# EXPLORATION AND MINIMIZATION OF THERMAL BRIDGING DUE TO EXTERIOR ARCHITECTURAL COMPONENTS AND ANALYSIS OF ALTERNATIVE FAÇADE INSTALLATION METHODS

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# ABSTRACT

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ASHRAE 90.1 defines thermal bridging as an element that has higher thermal conductivity than the surrounding materials, which creates a path of least resistance for heat transfer. Thermal bridging commonly occurs in building envelope design and can directly impact a building’s energy usage, yet it often remains an overlooked and misunderstood concept in practice. An evaluation of existing resources and current practice methods has demonstrated that there is still room for improvement regarding considerations of thermal bridging impact. Current information is largely fragmented in terms of specific material use or usage type. This report provides a critical literature review for better understanding of how engineers can achieve more efficient thermal performance design through a comprehensive understanding of thermal bridging in terms of impact, measurement, and mitigation. This critical literature review is structured into three subsections corresponding to three common façade construction types, those being masonry veneer cladding, cantilever balcony slabs, and steel curtain walls.

# 1. Introduction

Thermal bridging poses both structural and thermal performance problems for building façade elements, thus limiting the lifespan and increasing the environmental impact of the building in many cases. ASHRAE 90.1 defines thermal bridging as an element that has higher thermal conductivity than the surrounding materials, which creates a path of least resistance for heat transfer. Thermal bridging commonly occurs in building envelope design and can directly impact a building's energy usage, yet it often remains an overlooked and misunderstood concept in practice. Today, reducing total building energy usage is a top priority for designers, and understanding the potential benefits of mitigating thermal bridging is one way to help achieve this (D'Aloisio et al., 2012).

## *1.1 Background and Motivation*

According to the International Energy Agency's latest report on building energy usage, operations of buildings account for 27% of global $CO_2$ emissions, 19% of which is an indirect result from the production of electricity and heat used in buildings. Despite the rising popularity of "green" building designs and increased stringency of minimum performance standards for buildings to address the urgency of climate change, the significant role of buildings in global energy usage and related $CO_2$ emissions has yet to sustain any reduction. From 2019 to 2020, the contribution of building operations to global energy usage decreased, largely due to COVID-19 restrictions, but has since increased and surpassed the amount it had been in 2019 by 2% (IEA, 2022).

In 2021, it was reported that electricity accounts for about 35% of building energy usage, and fossil fuels, the leading source of global $CO_2$ emissions, still account for at least 35% of the total energy demand of buildings. In addition to replacing appliances--such as lighting, air conditioning and heating units—with more efficient versions, and opting for energy sources that utilize renewable energy, improving a building's envelope to reduce its overall thermal energy needs is one accessible approach to reducing the building sector's emission contribution (IEA, 2022). Because a building's façade greatly contributes to its energy performance, focusing on its improvement can have a significant impact on its energy usage. Addressing the potential to decrease the operation of heating and cooling units, even by a small percentage, through thermal bridge mitigation, can contribute to the larger pursuit of minimizing overall building energy use and $CO_2$ emissions to combat global climate change.

## *1.2 Thermal Bridging*

All structural framing materials contribute to thermal bridging to some degree, yet structural engineers and designers do not often enough consider the effects of thermal bridging in their analysis and designs (D'Aloisio et al., 2012). Traditionally in the field of construction, structural engineers solely focus on the structural integrity, serviceability, and durability of the building, while working within the economical parameters presented to them. In this way, there is a discretion between which teams are tasked with thermal issues and considerations and those who are free to disregard thermal performance. The understood distribution of work typically leaves thermal analysis to the architect, mechanical engineers, or other subcontractors. Although most thermal performance contributions fall into the focus of these teams, thermal bridging as it relates to structural framing and building envelopes is one element of interest that structural engineers may contribute (D'Aloisio et al., 2012).

The lack of consideration for thermal bridging by structural engineers is not by fault of their own, but rather, the result of misconceptions regarding the level of impact thermal bridging has on overall thermal performance and the lack of broad research on specific detail connection types (D’Aloisio et al., 2012). More recent research has provided us with results demonstrating the larger impact thermal bridging has on a building, creating a sense of urgency to address the issue. Additionally, most sources of thermal bridging result from structural connections, which structural engineers often prefer to source from typically used designs. In these cases, engineers may hesitate to question or replace their previously reliable detail. One might suggest additional components within a connection or new plastic materials to create a thermal break; however, the lack of wide use and testing of such designs may not provide structural engineers with the confidence they require (D’Aloisio et al., 2012).

Aside from this, building owners are increasingly favoring adherence to sustainability and energy conservation design proposals. Programs like Leadership in Energy and Environmental Design (LEED) have risen in popularity and encouraged owners to pursue higher sustainability standards beyond those provided by general building codes (Roppel et al., 2012). However, many specification and code institutions have also begun to follow suit by providing more stringent minimum performance standards. The American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) and International Green Construction Code (IGCC) provide codes for both baseline and high-performance green buildings and have demonstrated efforts to strengthen their standards according to sustainability concerns (D’Aloisio et al., 2012).

For example, energy conservation standards often reference the ASHRAE 90.1 code for minimum energy requirements for a building (Roppel et al., 2012). This document produces tables including maximum U-values for various envelope assemblies and minimum R-values for insulation. The latest version of ASHRAE 90.1 has introduced specifications and requirements for measuring and adjusting for effects of thermal bridges. The code requires that thermal bridges, so long that they fall within a specified criterion, be evaluated in a computer-based simulation program. EnergyPlus and DOE-2 are two programs suggested by the code. ASHRAE 90.1-2022 now also provides tables containing minimum thermal transmittance factors that take into account thermal bridging mitigation and require effective U-factors of assemblies with thermal bridging to be adjusted in accordance with these tables (ASHRAE 90.1).

Lack of adequate understanding of thermal bridging effects is also a result of measurements with inaccuracies or lack of precision. Thermal bridging analysis can be quantified in terms of an assembly's effective R-value, which is the measure of resistance to heat flow, or U-factor, which is the measure of the ability to transfer heat. By quantifying the effective R-value, which is the resulting R-value of an assembly after the inclusion of thermal bridging effects, one can better evaluate the effects of thermal bridging and develop an alternative design specific to the problem at hand (D'Aloisio et al., 2012). Accurately calculating the effective R-values of the building façade may also allow for a proper estimation of total building energy usage and design of a more compatible HVAC system (Roppel et al., 2012).

