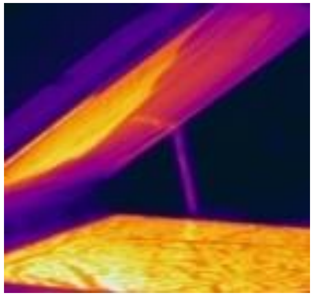
A New Approach for Analysis of Complex Building Envelopes in Whole Building Energy Simulations



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***** Polish Academy of Sciences www.ippt.pan.pl/en/home.html**

Buildings XIII – Thermal Performance of the Exterior Envelope of Whole Buildings Conference
Dec. 8th 2016, Clearwater Beach, FL

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Background & Motivation

- During last half of the century, numerous wall technologies have been introduced. Some of them represent the **complex three-dimensional networks of structural components and thermal insulation**
- Moreover, building structural systems are getting more advanced, and every year variety of new materials are introduced by builders. Consequently, buildings are often becoming unforgiving for design errors or assembly imperfections
- Overall thermal efficiency of a building is a function of the thermal performance of the planar exterior envelope elements (e.g. wall, roofs, windows)
- Large local heat losses, caused by the heat conducting components of the building's envelope, can occur around these planar elements at many different locations. These areas of intense local heat flow, commonly known as thermal shorts or thermal bridges, can have a significant impact on the thermal performance of the building envelope and the overall building energy consumption
- **Thermal bridging and construction details in the building envelope change thermal performance of envelope components. These features have both steady-state as well as dynamic repercussions**
- **Capability for reduction of building thermal loads** and a successful whole-building integration are dependent on the **ability to use either accurate predictions of the building envelope thermal characteristics** or actual test generated data
- **The goal is** to achieve the addition of the **multifunctional and dynamic modeling capabilities** to the THERM and WINDOW tools, which will allow **accurate analysis of complex building envelop components** and convert these components into the one-dimensional (1-D) computational format utilized by EnergyPlus

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Layout

- What to start with? **THERM AND WINDOW FRAMEWORK**
- Basic knowledge (I): **DEFINITION OF THERMAL BRIDGES AND COMMON CONSEQUENCES**
- Basic Knowledge (II): **VARIETY AND COMPLEXITY OF COMMON TYPES OF THERMAL BRIDGES**
  - Thermal bridges generated by building geometry and architectural details.
  - Thermal bridges associated with building materials and structural subsystems
  - Construction thermal bridges
  - Hybrid thermal bridges
- **MAJOR ACCURACY CHALLENGES ASSOCIATED WITH THERMAL BRIDGE ANALYSIS FOR BUILDINGS CONSTRUCTED WITH USE OF NORTH AMERICAN CONSTRUCTION METHODS**
- **METHODOLOGY FOR THEORETICAL CONVERSIONS OF THREE-DIMENSIONAL THERMAL BRIDGING EFFECTS INTO ONE-DIMENSIONAL EQUIVALENTS**
  - Structure Factors for Multilayer Wall Assemblies
  - Relationships between the Structure Factors and the Response Factors
- **PROCEDURE FOR GENERATION OF THE EQUIVALENT WALL**
- **WHAT NEW FEATURES WILL BE AVAILABLE IN UPGRADED VERSION OF THERM TO ENABLE GENERATION OF THE EQUIVALENT WALL AND INTEGRATION WITH ENERGYPLUS?**
- **SUMMARY**

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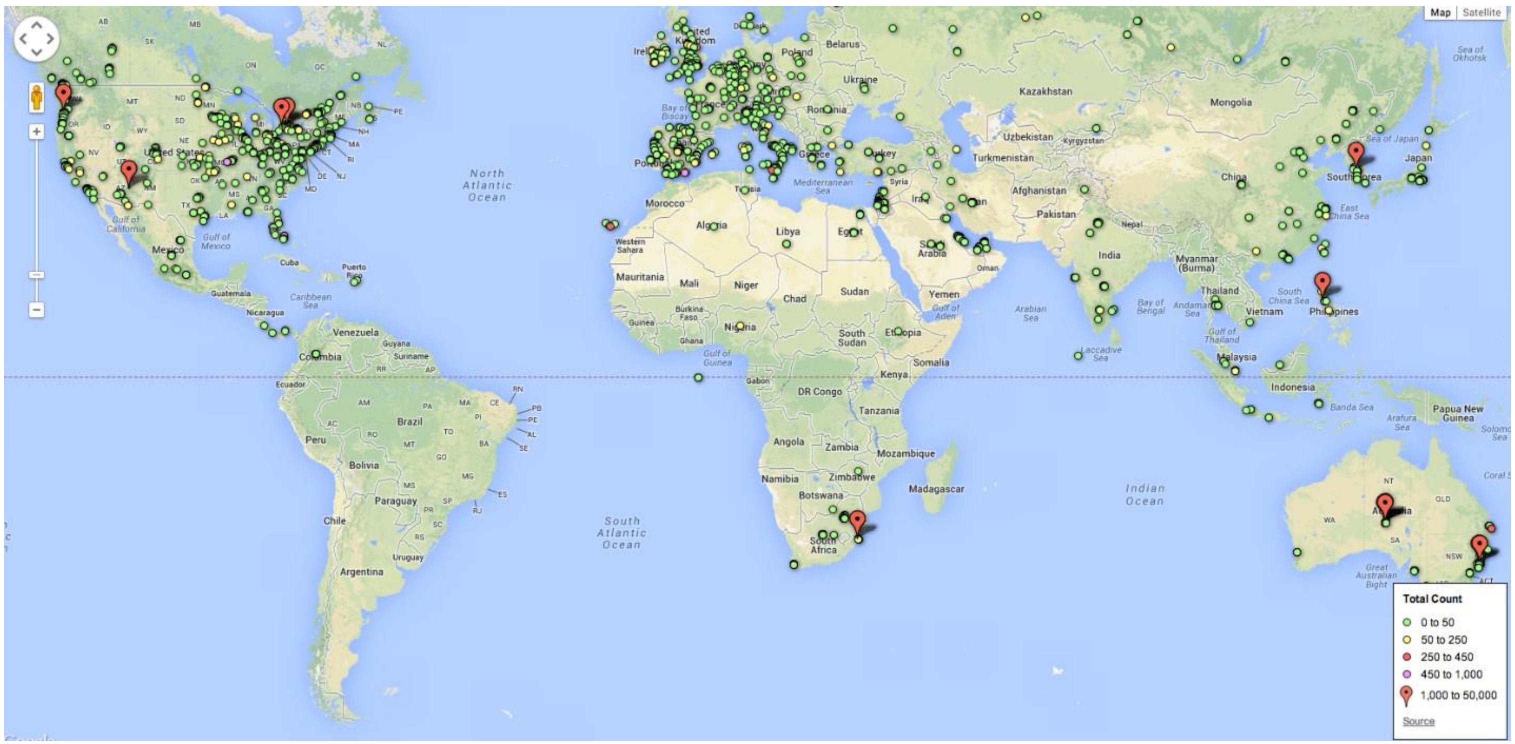
THERM AND WINDOW FRAMEWORK

