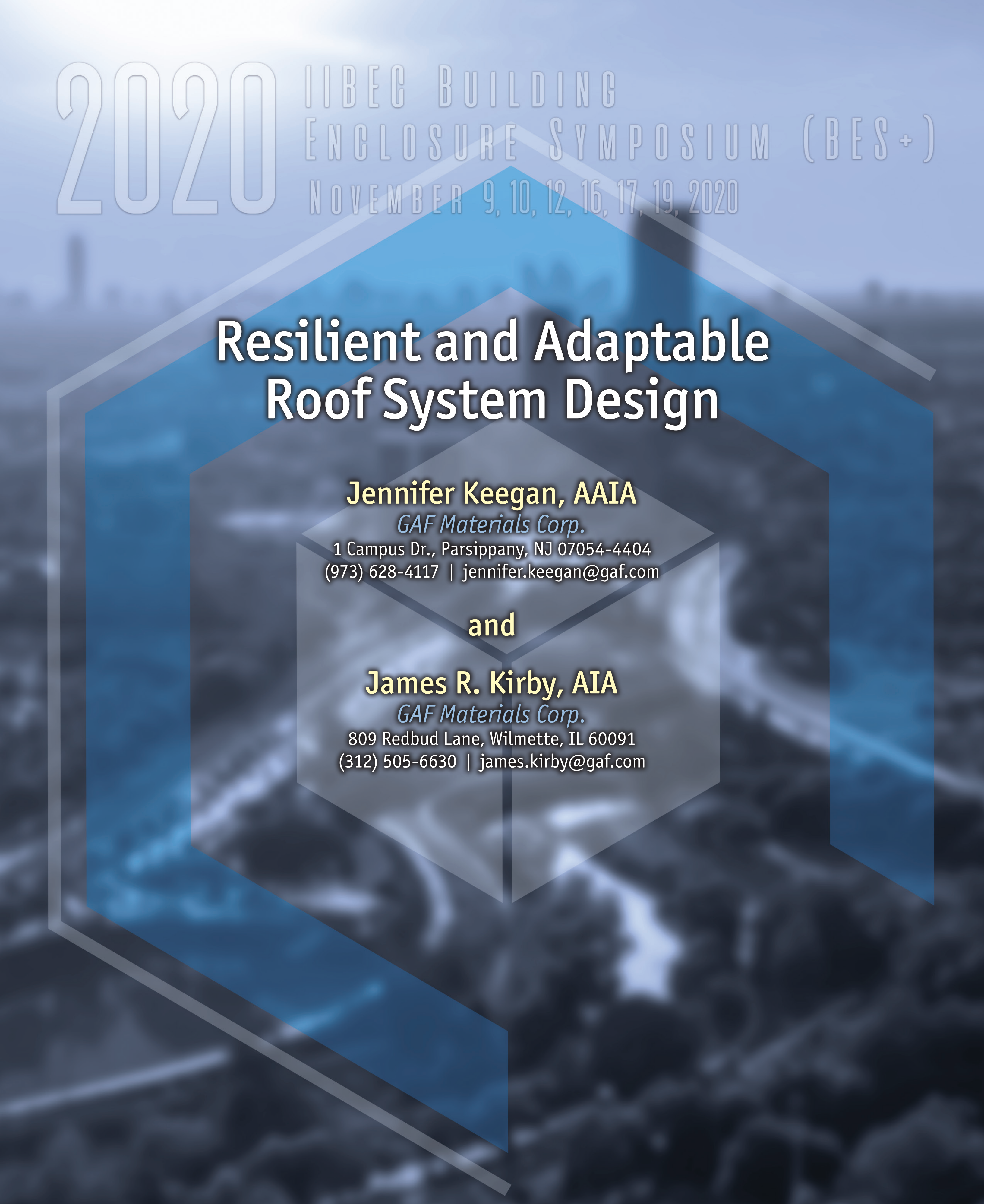

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Resilient and Adaptable Roof System Design

Jennifer Keegan, AAIA
GAF Materials Corp.
1 Campus Dr., Parsippany, NJ 07054-4404
(973) 628-4117 | jennifer.keegan@gaf.com

and

James R. Kirby, AIA
GAF Materials Corp.
809 Redbud Lane, Wilmette, IL 60091
(312) 505-6630 | james.kirby@gaf.com

ABSTRACT

Weather events are trending to be more destructive. Sustainability focuses on roofing products' effects on the future; resilience focuses on roofing assemblies' ability to endure. But how do we adapt roof system designs for an unpredictable climate and energy future in the U.S. and globally?

