



Twenty-Eighth Westford
Symposium on Building Science

Buildings Move, Buildings Leak:
Revisiting the Critical Link Between Engineering Mechanics
and Enclosure Performance

Jonathan Porter, PE, Assoc. AIA
Kraus-Anderson Construction Company

Buildings Move, Buildings Leak

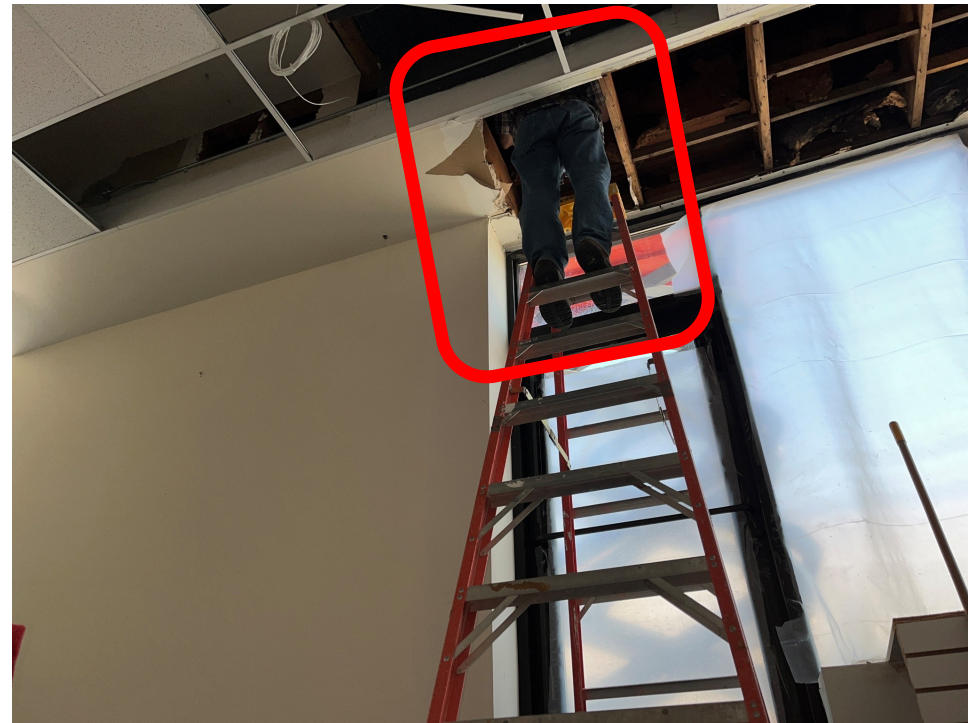
- Agenda
 - Introduction/Topic Overview
 - Structural/Movement Principles
 - Process Gaps
 - Case Studies
 - Recommendations/Conclusions

Buildings Move, Buildings Leak

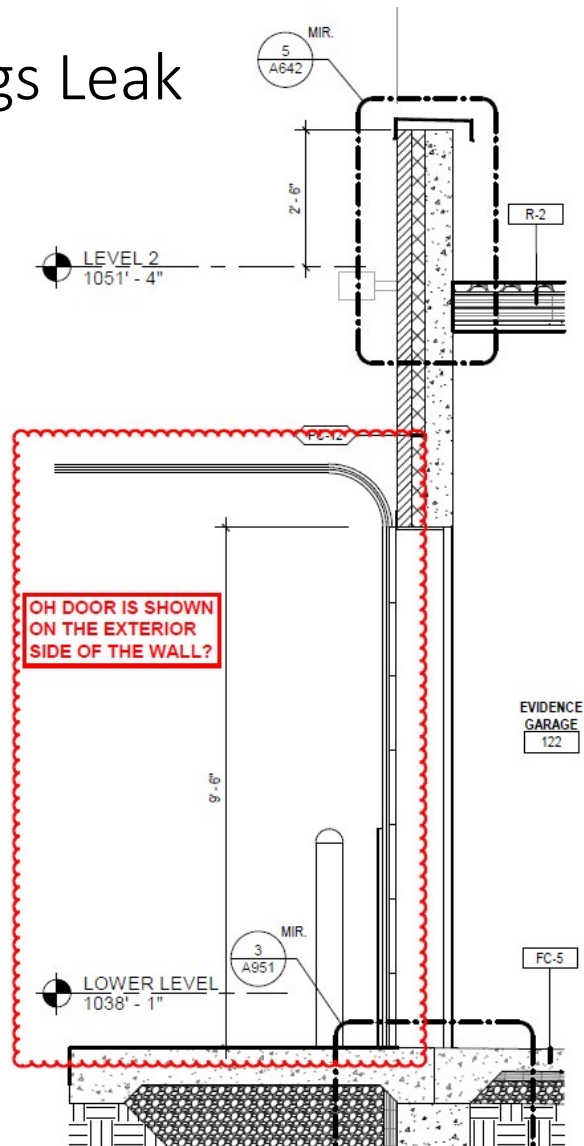
**WHAT MY MARKETING
DEPARTMENT THINKS I DO**



**WHAT I
REALLY DO**



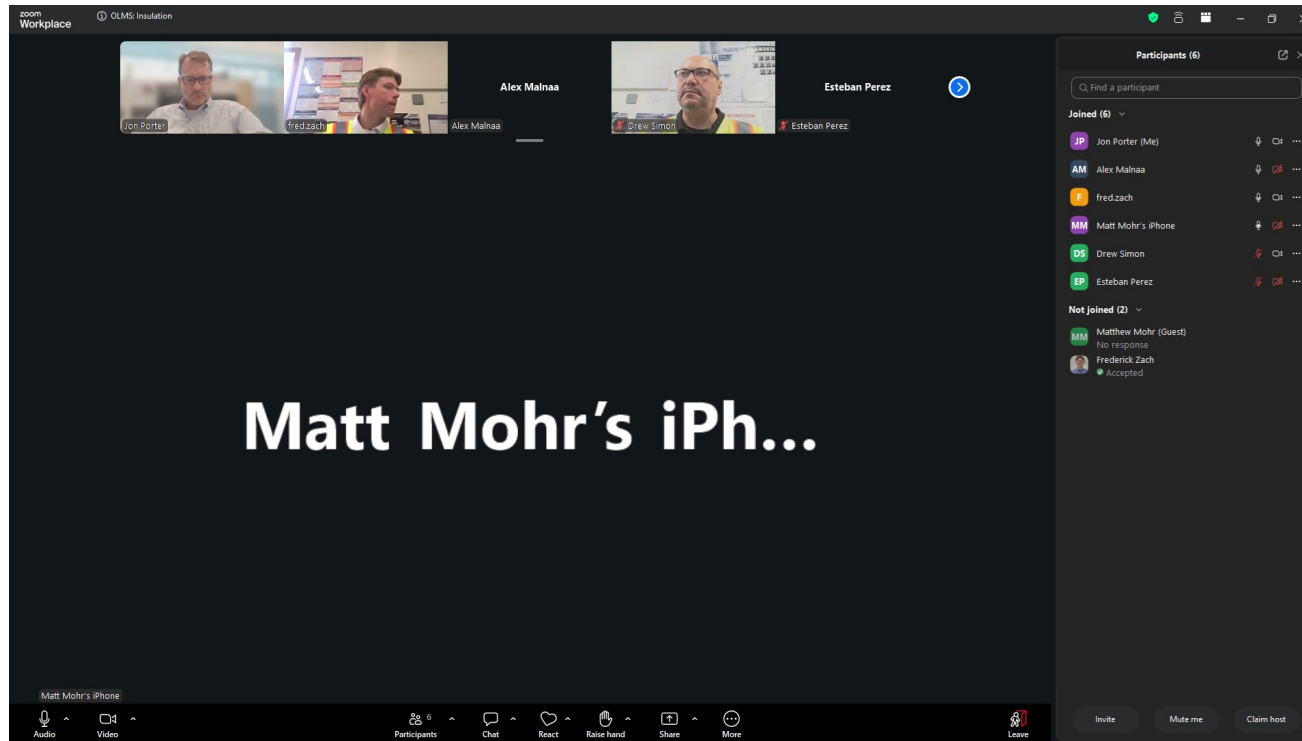
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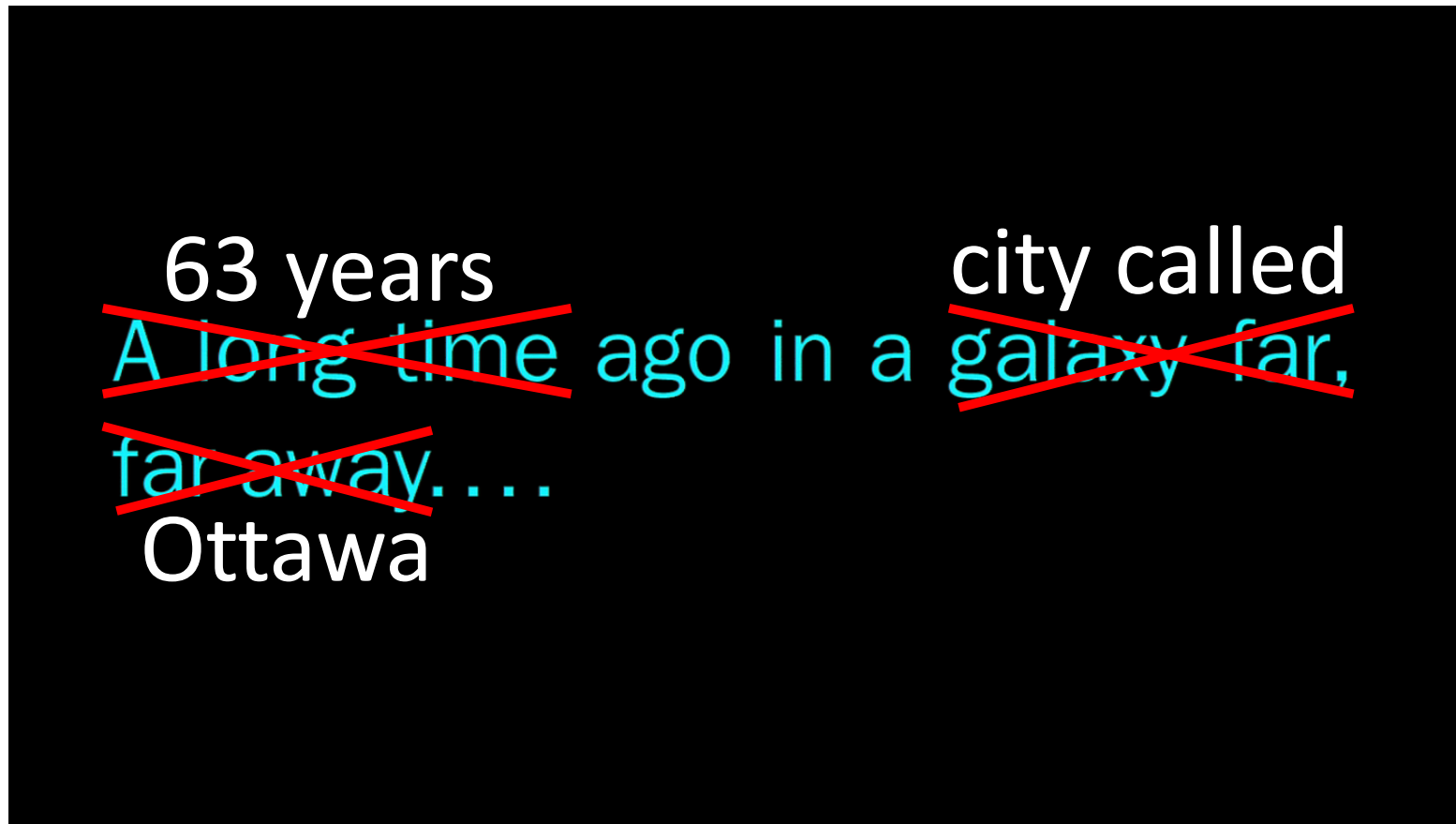
- Topic Overview, or “Why are we Here?”

Buildings Move, Buildings Leak

A long time ago in a galaxy far,
far away....

Lucas, 1977

Buildings Move, Buildings Leak



Lucas, 1977

Buildings Move, Buildings Leak

CANADIAN

BUILDING DIGEST

DIVISION OF BUILDING RESEARCH • NATIONAL RESEARCH COUNCIL


CANADA

Requirements for Exterior Walls

by N. B. Hutcheon

UDC 69.022.3

Designs for exterior walls for buildings have seldom been developed in a systematic, rational way. They have evolved slowly, keeping pace with gradual changes in social and economic patterns and environmental requirements. Today, with a dynamic architecture and many new materials, components and construction techniques available, a large number of new designs are possible. Unfortunately, some are being adopted without adequate consideration, and evaluation by the slow trial by use methods of the past is no longer adequate.

Although trial by use must always be the ultimate test, the cost of full-scale experiments is usually so great that considerable study and effort is justified in order to ensure that the design will perform satisfactorily. It must be recognized also that the conditions for such full-scale, long-time trials in use may not be those for which the information is later required. This is particularly true in Canada today where important changes such as humidification in winter are being introduced. It is now possible with the aid of building science to recognize the pertinent factors affecting the performance of walls and to analyse wall designs systematically as to probable performance in respect of their varied requirements. With this capability one may begin to discriminate between various designs for particular uses, and, even more important, to provide a basis for the development of improved designs.

Functions of a Wall

It is important, at the outset, to recognize that the over-all function of an exterior wall, in conjunction with floors and roofs, is to provide a barrier between indoor and outdoor environments, so that the indoor environment can be adjusted and maintained within acceptable limits. The requirements for a wall must, therefore, relate to its ability to remain in place and to be durable for a required length of time, while providing the necessary barrier or filter to wind, rain, solar radiation, heat, noise, fire, particulate matter, insects, animals and even humans. It may be required to transmit light (windows), while imposing a barrier to other factors; must not itself be a hazard to life or property; must contribute suitably to the form and aesthetics of the building generally; and finally must satisfy a number of lesser requirements such as colour, texture and porosity. All of this must be achieved as far as possible at an acceptable cost, including both initial and maintenance costs.

A complete list of all possible requirements could be a very long one. Fortunately it is seldom necessary to consider all of them in any given case. Further, many may be omitted from direct consideration as they will usually be satisfied automatically when others are met.

Principal Requirements of a Wall

1. Control heat flow; ✓

2. Control air flow; ✓

NRCDBROTTAWADECEMBER 1963

CBD 48

Hutcheon, *Requirements for Exterior walls*, 1963

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Principal Requirements of a Wall

1. Control heat flow; ✓
2. Control air flow; ✓

3. Control water vapour flow; ✓
4. Control rain penetration; ✓
5. Control light, solar and other radiation;
6. Control noise;
7. Control fire;
8. Provide strength and rigidity; ✓
9. Be durable;
10. Be aesthetically pleasing;
11. Be economical.

Any such list is a compromise of sequence and coverage and has, inevitably, strong inter-relationships between items so that it is necessary always to consider several of these requirements simultaneously.

Exterior Wall as a Barrier

Items 1 to 7 of the requirements listed relate to the service required of a wall as a selective separator between indoor and outdoor environments. An actual or potential flow of matter or energy is involved. The greater the differences between the inside and outside environments, the greater is the stress or duty imposed on the wall.

Thus, the elements of the wall must be selected so that in the first instance they impart the necessary resistance to keep heat, moisture, air and other flows within acceptable limits. The way they are arranged, however, is also important; this will determine the variations in conditions throughout the wall. These provide the environment in which the various parts of the wall must continue to function, and are seldom linearly graded from outside to inside. Interactions between the various factors involved may produce conditions within the wall that require special attention. Some understanding of the phenomena involved is therefore necessary so that they can be judged quantitatively and wall designs evaluated.

Over-all Requirements

Items 8 to 11 may be regarded as general or over-all requirements that must be satisfied at the same time as the wall fulfils its basic function as a separator. They may apply to individual elements of the wall as well as to the wall itself, and even to the complete building, of which the wall is only a part.

Durability is an overriding consideration. Taken broadly it can be measured in terms of the time until some loss of function occurs that renders the service provided unacceptable. It is not a fundamental property of a material; it depends on the degrading effects of the service and the environment to which it is exposed. It is more appropriate to refer to service life, as this properly implies the effects of the particular conditions of service.

The environment at any plane in the wall may be determined by the arrangement and selection of the materials used. The designer may, therefore, by judicious arrangement greatly ease the requirements for the various elements and thus broaden his choice. The real importance of durability is reflected in the cost of maintaining all the required functions of the wall over the required service life.

The requirement for *economy* is almost always present. The number of buildings that can be designed without regard for cost are so few that they need not be considered in this discussion. Both initial and operating costs, then, become an important but complex overall consideration in most designs. The designer may often be required, as part of the design problem, to vary the proportion of anticipated initial to operating costs to suit the economies of a particular venture. Initial costs may be reduced by selecting lower quality components at the expense of increased maintenance or reduced service life, or compromises may be adopted in other directions. Insulation may be reduced at the expense of heating cost or a simpler wall or window arrangement, with some sacrifice in function, may be adopted.

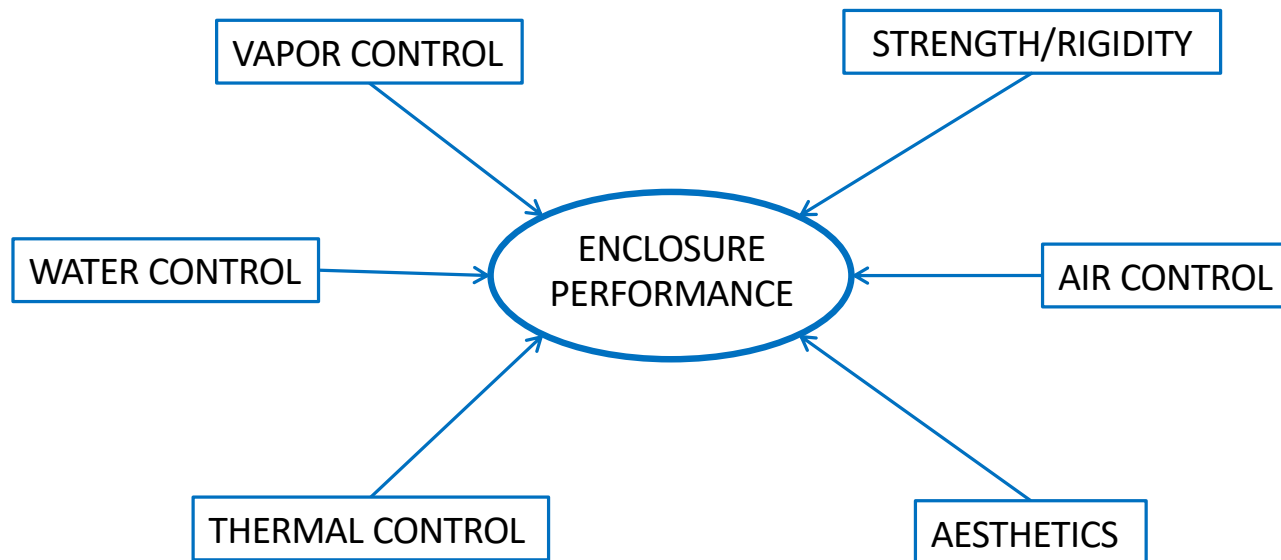
Aesthetic quality can also become a major factor in cost, although this is not always so. Form, colour, texture and pattern can usually be varied over a wide range without affecting other requirements. But insistence upon a particular aesthetic feature or quality may make it difficult to satisfy the service requirements or may force unsatisfactory solutions.

Aesthetic considerations frequently become involved in other ways. For example, inadequacies in design may allow cracks to develop so that water-staining occurs, surfaces spall or

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Interactions between the various factors in the wall produce conditions within the wall that require special attention. Some understanding of the phenomena involved is therefore necessary so that they can be judged quantitatively and wall designs evaluated.

Overall Requirements

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The environment at any plane in the wall may be determined by the arrangement and selection of the materials used. The designer finishes degrade. Thus the aesthetic qualities of a building will be more readily maintained when the basic requirements have been satisfied.

The last of the requirements to be discussed, strength and rigidity, is a functional requirement that has important interrelationships with other requirements. There are numerous connections with walls because they must interact with the structural frame to maintain strength and rigidity. The interrelationship may vary widely at the designer's choice: curtain walls supported on the frame to designs in which walls contribute racking strength and rigidity or assist in resisting vertical loads. The extent of the inter-dependence must be considered in the structural design of both frame and wall.

There are, in addition, loads arising from wind that must be borne by the exterior wall and its parts; these must be transferred, together with the dead load of the wall, through suitable structural connections with the structural frame. This kind of structural analysis and design has been well established for many years and need not be discussed further. There is, however, one kind of loading arising out of dimensional changes in materials that deserves far more attention, particularly in the design of exterior walls and building frames, than it has yet received.

Dimensional Changes and Induced Loading

The strains and deformations in building elements from stresses produced by loading are well recognized and are regularly dealt with in structural design. But other small dimensional changes take place in materials due to causes other than loading. These may give rise to deformations, loads and stresses that are not always adequately taken into account. Creep, a deformation with time under load, and thermal expansion and contraction are usually considered in the analysis of the structural frame, but they may be neglected in the design of the wall itself. Dimensional changes may also result from changes in moisture content in certain materials and from aging and degrading effects produced by environment.

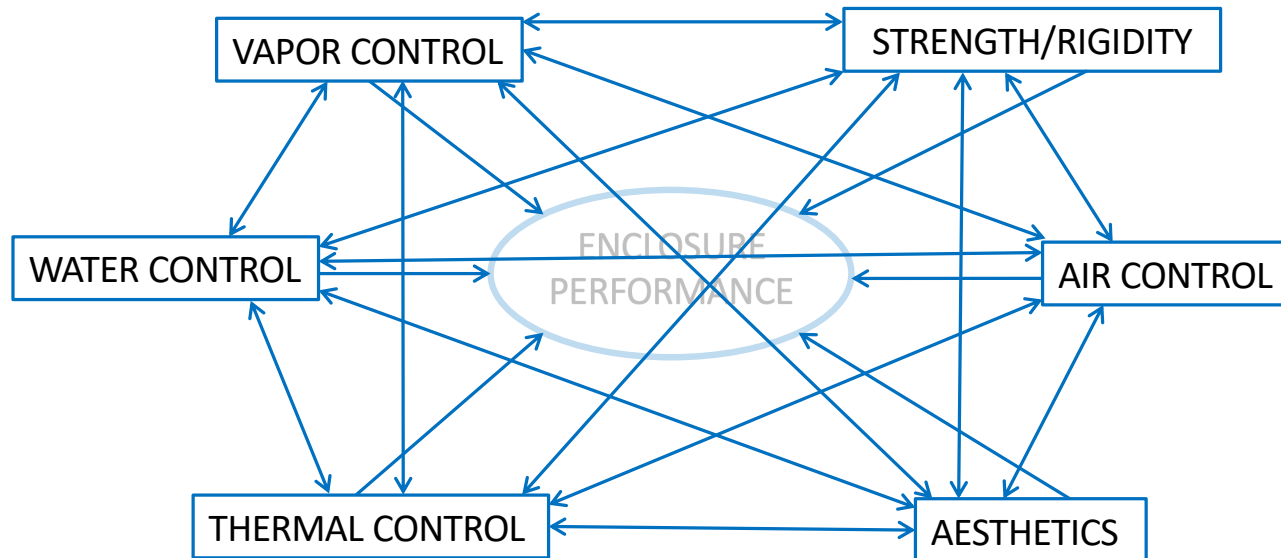
When these expansions or contractions are not restrained, the element merely changes dimension. This in itself may often be a problem. For example, a temperature differential of 100 deg in steel or concrete gives rise to dimensional changes of about 0.06 per cent. When these are restrained by adjacent material or by an adjoining element, strains and corresponding stresses can develop. A strain of only 0.01 per cent is required to fail normal plain concrete in tension. A dimensional change of this magnitude can be produced by a temperature change of about 30 deg. Normal concrete blocks will shrink as much as 0.04 per cent when dried from a saturated state. Cracking, crazing or buckling of exposed surfaces or of surface coatings often occur as a result of temperature or moisture changes that promote either shrinkage or expansion.