- **THERM** is a computer program for calculating **two-dimensional (2-D) heat transfer in building components** such as windows, walls, foundations, roofs, and doors as well as other building shell components where thermal bridges are of concern
- THERM is based on the **finite element numerical method** (FEM) and incorporates sophisticated automated meshing and error estimation for rapid model generation and ensuring accurate results
- THERM program has been developed and is maintained by LBNL, with funding from US DOE. Current released version is 7.2 and current version under development is 7.3
- The development of **THERM started in 1992**, with the version 1.0 released in 1995. In addition to English version, there are also Russian and Chinese versions of the program. THERM is used by building component manufacturers, engineers, educators, students, architects, and others, but most prominently it is used as an official tool in National Fenestration Rating Council's (NFRC) fenestration rating and certification
- THERM's heat-transfer analysis allows evaluation of a product's energy efficiency and local temperature patterns, which may relate directly to problems with condensation, moisture damage, and structural integrity
- THERM includes **material database, which contains about 100 building materials**
- THERM has two-way interface to the WINDOW program and allows WINDOW to determine total window product U-factors, Solar Heat Gain Coefficients, Visible Transmittance and Condensation Resistance

THERM AND WINDOW FRAMEWORK

- THERM and WINDOW have large user base, both nationally and internationally
- Latest user and usage statistics show that there are **over 50,000 unique downloads** of the program in the last year and a half with over **1 million starts**



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DEFINITION OF THERMAL BRIDGES AND COMMON CONSEQUENCES

- **Building exterior skin provides a separation** between the interior space and the exterior environment
- This **separation should be as continuous as possible**. This obligation applies specifically to the building thermal insulation as well as to the air and moisture barriers
- **Thermal bridges provide a path of higher heat conduction through the insulation, allowing for more heat to bypass the building thermal barrier.** Considering that in building components exposed to a temperature gradient, heat always travels across any higher conducting element, and taking into account complexity of today's building envelopes, these thermal pathways have often a strong multi-dimensional character
- **Thermal bridges are most often caused by discontinuities in any thermal barrier and are more pronounced when the material creating the bridge is highly conductive**
- From the envelope designer's perspective, **a thermal bridge is an element or location with missing thermal insulation, less insulation, or reduced insulation performance relative to the adjacent areas of the thermal envelope**
- **The intensity of thermal bridge is a function of the local area of the heat flow path and thermal conductivity proportions between neighboring materials**

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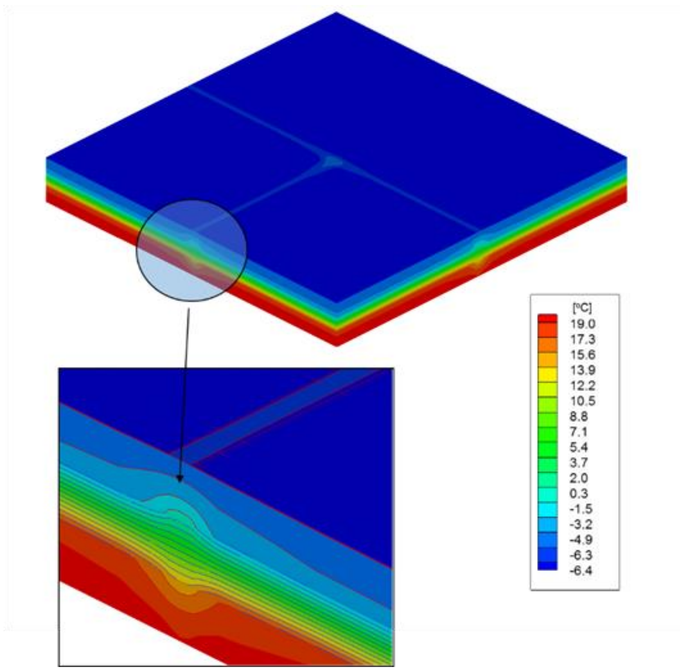
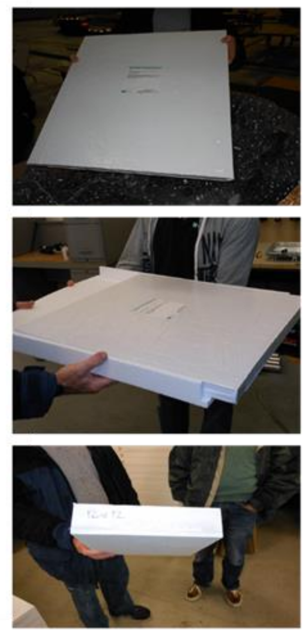
Example: Thermal bridges provide a path of higher heat conduction through the insulation, allowing for more heat to bypass the building thermal barrier

- Even thermal insulation material can generate thermal bridge effect.
- In the case of a significantly less conductive vacuum insulation panel (VIP) packed in to the foam casing. The reason: the plastic foam is about ten times less thermally resistive than the core of the VIP.