Long-term building performance necessitates an inherent and essential capacity to design for resilience in the face of vulnerability, and buildings that can adapt to the changing environments in which they were built. What do resilient and adaptive buildings *look* like, how do they *behave*, and how do we *design* for this belt-and-suspenders approach that requires such elasticity? And what role does roof selection and design play?

SPEAKERS

Jennifer Keegan, AAIA
GAF Materials Corp. | Parsippany, NJ

Jennifer Keegan is the director of building and roofing science for GAF, focusing on overall roof system design and performance. She has over 20 years of experience as a building enclosure consultant specializing in assessment, design, and remediation of building enclosure systems. Keegan provides technical leadership within the industry as the chair of the ASTM D08.22 Roofing and Waterproofing Subcommittee, and the Education Committee chair for IIBEC. She also serves as an advocate for women within the industry as an executive board member of National Women in Roofing and a board member of Women in Construction.

James R. Kirby, AIA
GAF Materials Corp. | Wilmette, IL

James R. Kirby is a GAF building and roofing science architect with a masters of architecture (structures option) degree. He has over 25 years of experience in the roofing industry covering low-slope, steep-slope, metal, SPF, and vegetative roofs, as well as rooftop photovoltaics. He understands the effects of heat, air, and moisture on a roof system. Kirby presents building and roofing science information to architects, consultants, and building owners, and he writes articles and blogs for building owners, facility managers, and the roofing industry at large. Kirby is a member of AIA, ASTM, ICC, IIBEC, NRCA, and WSRCA.

Resilient and Adaptable Roof System Design

INTRODUCTION

Our climate and weather very much influence the design and construction of our building enclosure systems, especially roof systems and assemblies. While codes provide the minimum requirements for construction, there are few provisions related to resilience and adaptability. Weather events are becoming more extreme and destructive; and unfortunately, today's solutions for improving resilience and adaptability of the built environment may not be sufficient. Compounding the effects of the changing climate is the increasing urban population, which makes resilience and adaptability even more important and challenging.

SUSTAINABILITY, RESILIENCE, ADAPTATION

Above-code design considerations are required when implementing sustainability, resilience, and adaptability characteristics into buildings and structures. Each has its own set of principles and objectives. Sustainability and resilience are often coupled and can be opposing at times. Adaptability considerations that take into account climate trends when designing building enclosures are important for the long-term performance of wall and roof system design.

Broadly, sustainability is the capacity for human health and well being, economic vitality and prosperity, and environmental resource abundance. Being sustainable means meeting present needs without compromising the ability of future generations to meet their needs. The long-term prosperity of people, the economy, and the environment is the essence of sustainability, and there is a "material" focus embedded within the concept of sustainability. Products have Environmental and Health Product Declarations (EPDs and HPDs); the content of materials and how they are manufactured is relevant. The life cycle and length of use are important considerations for the selection of sustainable materials and methods.

The key questions related to sustainability and the built environment include:

- Are materials safe for humans and the ecosystem?
- Is a design efficient in terms of energy and resource use?
- Is a material available or will its use today cause a shortage in the future?

Resilience is the capacity to overcome unexpected problems, continue or rapidly bounce back from extreme events, and prepare for and survive catastrophes. A number of definitions exist; all are similar in concept. The American Institute of Architects defines resilience as "mitigating risk for hazards, shocks, and stresses and adapting to changing conditions."[1] And the National Academies of Science defines resilience as "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events."[2]

There is a "system-focus" effort embedded within the concept of resilience. Recognizing that resilient design is a system approach means the implementation of the desired performance requirements is paramount for long-term success.

The key questions related to resilience and the built environment include:

- Can a structure be occupied and functional after wind events or flooding?
- Will occupants be able to function in the absence of utilities?
- What reduction in occupational capacity is acceptable?

Adaptation is the ability to adjust to changing conditions, modify behavior in response to new circumstances, and prepare for and survive long-term change. Adaptation in the built environment can be summarized as "...the accommodation of needs throughout service life." Designing for the adaptation of buildings focuses on large-scale recent and future trends in the weather and climate.