Once cracks have developed, severe wetting of the wall will usually follow. This results not only from direct penetration of rain but also from the condensation of water vapour carried in air leaking outward through the cracks.

Obviously this whole subject of dimensional changes in materials and the induced loads and failures that can result merits more extended treatment. There is some discussion of the subject in CBD 30 and this will be extended in future Digests. It has been introduced here because of its obvious relationship with other requirements. Dimensional stability, although a highly desirable characteristic of all materials, elements and components, and having particular implications in exterior wall design, has not been listed as a requirement. It is implicit in the requirements for strength and durability and in the barrier requirements, because these influence temperature, moisture and other conditions that may produce dimensional changes. Discussion of it has been left to specialists because of the interrelationships and the inter-dependence of the various requirements in the overall design. It has also demonstrated the importance of a knowledge of the dimensional stability characteristics of elements and components as well as of materials in any rational approach to wall design.

The Words
INTERRELATIONSHIP(S)
INTERACTIONS
INTERACT
INTERDEPENDENCE
Are Used 8 Times!

Buildings Move, Buildings Leak



SYSTEMS THINKING!!!

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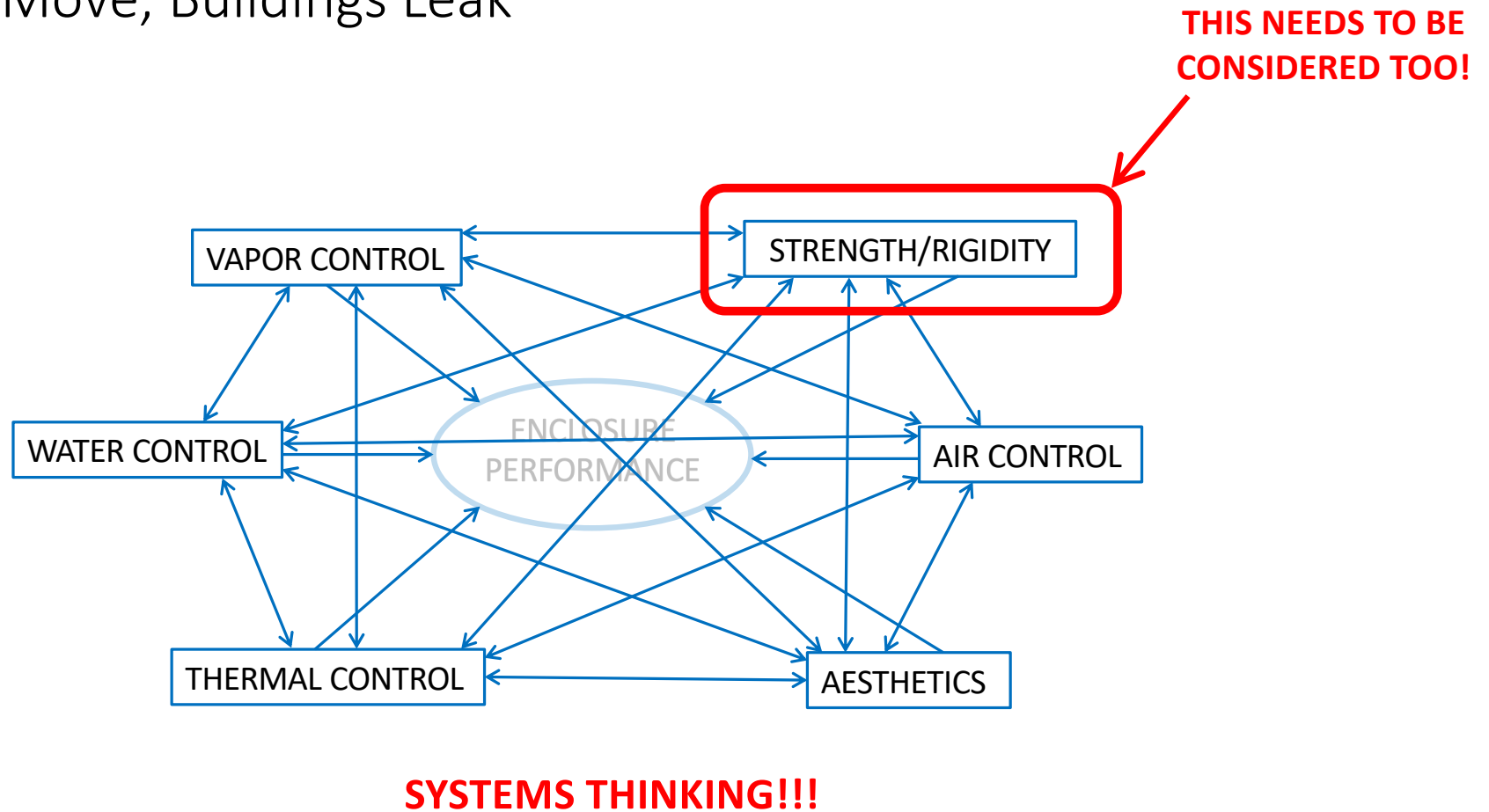
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Dimensional Changes and Induced Loading

Buildings Move, Buildings Leak



Buildings Move, Buildings Leak

- Systems Thinking With a Twist

Conventional Paradigm

What if inadequate consideration of enclosure control layers results in a compromised structure???

Broader Paradigm

What if inadequate consideration of structural movement (and engineering mechanics movement in general) results in compromised control layers???

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Same Thesis, 63 Years Later

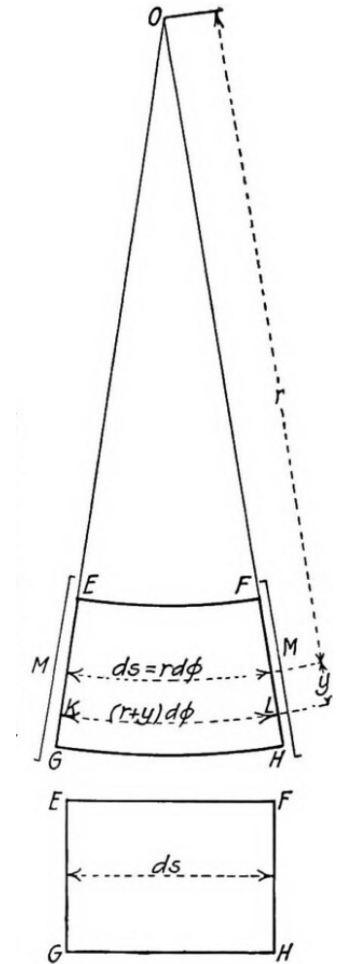
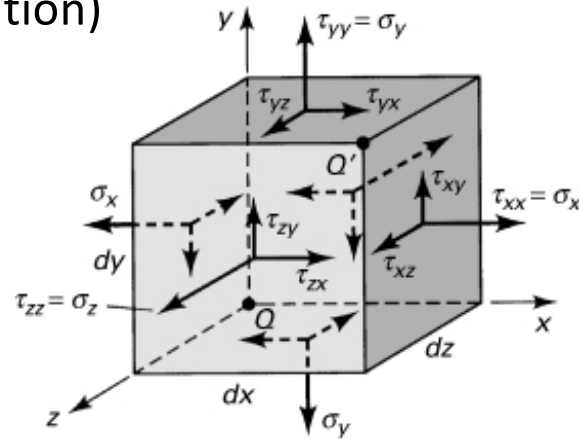
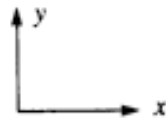
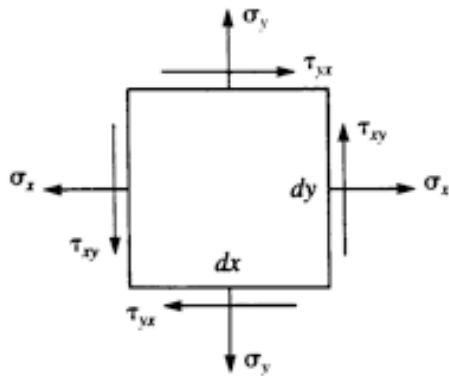
One of the more significant functional aspects that continues to receive inadequate consideration in the design and construction of building enclosures are structural and movement effects on the building enclosure itself.

Buildings Move, Buildings Leak

- Structural and Movement Principles, AKA Engineering Mechanics 101

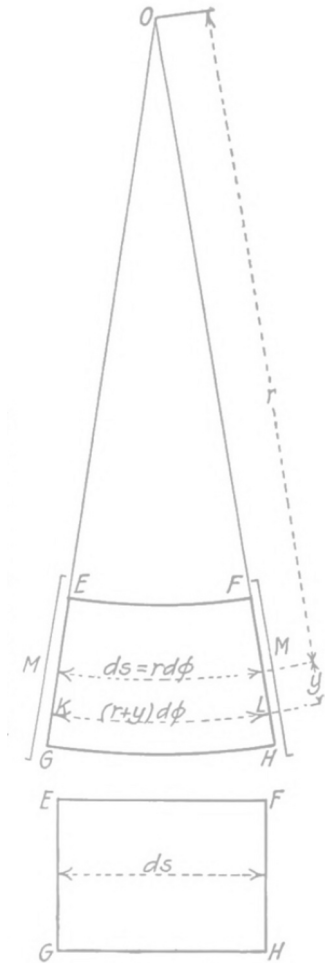
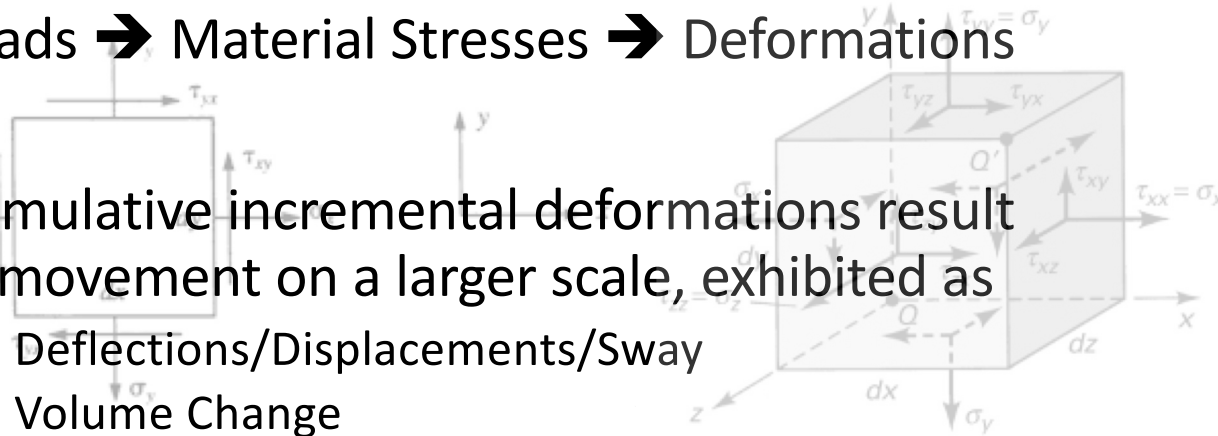
Buildings Move, Buildings Leak

- Movement in 3 easy steps
 - Load is applied
 - Material experiences Stress
 - Stress induces strain (deformation)



Buildings Move, Buildings Leak

- Engineering Mechanics 101
- Loads $\rightarrow$ Material Stresses $\rightarrow$ Deformations
- Cumulative incremental deformations result in movement on a larger scale, exhibited as
 - Deflections/Displacements/Sway
 - Volume Change



Buildings Move, Buildings Leak

- Engineering Mechanics 101
- Material/Assembly/System that wants to move but is inhibited = Restrained
- Material/Assembly/System that wants to move and is allowed to = Unrestrained



Buildings Move, Buildings Leak

Table 2.4: General category of loadings and related functions

		Category of functions			
		Specific loadings			
Causal phenomenon or loading		Interior Finish	Support	Control	Exterior finish
Essentially structural	Gravity – Dead (assembly, etc.)	●	●		
	Gravity – Live (people, snow, etc.)	●	●		
	Wind	●	●	○	
	Ground Movement (seismic, settlement, etc.)	●	●		
	Explosion	●	●		
	Rheological (creep, shrinkage, etc.)	●	●		○
	Impact (vehicles, missiles, people, etc.)	●	●	●	●
	Fire	●	○	●	●
	Heat (thermal, etc.)		○	●	
	Air (pressure, movement, leakage, etc.)		○	●	
Essentially environmental	Moisture (built-in, rain, condensation, etc.)		○	●	○
	Smoke			●	
	Solar radiation (incident, reflected, etc.)			●	○
	Chemical attack/atmospheric (acid rain, etc.)		●	●	○
	Radon gas (1st, VOCs, etc.)		●	●	
Essentially perceptual	People (wear & tear, etc.)	●	○		●
	Insects, birds, animals, (termites, rodents, etc.)			●	○
	Light (natural, incandescent, fluorescent, etc.)		●	●	
	Sound	○	●	●	○
	Visual – local	●			●
	Visual – contextual	●			●

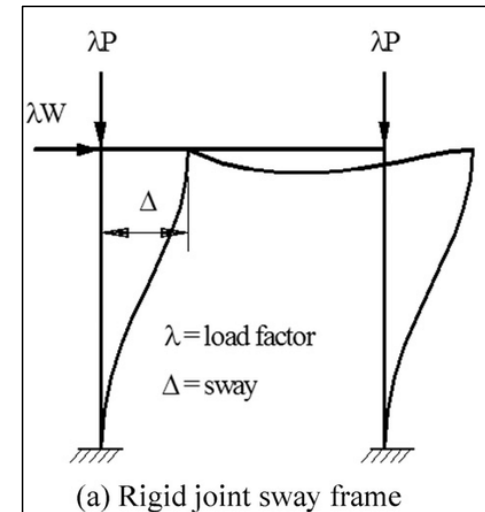
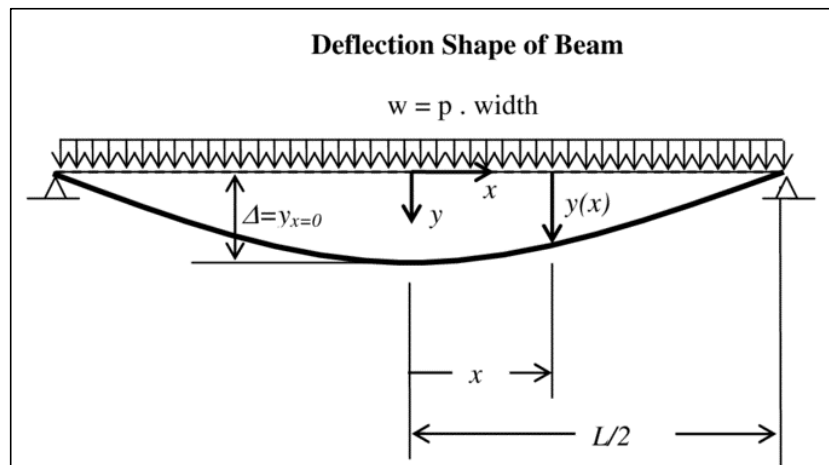
Primary significance ●
 Secondary significance ○
 Tertiary significance •

DEFLECTION
 DISPLACEMENT
 SWAY
 VOLUME
 CHANGE

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	Impact (vehicles, missiles, people, etc.)
	Fire
	Heat (thermal, etc.)
	Air (pressure, movement, leakage, etc.)
Essentially environmental	Moisture (built-in, rain, condensation, etc.)
	Smoke
	Solar radiation (incident, reflected, etc.)
	Chemical attack/atmospheric (acid rain, etc.)

Buildings Move, Buildings Leak

- Loads more often associated with Deflections, Displacements, or Sway (Structural Loads)



Buildings Move, Buildings Leak

DEAD



LIVE



SNOW



Buildings Move, Buildings Leak

WIND



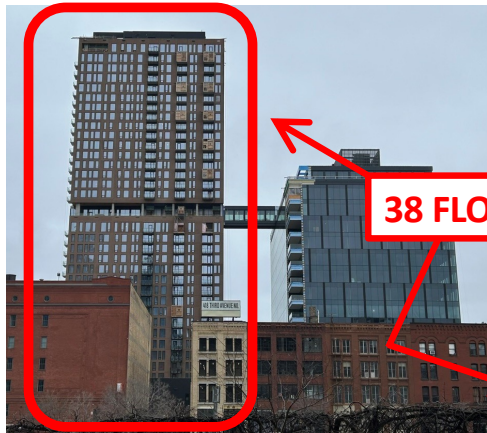
SEISMIC



*NRC, Practical Lessons from the
Loma Prieta Earthquake, 1994*

Buildings Move, Buildings Leak

- Creep – “Plastic Flow”
- Discussion limited to
 - Common Structural Materials
 - Behavior within service temperature ranges



38 FLOORS = 5"

DESIGN STRUCTURAL MOVEMENTS:

1. STORY DRIFTS UNDER WIND LOADS

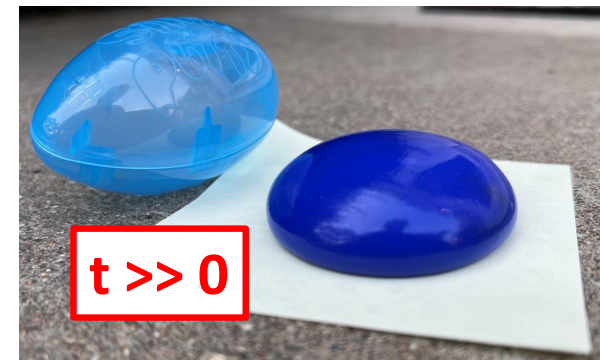
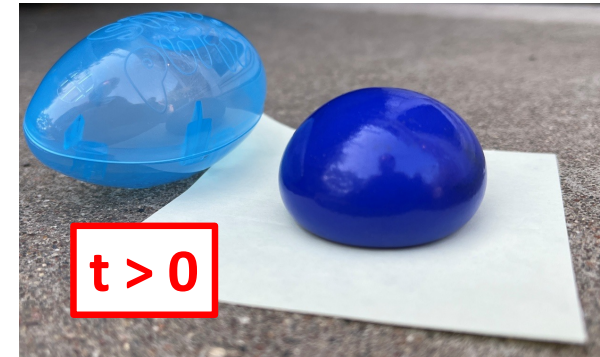
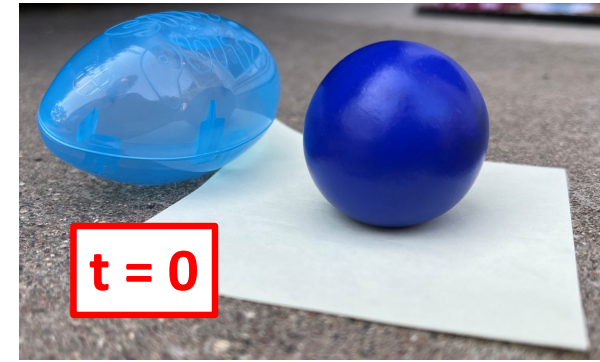
- a. OFFICE TOWER: H/500 (50-YEAR WIND), H/700 (10-YEAR WIND)
- b. RESIDENTIAL TOWER: H/350 (50-YEAR WIND), H/500 (10-YEAR WIND)
- c. ONE-STORY F+B BUILDING: H/300 (50-YEAR WIND), H/400 (10-YEAR WIND)

2. FLOOR SLAB DEFLECTION (LONG-TERM)

- a. OFFICE TOWER: 1/2"
- b. RESIDENTIAL TOWER: 1/2"

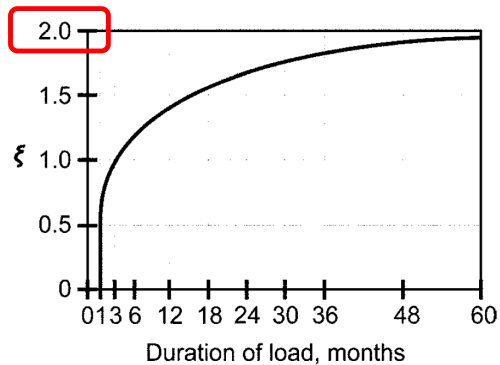
3. LONG-TERM CREEP AT PERIMETER RC COLUMNS (RESIDENTIAL TOWER)

- a. 1/8" MAX PER FLOOR (FLOOR HEIGHT $\leq 11'-0"$)
- b. 1/4" MAX PER FLOOR (FLOOR HEIGHT $> 11'-0"$)

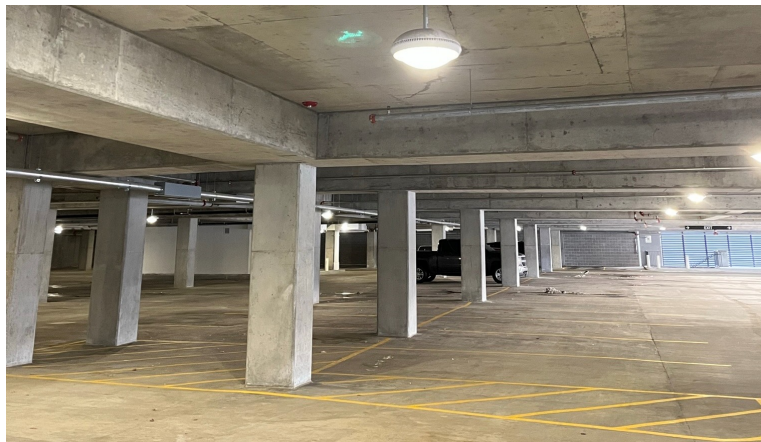


Buildings Move, Buildings Leak

- Common structural materials that creep:
 - Concrete
 - Wood



bsc SCXXVIII



The creep deflection varies anywhere from zero to twice the initial deflection. This means that the total deflection can vary from the initial deflection to as much as three times the initial deflection.