VIP panel

VIP panel and plastic foam shell

VIP panel packed in foam

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DEFINITION OF THERMAL BRIDGES AND COMMON CONSEQUENCES

- **Interface details and architectural components** make a difference
- The consequences of **poorly selected connections between envelope components** are severe
- **Interface details can easily impact as much as 50% of the overall elevation area.**
- For some conventional wall systems, the **whole-wall R-value can be as much as 40% less than what is measured for the clear wall section**
- **Local heat losses through some wall interface details may be twice that estimated by simplified design calculation procedures** that focus only on the clear wall, or clear field roof areas
- **Thermal bridging may affect dynamic thermal performance of a building**
- **Poor interface details also may cause excessive moisture condensation and lead to stains and dust markings on the interior and exterior finishes**, which reveal envelope thermal shorts in an unsightly manner
- This moist surface area can encourage the propagation of **molds and mildews**, which can lead to **poor indoor air quality**

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VARIETY AND COMPLEXITY OF COMMON TYPES OF THERMAL BRIDGES

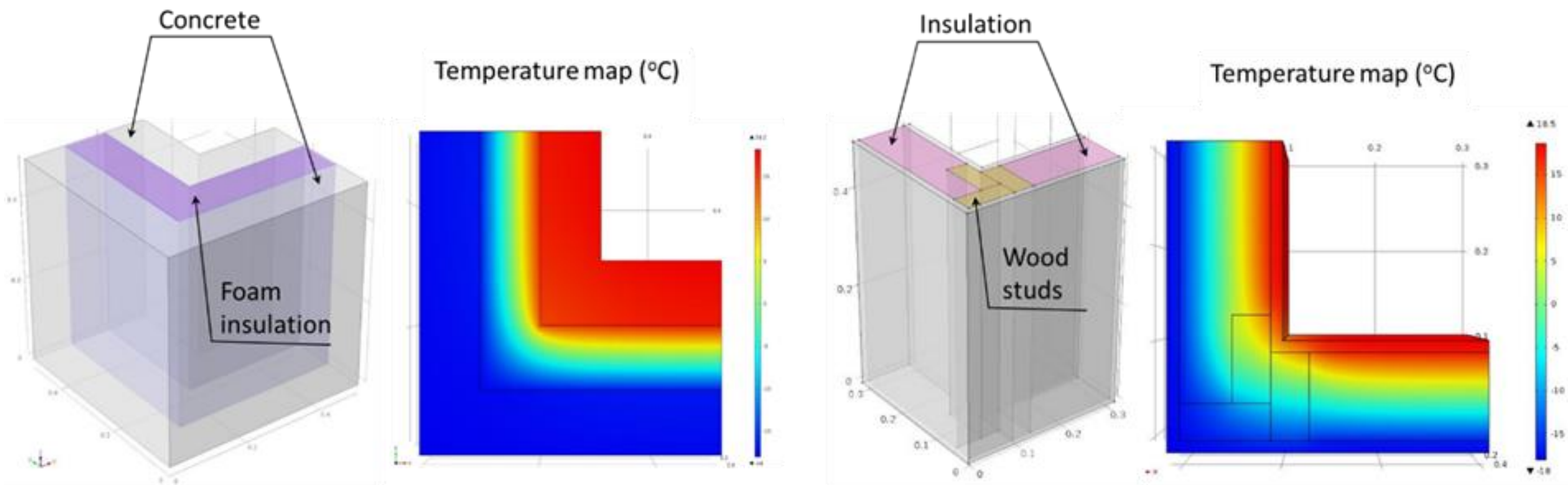
- Building envelopes in North America are usually complex **three dimensional networks of structural and insulation materials**
- In building structures, there are **three very distinct types of thermal bridges**:
  - **Geometric and architectural detail thermal bridges,**
  - **Material and subsystem thermal bridges, and**
  - **Thermal bridges generated by structural components and intersections**
- In addition, there is a group **of hybrid thermal bridges**, representing mixed characteristics of listed above basic types
- Thermal bridges are always **associated with relatively higher conductive building materials** or **elements that penetrate the envelope thermal insulation**, thereby leading to increased heat flow rates

Geometric and architectural detail thermal bridges

- Geometric and architectural thermal bridges are typical to building geometric **details and architectural components** (corners, overhangs, wall/floor, wall/roof, wall/internal partition interfaces, window and door perimeters, etc.)
- In these locations **increased heat flow** across building envelope can be observed
- Component details are high strength, high conductivity element assemblies that serve to hold or connect building structural or architectural components within the envelope (balconies, wall connections with terraces, perimeters of wall openings, window and curtain wall mullions, etc.)
- Geometric thermal bridges do not form literal thermal shorts in the way, for example, construction thermal bridges do
- More intense heat transfer can occur in the areas where nominal insulation thickness and insulation continuity are maintained
- Usually, geometric thermal bridges can be found in **locations where the area of the external building surface is significantly different from the corresponding internal surface area**
- **Geometric thermal bridges are unavoidable**. However, the energy impact of geometric thermal bridging generally increases with the complexity of the building form

Geometric and architectural detail thermal bridges

- Best identifiable geometric thermal bridge effects refer to constructions at corners which accentuate two-dimensional heat flow paths that exist at corners



Concrete-Foam-Concrete Sandwich Corner

Three Stud Corner

Example temperature map for the concrete-foam-concrete sandwich corner and thermal insulation discontinuity in the corner configuration using wood studs.

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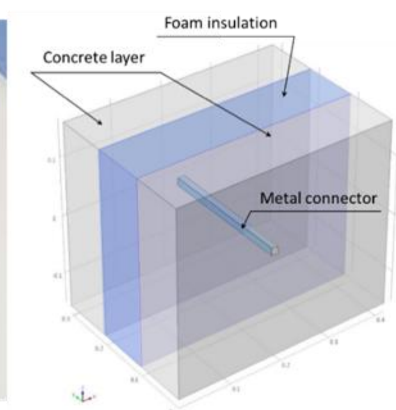
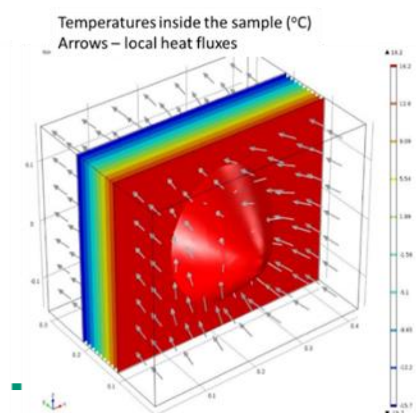
Thermal bridges associated with building materials and structural subsystems

- Construction thermal bridges are **highly localized and repetitive** along the length of the structure
- In high performance buildings, using very often in thick foam insulation applications (high R-value walls or roofs), the foam sheathing is connected with the structural substrate with relatively thick metal connectors
- Beyond their high prices, these connectors often seriously compromise the overall system thermal and hygrothermal performance
- Metal connectors in concrete sandwich panels (two layers of concrete divided by a layer of foam) are a good example of such thermal bridges