The key points related to adaptability and the built environment include:

- Will today's structures be appropriate for long-term climate change?
- Can building design adapt and maintain resilient and sustainable practices?
- Understand that adaptation should not accelerate negative change!

This paper will focus on roof systems and assemblies that achieve roof system resilience and adaptability.

> Weather events are becoming more extreme and destructive; and unfortunately, today's solutions for improving resilience and adaptability of the built environment may not be sufficient.

CLIMATE TRENDS

Climate directly affects the long-term performance of roof systems, and this is reflected in the model building codes. Building code requirements for fire, wind, impact, reflectance, and insulation are influenced by, in broad terms, the weather and climate. However, the science behind modern model building codes is often based on decades-prior data. While predicting the climate accurately is impossible, looking backward to establish requirements may not be the right way to determine minimum construction requirements.

Analyzing recent climate trends—trends that are often not yet captured for minimum construction requirements—lends credibility to the idea that designing “above code” is appropriate and necessary to design and build resilient and adaptable buildings and roof systems.

For the purposes of this paper, “climate” includes wind, temperatures, hail, precipitation, and fire. Large trends are discussed for each.

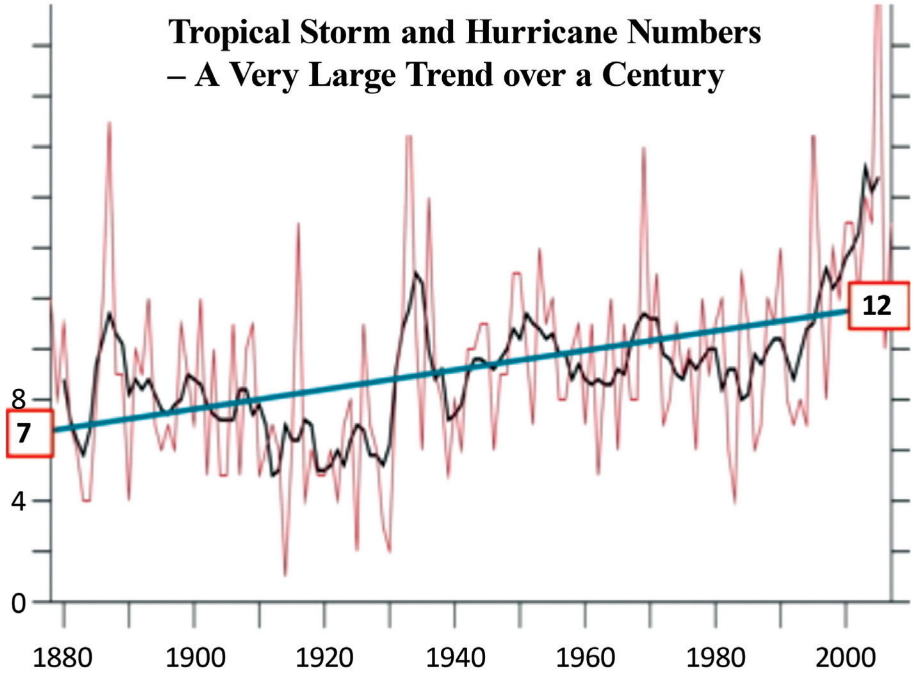


Figure 1 – Tropical Storm and Hurricane Numbers--A Very Large Trend over a Century. Source: https://www.aoml.noaa.gov/hrd/Landsea/gw_hurricanes/index.html.

