bowery Hotel
New York, New York
Facade and Roof Rehabilitation

Aramark Tower
Philadelphia, Pennsylvania
Facade Rehabilitation

Morgan Stanley
Purchase, New York
Garage Repair and Site Rehabilitation

The George Washington University, Lisner Auditorium
Washington, District of Columbia
National Historic Landmark Restoration

G. Fox Building
Hartford, Connecticut
Masonry Veneer Stabilization

4 New York Plaza
New York, New York
Facade Consultation and Repairs

Rockland Psychiatric Center
Orangeburg, New York
Facade Investigation

One American Row
Hartford, Connecticut
Pedestrian Bridge Rehabilitation

Ericsson, Piscataway Campus
Piscataway, New Jersey
Roof Replacement

Verizon, 95 William Street
Newark, New Jersey
Partial Facade Reconstruction

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framing allow for cost-effective enclosure systems, the downside is that the beneficial qualities of these new materials come at the expense of other properties. Brick masonry that is brittle and thin stone that tends to distort and bow demand more aggressive strategies for managing movement than did the stolid mass walls of the past.

Historic loadbearing mass walls were not built with expansion joints, but the compression from dead and live loads tended to offset the effects of movement. For modern structures, judicious use of movement joints, isolation of materials with differing movement properties, and careful selection of materials appropriate to the exposure and stress conditions are critical considerations in the design process. Rehabilitation of contemporary existing buildings often involves remediation of movement-related distress, in the form of cracking, displacement, spalling, and, even, structural failure.

Periodic evaluation should aim to identify early warning signs of restrained movement, from longitudinal cracks at building corners to shifting of parapet walls, with a rehabilitation plan to rectify the condition before it becomes hazardous. For new construction, design should consider the anticipated behavior of all proposed materials in relationship to one another and to the environment, anticipating and allowing for dimensional and volume changes without compromising building integrity. ■

Cracks at foundation-cladding interfaces *(left)*, crumbling pavers at expansion joints *(center)*, and displaced stone or masonry *(right)* point to insufficient provisions for material movement.

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