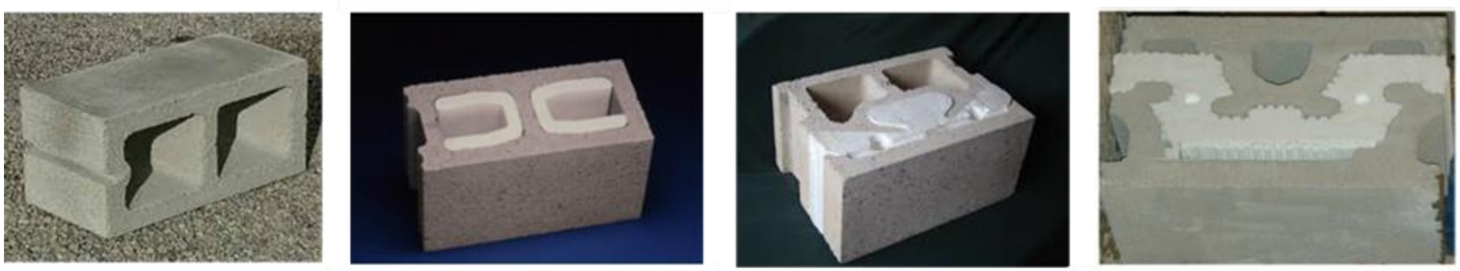




Thermal bridges associated with building materials and structural subsystems

- A different illustration of these kind of thermal bridges can be found in concrete masonry blocks
- Concrete masonry units have different designs of a central core area. However, they usually have two or three **concrete webs joining the external and internal concrete skins**
- In situations where the interior of the concrete block is either empty or filled with thermal insulation, these webs generate thermal bridge effects. In some cases, thermal bridge effect can be minimized by an application of the interlocking insulation inserts using a continuous layer of foam

Concrete webs connect both sides of CMU — Opposite sides of CMU are not connected by concrete webs



Uninsulated CMU — Insulated CMU – still concrete webs act as thermal bridges — Insulated CMUs with continues layer of thermal insulation

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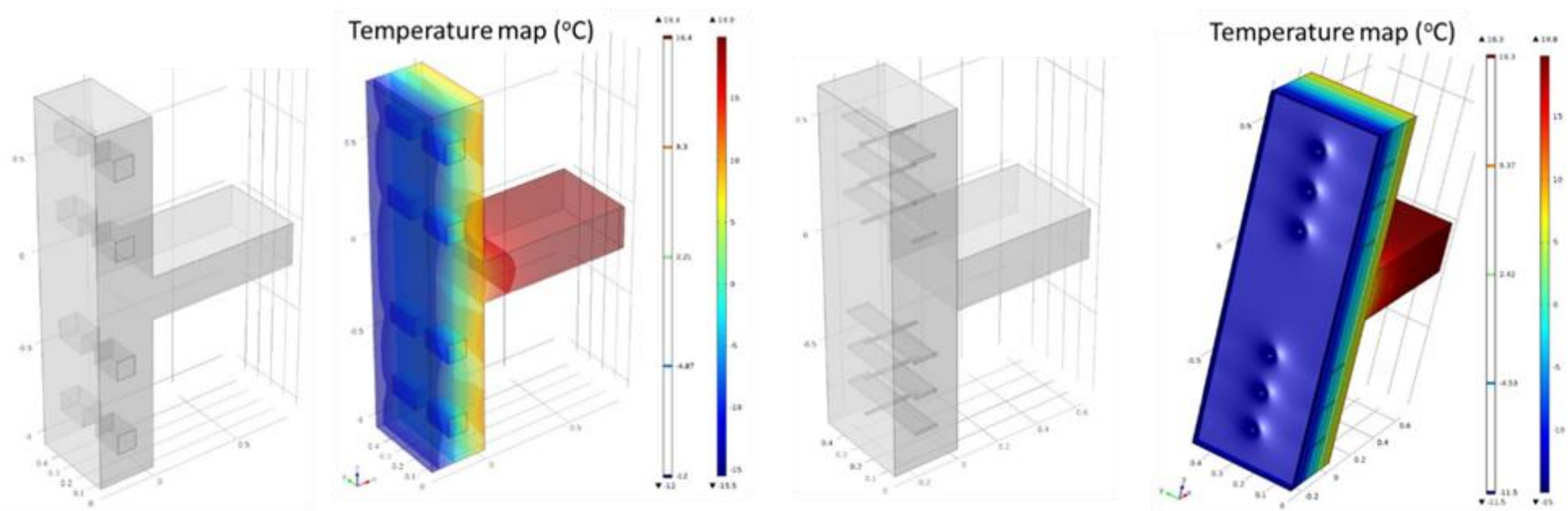
Construction thermal bridges

- Construction thermal bridges are perhaps the **largest and most commonly seen in buildings**
- Construction thermal bridging is usually **associated with the existence of structural components** combined with discontinuities in thermal insulation
- Configurations of construction thermal bridge are not only the **easiest type to recognize in real buildings**, but also relatively easy to comprehend
- Construction thermal bridges are relatively easy to mitigate through corrections in design
- Construction thermal bridges can be easily identified in places where highly conducting components are passing through the exterior thermal insulation barrier
- Very often construction thermal bridges are point thermal bridges
- The concrete floor slab don't penetrate the vertical wall insulation are also considered as construction thermal bridges

Construction thermal bridges

- The floor-wall connections are often the site of significant thermal bridging when the metal floor joists or concrete floor slabs pass through the wall insulation layer

Concrete Sandwich Wall – Floor Intersection with Core Foam Insulation



Concrete connectors

Metal tie connectors

Concrete-Foam-Concrete Sandwich; 0.12-m./0.12-m./0.12-m. (4-in./4-in./4-in.)