In the occasion of a thermal bridge, conductive heat flows through a parallel heat path. A parallel heat path is created by the interruption of a material plane by another material with different thermal properties, thus creating a "bridge." A parallel heat path is more complicated to measure in terms of the R-value compared to a series path, in which material planes are simply adjacent to one another (D'Aloisio et al., 2012). Traditionally, engineers calculate the R-value of a parallel heat path using the area-weighted average equation ($R_{effective} = A_{total} / [(A_1 * U_1) + (A_2 * U_2)]$). Though a relevant and useful method, the formula assumes fully effective thermal heat transfer of the entire component, meaning it often overestimates the R-value reduction and should only be used as a supplementary calculation (D'Aloisio et al., 2012).

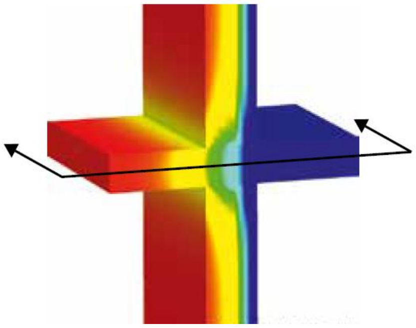


Illustration of linear thermal bridge on linear balcony connection.
Sourced from: Lawton, M. R. P., & Roppel, P. (2014)

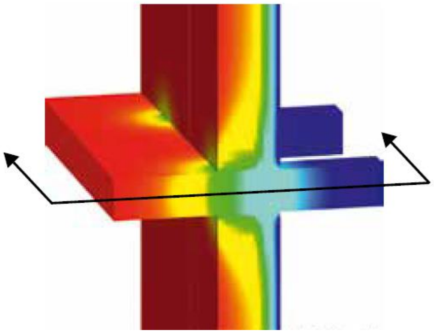


Illustration of point thermal bridge on a punctiform balcony connection.
Sourced from: Lawton, M. R. P., & Roppel, P. (2014)

Physical testing of components and assemblies is one measurement method that does not require modeling. Infrared imaging is one example that utilizes infrared radiation cameras to capture a visual status of heating or cooling energy losses through a building envelope by assessing surface temperatures. However, physical testing such as this is often more suitable for built structures and identifying existing problems, rather than designing for prevention (D’Aloisio et al., 2012).

Thermal analysis models and simulations provide some of the most accurate estimations of effective thermal performance of building envelopes. There are several existing software programs that allow input of a façade section for either 2-dimensional or 3-dimensional thermal simulation (Roppel et al., 2012). These programs have the ability to model components of assembly sections with discrete conditions and thermal properties assigned to specific materials or elements. Typically, designers may model sections with and without the presence of a thermal bridge source to quantify the impact of the thermal bridge on thermal transmittance (D’Aloisio et al., 2012). By implementing these tools into preliminary design of building facades and collecting more accurate data regarding effective R-values or U-values, engineers can be better equipped to both understand the actual effects of thermal bridging and develop more precise mitigation methods.

Thermal bridging can directly impact the amount of operational building energy usage by compromising the intended efficiency of the building envelope insulation and heat transfer resistance. In both heating and cooling conditions, thermal bridging creates points in the envelope through which exterior temperatures may penetrate and influence interior surface temperatures. Colder or warmer interior surfaces cause occupants to experience cooler or warmer indoor temperatures than the actual ambient air temperature. In this way, the utilization of air conditioning or heating units is increased in order to compensate for the interior surface temperature changes and maintain thermal comfort (D'Aloisio et al., 2012). However, because thermal bridges often occupy a small percentage of the exterior wall surface area when considering overall building envelope area, evaluation of potential thermal bridge sources is often overlooked or inaccurately assessed.

In addition to the effects on building energy consumption and greenhouse gas emissions, thermal bridging may also create an environment prone to moisture problems. Particularly in the case of colder climates, when the exterior temperature is colder than the indoor temperature of the building, a thermal bridge is likely to create a chilled interior surface area. When the indoor air is warm and moist, a colder surface temperature that reaches below the internal air dew point will begin to collect condensation. Because building envelopes are often designed without adequate analysis of potential thermal bridging effects, proper condensation resistance in these instances are not installed at many of these intersection components (Roppel et al., 2012).

Lack of moisture control due to thermal bridging can lead to several different problems. The first major problem resulting from moisture is the potential for mold development. Mold thrives in the presence of water (in this case condensation), warmth, a source of food (like paper-faced gypsum board or processed wood), time, and consistency. When these elements are present in combination over a period of time, mold is likely to grow. The addition of insulation also reduces water's ability to drain properly and dry in time to prevent this development. In turn, mold growth within buildings presents the threat of health risks to its occupants if not properly maintained (Lstiburek et al., 2002). In addition to mold, condensation due to thermal bridging may also compromise the intended lifespan of a building by provoking unexpected corrosion of metal elements or decay of wood-based materials within the façade. By mitigating potential thermal bridges, engineers can prevent this patterned source of condensation and thus better preserve the integrity of their buildings (Lawton & Roppel, 2014).

Currently, the problem resides in the under estimation of thermal bridging effects, due to vague criteria for measuring thermal bridging effects within façade assemblies. Additionally, studies that do sufficiently measure and communicate the effects of thermal bridging and propose potential mitigation designs are individualized. These studies seem to typically focus on a particular element of thermal bridging, resulting in a fragmented database that is difficult to navigate for designers, who ideally need a selection of pre-assessed construction details.

By placing an emphasis on accurately modeling and measuring the contributions of thermal bridging in building envelope design, while understanding the full potential effects of thermal bridges, engineers would be better equipped to prevent these discussed consequences. This report intends to clarify an understanding of the impact thermal bridging has on overall building performance and to layout various modeling tools and design procedures used to avoid thermal bridging in building façade systems.

### *1.3 Research Objective*

The overall objective of this project is to synthesize existing research regarding the impact of thermal bridging on building envelope performance, while emphasizing the importance of integrating regular consideration of thermal bridging in building envelope design.

An evaluation of existing resources and current practice methods has demonstrated that there is still room for improvement regarding considerations of thermal bridging impact. Current information is largely fragmented in terms of specific material use or usage type. The intent of this report is to provide a reference for better understanding of how engineers can achieve more efficient thermal performance design through a comprehensive understanding of thermal bridging regarding impact, measurement, and mitigation.