AMERICAN WOOD COUNCIL WEBSITE

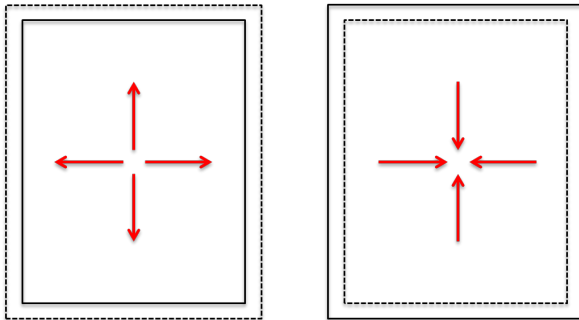
<https://awc.org/faq/what-is-creep-and-how-can-i-address-it/>



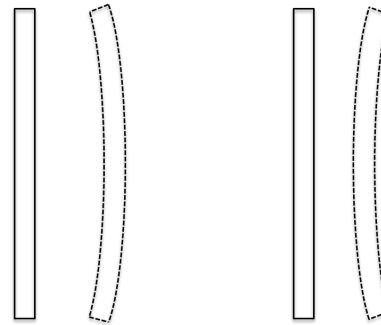
Buildings Move, Buildings Leak

- Loads more often (but not always) associated with Volume Change

ABSOLUTE VOLUME CHANGE



DIFFERENTIAL VOLUME CHANGE



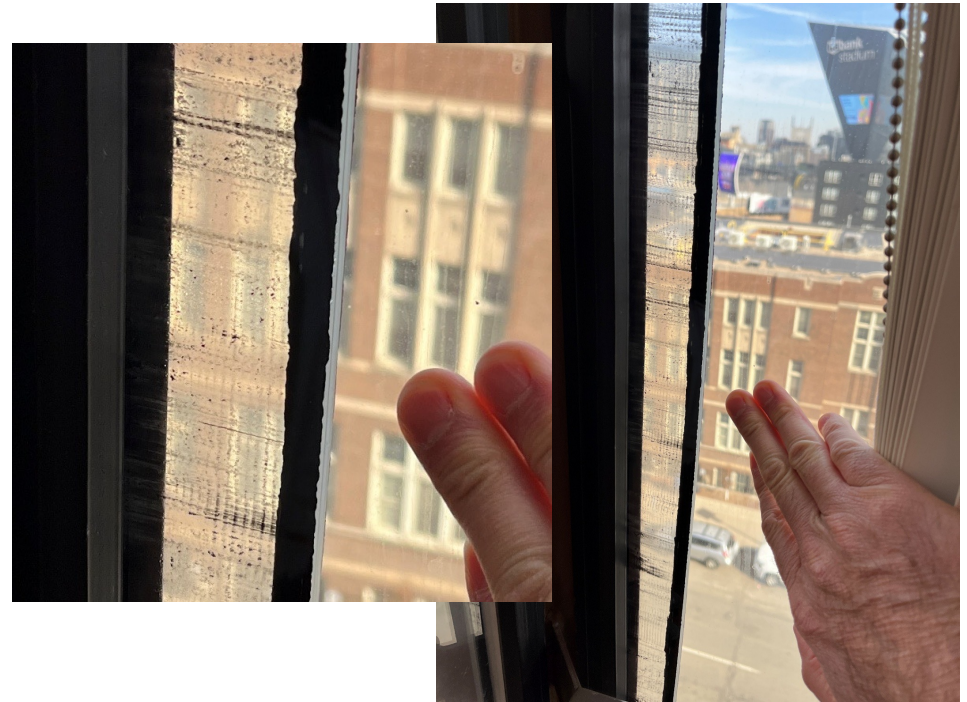
Buildings Move, Buildings Leak

SHRINKAGE



Buildings Move, Buildings Leak

HEAT



Buildings Move, Buildings Leak

AIR



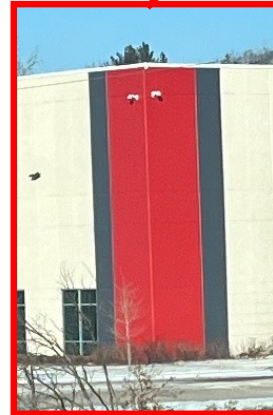
Buildings Move, Buildings Leak

CHEMICAL



Buildings Move, Buildings Leak

UV



Buildings Move, Buildings Leak

Wood you like to see an example of Moisture as a Movement Load?



Buildings Move, Buildings Leak



Buildings Move, Buildings Leak

- Most materials are subject to Volume Change oriented Loads, even if they are not typically affected by Structural oriented loads
- Both structural deflection and material volume change can occur in one, two or three dimensions

Buildings Move, Buildings Leak

- Process Gaps – where can/do things go wrong?

Buildings Move, Buildings Leak

- Where can/do things go wrong?

1) When performance criteria related to movement is not adequately specified, communicated or followed

- Importance of communication might not be understood by the specifier
- The specifier might not have experience with a particular material, or understand its limits



fuzheado –

<https://www.flickr.com/photos/49503124323@N01/52135935326/>

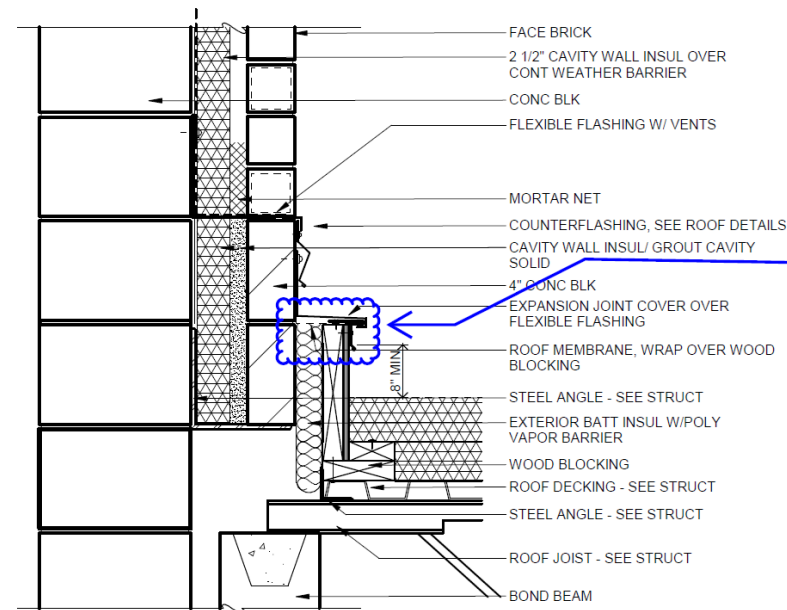
Buildings Move, Buildings Leak

- Where can/do things go wrong?

1) When performance criteria related to movement is not adequately specified, communicated or followed

- Expecting an outcome
(*bad \$h!t NOT happening*)

without defining the attributes
that will ensure success
(*performance criteria*)



HOW MUCH HORIZONTAL
MOVEMENT DOES THIS COVER
AND THE FLASHING BELOW
NEED TO ACCOMODATE?

Buildings Move, Buildings Leak

- Where can/do things go wrong?

2) When movement behavior is considered, but not deeply enough

- Dichotomous thinking

“material B is better than material A, therefore I no longer need to worry about _____”

“Wood is more dimensionally stable than Vinyl, therefore if I use Wood I no longer need to worry about dimensional stability”

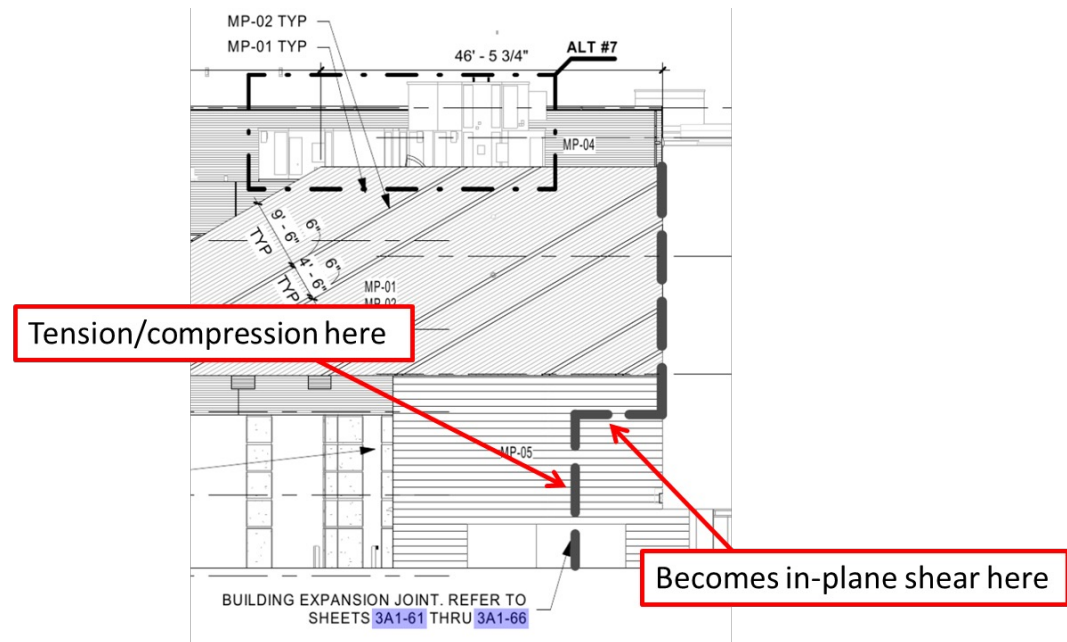


Buildings Move, Buildings Leak

- Where can/do things go wrong?

2) When movement behavior is considered, but not deeply enough

- Incomplete recognition of system response

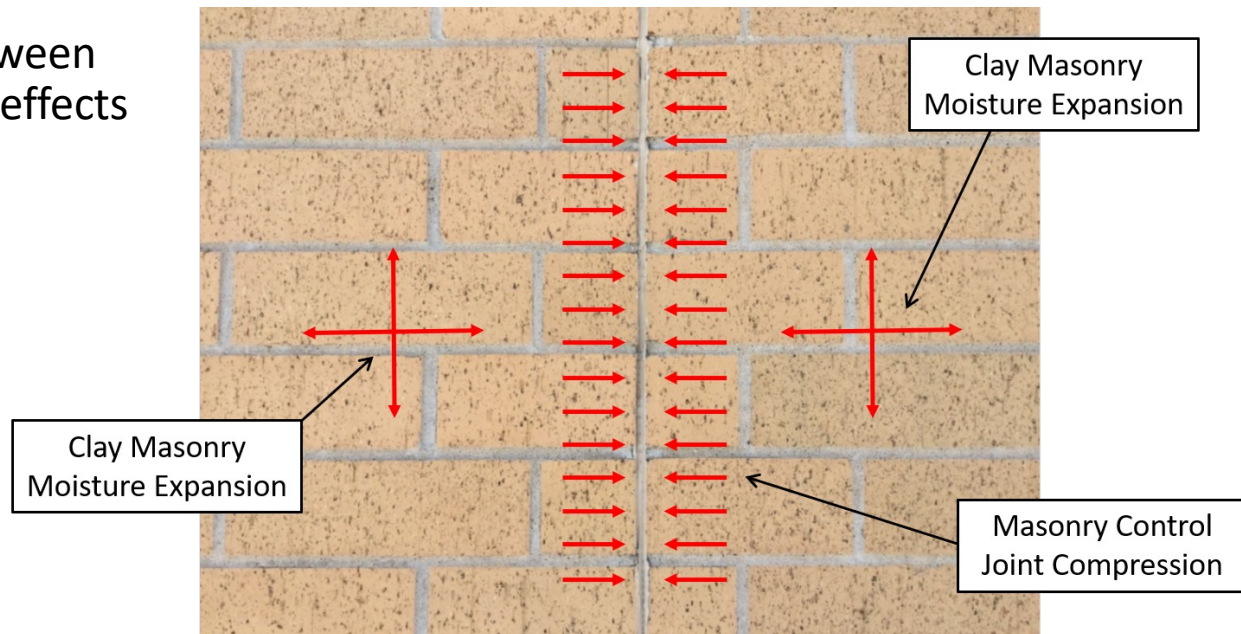


Buildings Move, Buildings Leak

- Where can/do things go wrong?

2) When movement behavior is considered, but not deeply enough

- Missing the connection between downstream and upstream effects



Buildings Move, Buildings Leak

- Review of Selected Case Studies

Obviously this whole subject of dimensional changes in materials and the induced loads and failures that can result merits more extended treatment. There is some discussion of

finishes degrade. Thus the aesthetic qualities of a building will be more readily maintained when the basic requirements have been satisfied.

The last of the requirements to be discussed, *strength and rigidity*, is a functional requirement that has important inter-relationships with other requirements. There is a further complication with walls because they may interact with the structural frame to contribute to its strength and rigidity. This inter-relationship may vary widely at the designer's choice, from curtain walls supported on the frame to designs in which walls contribute racking strength and rigidity or assist in carrying vertical loads. The extent of this inter-dependence must be considered in the structural design of both frame and wall.

There are, in addition, loads arising from wind that must be borne by the exterior wall and its parts; these must be transferred, together with the dead load of the wall, through suitable structural connections with the structural frame. This kind of structural analysis and design has been well established for many years and need not be discussed further. There is, however, one kind of loading arising out of dimensional changes in materials that deserves far more attention, particularly in the design of exterior walls and building frames, than it has yet received.

Dimensional Changes and Induced Loading

The strains and deformations in building elements from stresses produced by loading are well recognized and are regularly dealt with in structural design. But other small dimensional changes take place in materials due to causes other than loading. These may give rise to deformations, loads and stresses that are not always adequately taken into account. Creep, a deformation with time under load, and thermal expansion and contraction are usually considered in the analysis of the structural frame, but they may be neglected in the design of the wall itself. Dimensional changes may also result from changes in moisture content in certain materials and from aging and degrading effects produced by environment.

When these expansions or contractions are not restrained, the element merely changes dimension. This in itself may often be a problem. For example, a temperature differential of 100 deg in steel or concrete gives rise to dimensional changes of about 0.06 per cent. When these are restrained by adjacent material or by an adjoining element, strains and corresponding stresses can develop. A strain of only 0.01 per cent is required to fail normal plain concrete in tension. A dimensional change of this magnitude can be produced by a temperature change of about 20 deg. Normal concrete blocks will shrink as much as 0.04 per cent when dried from a saturated state. Cracking, crazing or buckling of exposed surfaces or of surface coatings often occur as a result of temperature or moisture changes that promote either shrinkage or expansion.

Once cracks have developed, severe wetting of the wall will usually follow. This results not only from direct penetration of rain but also from the condensation of water vapour carried in air leaking outward through the cracks.

Obviously this whole subject of dimensional changes in materials and the induced loads and failures that can result merits more extended treatment. There is some discussion of the subject in CDD 50 and this will be extended in future Digests. It has been introduced here because of its obvious relationship with other requirements. Dimensional stability, although a highly desirable characteristic of all materials, elements and components, and having particular implications in exterior wall design, has not been listed as a requirement. It is implicit in the requirements for strength and durability and in the barrier requirements, because these influence temperature, moisture and other conditions that may produce dimensional changes. Discussion of it has served to emphasize further the inter-relationships and the inter-dependence of the various requirements that have been set out. It has also demonstrated the importance of a knowledge of the dimensional stability characteristics of elements and components as well as of materials in any rational approach to wall design.

Buildings Move, Buildings Leak

- Review of Selected Case Studies
 - Category A: Structural Frame Deflection (Deflections/Displacements/Sway) impacting Enclosure Control Layers
 - Category B: Material Volume Change (Shortening/Elongation) impacting Enclosure Control Layers

Buildings Move, Buildings Leak

- DISCLAIMER!



Ogden, *Fire and Ice: Titanic Passengers*, 1912

Buildings Move, Buildings Leak

- Category A: Structural Frame Deflection(Deflections/Displacements/Sway) impacting Enclosure Control Layers

Buildings Move, Buildings Leak

- Case Study 1: Compounded Deflections and Curtain Wall



Buildings Move, Buildings Leak

- Case Study 1: Compounded Deflections and Curtain Wall

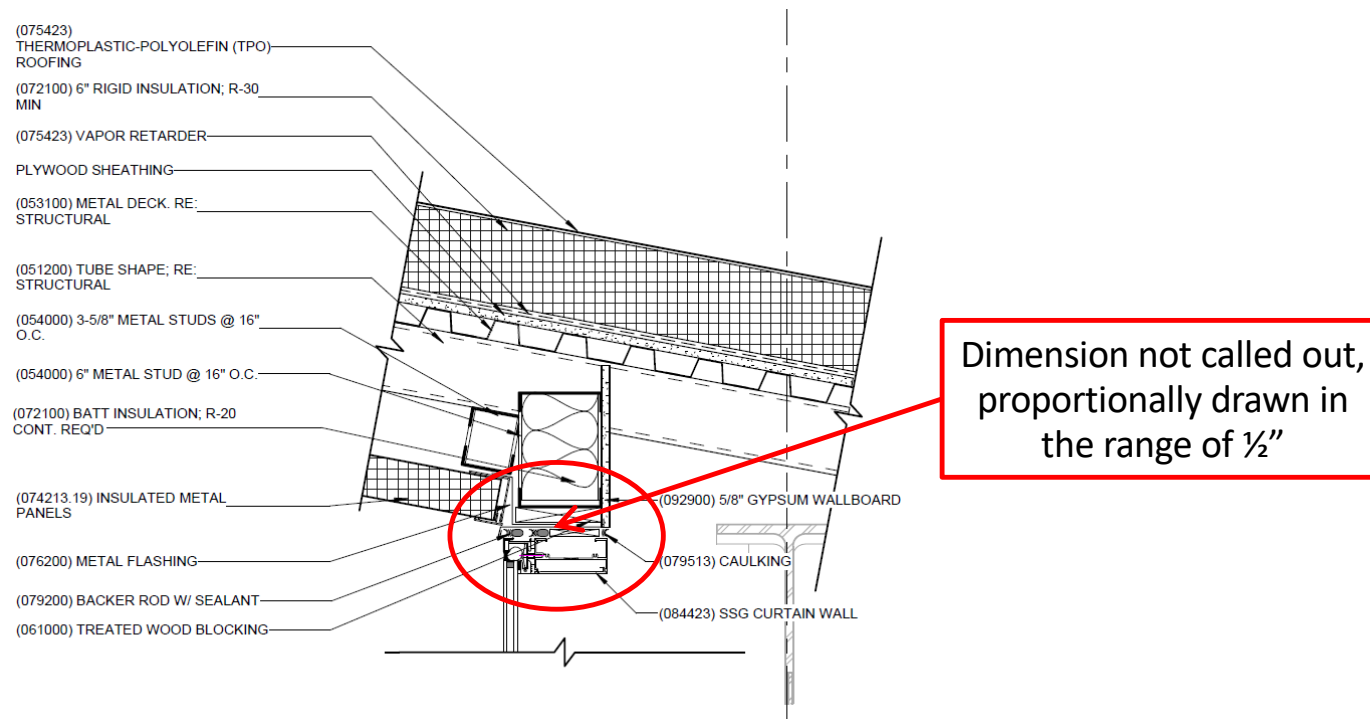
PART 2 - PRODUCTS

2.1 PERFORMANCE REQUIREMENTS

- A. Delegated Design: Engage a qualified professional engineer licensed in the State of Minnesota, as defined in Section 01 40 00 "Quality Requirements," to design glazed aluminum curtain walls.
- B. General Performance: Comply with performance requirements specified, as determined by testing of glazed aluminum curtain walls representing those indicated for this Project without failure due to defective manufacture, fabrication, installation, or other defects in construction.
 - 1. Glazed aluminum curtain walls shall withstand movements of supporting structure including, but not limited to, story drift, twist, column shortening, long-term creep, and deflection from uniformly distributed and concentrated live loads.

Buildings Move, Buildings Leak

- Case Study 1: Compounded Deflections and Curtain Wall



Buildings Move, Buildings Leak

- Case Study 1: Compounded Deflections and Curtain Wall
- RFI Question #1: How much movement of structure should the head of curtainwall accommodate?
- RFI Response #1: Use $L/360$ to determine joint size

Buildings Move, Buildings Leak

- Case Study 1: Compounded Deflections and Curtain Wall



Buildings Move, Buildings Leak

- Case Study 1: Compounded Deflections and Curtain Wall



Buildings Move, Buildings Leak

- Case Study 1: Compounded Deflections and Curtain Wall

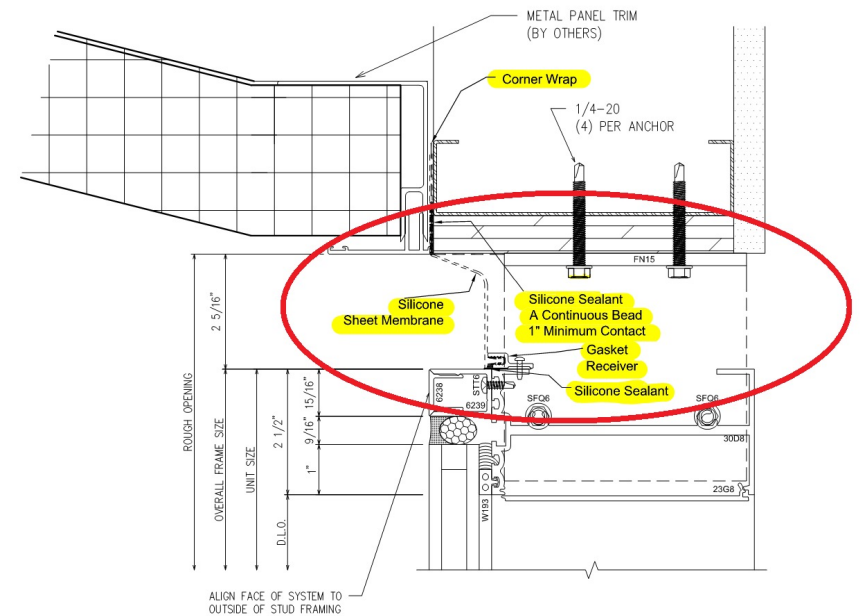
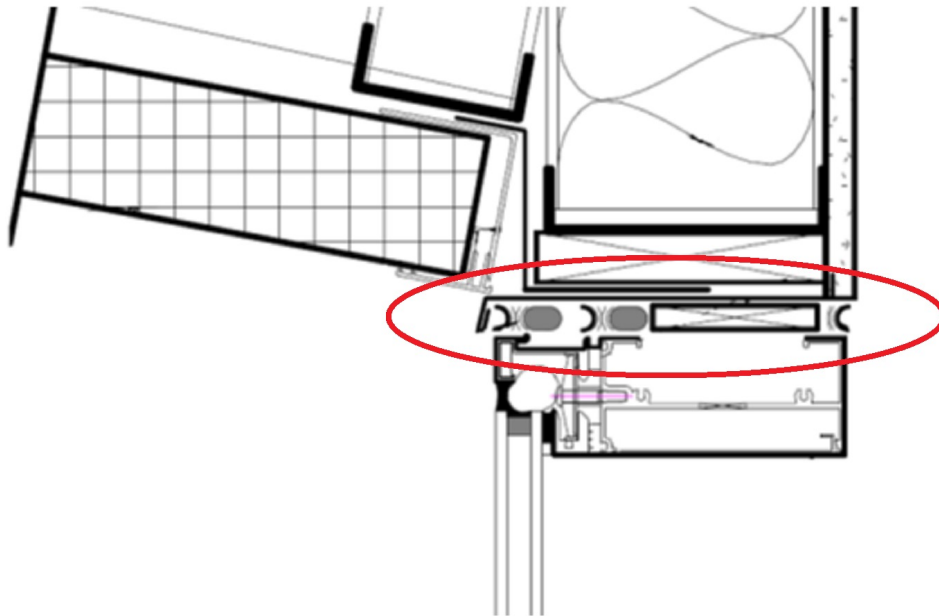


Buildings Move, Buildings Leak

- Case Study 1: Compounded Deflections and Curtain Wall
- RFI Question #2: Are you sure?
- RFI Response #2: Use 2-5/16"
(L/360 at the largest span was 1")