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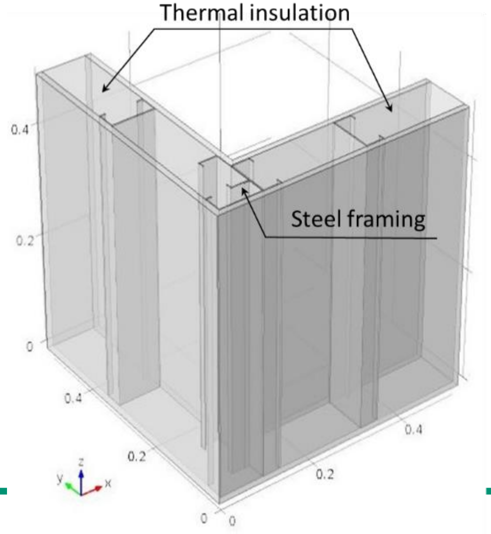
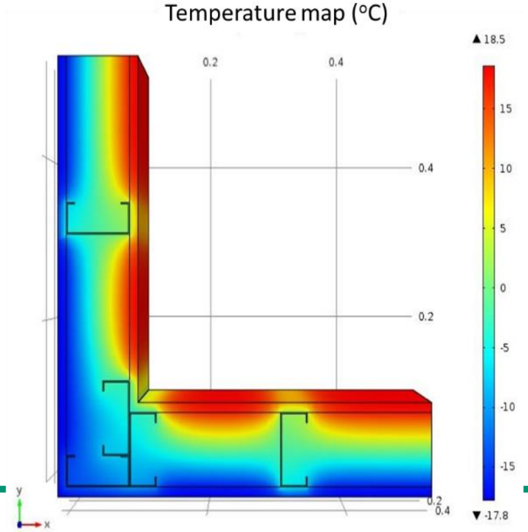
Hybrid thermal bridges

- Hybrid thermal bridges **combined features of different types of thermal bridges**. In many cases, geometric thermal bridges also include an element of construction thermal bridging. For example, an external wall corner while being a geometric thermal bridge will also tend to have additional structure creating construction thermal bridging
- Very good examples of combined thermal bridges are corners with highly conducting metal studs. In this case, increased heat flow through this architectural detail is caused by the intense heat transfer through the metal studs, as well as by the corner shape effect (different heat exchange areas on the interior and exterior surfaces)





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MAJOR ACCURACY CHALLENGES ASSOCIATED WITH THERMAL BRIDGE ANALYSIS FOR BUILDINGS CONSTRUCTED WITH USE OF NORTH AMERICAN CONSTRUCTION METHODS

Opening Topics:

- **Variety of thermal and whole building energy tools** are used today in North America for determining the local thermal performance as well as the overall energy efficiency of buildings
- The energy efficiency for the building enclosure is typically based on individual R-values, or U-factors of various building envelope components. The **effects of thermal bridges are approximated** in these calculations
- Currently available whole building energy tools do not always accurately reflects thermal performance of envelope interface configurations, such as for example window-to-wall, wall to partition, wall to foundation, wall to roof, interfaces, etc…
- It is even more difficult to consider thermal bridges formed by steel framing
- In these cases, **two and three-dimensional heat transfer software needs to be used** to better determine local R-values; the overall energy analysis can then be carefully modified to better consider these effects

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Existing Standards:

- In 2013, the ASHRAE HoF introduced the **Linear Thermal Transmittance Method** (LTTM), which has been used in Europe since 2007 - see ISO 14683:2007. It contains specifications for developing thermal models of thermal bridges and for determination of heat losses and minimum surface temperatures
- In the LTTM, the thermal effect of this thermal bridge is characterized by its **linear thermal transmittance, which is expressed by the Ψ-value** [W/mK]. The Ψ-value represents the additional heat flow through the area of the linear thermal bridge, which is above the heat flow for the adjacent, thermally undisturbed area
- Two types of thermal bridges are specified: **linear and point thermal bridges**
  - A linear thermal bridge is one with a uniform cross-section along one of the three orthogonal axes (see: ISO, 10211:2007). This type of thermal bridges is most commonly found in architectural intersections and structural junctions
  - Example of point thermal bridges, can be visualized by a metal fastener penetrating an envelope assembly, shelf angles, slab edges, balconies, etc…

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Key LTTM Assumption which doesn't Work for North American Construction Methods:

- The LTTM was **developed in Europe with consideration to major European construction methods** (great majority of European buildings are using concrete or masonry technologies)
- Theoretical base for the LTTM is the **assumption that thermal effects generated by adjacent thermal bridges do not overlap each other** (see: ISO, 10211:2007 and ASHRAE HOF 2013
- The above leads to the **assumption of 1-m. or 3-ft thermal zone of influence for thermal bridges**. This theoretical assumption is difficult to justify for the North American buildings, - often built with **very dense highly conductive framing and busy elevations**

MAJOR ACCURACY CHALLENGES ASSOCIATED WITH THERMAL BRIDGE ANALYSIS FOR BUILDINGS CONSTRUCTED WITH USE OF NORTH AMERICAN CONSTRUCTION METHODS

Key Question:

- **How it can be assumed that typical North American construction details do not thermally interfere with each other???**
- Let's consider that for **example of the thermal zone of influence generated by the window header** as 1-m. (40-in.), and that the range of the located above **wall/floor intersection** is also 1-m. (40-in.), the **edges of these two details will have to be spaced by min. 2-m. (over 6-ft.), to follow the earlier theoretical assumption**