This project consists of a literature review with two main objectives:

1. To discuss previous studies addressing potential thermal bridging mitigation strategies and highlight some of the most successful approaches.
2. To investigate and evaluate common thermal performance modeling techniques and how these can successfully demonstrate the effects of thermal bridging and its mitigation.

This research intends to provide a comprehensive literature review of relevant research to identify and compile a set of effective thermal bridging mitigation strategies. As such, the review provides both potential mitigation options and suggested methods of evaluation for possible new mitigation designs.

## 2. Methodology

To compile relevant research regarding potential thermal bridge mitigation strategies, I performed different selection methods.

Throughout this curation process, I prioritized works that provided and analyzed common thermal bridging sources in the context of common building envelope construction details. For example, masonry cladding envelopes are a long-standing popular building façade type. Masonry walls are typically built within a standard connection practice using a steel shelf angle, which is also a common example of continuous thermal bridging. Several works have been published analyzing this topic and suggest potential mitigation strategies. The intention is to focus on at least three different common building envelope details and look at multiple works addressing the thermal bridging of that specific construction type to evaluate the success of possible alternative designs.

To begin this compilation and selection, I reviewed research documents published by building codes and standards institutions. In this case, I discovered a document published by the American Institute of Steel Construction (AISC) and another by ASHRAE, both of which provided broad investigations of various thermal bridging sources and potential mitigation designs. From these, I was able to extract sources that cited one or both of these documents to identify studies that expanded on a particular detail discussed in the two initial documents. This strategy provided us with a starting point and led us to narrow down our construction types of focus, which are masonry veneer cladding, concrete balconies, and steel curtain walls. These details were selected due to their representation of different structural materials, as well as their popularity in use throughout the construction industry. After preferencing these three construction details, I was able to further search and select sources that targeted one of these topics, provided relatively simple and accessible mitigation strategies for the corresponding detail type, and utilized some form of thermal modeling and analysis tool.

The intention of the literature review of these studies is to identify potential thermal bridge mitigation solutions, as well as common effective approaches to minimizing thermal bridging. Throughout this process I will also identify what common measurement methods and considerations produce a strong argument for a successful thermal bridge mitigation design.

It is necessary to note that this is not an exhaustive compilation or review of existing works regarding thermal bridging. There are a number of existing works that discuss thermal bridging mitigation that are not included in this report. This project is not meant to suggest industry use, but rather provide an understanding of potential areas for improvement that have been suggested to have a significant impact and possible ways to mitigate this. The purpose of this report is to provide a critical literature review, as well as encourage and provide direction for further research and development on the subject.

## 3. Critical Literature Review

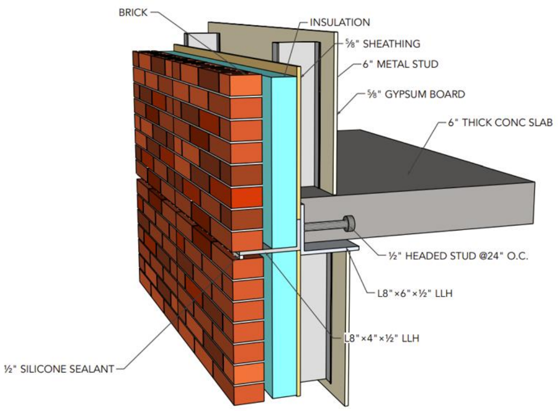
This critical literature review is structured in three subsections corresponding to three common façade construction types, those being masonry veneer cladding, cantilever balcony slabs, and steel curtain walls.

### *3.1 Masonry Veneer Cladding*

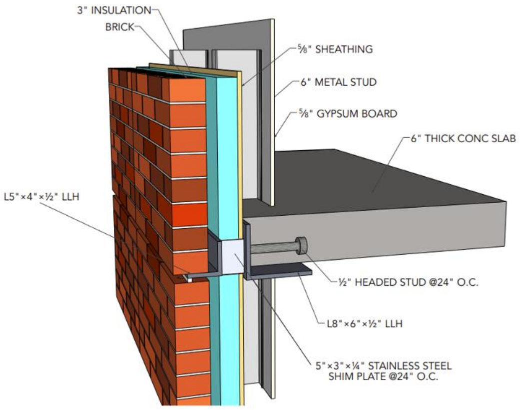
Connecting masonry veneers to a structural backup wall is a widely used building envelope design with relatively standard practice connection design. However, despite this simplicity and practicality, such connection details produce a major source of thermal bridging. In the effort to better comply with thermal performance codes, typical masonry veneer building envelope designs have shifted to including exterior semi-rigid or rigid insulation behind the exterior masonry veneers (Finch et al. 2013). Though a seemingly effective approach to improving the efficiency of the assembly insulation, this placement of exterior insulation encourages an opportunity for components, typically highly conductive metal, that support the load of the masonry veneers to cut through this insulation layer and connect to the structural frame of the building, thus creating a thermal bridge. One example of this is the use of a shelf angle. Traditionally, a shelf angle is used to hold the intended wythe of stacked exterior masonry veneers, spanning the length of the wall assembly. This shelf angle is often directly attached to the concrete or other structural slab of the main building frame. The shelf angle is often a type of steel or other highly conductive metal which can be welded to embedded plates that are cast into the slab edge or bolted with adhesive or expansion anchors (Finch et al., 2013). While the bottom leg of the shelf angle passes through the insulation and connects directly to the slab, heat may bypass the insulation by travelling through this conductive path, thus creating a continuous thermal bridge. Because the shelf angle typically represents less than 0.5% of the wall surface, a designer may intuitively compensate for loss of thermal resistance with a thicker layer of insulation; however, this would require a shelf angle with a longer leg and thus a thicker steel support element, only further increasing the conductivity of the thermal bridge it creates (D’Aloisio et al., 2012)( Finch et al., 2013). The following works reviewed analyze and compare various mitigation approaches that target this paradoxical issue of thermal bridging in masonry veneer walls.