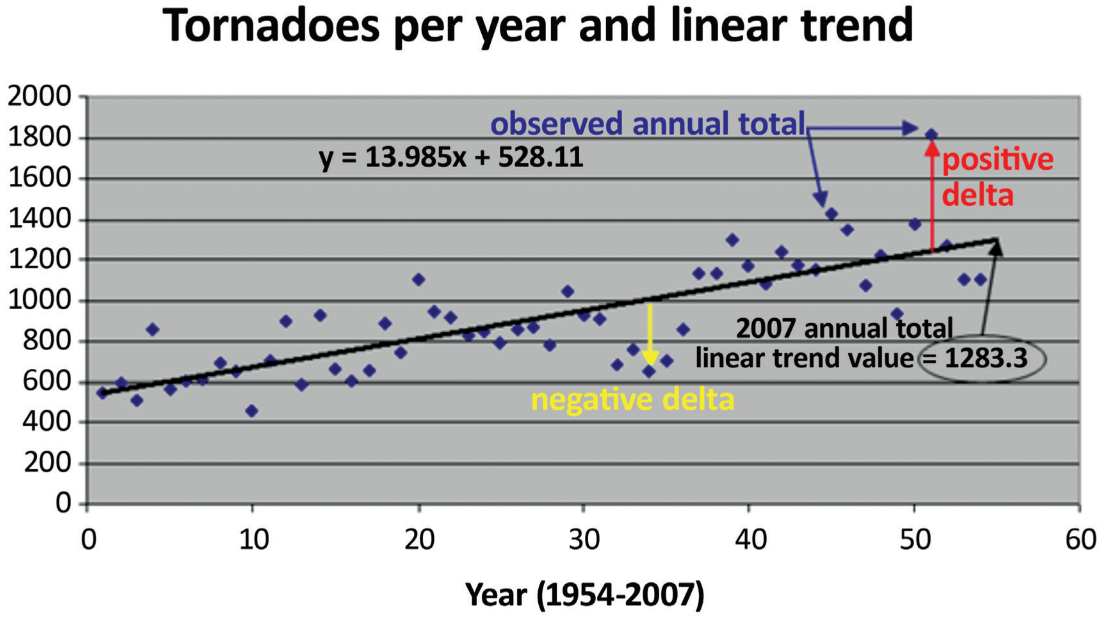


Figure 2 – Graphic showing the upward trend of the number of tornadoes per year over a 53-year period. Source: https://www.spc.noaa.gov/wcm/adj.html.

Wind

In general, hurricanes are growing stronger,[3] and tornadoes are increasing in frequency. The data are somewhat noisy but it can be interpreted that the trend is towards stronger storms. *Figure 1* provides tropical storm and hurricane numbers from more than a century.

The same is true for tornadoes. There is a strong upward trend[4] in the quantity of tornadoes every year, as shown in *Figure 2*. Technology has been available for the past few decades to adequately detect and report tornadoes in the U.S. Even with the increase in tornado awareness and improved reporting, *Figure 2* also shows there has been an upward trend since 2000.

Temperatures

The data from the National Aeronautics and Space Administration (NASA) indicate the global annual mean surface air temperature is increasing.[5] The data are based on land and ocean data from the past nearly 140 years; see *Figure 3*. Data such as this leads to revisions in the requirements for the construction industry. For example, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recently revised the climate zone classification for many counties in the U. S. Every revision was to a lower climate zone, indicating the climate is getting warmer in those counties.

Hail

National Oceanic and Atmospheric Administration (NOAA) reported on the increase in medium and large hail reports from the early 1950s to 2003.[6] Analysis of this data shows a significant increase in reports of hail greater than 1 in. in the last 20 years of that study.

Factory Mutual (FM) Approvals provides product testing and certification programs for the roofing industry and has many industry-recognized testing standards. FM Global

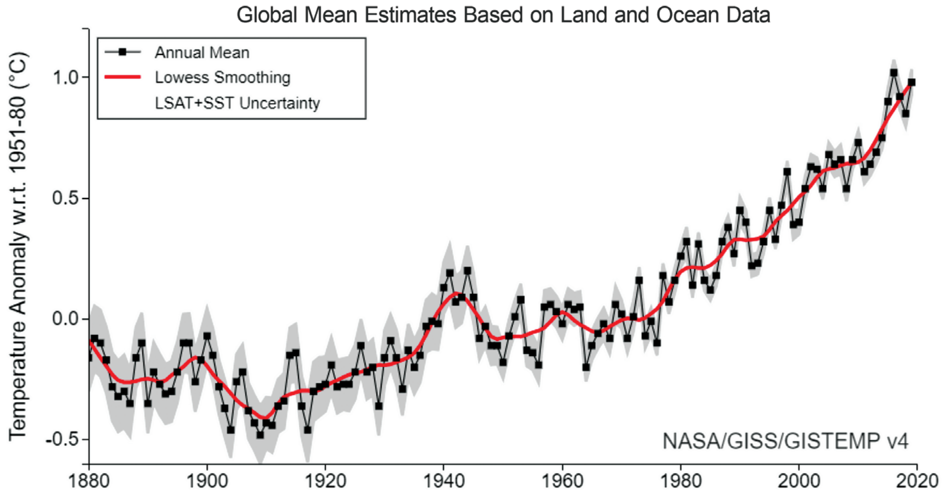


Figure 3 – Graphic showing that the global annual mean surface air temperature is increasing. Source: https://data.giss.nasa.gov/gistemp/graphs_v4/.