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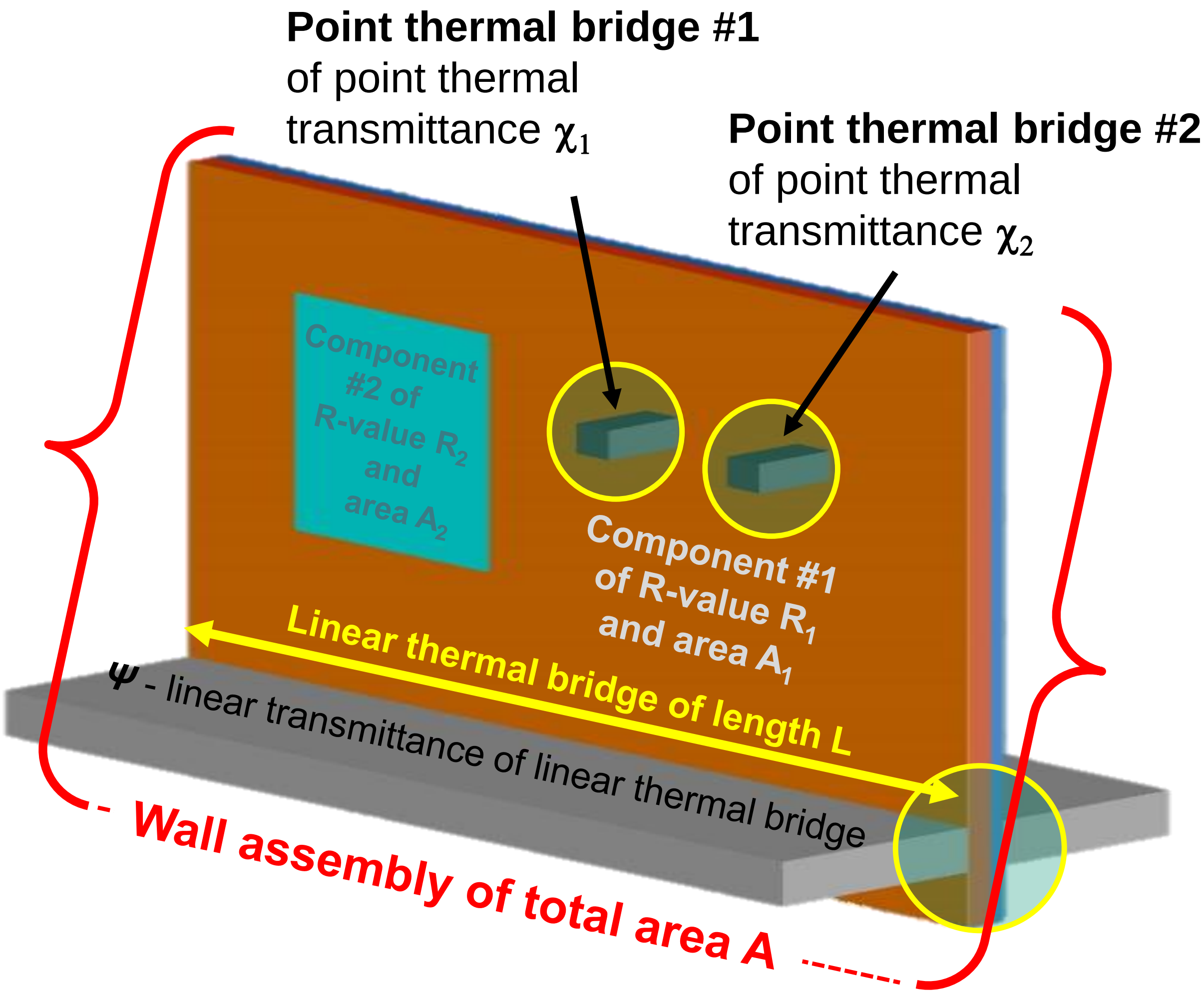
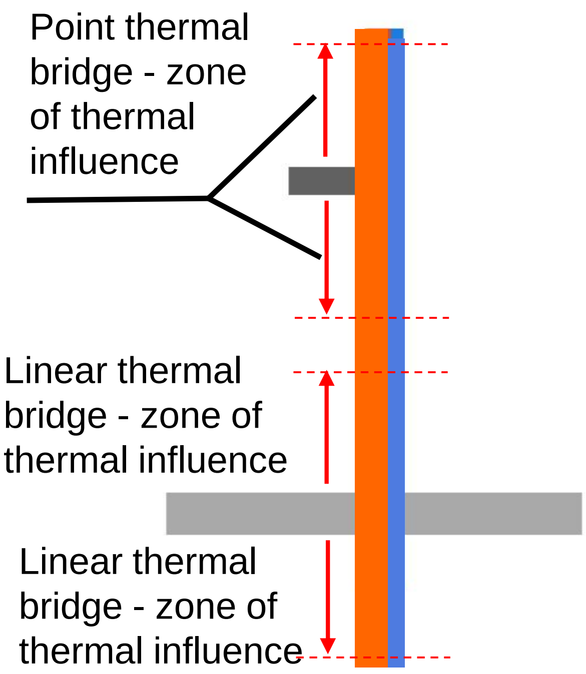
LTTM Illustration:



$$H = \frac{A_1}{R_1} \quad \frac{A_2}{R_2} + L\Psi + \chi_1 + \chi_2$$

$$R_{overall} = \frac{A}{\frac{A_1}{R_1} + \frac{A_2}{R_2} + L\Psi + \chi_1 + \chi_2}$$



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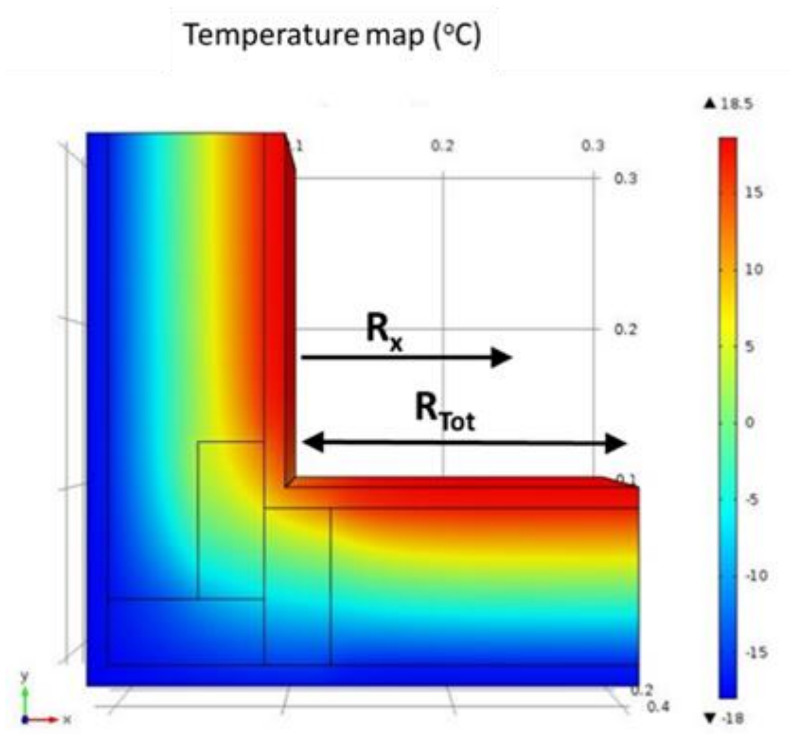
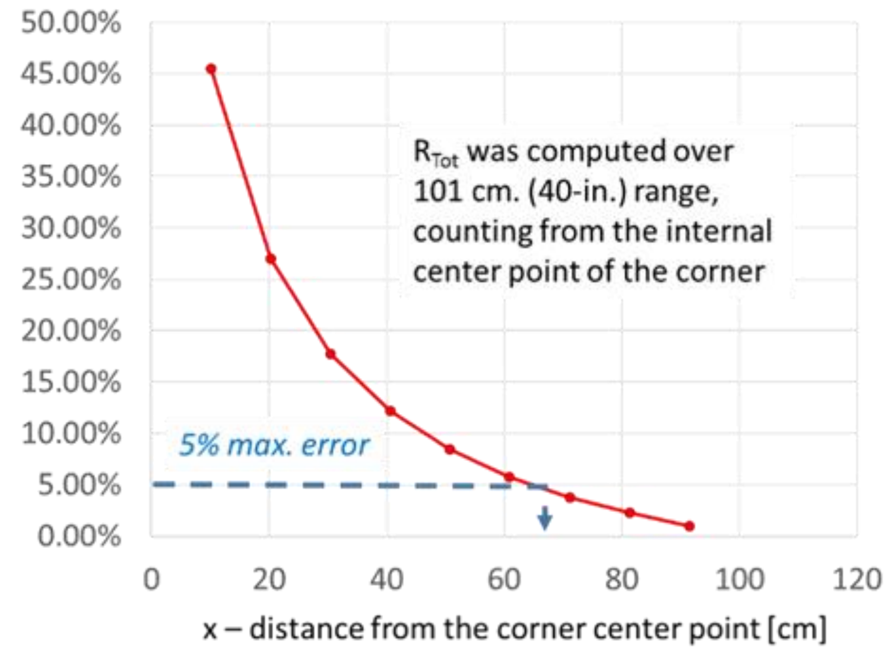
Methodology Used for Estimation of the Detail Zone of Thermal Influence?