D’Aloisio et al. (2012) presented a brief study in collaboration with the Structural Engineering Institute (SEI) and the AISC Thermal Steel Bridging Task Committee assessing several different common sources of thermal bridging in masonry cladding design. The report reviewed each case and its respective mitigation strategy to determine the level of influence the thermal bridge and mitigation had on the overall energy performance of a prototype building. This prototype building included three stories and a 9000 square foot steel framed masonry clad structure, which was simulated in the context of a predominately cooling location, Phoenix, Arizona, and a predominately heating location, Chicago, Illinois. To analyze these cases, D'Aloisio utilized THERM to create a 2D simulation and generate an average effective U-value of each detail with and without thermal bridge mitigation to apply to the overall building energy consumption simulation in TRACE 700. This measurement strategy allowed them to estimate the average annual heating and cooling savings produced by each outcome in each location.

Detail 3 of this study was concluded to be the most successful mitigation approach, in both its cost effectiveness and improvement on building energy performance. Detail 3 targeted the continuous thermal bridge formed by the shelf angle support design of a typical masonry cladding wall detail. D'Aloisio et al. proposed an improvement by integrating intermittent stainless steel supports (1/4 in. x 3 in. wide vertical knife plates) at 24 inches on center across the insulation plane. The use of stainless steel provides a less conductive path as it has an R-value three times greater than that of typical carbon steel (2012). This alternate design places the continuous shelf angle outside of the insulation, with only the spaced knife plates cutting through the insulation to transfer the loads from the shelf plate to the structural building frame. This approach both minimizes the thermal bridge area through the insulation and provides a less conductive connection path.



Typical detail without mitigation.
Sourced from: D'Aloisio (2012)



Detail incorporating stainless steel knife plate.
Sourced from: D'Aloisio (2012)

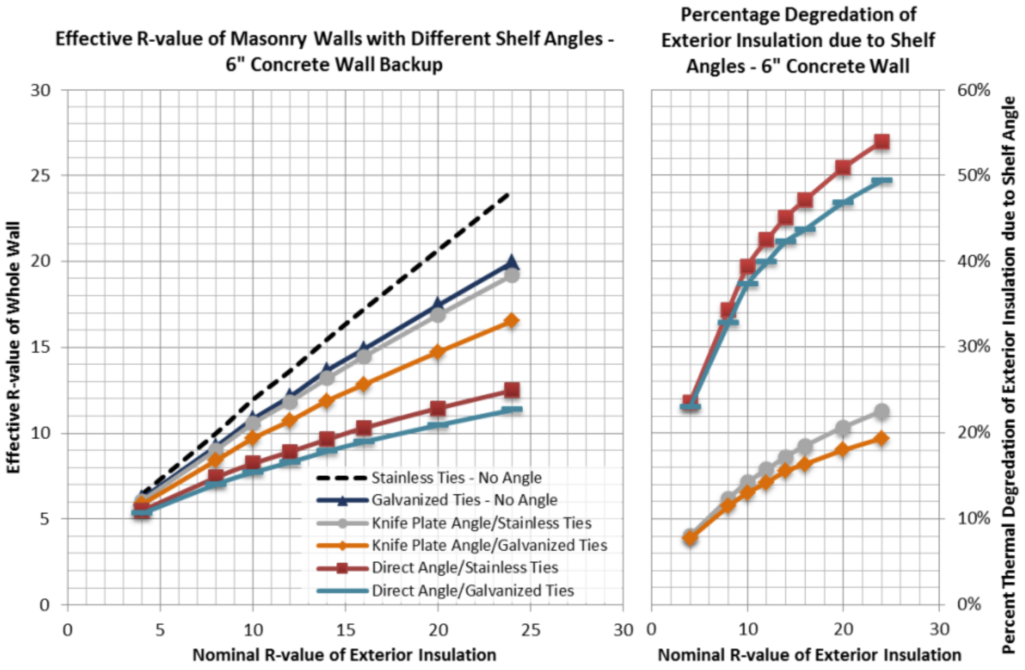
The final results of this detail simulation showed that the total expected cost of construction increases by about 1% due to the four times greater cost of stainless steel compared to that of carbon steel. However, the estimated potential annual energy savings cost increased by about 1.4% which results from the 76% - 77% energy efficiency improvement of the detail due to the integrated knife plates compared to the standard detail. These results show that a fairly simple and accessible adjustment to this standard detail can greatly minimize the degradation of exterior insulation in a masonry veneer wall while also providing a more economical solution.

Finch et al. (2013) presented a study that continues a similar line of thought in its consideration of intermittent plates to break the continuous thermal bridge of the shelf angle; however, this research turns its focus toward the effects of material choice for these conductive point connections. In addition to analyzing the impact of material choice for intermittent knife plates connecting the shelf angle, Finch investigates the material choice of masonry ties that similarly present point sources of thermal bridging. Masonry ties, like shelf angles, are constructed of conductive metals, typically galvanized steel, and are regularly dispersed throughout the brick wythe to maintain stabilization in relation to the backup wall.

This study utilizes HEAT3 to perform a three-dimensional thermal modeling analysis on various types of materials used for ties and shelf angles, as well as varying levels of insulation within the wall assembly and various backup wall construction types. The first series of thermal models compared the effective R-values of details using 2-inch x 16 gauge L-brick ties. Galvanized and stainless steel ties were tested, both as standard components as well as ties with punched holes, with the intent to reduce the area of conductive steel. Additionally, a basalt fiber tie, which has a non-conductive nature, was tested in the case of a concrete backup wall.

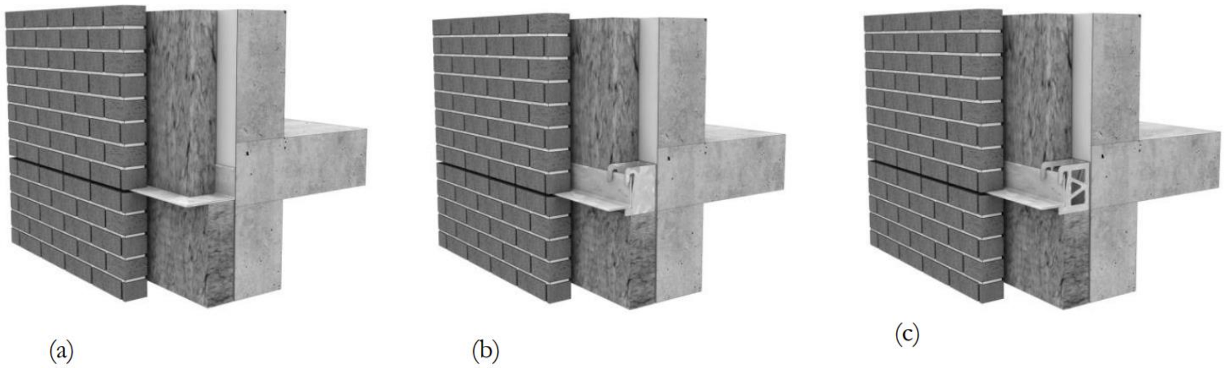
Results for the ties determined that stainless steel clearly reduces the effects of thermal bridging effects on degrading exterior insulation. For stainless steel over a concrete or steel wall, insulation reduces by only 5% - 12%, while galvanized steel reduces insulation efficiency by 15% - 28%. Ties with punched holes further improve upon these results; however, the standard stainless steel tie design remains more effective than a galvanized tie with punched holes.