Buildings Move, Buildings Leak

- Case Study 1: Compounded Deflections and Curtain Wall

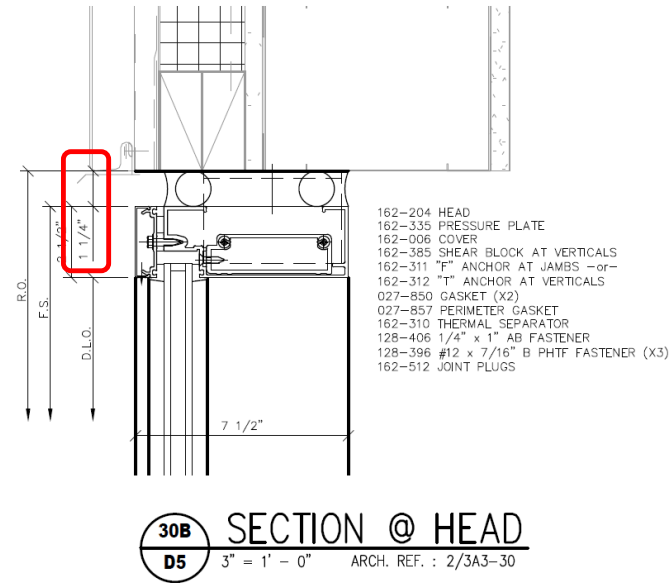
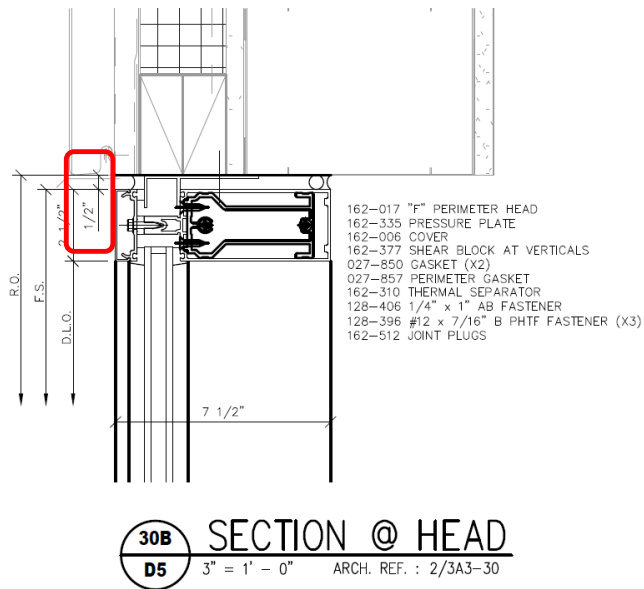


Buildings Move, Buildings Leak

- Case Study 1: Compounded Deflections and Curtain Wall
 - 6-week delay (RFI process and coordination)
 - Change order
- Optimal Scenario: movement is defined in contract documents before bidding
- Last Call Scenario: movement is coordinated during shop drawing phase
 - The sooner everyone knows what needs to happen, the more efficiently they can act upon it

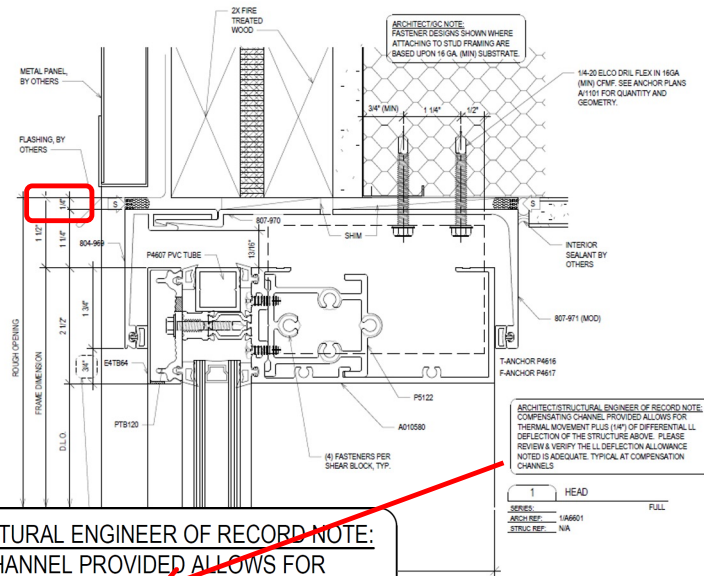
Buildings Move, Buildings Leak

- Case Study 1: Compounded Deflections and Curtain Wall
- Isolated incident? Not really



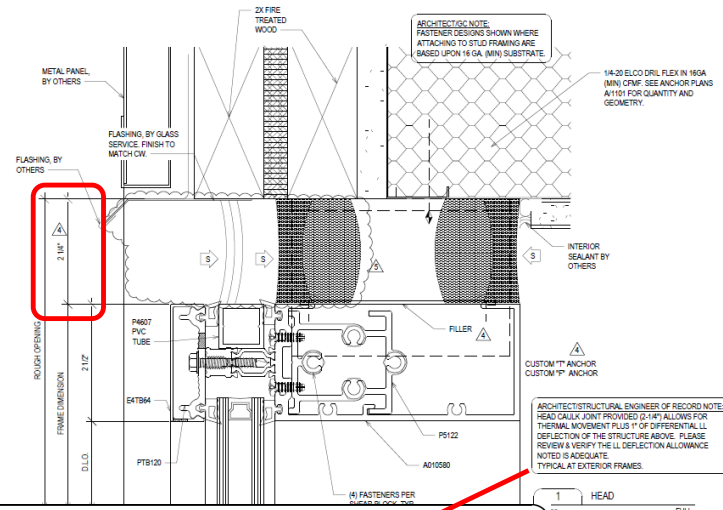
Buildings Move, Buildings Leak

- Case Study 1: Compounded Deflections and Curtain Wall
- If I was an investor, I would call this a growth market



ARCHITECT/STRUCTURAL ENGINEER OF RECORD NOTE:
COMPENSATING CHANNEL PROVIDED ALLOWS FOR
THERMAL MOVEMENT PLUS (1/4") OF DIFFERENTIAL LL
DEFLECTION OF THE STRUCTURE ABOVE. PLEASE

bsc SCXXVIII DWANCE
SATION



ARCHITECT/STRUCTURAL ENGINEER OF RECORD NOTE:
HEAD CAULK JOINT PROVIDED (2-1/4") ALLOWS FOR
THERMAL MOVEMENT PLUS 1" OF DIFFERENTIAL LL
DEFLECTION OF THE STRUCTURE ABOVE. PLEASE
REVIEW & VERIFY THE LL DEFLECTION ALLOWANCE
NOTED IS ADEQUATE.
TYPICAL AT EXTERIOR FRAMES.

Buildings Move, Buildings Leak

- Building Science Game Show Time!
- Case Study 1:
which loadings were involved?

rain smoke radiation fire
impact snow chemical
air live animals solar
wind birds moisture creep
heat shrinkage dead insects
particulates gravity seismic



Buildings Move, Buildings Leak

- Building Science Game Show Time!
- Case Study 1:
which loadings were involved?

rain smoke radiation fire
impact **snow** chemical
air **live** animals solar
wind birds moisture creep
heat shrinkage **dead** insects
particulates **gravity** seismic



Buildings Move, Buildings Leak

- Case Study 2: Parking Deck Surface Slopes/Water Infiltration
- American Concrete Institute (ACI) Committee 362 – Parking Structures
 - Slope slabs surfaces so that positive water flow occurs without ponding
- Industry best practice is to design to 1½% - 2% minimum
 - Intent is after deducting slope for construction tolerances and deflections, positive water flow will still occur (not less than 1%)

Buildings Move, Buildings Leak

- Case Study 2: Parking Deck Surface Slopes/Water Infiltration
- Primary goal for ACI is to prevent standing water, which will reduce
 - Water intrusion INTO slab thickness
 - Accelerated deterioration of reinforcing and concrete

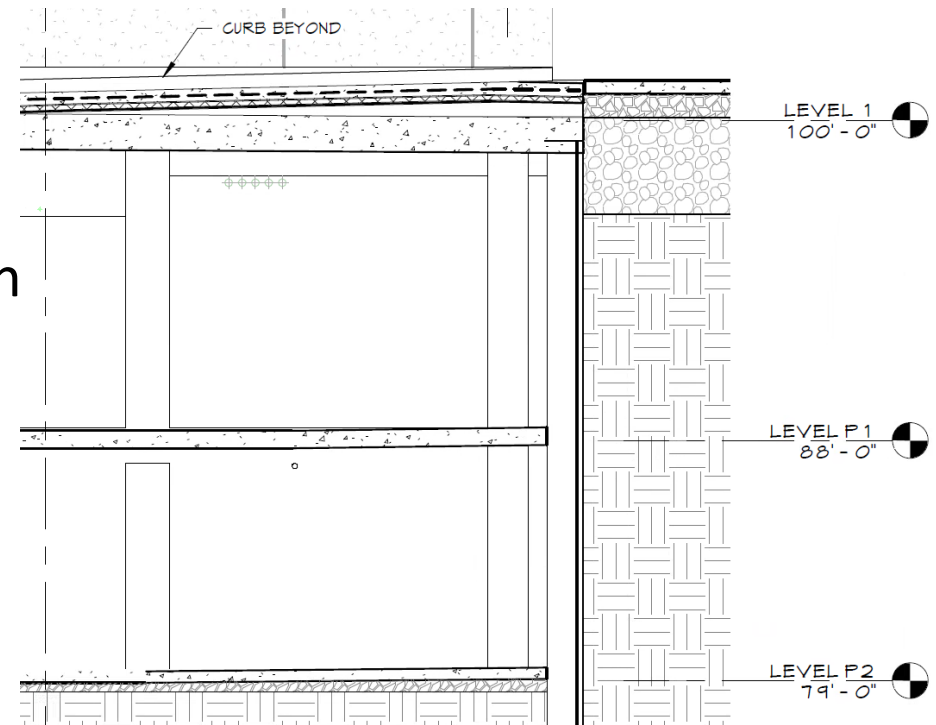


Buildings Move, Buildings Leak

- Case Study 2: Parking Deck Surface Slopes/Water Infiltration
- Fun Fact!
- Concrete not exposed to atmosphere remains high in alkalinity (pH 12.5±)

Buildings Move, Buildings Leak

- Case Study 2: Parking Deck Surface Slopes/Water Infiltration
- Multi-level parking structure below grade
- Owner goal of minimizing excavation depths motivated design team to reduce surface slopes
 - Range of 1% - 1 ½%



Buildings Move, Buildings Leak

- Case Study 2: Parking Deck Surface Slopes/Water Infiltration
- After one seasonal cycle, car finishes on lower level began to show damage



Buildings Move, Buildings Leak

- Case Study 2: Parking Deck Surface Slopes/Water Infiltration
- Movement of slab changed surface slope from adequate to inadequate
- Persistent standing water on upper ramp level throughout winter months

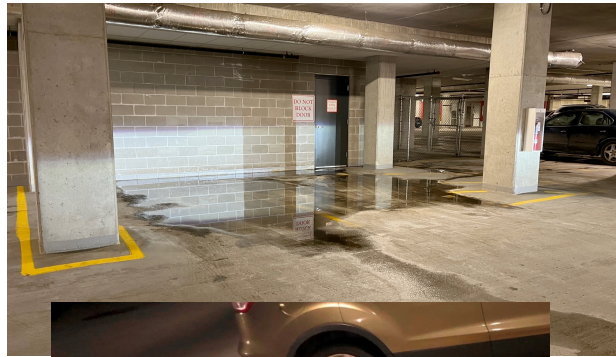
Buildings Move, Buildings Leak

- Case Study 2: Parking Deck Surface Slopes/Water Infiltration
- As moisture runoff percolated through slab, it converted from a neutral solution to an alkaline solution
 - Slab no longer protected cars below
- Vehicle owners converted from happy to upset
 - Parking structure owner paid for auto finish repair work
 - Vehicular traffic coating added ~ \$355,000

Buildings Move, Buildings Leak

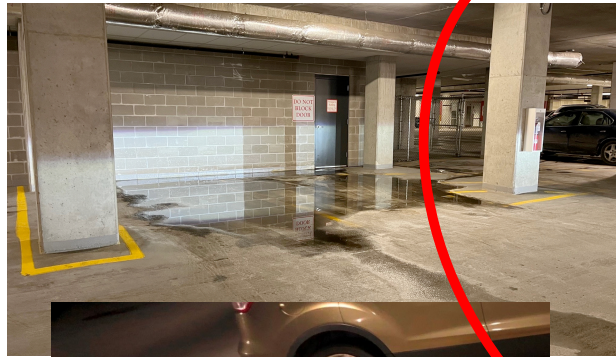
- Case Study 2:
which loadings were involved?

rain smoke radiation fire
impact snow chemical
air live animals solar
wind birds moisture creep
heat shrinkage dead insects
particulates gravity seismic



Buildings Move, Buildings Leak

- Case Study 2:
which loadings were involved?



rain smoke radiation fire
impact snow chemical
air **live** animals solar
wind birds moisture **creep**
heat shrinkage **dead** insects
particulates **gravity** seismic

rain smoke radiation fire
impact snow **chemical**
air live animals solar
wind birds **moisture** creep
heat shrinkage dead insects
particulates gravity seismic

Buildings Move, Buildings Leak

- Case Study 3: Wood Framed Stealth Deflections



Accommodating Shrinkage in Multi-Story Wood-Frame Structures

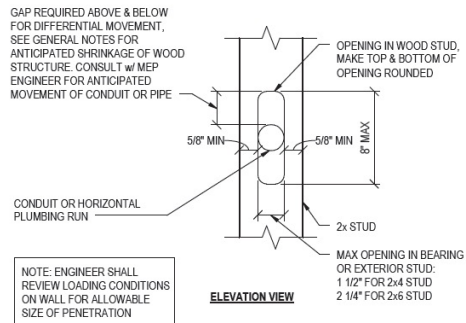
Richard McLain, MS, PE, SE, Technical Director, WoodWorks • Doug Steimle, PE, Principal, Schaefer

Buildings Move, Buildings Leak

- Case Study 3: Wood Framed Stealth Deflections
- Most of the usual suspects for shrinkage in mid-rise wood framed construction have been known for more than 10 years

FIGURE 19:

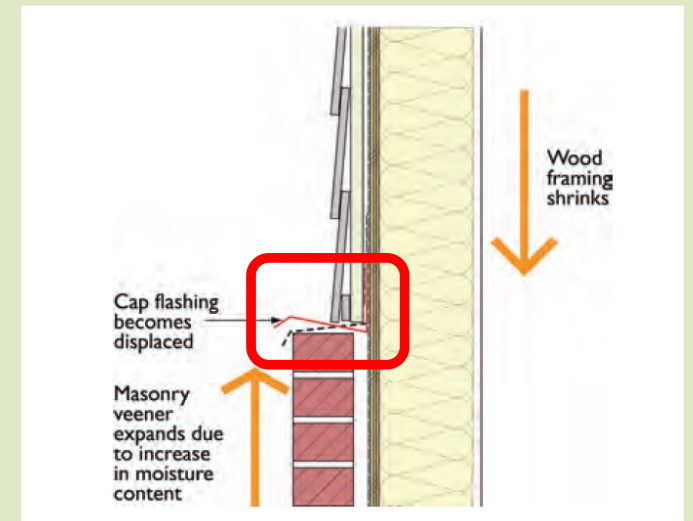
Example detail and photo showing the hole in a wood stud added to accommodate shrinkage around plumbing



Sources: (left) Schaefer; (right) Louisiana-Pacific Corporation

FIGURE 13:

Veneer transition issues due to lack of shrinkage accommodation



Source: RDH Building Science Inc.

Buildings Move, Buildings Leak

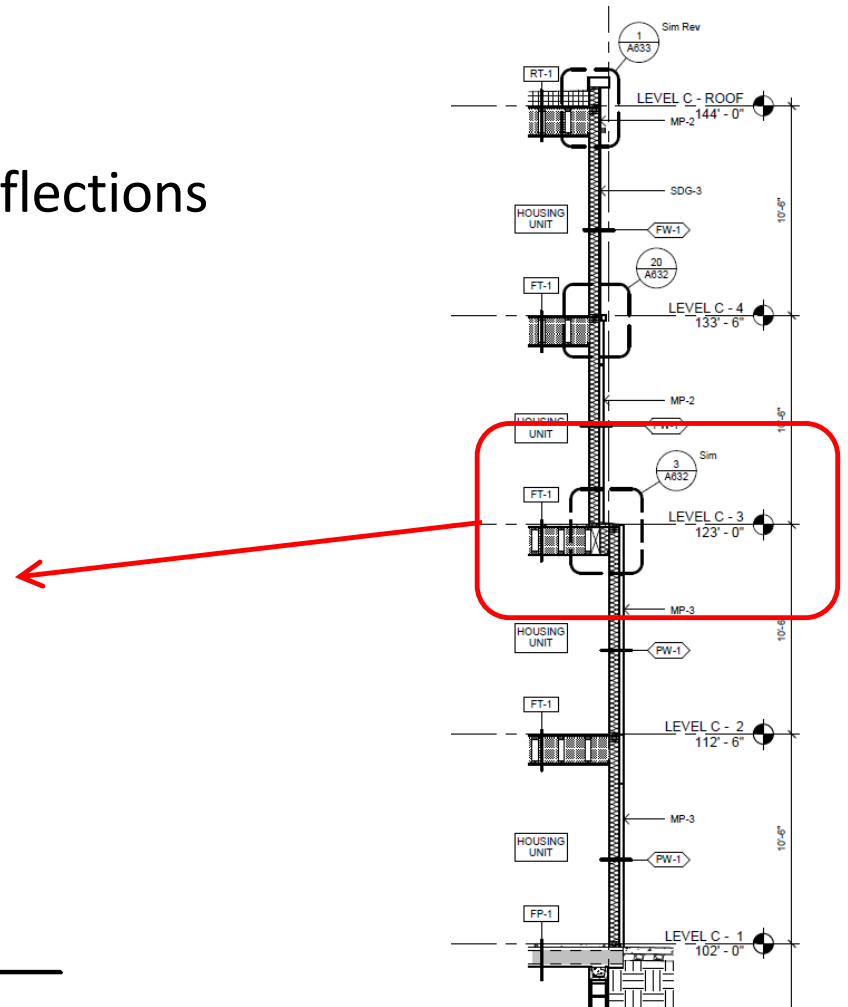
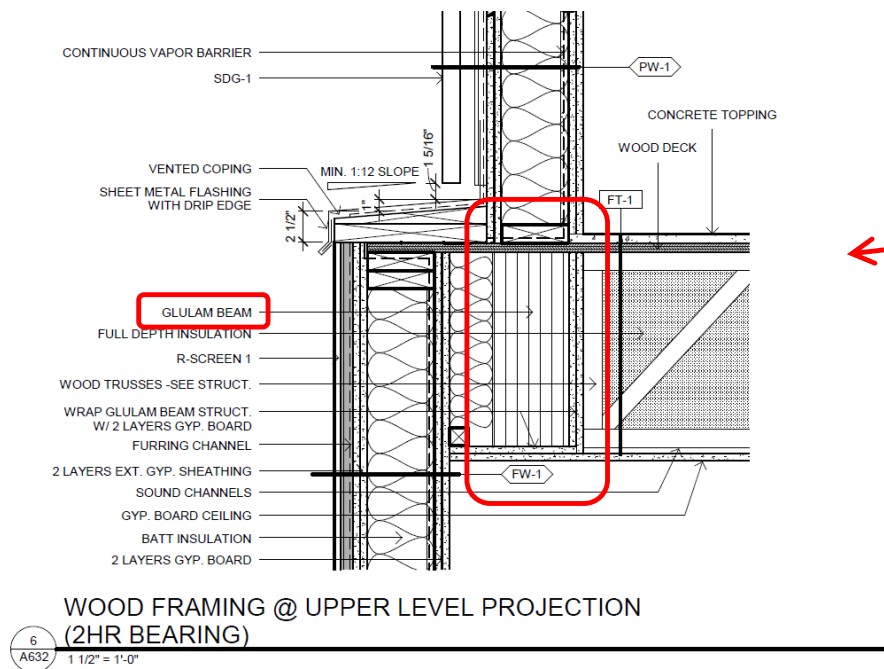
- Case Study 2: Wood Framed Stealth Deflections
- Sometime the movement potential is not as obvious



Image: Google Maps

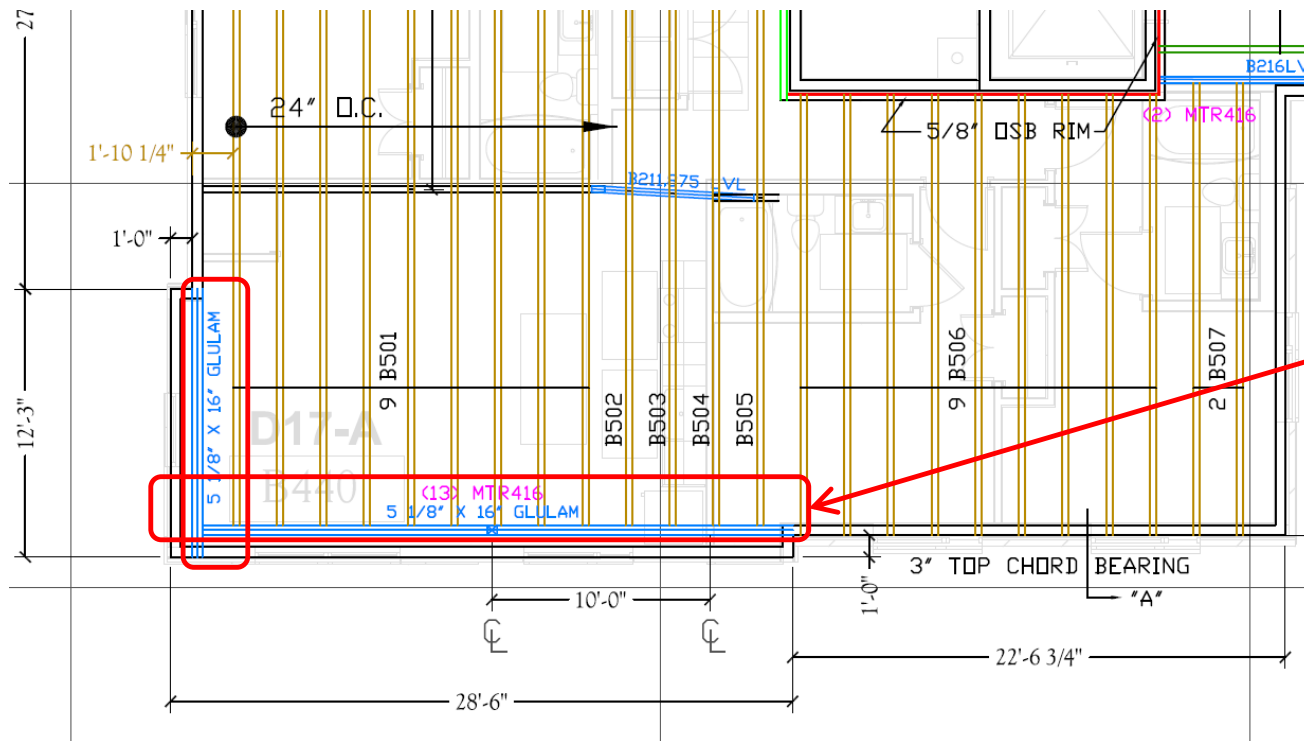
Buildings Move, Buildings Leak

- Case Study 3: Wood Framed Stealth Deflections



Buildings Move, Buildings Leak

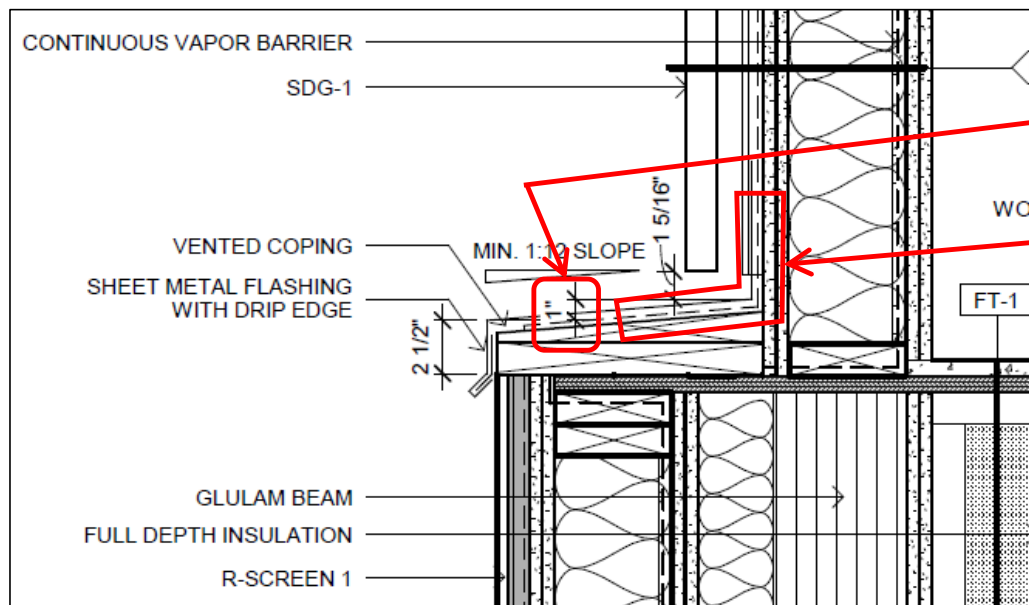
- Case Study 3: Wood Framed Stealth Deflections



**28' LONG GLULAM BEAM
TAKING AS MUCH AS 4 FLOORS
WORTH OF LOADBEARING
WALL WEIGHT**

Buildings Move, Buildings Leak

- Case Study 3: Wood Framed Stealth Deflections



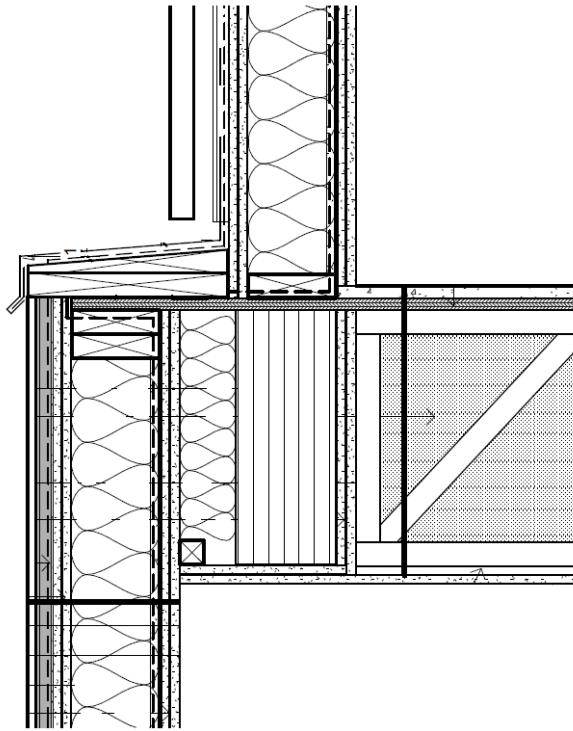
1" DROP (ASSUMING ZERO MOVEMENT)

SOME TYPE OF CONTINUATION OF MECHANICALLY ATTACHED AIR/WATER BARRIER???