develops and provides to the industry its Loss Prevention Data Sheets (LPDSs). LPDSs provide engineering guidelines for many types of roof systems and materials. The most recent version of FM LPDS 1-34, Hail Damage, includes a hail zone map which has a Very Severe Hail (VSH) zone affecting 14 states (*Figure 4*). The VSH portion first appeared in 2014, and the map was updated in 2018. The requirements for the use of highly impact-resistant roof systems continue to expand in scope and coverage.

Water

The rise in global temperatures is connected to the rise in sea level. According to the U.S. Environmental Protection Agency, sea level has increased nearly 10 inches since 1880, and the rate of annual increase has accelerated in recent years.[7] See *Figure 5*.

In addition, Munich Re, a re-insurance company, reports a significant increase in the number of floods, landslides, and avalanches.[8] Data show approximately 50 floods in 1980 and nearly 400 floods in 2016. See *Figure 6*. Floods, in particular, can be devastating to the existing infrastructure, which can also be exacerbated by zoning and land use practices. Many predictions for coastal areas, such as San Francisco Bay and New York City, are forecasting sea level rise measured in feet, not inches.[9] See *Figure 7*.

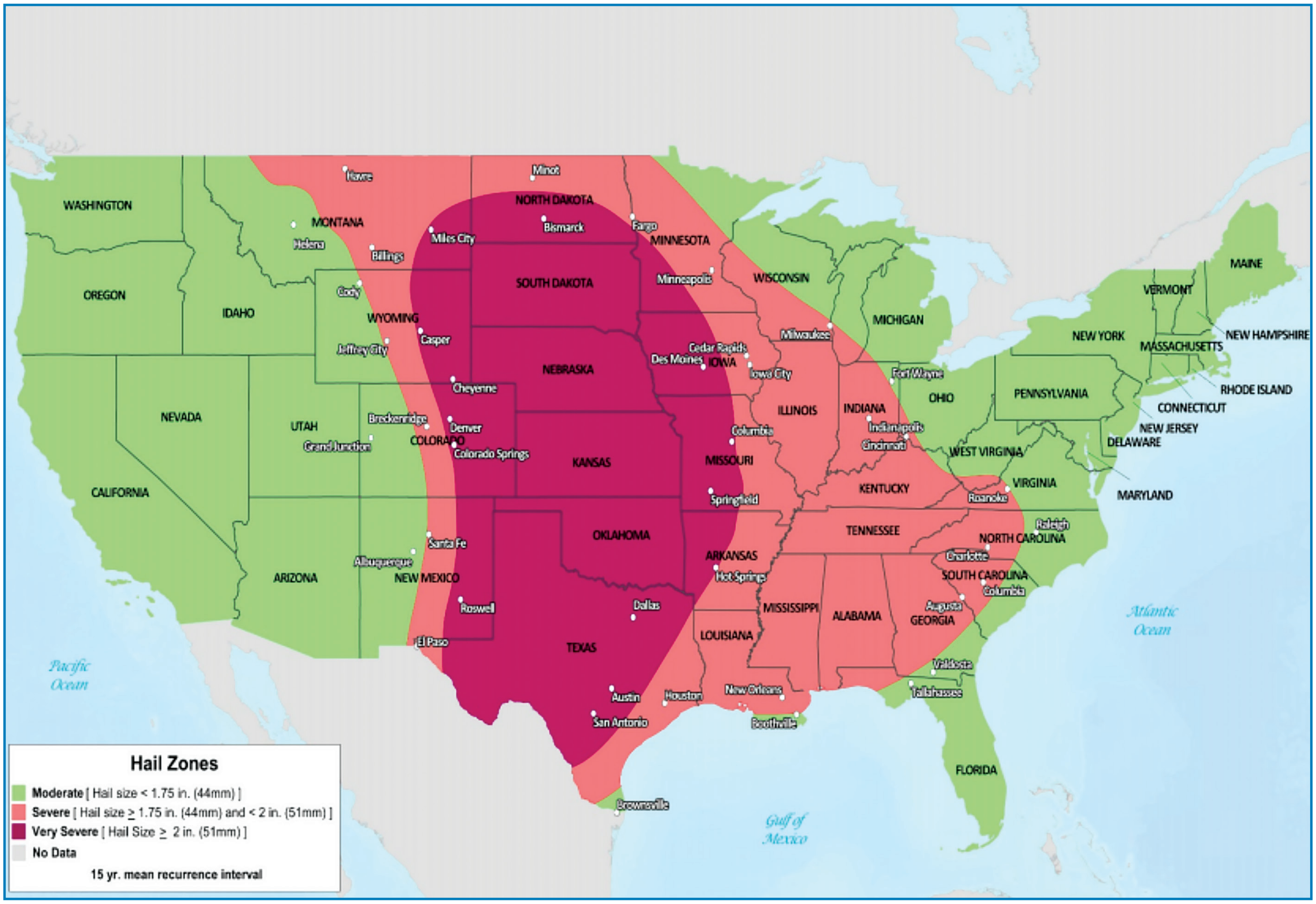


Figure 4 – Hail zone map from FM Global Property Loss Prevention Data Sheet 1-34. Source: FM Global Property Loss Prevention Data Sheet 1-34, Hail Damage, 2018.

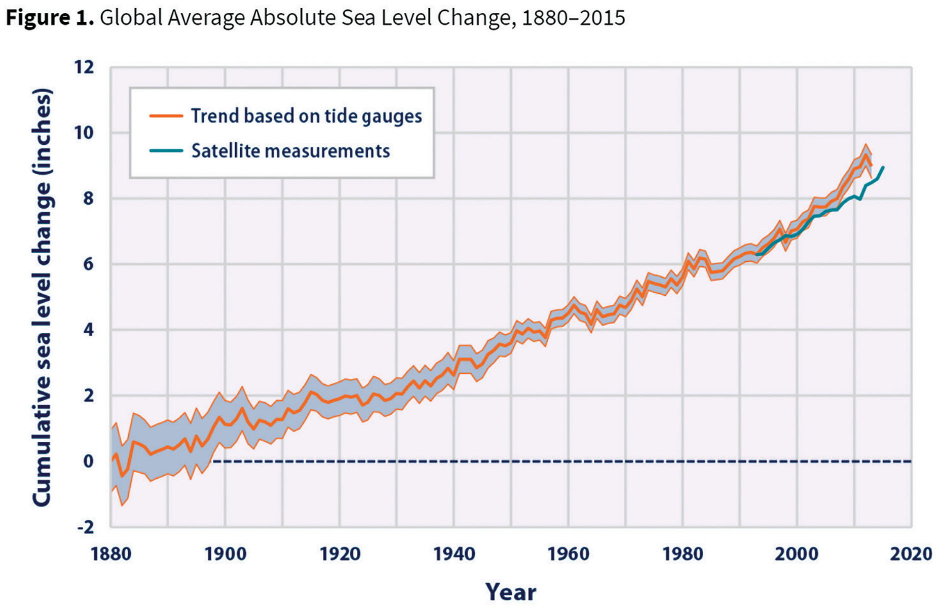
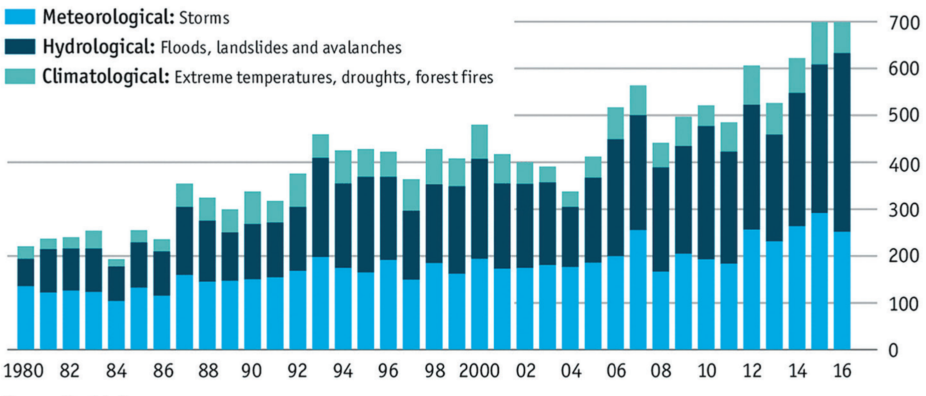


Figure 5 – Graphic showing global average absolute sea level change. Source: https://www.epa.gov/climate-indicators/climate-change-indicators-sea-level.