Finch then goes on to provide a complementary analysis to the masonry tie results by modeling galvanized and stainless steel ties with and without the addition of steel knife plates that place the shelf angle outside of the exterior insulation, resemblant of the design from D'Aloisio et al. (2012). In this case, the addition of knife plates to the shelf angle connection provided a greater reduction of exterior insulation degradation compared to adjustments of masonry tie material. The exterior insulation R-value reduction factors were decreased to a range of 15% - 17% with the knife plates compared to the reduction factors without plates, 40% - 55%. These results further demonstrate the considerable influence a continuous thermal bridge has on the effectiveness of exterior insulation despite its minimal and seemingly negligible occupation of surface area.



Effective R-value of Masonry Wall with alternate shelf angle supports and brick tie combinations.
Sourced from: Finch et al. (2013)

Di Placido et al. (2019) explores this notion regarding shelf angle placement and connection through the investigation and development of a more efficient connection element which improves upon the standard knife plate design. Di Placido produces a shelf angle support mockup to replace the standard knife plate which intermittently cuts through the insulation to connect the exterior shelf angle to the building frame. This element consists of a galvanized steel shelf angle support bracket that is a C-like shape with an inclined slot for anchor bolts and triangular-perforated side walls. The mockup specimen was used for physical thermal testing with an ASTM C177 large-scale guarded hot plate apparatus to produce calibration data for the simulation model. The thermal transmittance simulation included three models—standard shelf angle directly connected to the slab edge, intermittent brackets without the triangular perforations, and intermittent brackets with perforations.



Schematic of (a) direct shelf angle attachment, (b) shelf angle standoff with nonperforated bracket, and (c) shelf angle standoff with perforated bracket.
Sourced from: Di Placido et al. (2019)

Results provided that the directly attached shelf angle degraded the effective R-value of the insulation by almost 50%. The bracket without perforations degraded the effective R-value by only 16.8% and the bracket with perforations, by 14.4%.

The discussed studies regarding thermal bridging in masonry veneer clad walls have investigated various aspects of connection influence on thermal performance of insulation, providing results that complement each of the other research findings. D’Aloisio et al. (2012) provides a broader evaluation of various sources of thermal bridging in a standard masonry wall to provide an understanding of the level of impact these sources may have on thermal performance relative to an unmitigated design and the proposed alternatives. Although 2D modeling rather than a more accurate 3D model simulation was utilized, this was a suitable demonstration of how 2D modeling can generate higher level results and insight into which areas demand greater attention and indicate greater potential for improvement. This serves as a valuable source of preliminary suggestions for selecting a detail within the standard wall design that has the greatest and most accessible opportunity for improvement. In this case, that is the integration of intermittent steel knife plates to eliminate the shelf angle as a continuous thermal bridge.

Finch et al. (2013) investigates the influence of material choice and concludes the clear improvements by use of stainless steel rather than typical galvanized steel. Though these results outline the similar benefits of integrating steel knife plates, Finch fails to evaluate the cost adjustments and potential savings given the greater cost of stainless steel components. Di Placido et al. (2019), on the other hand, investigates an alternative geometry for these knife plates, while still using galvanized steel. Because galvanized steel is one of the more accessible and commonly used materials for such connections, it is necessary to provide a reasonable argument for replacing such practices with a more costly material like stainless steel. D'Aloisio et al. (2012) does estimate a cost analysis regarding the benefit of implementing stainless steel knife plates versus no knife plates, concluding that such a design is both an easily accessible and cost-effective solution. Although cost analysis may require further evaluation for more precise estimates in the context of a particular building and location, these studies have cultivated a sensible argument for the use of a shelf angle standoff approach.

## *3.2 Concrete Balconies*

Traditional balcony slab design creates one of the most problematic sources of thermal bridging compared to other thermal bridges (Wakili et al., 2007). Because both existing and newly constructed multi-unit residential buildings often repetitively include these balconies in their designs, mitigating thermal bridging through balcony slabs presents a major opportunity for improvement upon building energy performance. A typical balcony slab detail consists of the extension of the interior building structural slab which cuts through the building envelope, forming a direct conductive pathway for heat flow into the interior building. This design does not regularly include thermal breaks to combat the highly conductive materials in the slab, which are commonly reinforced concrete with regular steel rebar or steel beams (Aghasizadeh et al., 2022).

Two of the most accessible and researched improvements to balcony thermal bridging is the insertion of a thermal break, as well as adding insulation to the exterior of the balcony slab (Aghasizadeh et al., 2022).