AS – BUILT DETAIL

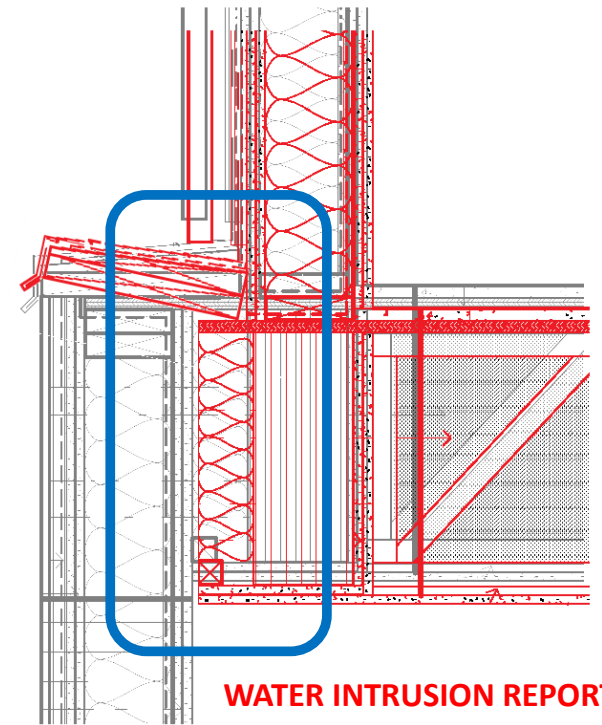
Buildings Move, Buildings Leak

- Case Study 3: Wood Framed Stealth Deflections



CONDITION AT TIME
OF COMPLETION

CONDITION AFTER
4½ YEARS



WATER INTRUSION REPORTED

Buildings Move, Buildings Leak

- Case Study 3: Wood Framed Stealth Deflections
- Repairs made at all setback locations
 - New pitch of 2:12
 - High temp self adhered membrane flashing suitable for use on low slope surfaces



Buildings Move, Buildings Leak

- Case Study 3:
which loadings were involved?



rain smoke radiation fire
impact snow chemical
air live animals solar
wind birds moisture creep
heat shrinkage dead insects
particulates gravity seismic

Buildings Move, Buildings Leak

- Case Study 3:
which loadings were involved?



rain smoke radiation fire
impact snow chemical
air live animals solar
wind birds moisture creep
heat shrinkage dead insects
particulates gravity seismic

Buildings Move, Buildings Leak

- Case Study 4: Roof Ponding/Adaptive Reuse Project



Buildings Move, Buildings Leak

- Case Study 4: Roof Ponding/Adaptive Reuse Project
- New buildings: all structural code provisions apply
- Existing building modifications: retrofitting of structure is governed by code provisions for existing buildings
 - Varying thresholds of retrofit scope triggered by degree of modifications

Buildings Move, Buildings Leak

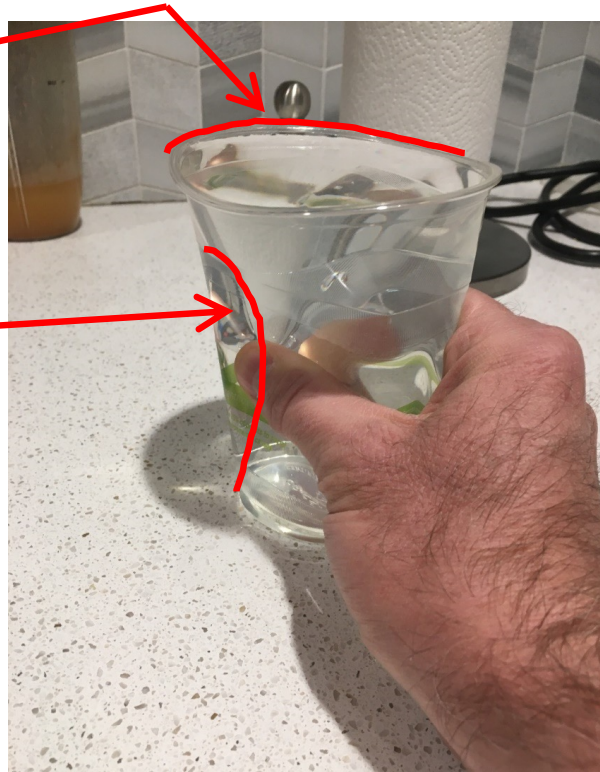
- Case Study 4: Roof Ponding/Adaptive Reuse Project
- New buildings: Roofs designed to less than $\frac{1}{4}$ " per foot slope must be analyzed for progressive deflection (ponding instability)
 - Local jurisdictions might prohibit shallower slopes
 - Manufacturers warranties might exclude shallower slopes

Buildings Move, Buildings Leak

- Progressive deflection, AKA Ponding Instability

ORIGINAL
HEIGHT OF
WATER

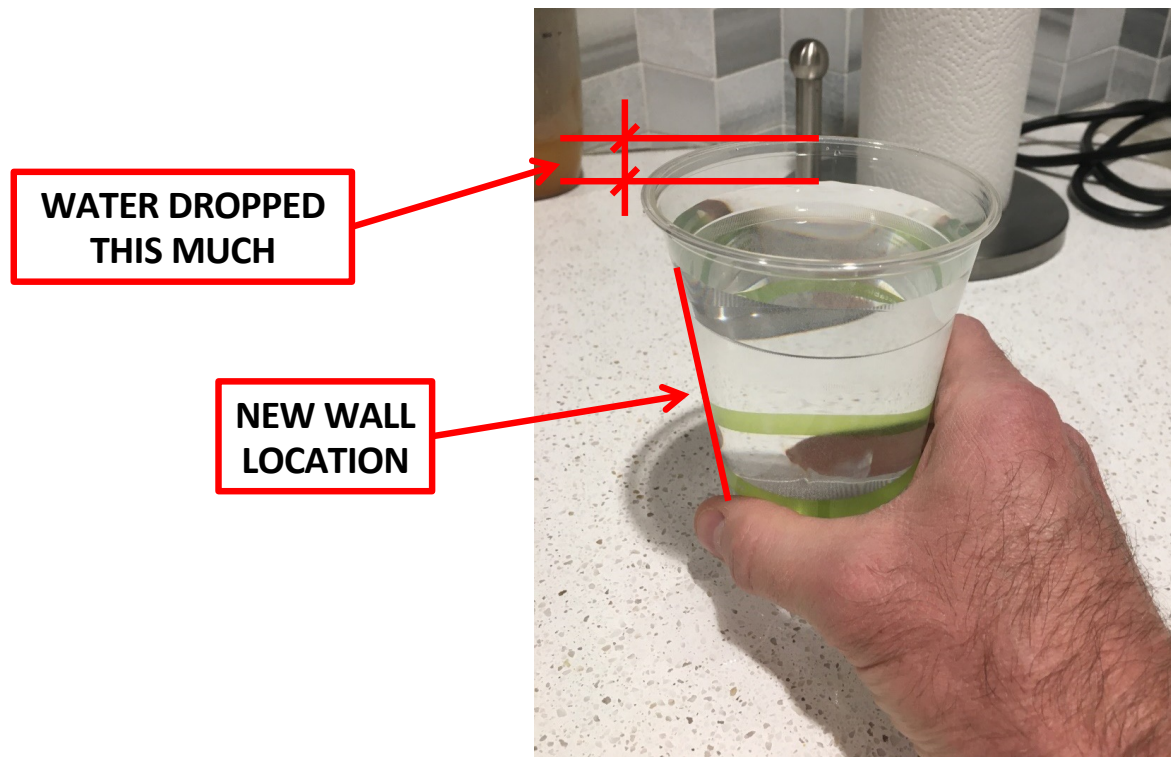
ORIGINAL WALL
LOCATION



SOLO CUP
SCIENCE!!!

Buildings Move, Buildings Leak

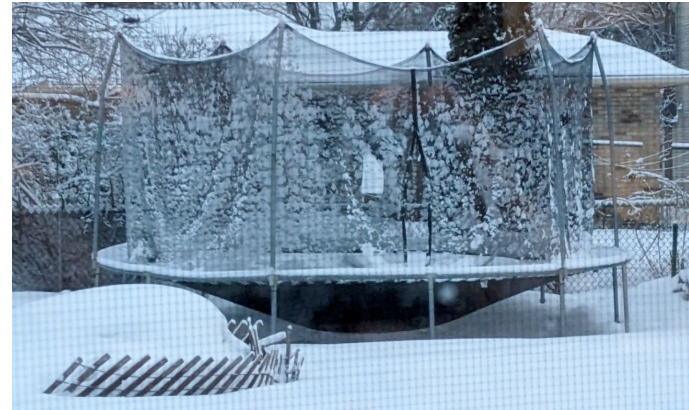
- Ponding Instability



SOLO CUP
SCIENCE!!!

Buildings Move, Buildings Leak

- Ponding Instability



Buildings Move, Buildings Leak

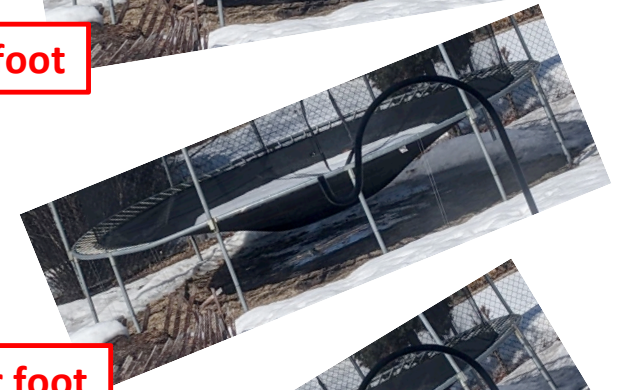
- Ponding Instability
- What's the deal with this $\frac{1}{4}$ " per foot "line in the sand"?
- Roof design slope is the most significant relief valve for ponding instability



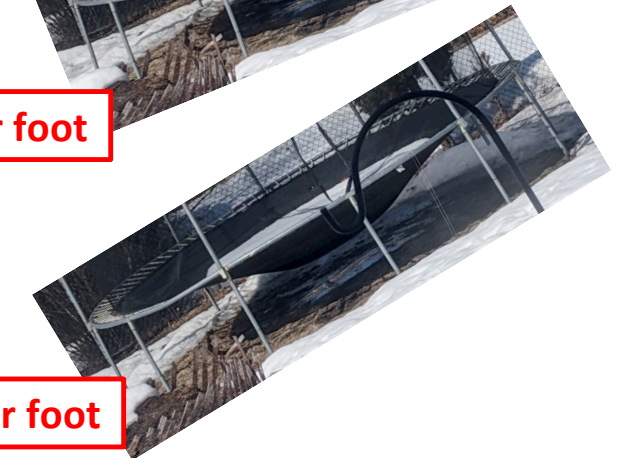
"dead flat"



$\frac{1}{8}$ " per foot



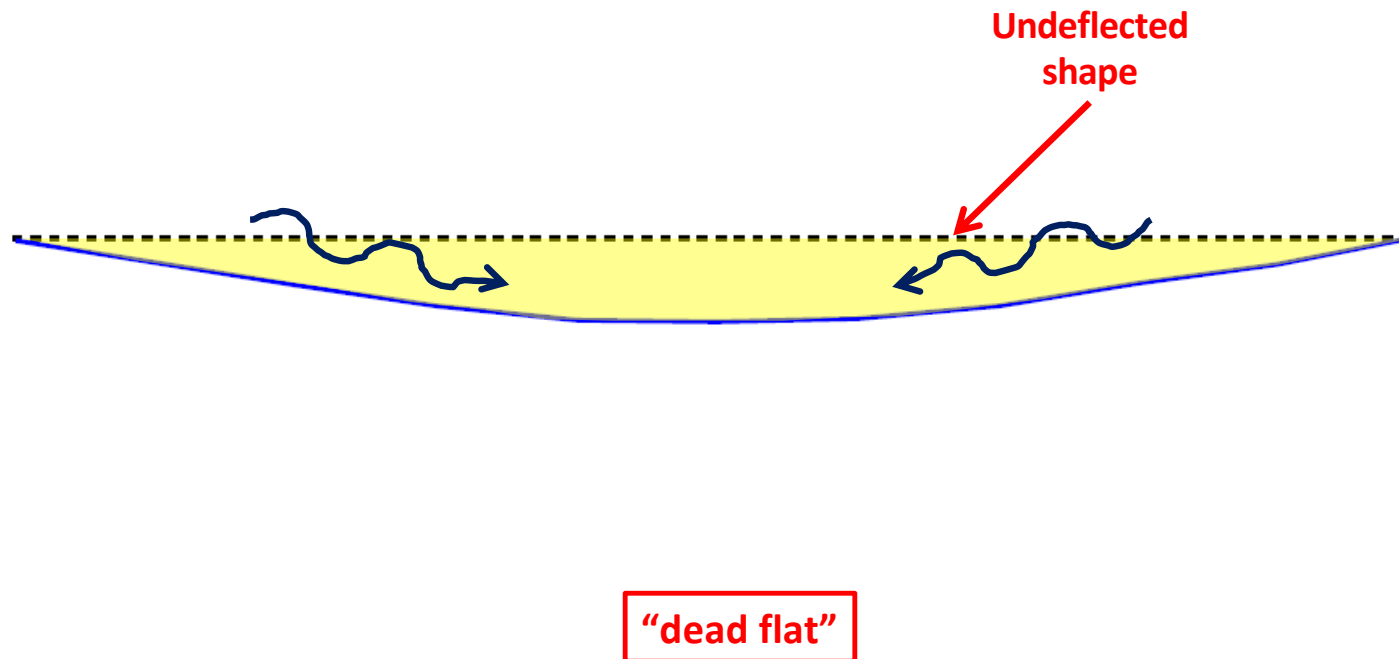
$\frac{1}{4}$ " per foot



$\frac{3}{8}$ " per foot

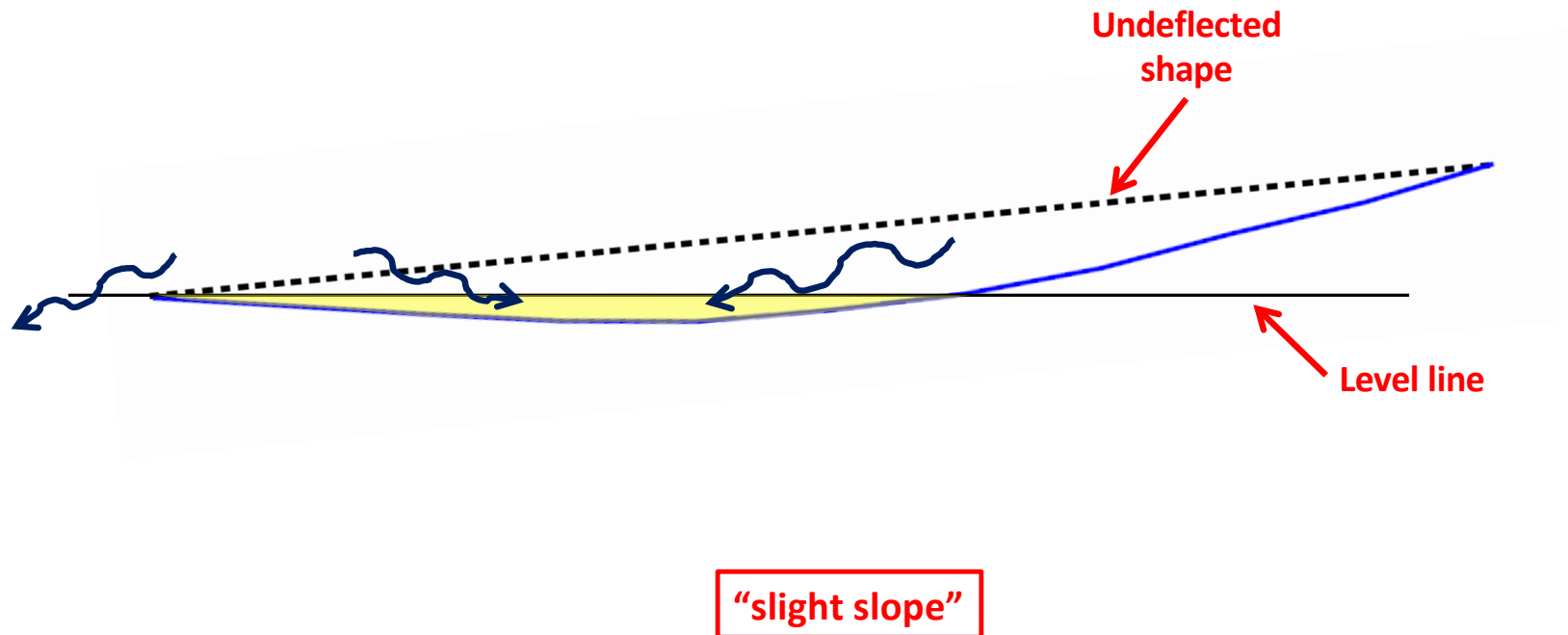
Buildings Move, Buildings Leak

- Roof design slope is the most significant relief valve for ponding instability



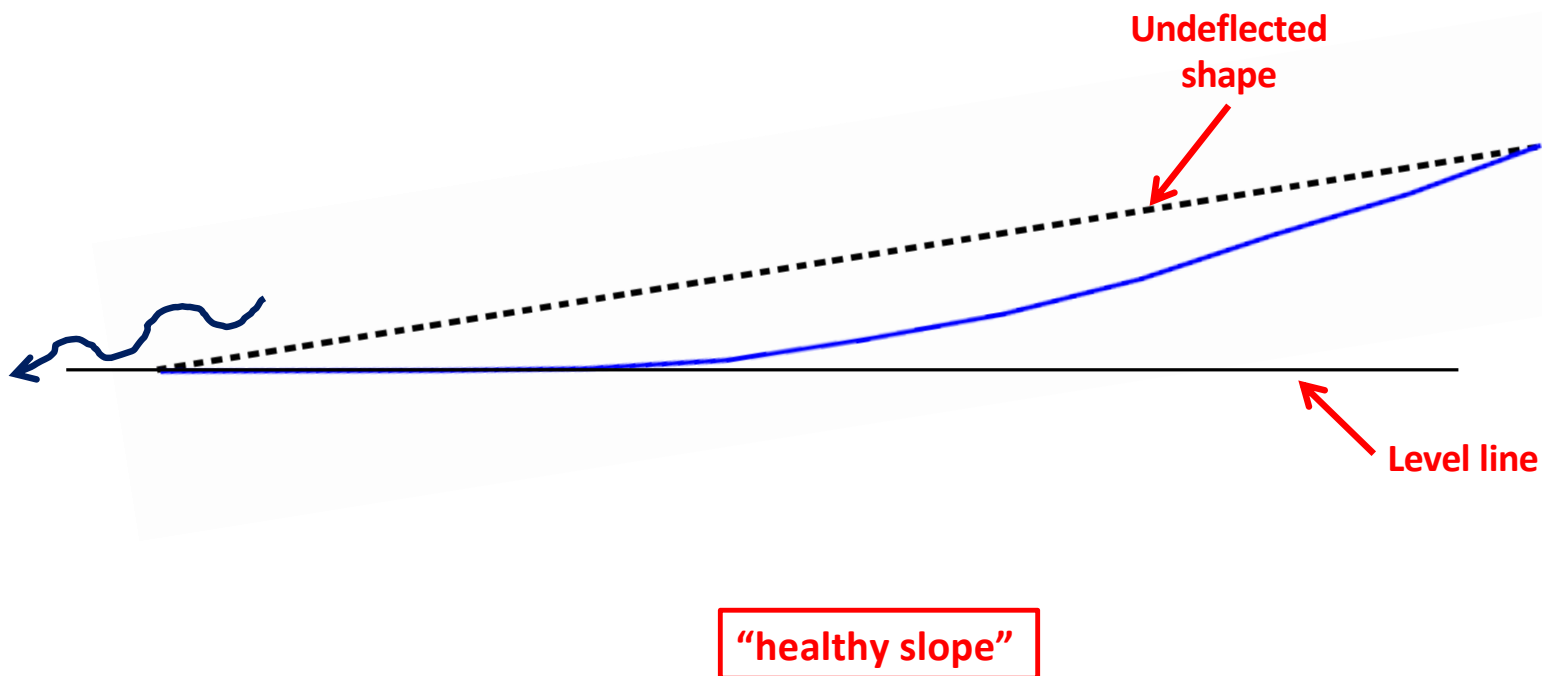
Buildings Move, Buildings Leak

- Roof design slope is the most significant relief valve for ponding instability



Buildings Move, Buildings Leak

- Roof design slope is the most significant relief valve for ponding instability



Buildings Move, Buildings Leak

- Case Study 4: Roof Ponding/Adaptive Reuse Project
- Existing roof structure design was only marginally above original code minimums
 - Open web steel joists
 - Roof framing sloped 1/8" per foot
 - Existing roof assembly saturated



Buildings Move, Buildings Leak

- Case Study 4: Roof Ponding/Adaptive Reuse Project
- Local Code allowed for roof slopes shallower than $\frac{1}{4}$ " per foot when reroofing
- Modifications did not trigger extensive retrofit requirements
 - Ponding analysis was not performed by design team

Buildings Move, Buildings Leak

- Case Study 4: Roof Ponding/Adaptive Reuse Project



Buildings Move, Buildings Leak

- Case Study 4: Roof Ponding/Adaptive Reuse Project
- Design team went back and performed ponding analysis
 - Existing framing confirmed to be stable and adequate under ponded load

Buildings Move, Buildings Leak

- Case Study 4: Roof Ponding/Adaptive Reuse Project
- There were early warning signs
 - Construction team could have alerted design team to birdbaths



Buildings Move, Buildings Leak

- Case Study 4: Roof Ponding/Adaptive Reuse Project
- This particular instance did not result in a critical life-safety issue
- Nevertheless –
 - Cumulative roof ponding as a result of not considering building movement is a serious issue that has resulted many roof collapses
 - Slopes shallower than $\frac{1}{4}$ " per foot always warrant careful consideration, regardless of code requirements.