$$Error\ \% = \frac{(R_{Tot} - R_x)}{R_{Tot}} * 100\%$$



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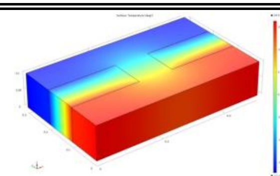
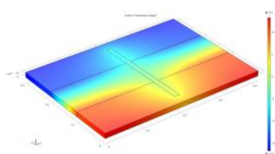
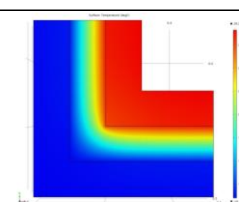
Is It a Real Accuracy Problem?

Summary of the results of finite difference thermal simulations, performed on concrete-foam-concrete sandwich technology for simple point and linear thermal ridges.

Type of Envelope Technology	Structural detail	Simulated Temperature Map	Target max. error in R-value estimates	Range of the Zone of Thermal Influence [m]-[in]
Concrete-Foam-Concrete Sandwich	**Concrete Bridge**		20%	0.61 - 24
0.12-m./0.12-m./0.12-m	0.12x0.12-m.		10 %	0.79 - 31
4-in./4-in./4-in.	4x4-in.		5 %	0.89 - 35
	Steel tie		20%	0.36 – 14
As above	l=0.25-m.; d=10-mm.		10 %	0.56 – 22
	l=10-in.; d=0.4-in.		5 %	0.74 - 29
	Corner		20%	0.30 – 12
As above	Interior surface calc.		10 %	0.51 – 20
	No connectors		5 %	0.71 – 28

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METHODOLOGY FOR THEORETICAL CONVERSIONS OF THREE-DIMENSIONAL THERMAL BRIDGING EFFECTS INTO ONE-DIMENSIONAL EQUIVALENTS

- Imperfections in the envelope do not only impact the **overall thermal resistance**, but also modify its **dynamic characteristics**. To take this into account, one should consider **general conditions between the structural and dynamic thermal characteristics** of an object
- Such conditions follow from the examination of the **integral formulas for the heat flow across the surfaces** of the separated wall element due to the temperature difference on its both sides - see ASHRAE RP1145 [2001]. **These formulas express the role of the heat storage effects in heat flow through an element**
- They lead to the notion of structure factors, **the dimensionless quantities representing the fractions of heat stored in its volume**, in transition between two different states of steady heat flow, which are transferred across each of its surfaces
- **These quantities (called thermal structure factors), together with total transmittance and capacity, are the basic thermal characteristics of a structure**
- But, in a three-dimensional case, through formal analogy with the case of a one-dimensional plane wall (Carslaw & Jaeger [1959]; Clarke [1985]), structure factors are not determined directly by the capacity and resistance distribution in its volume; to calculate them effectively, one has to solve the steady-state heat transfer problem

Structure Factors for Multilayer Wall Assemblies

- **The thermal structure of a wall is understood to be the thermal resistance and capacity distribution in its volume** – Kossecka & Kosny [1999]
- **Thermal structure factors represent, together with the total thermal resistance and heat capacity, the basic thermal characteristics of walls.** Thermal structure factors have their counterparts in structures where three-dimensional heat transfer
- Structure factors for a wall composed of *n* plane homogeneous layers, numbered from 1 to *n* with layer 1 at the interior surface are given as follows:

$$\varphi_{ii} = \frac{1}{R_T^2 C} \sum_{m=1}^{n} C_m \left[\frac{R_m^2}{3} + R_m R_{m-e} + R_{m-e}^2 \right]$$

$$\varphi_{ie} = \frac{1}{R_T^2 C} \sum_{m=1}^{n} C_m \left[-\frac{R_m^2}{3} + \frac{R_m R_T}{2} + R_{i-m} R_{m-e} \right]$$

$$\varphi_{ee} = \frac{1}{R_T^2 C} \sum_{m=1}^{n} C_m \left[\frac{R_m^2}{3} + R_m R_{i-m} + R_{i-m}^2 \right]$$

Where: *Rm and Cm denote the thermal resistance and capacity of the m-th layer respectively, whereas Ri-m and Rm-e denote the resistances for heat transfer from surfaces of the m-th layer to inner and outer surroundings, respectively.*
Also: $0 < \varphi_{ii} < 1$, $0 < \varphi_{ee} < 1$.