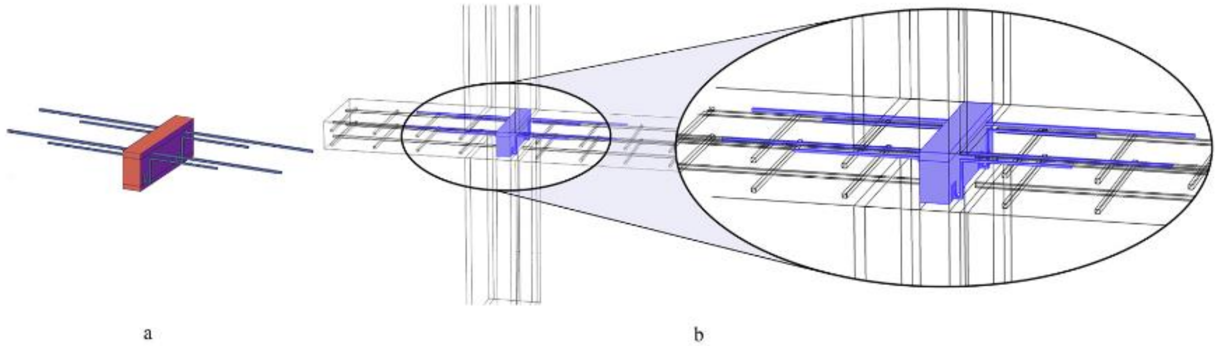
Roppel et al. (2012) presented a study with ASHRAE discussing 40 different generic interface details that consider the effects of thermal bridging. One set of these details includes a brief investigation of balcony thermal bridging and mitigation design, in particular, the placement of insulation on the exterior portion of the slab. The investigation utilized the 3D analysis software package by Siemens PLM, including FEMAP and Nx, along with Maya's TMG thermal solver. Three main design cases were analyzed, each involving the same base level adjacent wall and slab design, which included horizontal z-girts intersecting with a steel stud wall assembly and a concrete slab that extended 1 meter out from the exterior wall. The first case had no slab insulation, the second had insulation on the top side of the exterior balcony slab, and the third had insulation on both the top and bottom sides of the slab. Each of these were tested with three levels of exterior wall insulation (R-5, R-15, R-25).

The uninsulated slab detail clearly degraded the effective insulation significantly, increasing the thermal transmittance by 29% - 60% compared to the assembly without a balcony. Both the cases with slab insulation improved this degradation; however, the case with both top and bottom insulation proved to be more effective relative to the amount of insulation required. The second case reduced thermal transmittance by 12% compared to the first case, given that the insulation extended 0.4 meters from the wall, after which the improvement was minimal. On the other hand, if the insulation extended 0.4 meters for the third case, thermal transmittance decreased by 36% compared to the first case without insulation. Further comparisons demonstrated that insulation on the top and bottom that extends only 0.2 meters out had a similar effect as insulation on only the top that extends over 0.8 meters out. This shows that insulation on the balcony slab can help mitigate thermal bridging, but proper and strategic placement can minimize the amount of insulation material needed for the most effective thermal resistance.

Ge et al. (2013) investigates the alternative solution of inserting a thermal break into the balcony slab connection. To evaluate the impact of a thermal break on the heat transmittance of the assembly, Ge utilizes THERM to perform a 2D thermal analysis. The modeled detail included a concrete balcony slab, 210 mm thick and 1.8 meters long (exterior side). The thermal break consisted of an 80 mm thick expanded polystyrene (EPS) module, which is a non-conductive material, placed between the floor slab and balcony cantilever slab. Stainless steel tension and shear reinforcement bars pass through the separator to account for load transfers from the cantilever to the structural slab and frame. Effective U-values collected from THERM were then applied to the efficiency of the insulation in a hypothetical multi-unit residential building in order to estimate the overall impact on building energy consumption. eQuest was used to model this building, which included 26 stories and a fully glazed façade for the top 24 stories to represent generic construction.

Results showed that the thermal break reduced the U-value of the slab by 72% - 85% and 29% - 76% for the unit including adjacent walls. The greatest improvements were seen in cases with more efficient wall assemblies that surround the balcony, while the least improvement was seen for the poorest performing walls, such as sliding glass doors and spandrel panels. In the context of the entire building, the addition of thermal breaks into the balcony construction reduced the annual space heating energy consumption by 5% - 11% if the percentage of façade glazing were reduced to 34%. These results provide significant insight as the balconies only account for 4% of the cross-sectional area but may contribute to 11% of space heating energy consumption, depending on the amount of glazing.

The previous two studies have demonstrated the considerable impact balcony thermal bridging may have on buildings and potential mitigation strategies, those being thermal breaks and balcony insulation. Aghasizadeh et al. (2022) presented a study that compared the effectiveness of these two mitigation methods in the context of different balcony construction materials. This study conducted a 3D analysis of common balcony connections using COMSOL 5.2an to produce heat transfer modules. The central focus of this investigation was to evaluate the effectiveness of thermal breaks compared to balcony insulation for three different steel and concrete construction types. The first was a concrete-concrete slab and connection. The second was a steel-steel balcony and connection. The third was a concrete-steel detail, consisting of a concrete slab connected to a steel cantilever balcony. In addition, each case was simulated with various adjacent wall types of various levels of insulation efficiency.

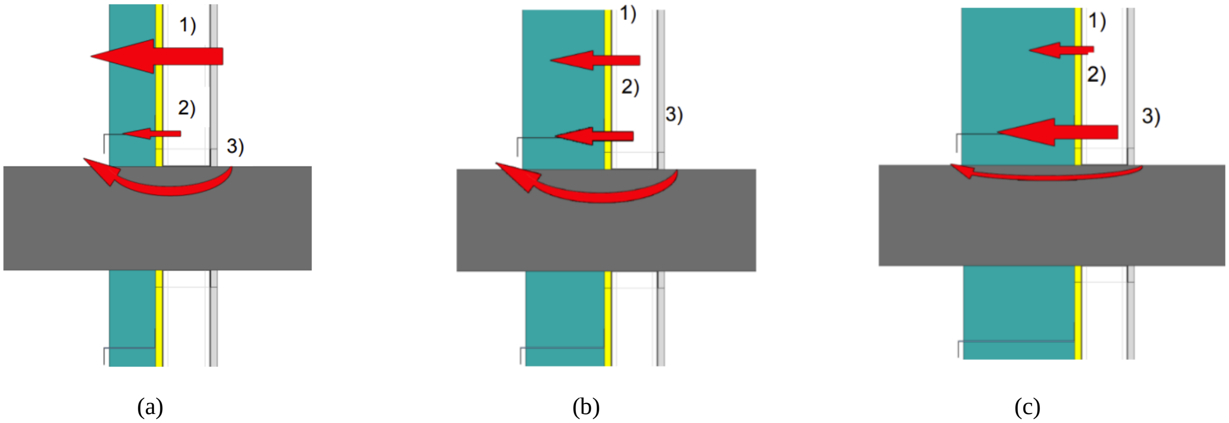


3D model of (a) thermally efficient load bearing connectors for the C-C structures, (b) the balcony slab with TIBC and reinforcement steel.
Sourced from: Aghasizadeh et al. (2022)

Results showed that the concrete-concrete balcony consistently experienced the greatest reductions of thermal transmittance. Concrete-concrete balconies experienced 75% - 51% decreases in thermal transmittance with thermal bridge solutions. The greatest improvement was generated with a combination of a thermal break and best performing wall assembly. With the same combination, the concrete-steel balcony experienced its greatest improvement, with a range of 65.6% - 48.7% reductions. The steel-steel balcony however, showed improvement within a range of 53% - 21.4%, the greatest thermal transmittance reduction resulting from the balcony insulation.