Buildings Move, Buildings Leak

- Ponding Instability:

Scaremongering with an Abstract and Theoretical Concept?

Not Really

Buildings Move, Buildings Leak

- Ponding Instability
- RIPPED FROM TODAY'S HEADLINES!!!!

- Okay, actually headlines from last year...

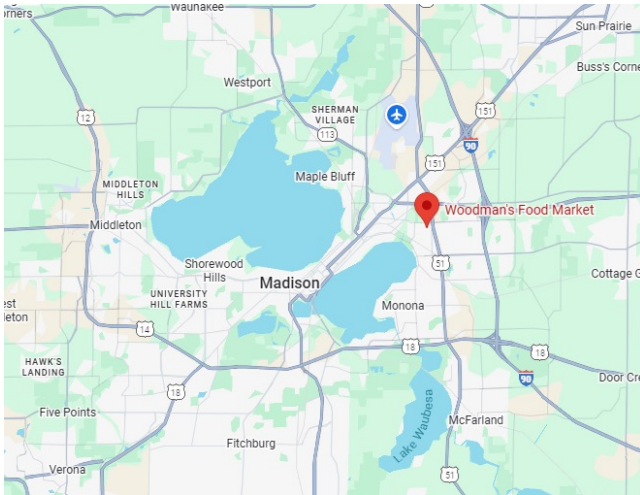


Image: Google Maps



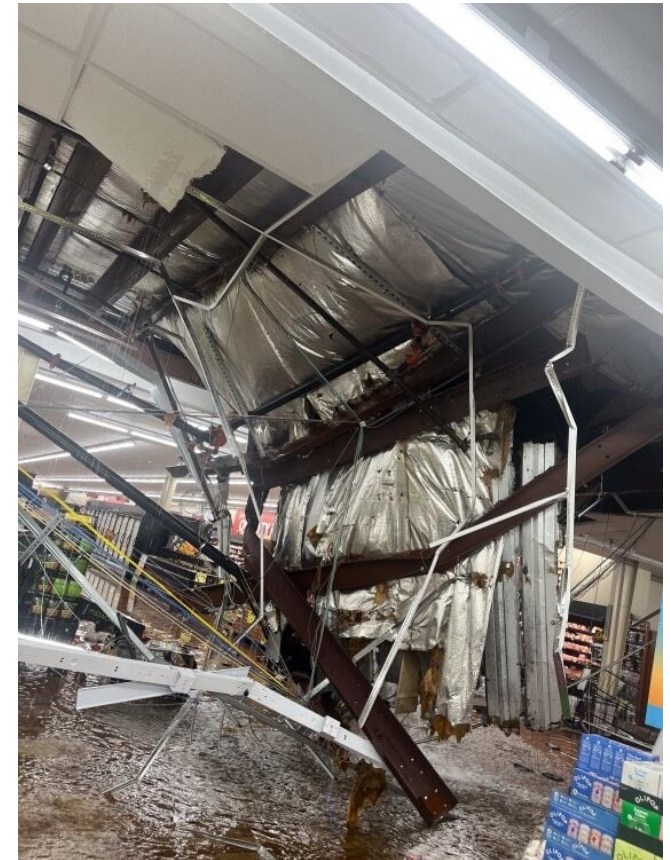
Buildings Move, Buildings Leak

- Ponding Instability

The Madison Fire Department says two drains on the roof were plugged with debris, which caused storm water to accumulate and part of the roof collapsed.

No customers or employees were injured. The store will remain closed until further notice.

WTMJ News



Images: City of Madison Fire Department

Buildings Move, Buildings Leak

- Case Study 4:
which loadings were involved?



rain smoke radiation fire
impact snow chemical
air live animals solar
wind birds moisture creep
heat shrinkage dead insects
particulates gravity seismic

Buildings Move, Buildings Leak

- Case Study 4:
which loadings were involved?



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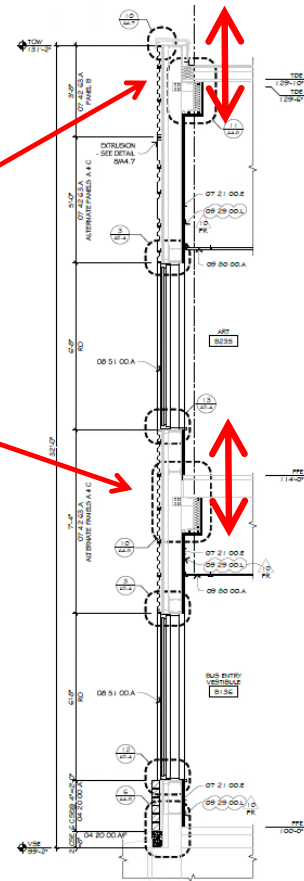
Buildings Move, Buildings Leak

- Case Study 5: Stacked Ribbon Window/Steel Stud Infill
- 2-story elementary school
 - Exterior wall assembly not interrupted by 2nd Floor slab edge or roof deck edge
 - Steel stud backup
 - Opaque wall areas received metal panel cladding



Buildings Move, Buildings Leak

- Case Study 5: Stacked Ribbon Window/Steel Stud Infill

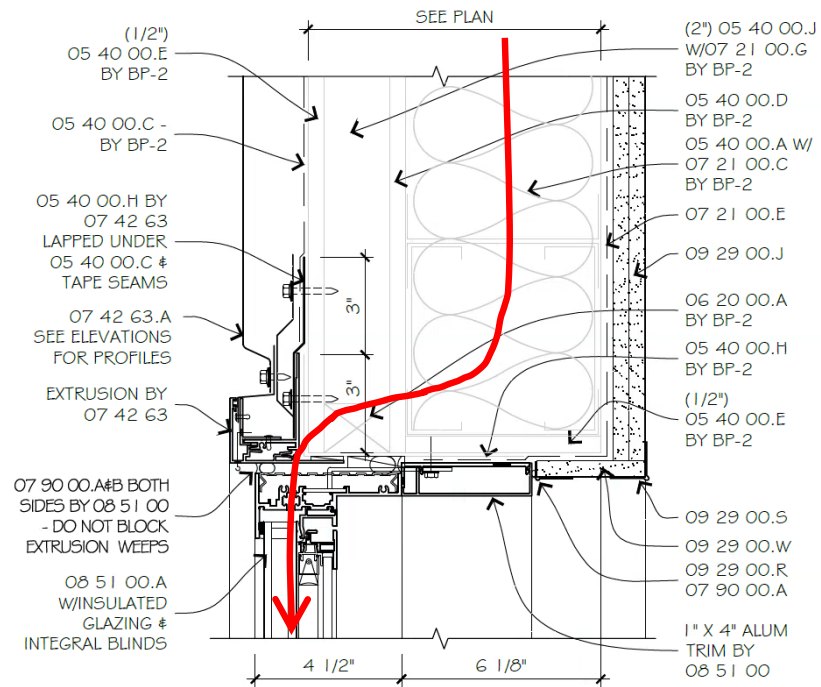


Wind load/deflection
connection only at steel
stud to slab or deck edge

Structure free to
deflect independent of
exterior wall assembly

Buildings Move, Buildings Leak

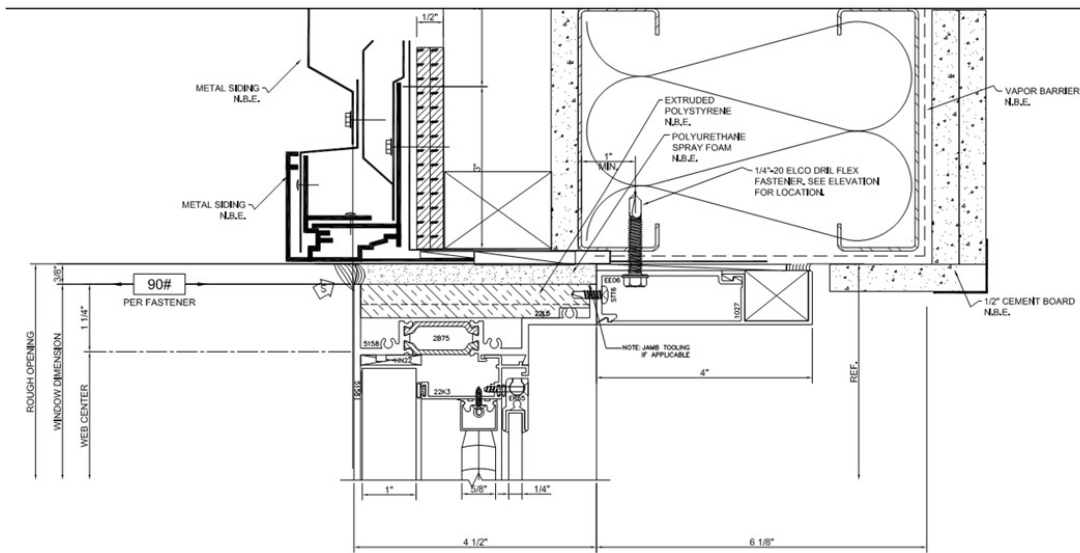
- Case Study 5: Stacked Ribbon Window/Steel Stud Infill



- WALL ABOVE BEARING LOAD ON TO WINDOW BELOW???
- BENDING MOMENT FROM WIND LOAD TRANSFERRING BETWEEN STUDS AND WINDOW???

Buildings Move, Buildings Leak

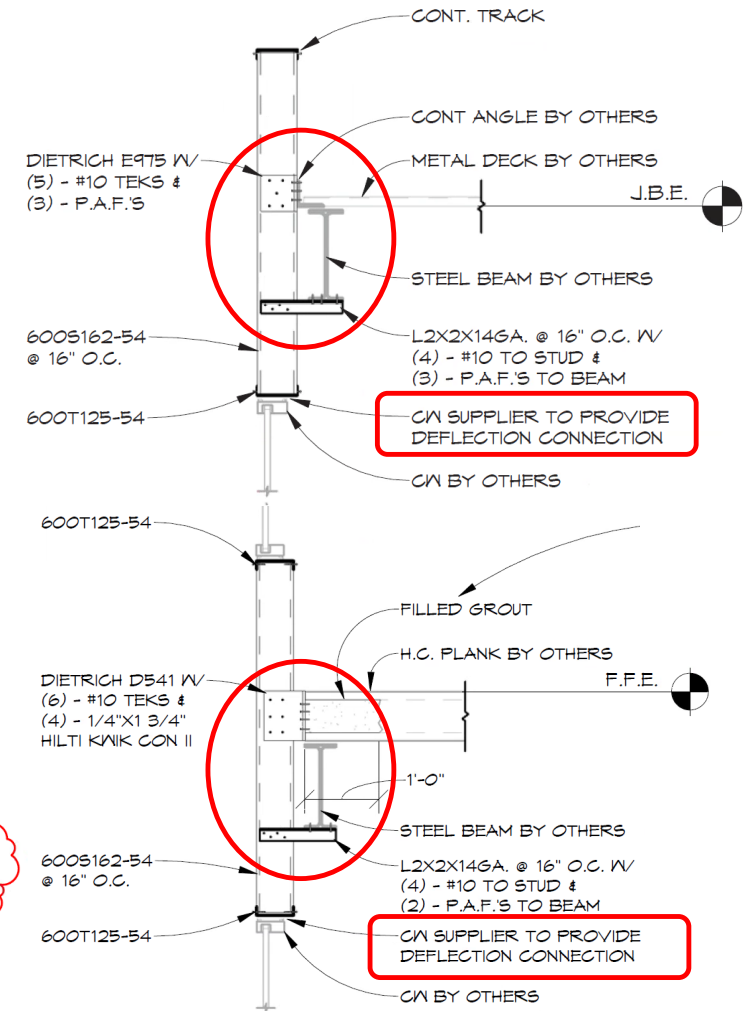
- Case Study 5: Stacked Ribbon Window/Steel Stud Infill



Window supplier's drawings showed static head joint consistent with contract documents

Buildings Move, Buildings Leak

- Case Study 5: Stacked Ribbon Window/Steel
 - But steel stud supplier's shop drawings
 - Requested change to fixed connection between studs and supporting structure
 - Requested that window supplier provide movement accommodation at their head framing condition



A.O.R./E.O.R. NOTE: APEX RECOMMENDS FRAMING AS SHOWN VERIFY LOAD PATH IS ACCEPTABLE. REF. 8, 28/34.5 FOR SIM. STUD LOAD PATH ATTACHMENT TO BEAMS. DETAIL CUT 5/34.4 DOES NOT WORK @ WIDE "RIBBON" WINDOWS.

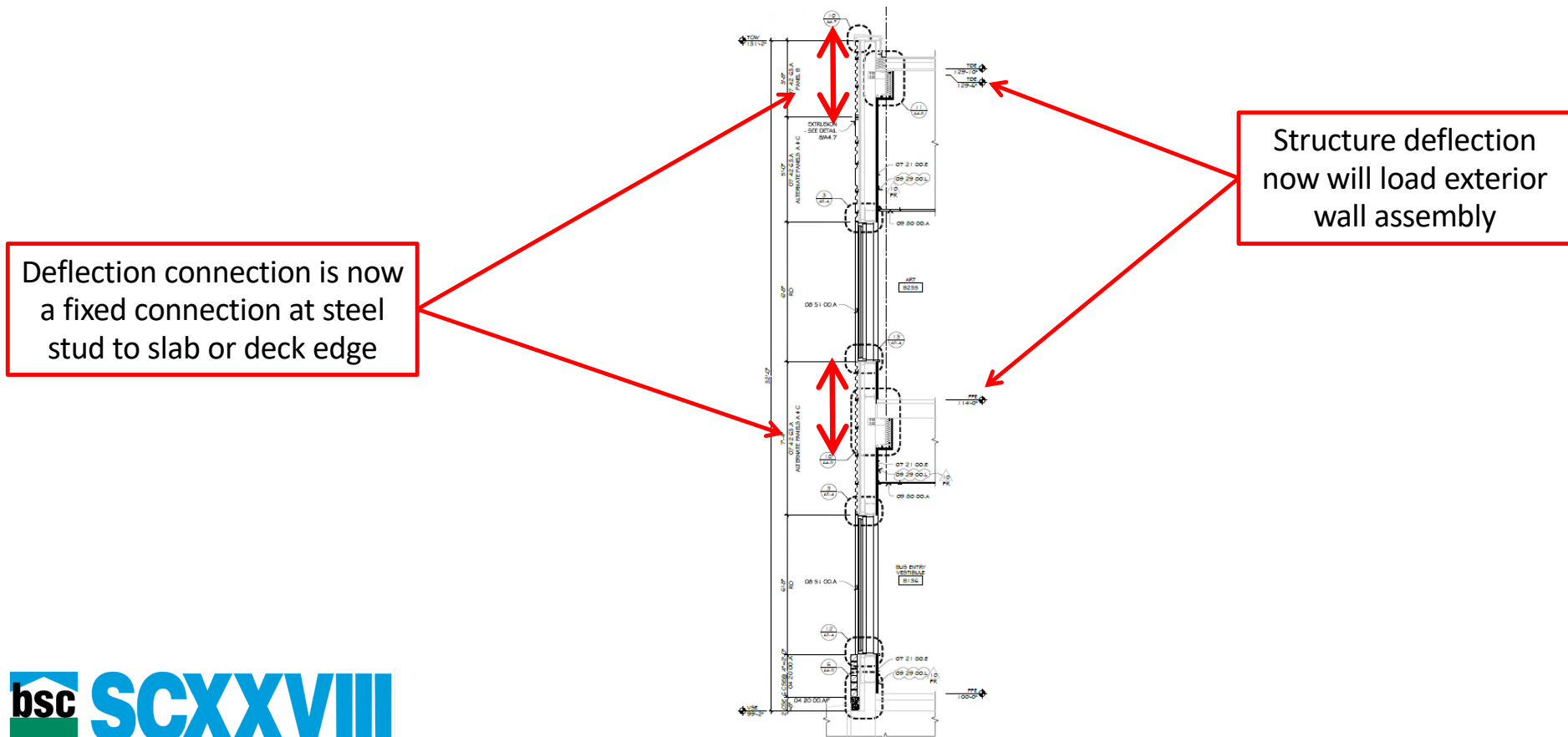
Buildings Move, Buildings Leak

- Case Study 5: Stacked Ribbon Window/Steel Stud Infill
 - Architect approved request, but change was not communicated to any other parties affected by the decision
 - Particularly the window supplier with a static head joint



Buildings Move, Buildings Leak

- Case Study 5: Stacked Ribbon Window/Steel Stud Infill



Buildings Move, Buildings Leak

- Case Study 5: Stacked Ribbon Window/Steel Stud Infill
 - Window head conditions would leak early spring after seasonal cycle of winter snow load deflection followed by spring snow melt relaxation



Buildings Move, Buildings Leak

- Case Study 5: Stacked Ribbon Window/Steel Stud Infill
- Multiple breakdowns in the QA/QC process:
 - Design team and window supplier
 - Did not recognize original stacked wall configuration would be problematic
 - Steel stud supplier
 - Identified issue but did not request change through proper documentation (RFI)
 - Design team
 - Did not issue change to contract documents
 - Construction manager
 - Did not coordinate change between all trades affected

Buildings Move, Buildings Leak

- Case Study 5: Stacked Ribbon Window/Steel Stud Infill
- Highlights the need to properly communicate and validate the continuity of decisions
 - Design
 - Documentation
 - Implementation



Buildings Move, Buildings Leak

- Case Study 5:
which loadings were involved?



rain smoke radiation fire
impact snow chemical
air live animals solar
wind birds moisture creep
heat shrinkage dead insects
particulates gravity seismic

Buildings Move, Buildings Leak

- Case Study 5:
which loadings were involved?



rain smoke radiation fire
impact **snow** chemical
air **live** animals solar
wind birds moisture creep
heat shrinkage **dead** insects
particulates **gravity** seismic

Buildings Move, Buildings Leak

- Category B: Material Volume Change (Shortening/Elongation) impacting Enclosure Control Layers

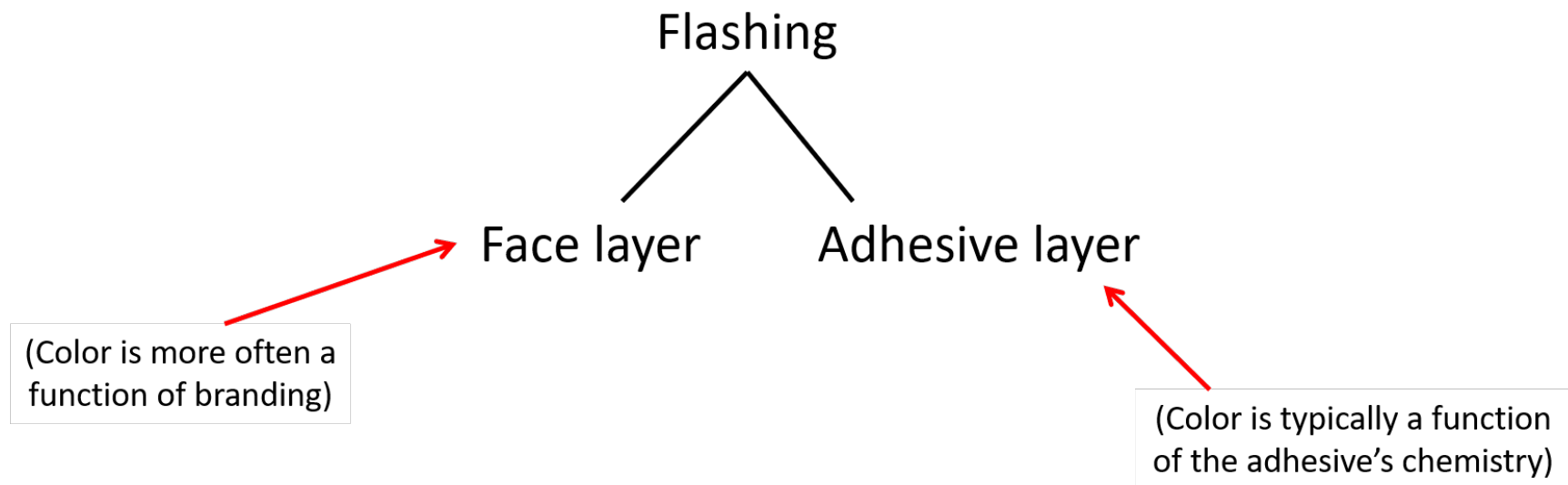
Buildings Move, Buildings Leak

- Case Study 6: Solar Heat Gain/Self-Adhered Membrane Flashing



Buildings Move, Buildings Leak

- Case Study 6: Solar Heat Gain/Self-Adhered Membrane Flashing



- Material color influences ability to reflect, absorb, and transmit heat

Buildings Move, Buildings Leak

- Case Study 6: Solar Heat Gain/Self-Adhered Membrane Flashing

- Integrated sheathing system
- Non-loadbearing steel stud wall
- Board joints/corners/openings required treatment for water and air control layer
 - Fluid applied flashing considered but ultimately not chosen
 - 15-mil acrylic-based flashing selected



Buildings Move, Buildings Leak

- Case Study 6: Solar Heat Gain/Self-Adhered Membrane Flashing
- Enclosure work occurred throughout winter (Climate Zone 6a)
 - End of December during installation, gapping or “fish mouthing” was discovered at outer edges of flashing
 - Raised folds also discovered in field of material



Buildings Move, Buildings Leak

- Case Study 6: Solar Heat Gain/Self-Adhered Membrane Flashing
- Flashing would
 - be flat/smooth before direct morning sunlight
 - gap open when exposed to sun
 - Then return to flat after sun set in afternoon



Buildings Move, Buildings Leak

- Case Study 6: Solar Heat Gain/Self-Adhered Membrane Flashing



Buildings Move, Buildings Leak

- Case Study 6: Solar Heat Gain/Self-Adhered Membrane Flashing
- Surface temperature readings taken
- Days with direct sunlight the surface temperatures would exceed 130 degrees
 - Ambient air temperatures around 30 degrees



Buildings Move, Buildings Leak

- Case Study 6: Solar Heat Gain/Self-Adhered Membrane Flashing

Facer color

➔ solar heat gain

➔ material expanded at a rate greater than substrate

➔ expansion overcame adhesive force

- Any fish mouths terminating on an upward edge determined to be a moisture infiltration risk

Buildings Move, Buildings Leak

- Case Study 6: Solar Heat Gain/Self-Adhered Membrane Flashing
- Remedial options considered



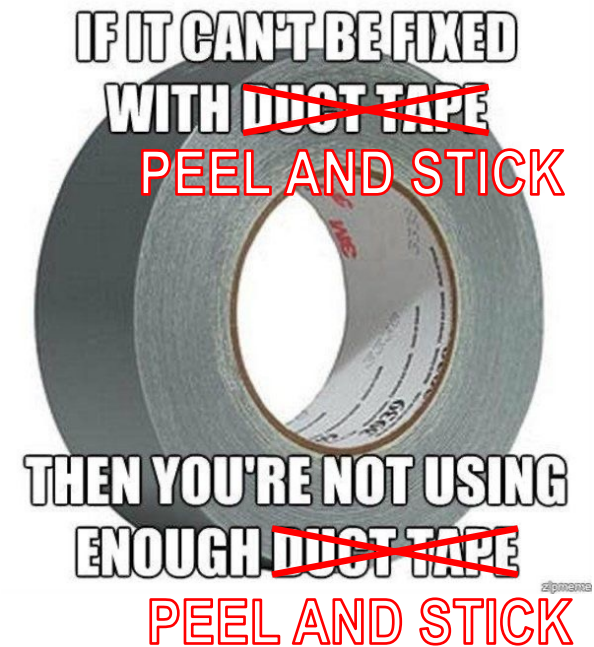
Buildings Move, Buildings Leak

- Case Study 6: Solar Heat Gain/Self-Adhered Membrane Flashing
- Remedial options considered



Buildings Move, Buildings Leak

- Case Study 6: Solar Heat Gain/Self-Adhered Membrane Flashing
 - Option selected was tested/validated across path of sun on southeast and southwest facing test locations
 - Total project delay not significant, however
 - Labor and material cost increase
 - Install schedule prolonged



Buildings Move, Buildings Leak

- Case Study 6: Solar Heat Gain/Self-Adhered Membrane Flashing
- Recommendations provided to manufacturer
 - Produce flashing material in a lighter color?
- Oh, and by the way...
 - PSA? Where's your J-roller?
 - What's your UV exposure limits?