- The structure factor φ_{ii} is comparatively large when most of the total thermal capacity is located near the interior surface $x = 0$ and most of the insulating materials (resistances) reside in the outer part of the wall, located near the surface $x = L$. The opposite statement holds for φ_{ee}
- Structure factor φ_{ie} is comparatively large if most of the thermal mass is located in the center of the wall and the resistance is symmetrically distributed on both sides of it

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Relationships between Structure Factors and Response Factors

- The products of structure factors and heat capacity are also identified in the **ISO Standard 9869** [1994]. Quantities $C\varphi_{ii}$, $C\varphi_{ie}$ and $C\varphi_{ee}$, determine the role of storage effects in transitions between different states of steady heat flow, affect particular modes of dynamic heat flux responses of a wall
- Quantities $C\varphi_{ii}$, $C\varphi_{ie}$ and $C\varphi_{ee}$ appear in the constraint conditions on dynamic thermal characteristics of walls such as the response factors, z-transfer function coefficients and also residues and poles of the Laplace Transfer Functions – see: Clarke [1985]; Kossecka [1992, 1996]
- Relationships between the response factors $X(m\delta)$, $Y(m\delta)$, $Z(m\delta)$ and structure factors φ_{ii}, φ_{ie}, φ_{ee} have the following form:

$$\delta \sum_{n=1}^{\infty} n\,X(n\delta) = -C\varphi_{ii}$$

$$\delta \sum_{n=1}^{\infty} nY(n\delta) = C\varphi_{ie}$$

$$\delta \sum_{n=1}^{\infty} n\,Z(n\delta) = -C\varphi_{ee}$$

- Similar conditions are satisfied by the response factors for wall elements of complex structure, in which three-dimensional heat flow occurs – Kossecka & Kośny [1999]

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Layout

- What to start with? **THERM AND WINDOW FRAMEWORK**
- Basic knowledge (I): **DEFINITION OF THERMAL BRIDGES AND COMMON CONSEQUENCES**
- Basic Knowledge (II): **VARIETY AND COMPLEXITY OF COMMON TYPES OF THERMAL BRIDGES**
  - Thermal bridges generated by building geometry and architectural details.
  - Thermal bridges associated with building materials and structural subsystems
  - Construction thermal bridges
  - Hybrid thermal bridges
- **MAJOR ACCURACY CHALLENGES ASSOCIATED WITH THERMAL BRIDGE ANALYSIS FOR BUILDINGS CONSTRUCTED WITH USE OF NORTH AMERICAN CONSTRUCTION METHODS**
- **METHODOLOGY FOR THEORETICAL CONVERSIONS OF THREE-DIMENSIONAL THERMAL BRIDGING EFFECTS INTO ONE-DIMENSIONAL EQUIVALENTS**
  - Structure Factors for Multilayer Wall Assemblies
  - Relationships between the Structure Factors and the Response Factors
- **PROCEDURE FOR GENERATION OF THE EQUIVALENT WALL**
- **WHAT NEW FEATURES WILL BE AVAILABLE IN UPGRADED VERSION OF THERM TO ENABLE GENERATION OF THE EQUIVALENT WALL AND INTEGRATION WITH ENERGYPLUS?**
- **SUMMARY**

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PROCEDURE FOR GENERATION OF THE EQUIVALENT WALL

- Procedure of numerical generation of the equivalent wall is based on **distribution of thermally massive and heat resistive components across the cross section of the wall assembly**
- **There are several ways the equivalent wall technique may generate a one-dimensional *n*-layer structure with similar dynamic thermal properties as the actual wall**
  - At first, a real 3-D or 2-D structure needs to be simulated to generate steady-state and transient thermal characteristics
  - Next, as described in earlier slides, a simplified, multilayer, 1-D model of the wall can be generated using the "*Equivalent Wall Theory*" – see; Kossecka & Kośny [1999]
- In general, the number of layers in the equivalent wall should be three or more
- However, three-layer structures are the simplest way of achieving a model that gives relatively accurate 1-D approximations
- **Many equivalent 1-D wall models can be obtained in this way for the same original 3-D wall assembly**
- Performance of the generated equivalent wall can be validated thru comparisons with the original 3-D structure. Response factors can be utilized for this purpose
- **This methodology was validated during the ASHRAE RP 1145 project**

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NEW FEATURES WILL BE AVAILABLE IN UPGRADED VERSION OF THERM TO ENABLE GENERATION OF THE EQUIVALENT WALL AND INTEGRATION WITH ENERGYPLUS

- We anticipate that, the development effort will include the following:
  - User-friendly interface GUI elements from modifications in THERM
  - Addition of time domain to the THERM's Finite Element Method numerical simulation engine
  - Modifications to the THERM's error estimator and automated mesh refinement
  - GUI modifications in WINDOW
  - An addition of opaque envelope configurator in WINDOW (Addition of R-value and U-value generator for the clear-wall-scale building envelopes and for architectural details)
  - Development of R-value, U-value report generator for design work and code approvals
  - Addition of the Equivalent Dynamic Performance calculation engine for E+
  - Upgrade of file format to xml based format. THERM already includes partial implementation of xml file format (.thmx), so this upgrade would complete full implementation of thermal model and equivalent dynamic performance calculation
  - Upgrade of CAD import functionality. Current CAD import in THERM includes DXF and bitmap trace-over functionality
- **Subject to availability of the program development funding**

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SUMMARY

- **With the initial DOE BTO funding, the preliminary effort was initiated** on upgrading the numerical capabilities of the THERM framework, to allow accurate simulations of complex building envelope assemblies
- The main objective of the described above project is to **extend analytical capabilities of EnergyPlus from simple one-dimensional geometries, to complex multi-dimensional features** commonly found in modern, highly efficient building envelopes
- This goal will be achieved by an addition of the multifunctional and dynamic modeling capabilities to the THERM tool, which will allow to **accurately analyze complex building envelop components** and **convert them into the one-dimensional computational format utilized by EnergyPlus**
- This work will utilize, developed almost two decades ago, and validated by ASHRAE, the **Equivalent Wall Methodology**
- The new upgraded THERM framework will not only allow detailed steady-state thermal evaluations of building envelope components (R-value and U-value computations – required for designing and code approval purposes), but it will also allow an accurate dynamic thermal simulations, supporting energy analysis and optimization of complex building envelopes and whole buildings

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THANK
YOU