Thermal bridging through cantilevered balconies can pose a complex problem for which one mitigation solution may not be the most effective for every standard balcony design. The previous studies have demonstrated that both balcony insulation and thermal breaks can be effective, but depending on the construction and material type, one may be more effective than the other. Unlike the solutions discussed for masonry veneer cladding, basic balcony design can still vary greatly in terms of materials and adjacent wall thermal performance.

It is important to note that given this nature of balcony construction, a quality evaluation of balcony thermal bridging mitigation must include several potential adjacent wall assemblies. This is often due to the phenomenon of linear thermal transmittance not necessarily decreasing as exterior insulation of the wall increases. The amount of heat flow through a component or material path may also be dependent on the conductivity of adjacent materials (Roppel et al., 2012). For example, an adjacent wall with low insulation (R-5) will experience more heat flow through it compared to the adjacent concrete balcony thermal bridge. However, if the insulation were to increase to R-15, lateral heat flow through the assembly would direct more heat to flow through the materials with less resistance, like the balcony. This increased lateral heat flow through the balcony and other conductive connections then has the potential to cancel out the benefits of thermal resistance through the wall insulation. A much greater wall insulation could have the potential to then offer some benefit, but understanding these relationships between wall assemblies and balcony thermal bridges is critical in design (Roppel et al., 2012).



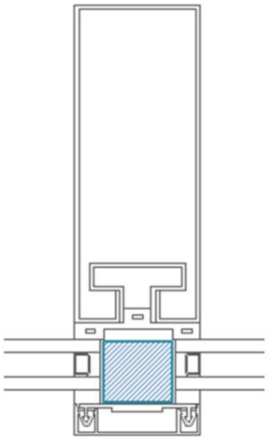
(a) (b) (c)

Schematic of heat flow path with exterior insulation and steel stud assembly with horizontal girts for cladding attachment.
(a) R-5 exterior insulation, (b) R-15 exterior insulation, and (c) R-25 exterior insulation
Sourced from: Roppel et al. (2012)

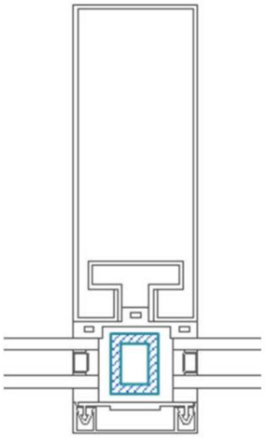
### 3.3 Steel Curtain Walls

Steel curtain wall panels have become an increasingly popular building envelope design for high-rise buildings. However, due to the heavily integrated amounts of conductive metal components throughout the assembly, thermal bridges have ample opportunity to inhabit these units. The lure of curtain wall usage comes from its simple and efficient manufacturing and assembly; however, this repetitive and preconstructed nature invites difficulty in addressing and managing alternative designs to mitigate thermal bridging. Joints and connections between curtain wall units and the structural frame can often form a grid-like case of thermal bridging that can affect a large portion across the entire building façade. This means that repetitive thermal bridge mitigation designs that can be integrated into the premanufactured curtain wall unit may provide a more accessible and effective option. Typically, curtain wall panels contain embedded insulation within the metal panels of the unit, and thermal breaks, consisting of non-conductive material within joint components, have become a more common line of defense as well, for combating thermal performance degradation. The following studies present an assessment of such methods along with potential alternative designs.

Ji Hyun Oh et al. (2016) presents a study regarding steel curtain wall design and thermal bridge mitigation, providing a brief evaluation of common thermal bridge mitigation techniques for steel curtain walls, namely, the comparison of ethylene propylene diene monomer (EPDM) filled air cavities, also called the rabbet space, in the curtain wall mullion frame, and thermal breaks contained within the aluminum connection profile. Two cases analyzed cavity spaces partially filled and entirely filled with EPDM, while the third contained a polyamide-bar thermal break, and the fourth contained an internal aluminum component joined with a polyurethane thermal break, representing a typical industry design.



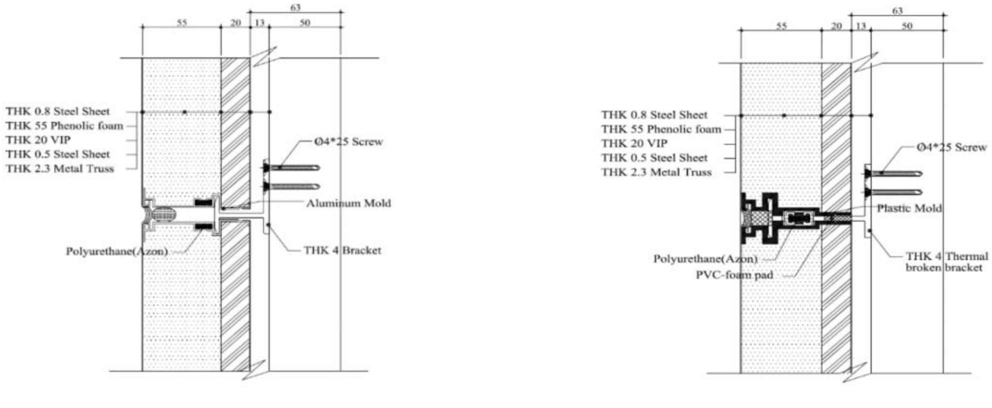
(a) polymer infill
Sourced from: Ji Hyun Oh et al. (2016)



(b) thermal break
Sourced from: Ji Hyun Oh et al. (2016)

Results of this study demonstrated that, although the third and fourth conditions are often used in industry practice, the first two cases using EPDM fill performed significantly better in terms of reducing baseline thermal transmittance. The second case in which the rabbet space was entirely filled with EPDM reduced the central mullion transmittance by 41.1%, while the third case containing the polyamide-bar thermal break only reduced thermal transmittance by 8.6%. These results demonstrate that, though internal thermal breaks can be somewhat effective and more beneficial compared to no mitigation at all, alternative methods may present a more effective design, such as EPDM cavity fill. Such a greater thermal transmittance may also be more influential on the overall building energy performance.