Buildings Move, Buildings Leak

- Case Study 6:
which loadings were involved?



rain smoke radiation fire
impact snow chemical
air live animals solar
wind birds moisture creep
heat shrinkage dead insects
particulates gravity seismic

Buildings Move, Buildings Leak

- Case Study 6:
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Buildings Move, Buildings Leak

- Case Study 7: Spray Polyurethane Foam (SPF) Shrinkage



Buildings Move, Buildings Leak

- Case Study 7: Spray Polyurethane Foam (SPF) Shrinkage
- Site-manufactured SPF
 - Two base components are produced by material manufacturer
 - Part “A” and Part “B” combined on-site during spraying operation to create foam plastic
 - Cellular structure/entrapped voids are result of site operation
- Very common in commercial construction
 - Thermal control
 - Air control
 - Vapor control

Buildings Move, Buildings Leak

- Case Study 7: Spray Polyurethane Foam (SPF) Shrinkage
- Quality control measures required before/during installation
 - Material shipping/handling/storage controls
 - Installation equipment maintenance and calibration
 - Mixture ratio
 - Processing controls – temperature/pressure/humidity
 - For material, substrate AND ambient

Buildings Move, Buildings Leak

- Case Study 7: Spray Polyurethane Foam (SPF) Shrinkage
- Possible install failure is excessive shrinkage after placement
 - Can initiate anywhere from several days to several months after placement
- Concern can be minor to major
 - Depends on intended control function of SPF and degree of shrinkage
 - Thermal control layer breached = relatively minor
 - Air control layer breached = bigger deal
 - Shrinkage damages other control layers = very big deal

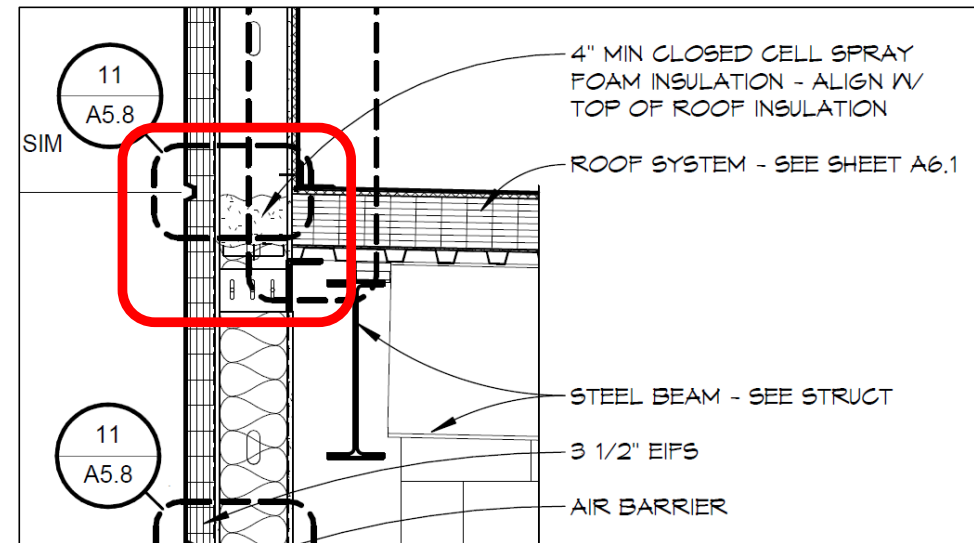


Buildings Move, Buildings Leak

- Case Study 7: Spray Polyurethane Foam (SPF) Shrinkage

- Project 1

- Exterior steel stud wall
- Fluid applied air/water resistive barrier on exterior sheathing
- Stud walls ran past second floor slab and roof deck edge



- At stud bypass of second floor and roof, SPF “plugs” placed in stud cavity to prevent air bypass

Buildings Move, Buildings Leak

- Case Study 7: Spray Polyurethane Foam (SPF) Shrinkage
- Distress first observed on outside face of exterior sheathing at roof deck elevation
- Inspection openings created on rear side of parapet wall



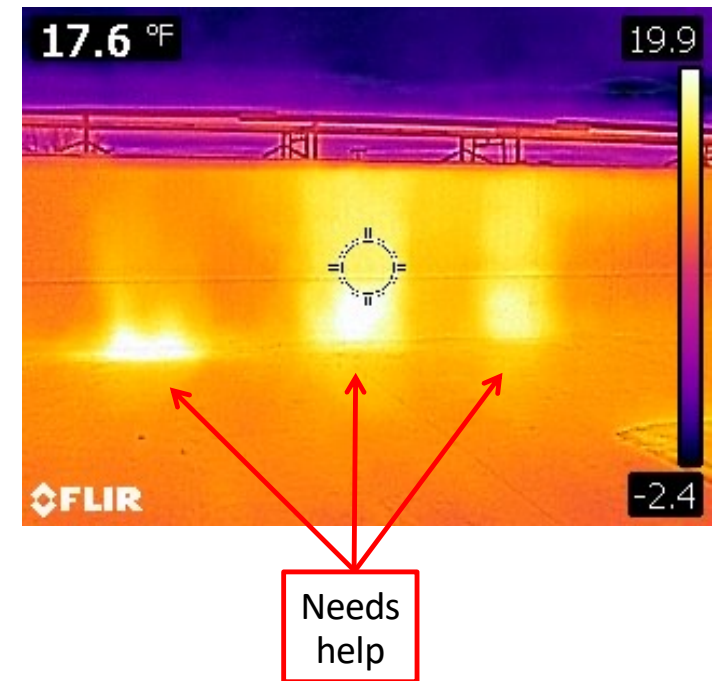
Buildings Move, Buildings Leak

- Case Study 7: Spray Polyurethane Foam (SPF) Shrinkage
- Condition also discovered at second floor slab edge
- Shrinkage pulled SPF away from studs and slab/deck edge face
 - Unacceptable air bypass condition



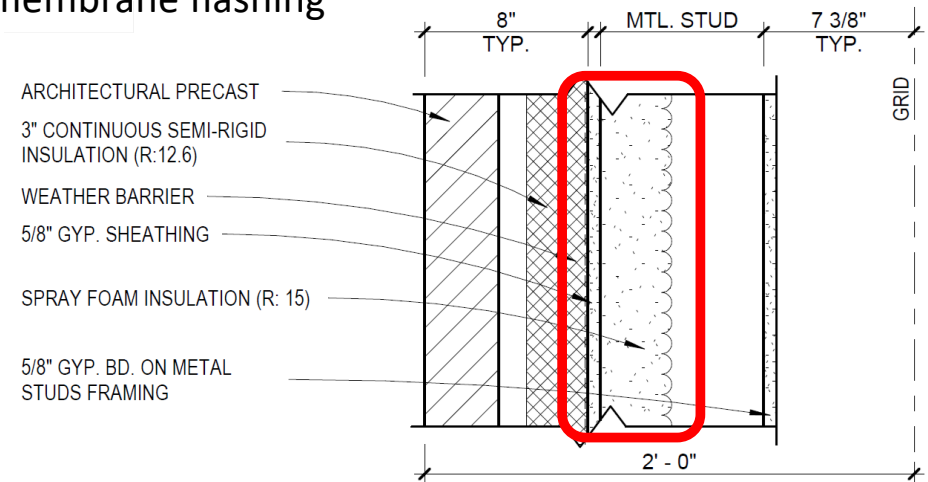
Buildings Move, Buildings Leak

- Case Study 7: Spray Polyurethane Foam (SPF) Shrinkage
- Fix determined:
 - Establish areas needing repair
 - IR imaging
 - Create relief cut in existing plug
 - Install new cap layer over top
 - With renewed focus on processing and placement controls
 - Validate repair with IR imaging



Buildings Move, Buildings Leak

- Case Study 7: Spray Polyurethane Foam (SPF) Shrinkage
- Project 2
 - Exterior steel stud wall
 - Fluid applied air/water barrier (AWB) on exterior sheathing
 - Sheathing joints treated with self-adhered membrane flashing
 - SPF applied full height in stud cavity as part of thermal control



Buildings Move, Buildings Leak

- Case Study 7: Spray Polyurethane Foam (SPF) Shrinkage
- Distress observed on outside face of sheathing
 - First noted ~3 months after install
 - Sheathing bowed inward
 - AWB cracked
 - Sheathing facer cracked



Buildings Move, Buildings Leak

- Case Study 7: Spray Polyurethane Foam (SPF) Shrinkage
- Inspection Openings Made
 - SPF shrinkage confirmed
- Site visit from both SPF Manufacturer & AWB Manufacturer



Buildings Move, Buildings Leak

- Case Study 7: Spray Polyurethane Foam (SPF) Shrinkage
- SPF function determined to still be acceptable
- AWB condition required repair
 - Cracks treated with additional flashing material

Buildings Move, Buildings Leak

- Case Study 7: Spray Polyurethane Foam (SPF) Shrinkage
- Both Projects:
 - Several months of additional work
 - Combined additional costs exceeding \$100,000
 - Due to lack of daily log during installation (and short-term memory loss), difficult to establish root cause(s) of shrinkage

Buildings Move, Buildings Leak

- Case Study 7: Spray Polyurethane Foam (SPF) Shrinkage
- Recommendations
 - For SPF applied in stud cavities, look for inward bowing or “scalloping” of exterior sheathing as sign that shrinkage has occurred



Buildings Move, Buildings Leak

- Case Study 7: Spray Polyurethane Foam (SPF) Shrinkage
- Recommendations – Proper Quality Control
 - Components kept at manufacturer's recommended temperature ranges during storage & handling
 - Spraying equipment calibrated to correct mixing ratio, line temperatures, pressures
 - Environmental conditions (temperature & humidity) of air and receiving substrate within manufacturer's recommended ranges
 - Maintain a Daily Log during Install
 - TALK ABOUT ALL THIS STUFF IN THE PREINSTALL MEETING!!!

Buildings Move, Buildings Leak

- Case Study 7:
which loadings were involved?



rain smoke radiation fire
impact snow chemical
air live animals solar
wind birds moisture creep
heat shrinkage dead insects
particulates gravity seismic

Buildings Move, Buildings Leak

- Case Study 7:
which loadings were involved?

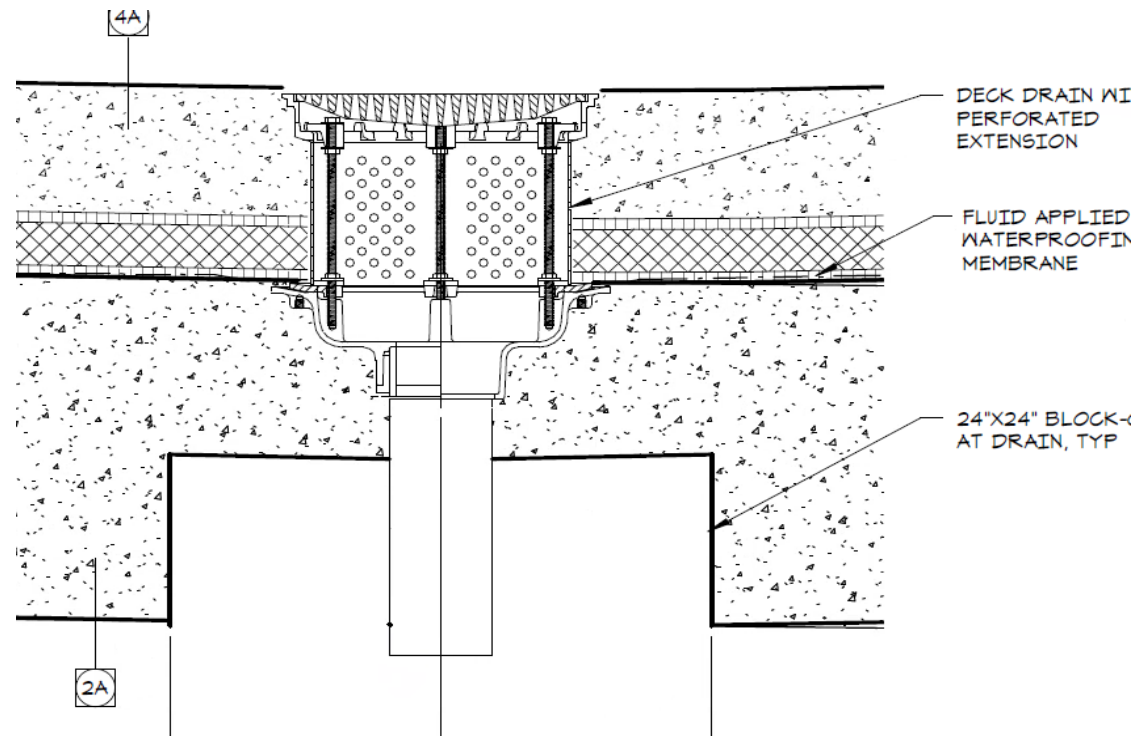


MAYBE???

rain smoke radiation fire
impact snow chemical
air live animals solar
wind birds moisture creep
heat shrinkage dead insects
particulates gravity seismic

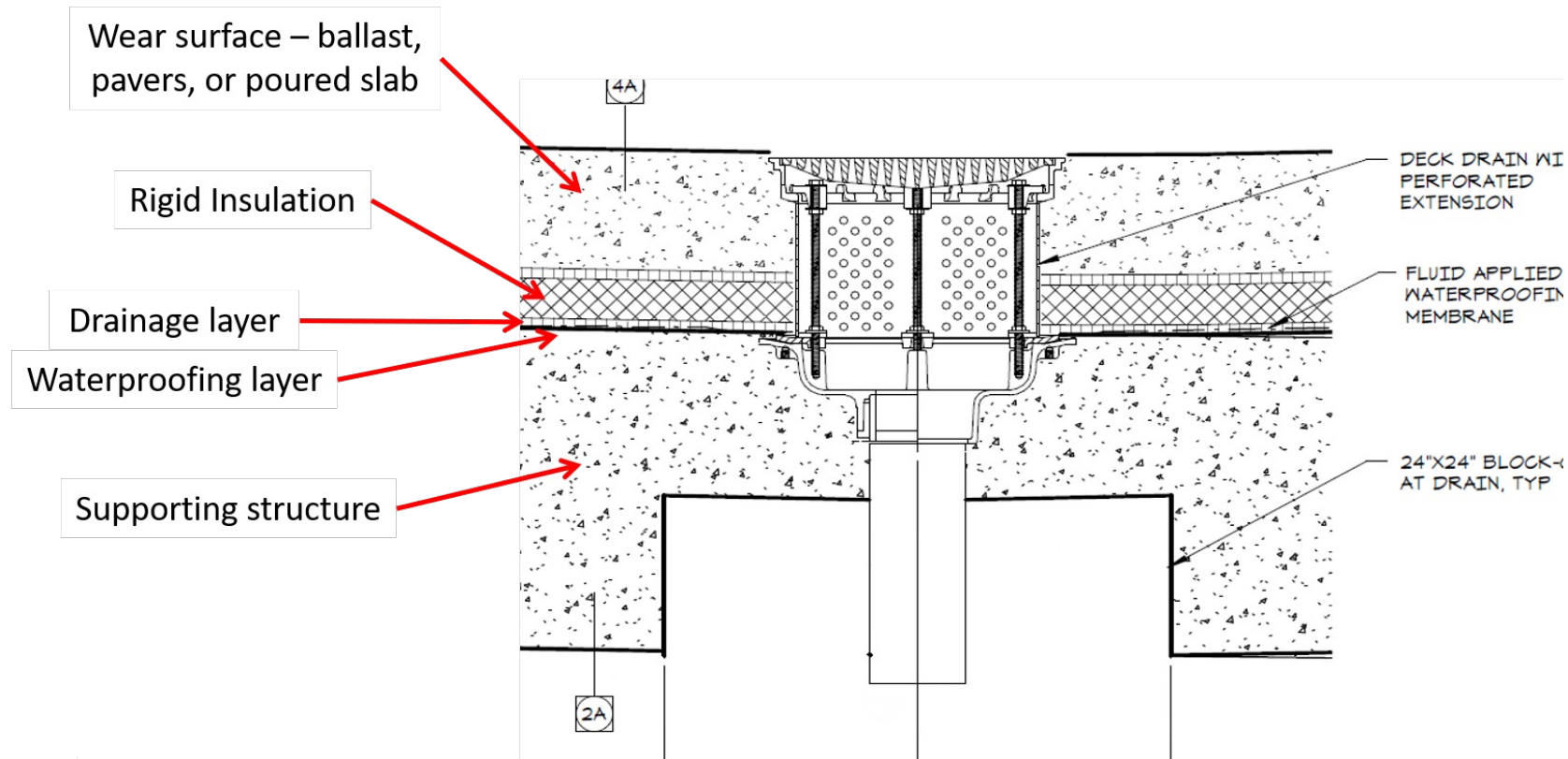
Buildings Move, Buildings Leak

- Case Study 8: Slab Jacking/Plaza Deck Assembly
- Plaza decks used as horizontal mediator between exterior above and interior below
- Also known as
 - Inverted roofs (IRMAs)
 - Protected roof membranes (PMRs)
 - Split slabs



Buildings Move, Buildings Leak

- Case Study 8: Slab Jacking/Plaza Deck Assembly



Buildings Move, Buildings Leak

- Case Study 8: Slab Jacking/Plaza Deck Assembly
- Case study will focus on cast-in-place concrete wear slabs for parking on top surface



Buildings Move, Buildings Leak

- Case Study 8: Slab Jacking/Plaza Deck Assembly
- Wear slabs → outside of control layers → subject to seasonal changes of exterior climate

Fig. 3.3.2 Annual average ambient relative humidity, percent

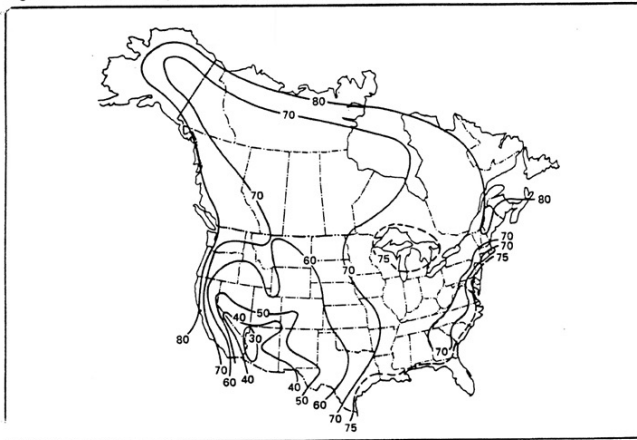
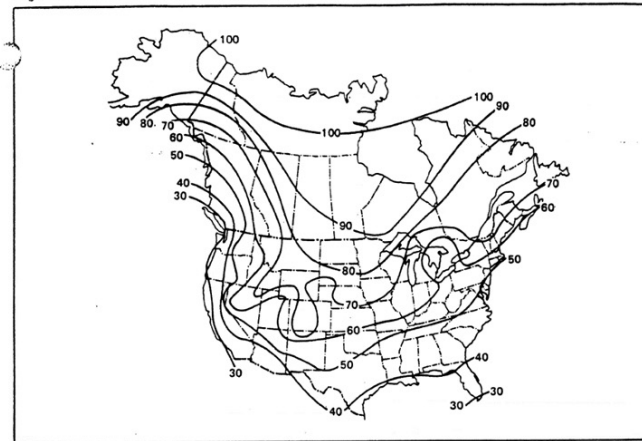


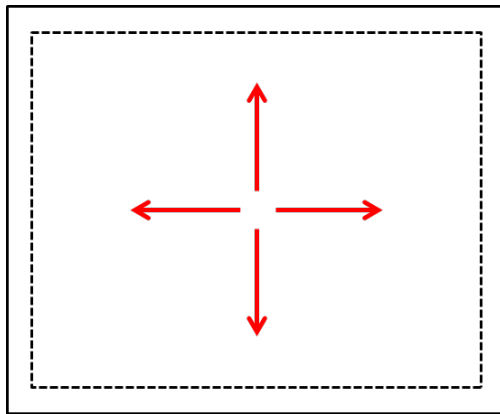
Fig. 3.3.1 Maximum seasonal climatic temperature change, deg F



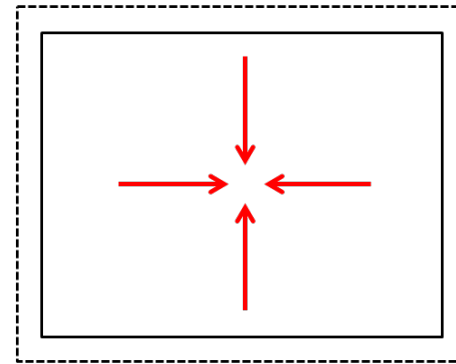
From PCI Design Handbook 3rd Ed., 1985

Buildings Move, Buildings Leak

- Case Study 8: Slab Jacking/Plaza Deck Assembly
- Wear slab detailing must accommodate movement



Increase in temperature
or moisture content



Decrease in temperature
or moisture content

Buildings Move, Buildings Leak

- Case Study 8: Slab Jacking/Plaza Deck Assembly
- Areas where waterproofing (WP) layer intersects wear slab must be protected from wear slab movement
 - Where WP turns up vertical surfaces – walls, light pole bases, steps in structural slab



Buildings Move, Buildings Leak

- Case Study 8: Slab Jacking/Plaza Deck Assembly
- Project 1
 - Typical Assembly Construction, but WP layer was 60 mil EPDM (not ideal)
 - Parking deck above auto dealership for auto storage



Buildings Move, Buildings Leak

- Case Study 8: Slab Jacking/Plaza Deck Assembly
- Original construction complete ~ 2006
 - Leaking first observed ~ 2008
 - Substantial exterior wall cracking/movement at building corners
 - Accelerated wear slab deterioration
- Numerous other issues, primarily structure-related



Buildings Move, Buildings Leak

- Case Study 8: Slab Jacking/Plaza Deck Assembly
- Project 2
 - Typical Assembly Construction, WP layer 215 mil hot rubberized asphalt (HRA)
 - Parking deck above retail