Jung-Min Oh et al. (2016) presents a study that further investigates improvements in typical thermal break usage. Rather than redirecting to a separate thermal bridge mitigation method, like EPDM fill in the previous study, J.M. Oh develops an alternative design for the typical aluminum mold which holds the thermal break. In this alternative design, the aluminum mold is replaced with an acrylonitrile butadiene styrene (ABS) plastic mold. This material achieves a significantly lower heat conductivity while providing stronger structural strength. The heat transfer analysis was executed using Physibel TRISCO for a 3D simulation, and annual heating and cooling was estimated using DesignBuilder v4.5. The entire building prototype consisted of a 10-story office building, and the individual modeled curtain wall units were 2000 mm wide and 1000 mm tall with a gypsum board interior.



(a) Existing metal panel curtain wall with aluminum mold and inserted polyurethane thermal breaker
(b) Alternative metal panel curtain wall with ABS plastic mold
Sourced from: Jung-Min et al. (2016)

The results of the thermal simulation showed that the inclusion of the ABS plastic mold decreased the effective U-value by 72% compared to the existing assembly using the aluminum mold. In the context of the entire protype building, the total heating energy needs of the building were reduced by 26% overall; however, the cooling energy needs increased by 7%. J.M. Oh concluded that this increase in cooling energy was likely a result of decreased heat loss through the building envelope in conjunction with internal and solar heat gains. This means that, in addition to the improvement of the building envelope performance, internal sources of heat may need to be evaluated and adjusted, unrelated to the thermal bridging. Overall, the total energy needs of the building decreased by 6%, which is a significant improvement despite the slight increase in cooling energy.

Treating thermal bridges within steel curtain walls can prove to be more challenging as they can occur at various points throughout the intricate and populous metal connections. Current practices that implement thermal breaks in combination with aluminum molds show some initiative and effort to treat thermal bridges in steel curtain walls; however, the above-mentioned studies have outlined both the minimal effects it provides and potential alternative designs. The results showing the minimal effects of typical thermal breaks underline the importance of accurate measurement of thermal bridging effects. By building a computer model and simulation of the detail, designers can decipher which points might be most problematic and where the thermal break is lacking in its intended function.

## 4. Discussion

The studies discussed have provided a general insight into what elements and measures considered in a thermal bridge mitigation evaluation generate a reliable and quality assessment of thermal bridging effects. Firstly, a successful evaluation of thermal bridging effects and the potential benefits of including a mitigation design utilizes 3D thermal modeling. Although 2D modeling can be insightful as well, as seen with D’Aloisio (2012), by providing approximate effective U-values for a broader scope comparison of details, 3D modeling more accurately portrays the relative thermal actions throughout the entire assembly detail.

Secondly, a complementary building model, either a specific building or prototype of some form, defines the context of the assembly detail. Only some of the discussed literature included a full building analysis; however, the ones that did were able to generate total building energy consumption and cost-analysis with and without the effects of thermal bridging mitigation. By estimating potential total energy and cost savings, designers are better equipped to make an informed decision on what mitigation elements to include in construction, based not only on effective U-values, but also on both upfront and long-term cost adjustments based on total building energy consumption and construction costs. Intentionally including these additional steps to building envelope investigation can encourage the implementation of such alternative designs as they are presented in real-world or hypothetical scenarios.

In addition to these two elements that construct a good quality evaluation, the consideration and investigation of structural performance is one factor that requires more research and attention. Though it was not noted in the discussed literature, additional investigation regarding the structural integrity and durability of proposed alternative connections should be thoroughly considered. In contrast to materials like steel and reinforced concrete, which have near exhaustive testing and documentation, cases of proprietary or less standardized materials may be less familiar to designers. This lack of structural strength testing may contribute to a designer’s reluctance to adopt some alternative designs, such as the ABS plastic mold for steel curtain walls, proposed by J. M Oh (2016).

In an ideal scenario, the combination of these three basic assessments could be applied into a set of typical building façade construction types which commonly initiate thermal bridging. Such a series of assessments and documentation could compose a database for a catalogue of detail alternatives or suggestions given a specific construction type, like reinforced concrete balcony slabs or masonry veneer cladding attachments. In other words, this data could provide reference material for designers so they do not need to run such extensive modeling or tests on potential designs. In this way, implementing thermal mitigation into industry practice could be more accessible by offering designers more confidence in these suggested details and less demanding analysis.

## 5. Conclusion

This report underlined a number of critical aspects of thermal bridging in building façade systems. This report synthesizes eight different studies investigating various façade installation methods. These methods namely target three common façade element types, those being masonry veneer cladding, cantilever balcony slabs, and steel curtain walls. These reviewed studies evaluate and propose alternative methods of connection to mitigate the thermal effects of thermal bridging. From the review and discussion of these studies, both in the context of thermal bridging analysis and the effectiveness of reducing thermal bridging impact, general conclusions were drawn. Firstly, the synthesis of these studies provided insight into what elements are necessary to sufficiently measure and assess the effective thermal transmittance of a building envelope assembly. The combination of 3D thermal modeling software and building energy usage analysis are two necessary components to generate a holistic presentation and argument for the use of an alternative thermal bridge mitigation design. Secondly, the synthesis of these studies under the category of their corresponding façade type provides a set of comparable proposals for thermal bridge mitigation. This comparison initiates an assessment of suggested thermal bridge mitigation designs against one another, allowing designers and researchers to identify more successful designs which can be further developed for industry use.

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Biography:

Sarah E. Forthuber was born in McAllen, Texas on June 18, 1999. She enrolled in the Cockrell School of Engineering and the Plan II Honors program at the University of Texas at Austin in 2018. During her time in college, she interned at a local structural engineering firm, Architectural Engineers Collaborative. In the summer following her fourth year, she studied emerging technologies in building design in London, under Professor Gregory Brooks of the University of Texas at Austin. She graduated with Engineering Honors in 2023 and plans to attend the University of Texas at Austin, Cockrell School of Engineering in the fall to complete her master's in civil engineering. Ms. Forthuber will continue to intern at Architectural Engineers Collaborative in Austin, Texas this summer.