Buildings Move, Buildings Leak

- Case Study 8: Slab Jacking/Plaza Deck Assembly
- Original construction complete ~ 2005
 - Leaking first observed ~ 2011
 - Substantial exterior wall outward movement
 - Accelerated wear slab deterioration
 - Tilting light pole bases



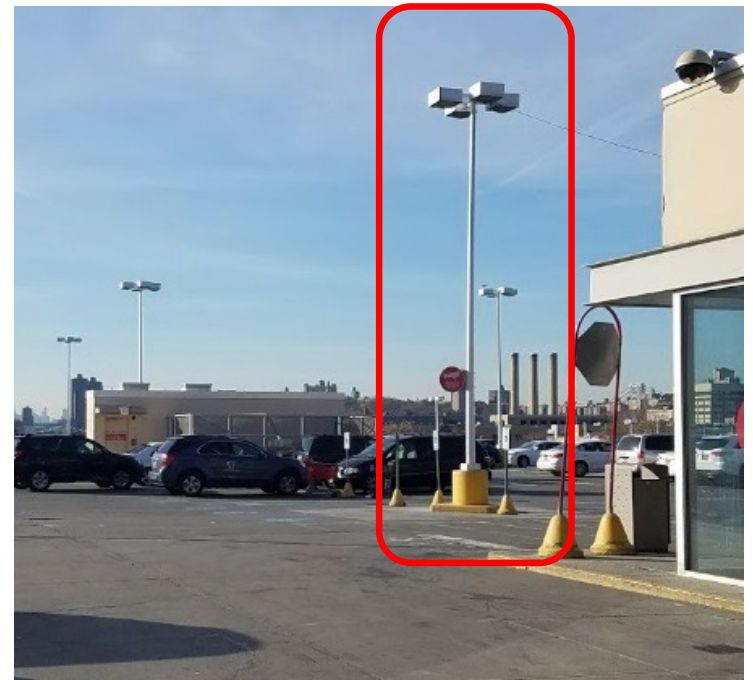
Buildings Move, Buildings Leak

- Case Study 8: Slab Jacking/Plaza Deck Assembly



Buildings Move, Buildings Leak

- Case Study 8: Slab Jacking/Plaza Deck Assembly



Buildings Move, Buildings Leak

- Case Study 8: Slab Jacking/Plaza Deck Assembly



PROJECT 1: 55,000± SQUARE FEET



PROJECT 2: 179,000± SQUARE FEET

Buildings Move, Buildings Leak

- Case Study 8: Slab Jacking/Plaza Deck Assembly
- Inadequate amount of expansion joints & sealed control joints
 - ➔ majority of wear slab expansion occurring at outer edges & corners
 - ➔ slab movement distressing waterproofing layer to failure

Buildings Move, Buildings Leak

- Case Study 8: Slab Jacking/Plaza Deck Assembly
- Progressive failure mechanism – Wear slab
 - Shrink over winter months
 - Open up untreated control joints & new tensile cracks
 - Gaps fill with debris/roadway grit
 - Swell over summer months
 - Expand against debris-filled gaps
 - Each successive seasonal cycle would establish new baseline of overall horizontal dimension
- Eventually force of jacking on vertical waterproofing surfaces would cause breach

Buildings Move, Buildings Leak

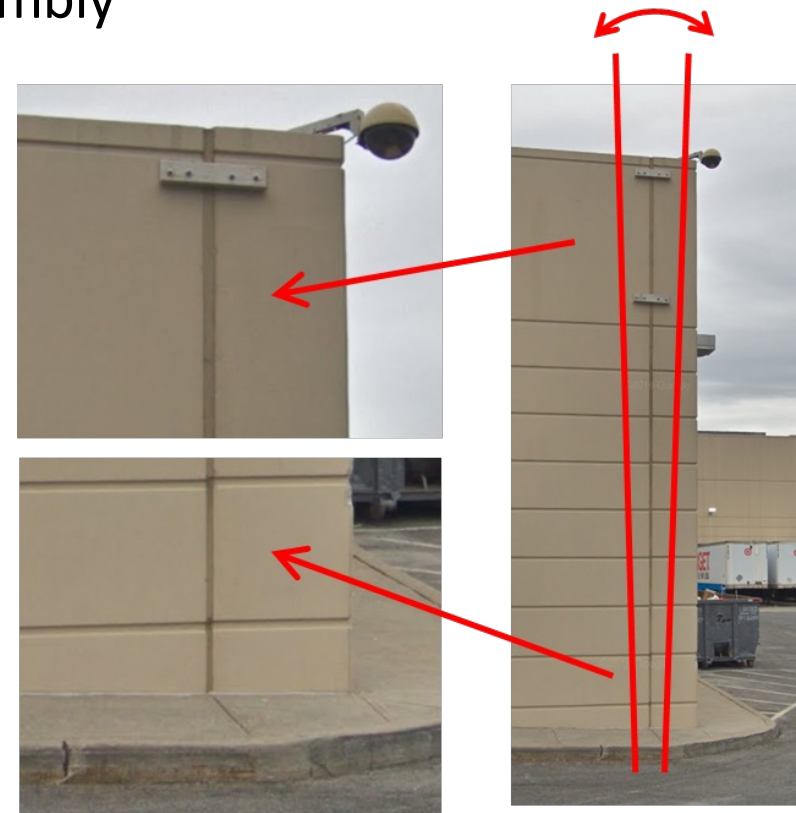
- Case Study 8: Slab Jacking/Plaza Deck Assembly



Frank Hurley/Scott Polar Research Institute, University of Cambridge/Getty Images

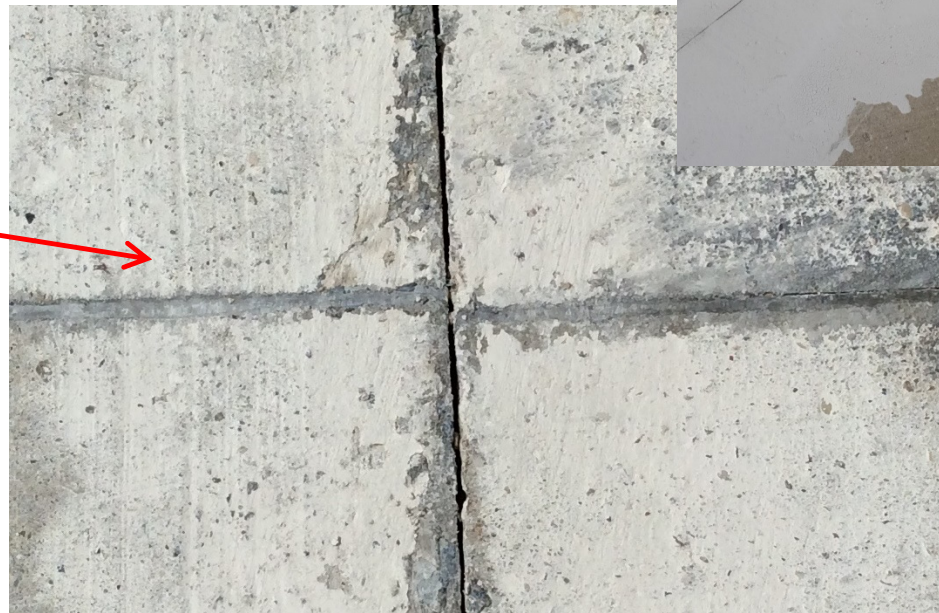
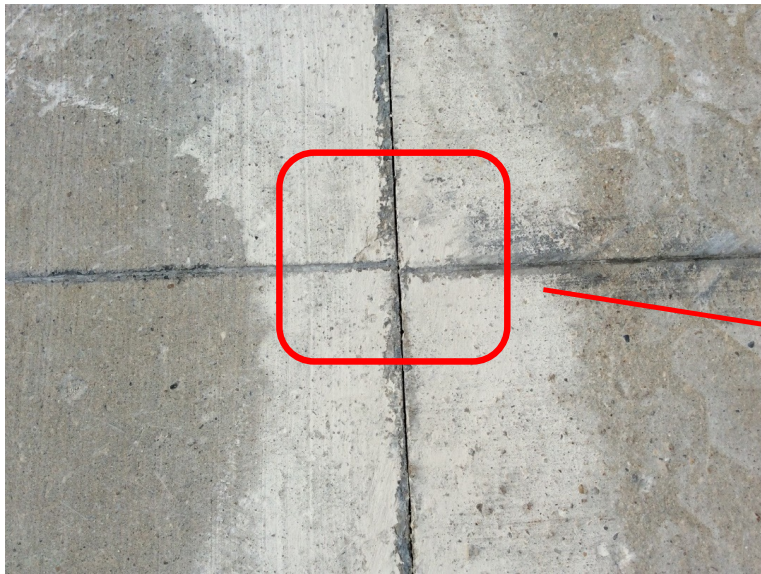
Buildings Move, Buildings Leak

- Case Study 8: Slab Jacking/Plaza Deck Assembly
- Slab volume change →
Restraint at vertical projections →
Distress at vertical surfaces
- Findings were controversial on project 2 –
“It has to be the snow plow impact force!”



Buildings Move, Buildings Leak

- Case Study 8: Slab Jacking/Plaza Deck Assembly
- Horizontal forces in project 1 were significant



Buildings Move, Buildings Leak

- Case Study 8: Slab Jacking/Plaza Deck Assembly
- Full removal & replacement on project 1 ~ \$7,000,000
- Limited removal & repair on project 2 ~ \$3,500,000



Buildings Move, Buildings Leak

- Case Study 8: Slab Jacking/Plaza Deck Assembly
 - Remove assemblies down to structural slab
 - Replace WP layer (215 mil HRA)
 - Rebuild of rest of plaza assembly above
 - Additional drainage layer included above insulation
 - New wear course slabs
 - Much tighter pattern of control joints, ALL SEALED
 - Additional expansion joints
 - Followed by maintenance program recommendations
 - Regular surface sweeping
 - Wash down of decks in spring and fall
 - Regular inspection of construction and control joints

Buildings Move, Buildings Leak

- Case Study 8: Slab Jacking/Plaza Deck Assembly
- Follow up thoughts
 - Insist on drainage layer both above and below insulation
 - Be wary of using single ply or hybrid systems with poured wear slab
 - Protect vertical regions of WP when abutting wear slab
 - Metal flashing
 - Rigid insulation
 - Asphalt impregnated board
 - Dual layer drains and $\frac{1}{4}$ " per foot slope
 - Always insist on a maintenance program!

Buildings Move, Buildings Leak

- Case Study 8:
which loadings were involved?



rain smoke radiation fire
impact snow chemical
air live animals solar
wind birds moisture creep
heat shrinkage dead insects
particulates gravity seismic



Buildings Move, Buildings Leak

- Case Study 8:
which loadings were involved?



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particulates gravity seismic



Buildings Move, Buildings Leak



Buildings Move, Buildings Leak

- Conclusion

that require special attention. Some understanding of the phenomena involved is therefore necessary so that they can be judged quantitatively and wall designs evaluated.

3. Control water vapour flow; ✓
4. Control rain penetration; ✓
5. Control light, solar and other radiation;
6. Control noise;
7. Control fire;
8. Provide strength and rigidity; ✓
9. Be durable;
10. Be aesthetically pleasing;
11. Be economical.

Any such list is a compromise of sequence and coverage and has, inevitably, strong inter-relationships between items so that it is necessary always to consider several of these requirements simultaneously.

Exterior Wall as a Barrier

Items 1 to 7 of the requirements listed relate to the service required of a wall as a selective separator between indoor and outdoor environments. An actual or potential flow of matter or energy is involved. The greater the differences between the inside and outside environments, the greater is the stress or duty imposed on the wall.

Thus, the elements of the wall must be selected so that in the first instance they impart the necessary resistance to keep heat, moisture, air and other flows within acceptable limits. The way they are arranged, however, is also important; this will determine the variations in conditions throughout the wall. These provide the environment in which the various parts of the wall must continue to function, and are seldom linearly graded from outside to inside. Interactions between the various factors involved may produce conditions within the wall

that require special attention. Some understanding of the phenomena involved is therefore necessary so that they can be judged quantitatively and wall designs evaluated.

Over-all Requirements

Items 8 to 11 may be regarded as general or over-all requirements that must be satisfied at the same time as the wall fulfils its basic function as a separator. They may apply to individual elements of the wall as well as to the wall itself, and even to the complete building, of which the wall is only a part.

Durability is an overriding consideration. Taken broadly it can be measured in terms of the time until some loss of function occurs that renders the service provided unacceptable. It is not a fundamental property of a material; it depends on the degrading effects of the service and the environment to which it is exposed. It is more appropriate to refer to service life, as this properly implies the effects of the particular conditions of service.

The environment at any plane in the wall may be determined by the arrangement and selection of the materials used. The designer may, therefore, by judicious arrangement greatly ease the requirements for the various elements and thus broaden his choice. The real importance of durability is reflected in the cost of maintaining all the required functions of the wall over the required service life.

The requirement for *economy* is almost always present. The number of buildings that can be designed without regard for cost are so few that they need not be considered in this discussion. Both initial and operating costs, then, become an important but complex over-all consideration in most designs. The designer may often be required, as part of the design problem, to vary the proportion of anticipated initial to operating costs to suit the economics of a particular venture. Initial costs may be reduced by selecting lower quality components at the expense of increased maintenance or reduced service life, or compromises may be adopted in other directions. Insulation may be reduced at the expense of heating cost or a simpler wall or window arrangement, with some sacrifice in function, may be adopted.

Aesthetic quality can also become a major factor in cost, although this is not always so. Form, colour, texture and pattern can usually be varied over a wide range without affecting other requirements. But insistence upon a particular aesthetic feature or quality may make it difficult to satisfy the service requirements or may force unsatisfactory solutions.

Aesthetic considerations frequently become involved in other ways. For example, inadequacies in design may allow cracks to develop so that water-staining occurs, surfaces spall or

Buildings Move, Buildings Leak

- Conclusion
- Sustained and effective control of heat, air and moisture is not possible if building movement is not considered

BE AWARE – COMMUNICATE - VALIDATE

Buildings Move, Buildings Leak

- Be Aware - Communicate - Validate

- Take a Deeper Dive into Movement!

CBD-48, Requirements for Exterior Walls

CBD-115, Performance of Building Materials

CBD-56, Thermal and Moisture Deformations in Building Materials

CBD-54, Deflections of Horizontal Structural Members

CBD-34, Wind Pressures On Buildings

CBD-119, Volume Change and Creep of Concrete

CBD-97, Look at Joint Performance

CBD-155, Joint Movement and Sealant Selection

CBD-244, Effects of Wood Shrinkage in Buildings

CBD-30, Water and Building Materials

CBD-125, Cladding Problems Due to Frame Movements

...And many other resources that address the topic

Buildings Move, Buildings Leak

- Be Aware - Communicate - Validate
- Get to know a Façade Delegated Design Engineer
 - What matters to them
 - What they look for



Minnesota Department of Public Safety

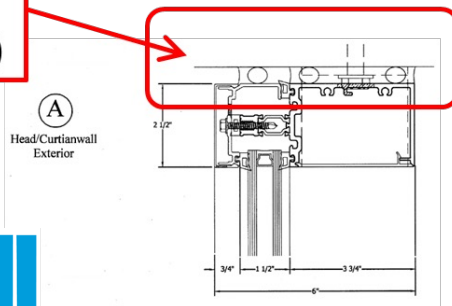
Buildings Move, Buildings Leak

- Be Aware - Communicate - Validate
- Effective performance specifications
 - If design is delegated, the assignee needs enough information to succeed
 - Literal, project-specific magnitudes of movement accommodation
 - Less information shared = less chances that expectations will be met

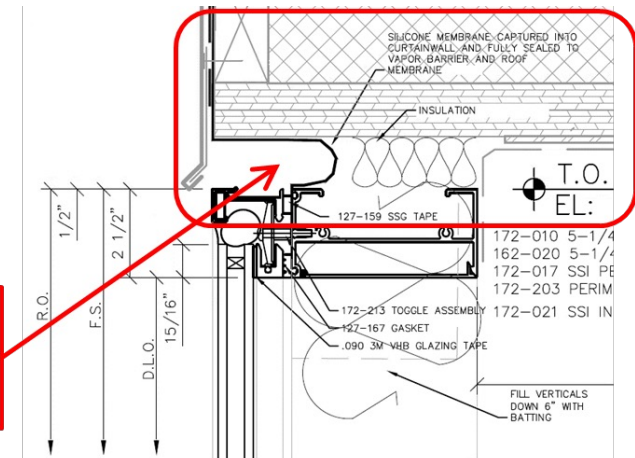
Buildings Move, Buildings Leak

- Be Aware - Communicate - Validate
- Include Movement Information on Field Use Drawings
- Draw beyond the line of “by others”, all the way to the point where the control layer(s) have been successfully handed off to the next trade
 - Common failure point = interface between work performed by different trades

Needs help
(actual detail
from submittal)



Much better, but we still
don't know how much
you think it will move



Buildings Move, Buildings Leak

- Be Aware + Communicate =

**Enclosure Design and Construction
is
a
Relay Event!**

Buildings Move, Buildings Leak

- Design/Construction Performance ➔ Enclosure Performance



AP Photo/Petr David Josek



<https://www.srf.ch/sport/leichtathletik/world-relays-in-yokohama-frauenstaffel-schaft-final-qualifikation>

Buildings Move, Buildings Leak

- Design/Construction Performance → Enclosure Performance

1: Architect

2: Structural Engineer

3: Delegated Design Engineer

4: Installing Subcontractor



Ann Arbor News, Ann Arbor High School Track Relay Team and Coach, 1937

Buildings Move, Buildings Leak

- Design/Construction Performance → Enclosure Performance

Enclosure Consultant ☺

1: Architect

2: Structural Engineer

3: Delegated Design Engineer

4: Installing Subcontractor



Ann Arbor News, Ann Arbor High School Track Relay Team and Coach, 1937

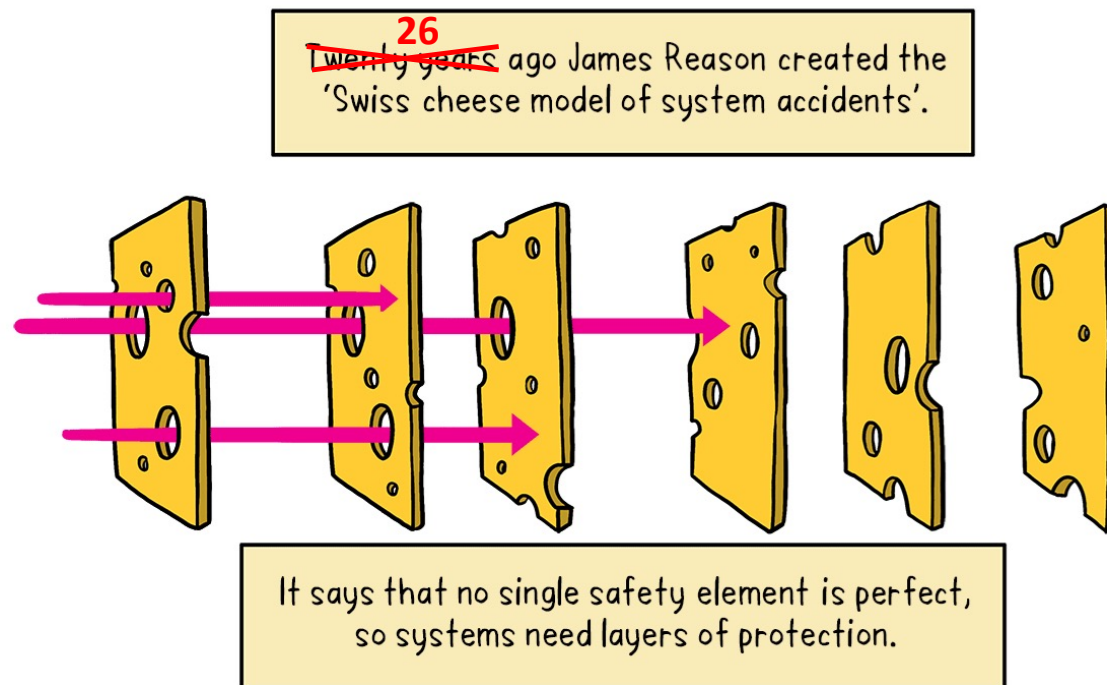
Buildings Move, Buildings Leak

- Be Aware - Communicate - Validate
- Use steps in the documentation and approval process as tollgates
- Don't assume that
“Somebody else will take care of it”



Buildings Move, Buildings Leak

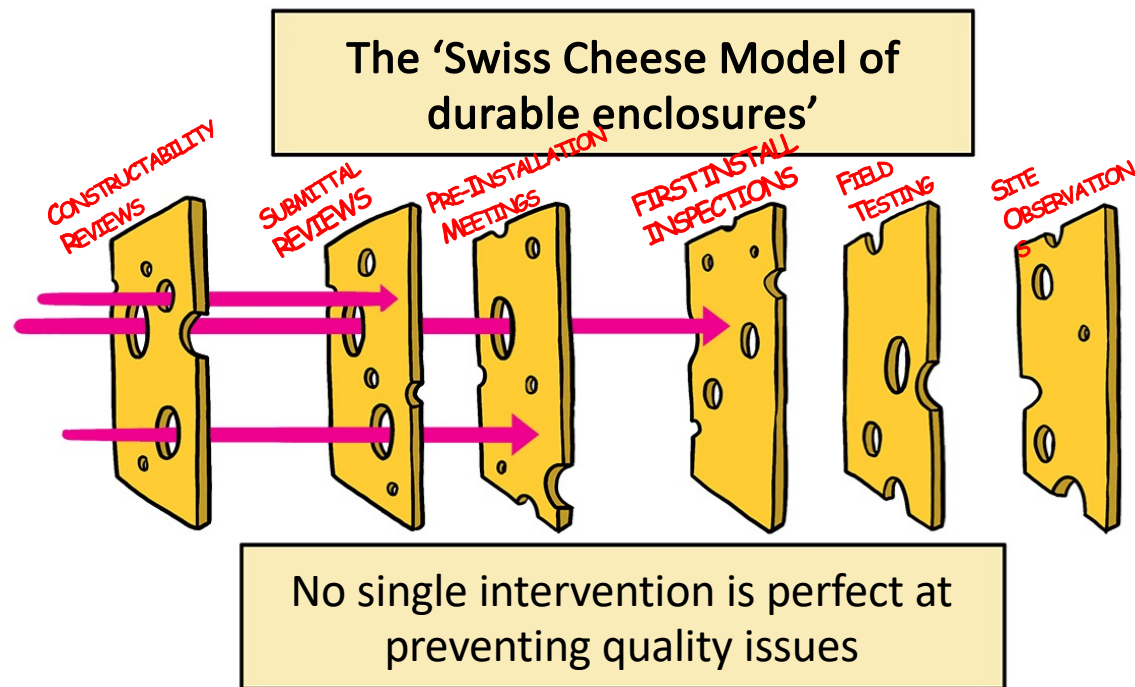
- Be Aware - Communicate - Validate



@SIOUXSIEW @XTOTL thespinoff.co.nz ADAPTED FROM JAMES REASON, IAN MACKAY, SKETCHPLANATIONS CC-BY-SA 4.0

Buildings Move, Buildings Leak

- Be Aware - Communicate - Validate



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Buildings Move, Buildings Leak

- Be Aware - Communicate - Validate
- Building enclosures can be successfully delivered and perform under the movement that they experience – if there is proper commitment from both design and construction professionals

Buildings Move, Buildings Leak

- Questions/Comments/Snorts of Derision?



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