Source: Munich Re

Figure 6 – Graphic showing the increase of floods, landslides, and avalanches. Source: https://www.economist.com/graphic-detail/2017/08/29/weather-related-disasters-are-increasing.

Fire

In addition, the intensity and frequency of fires around North America and the globe are also indicators of the overall changes that are occurring to the climate. For example, fires in California and Australia have penetrated the news and are being reported as extreme events. NASA reports, based on satellite data, that the rise in temperatures increases the frequency of extreme events, including fires.[10] These events can also be exacerbated by land use and management.

POPULATION TRENDS

The global population has increased significantly over the last century, and the population is becoming more urban. Urban areas are growing as rural areas are decreasing in population. As shown in *Figure 8*, by 2050, the United Nations International Children's Emergency Fund (UNICEF) reports that approximately 70% to 75% of the world's population could be urban.[11]

As the number and size of urban cities increases, the urban heat island (UHI) effect, as shown in *Figure 9*, is more pronounced. Urbanization of the population, coupled with warming temperatures globally, means cities' average temperatures and frequency of high temperatures are increasing as well.

As temperatures rise, an increased burden is placed on infrastructure. Temperature extremes stress the electrical power grid. With grid-based electricity, the loss of power means the loss of heating and air conditioning, lighting, communications, transportation, financial transactions, and safety and security systems.

As shown in *Figure 10*, overall weather events are increasing.[12] As such, storms are having a real and measurable impact on the built environment. The data and trends indicate more frequent and more intense weather events. These indicators can be used to inform our design decisions for our roof systems as resilience of our built environment becomes a higher priority.

LOOK FORWARD, NOT BACKWARD

The basis for many requirements contained in the building codes, both commercial and residential, is historical weather data. If the reported trends are a result of the increase in frequency, strength, and overall severity, it may not be prudent to rely on

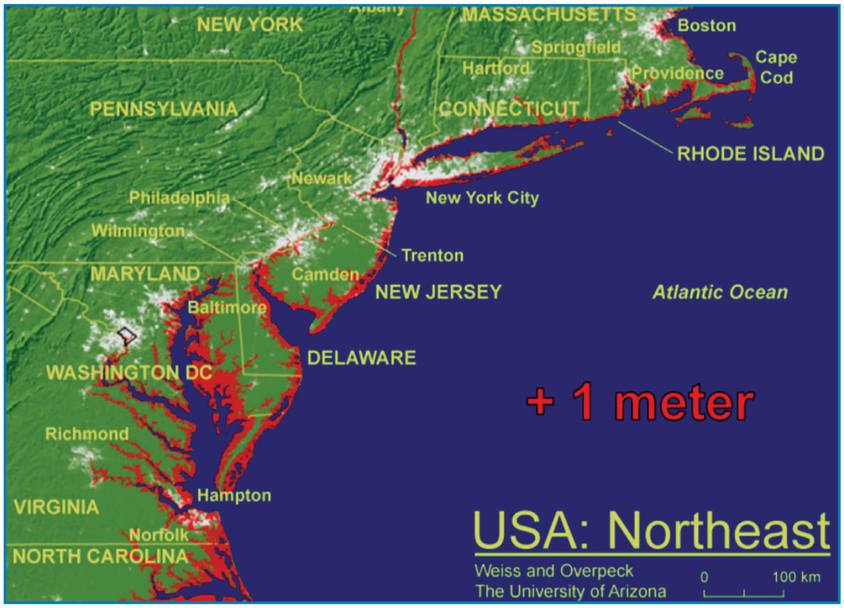


Figure 7 – Graphic showing the predicted rise in sea level in the northeastern U.S. Source: https://www.lpl.arizona.edu/~showman/climate.html.

historically based minimum code requirements. Given the data, building design should be based on a projected or expected future scenario.

There is a recent publication[13] that addresses the challenge of designing in the face of climate change. Elena Mihaly with the Conservation Law Foundation states, “Failure to act in the face of known climate risk could come with legal liability.” During the design phase, as greater focus can be placed on future climate change mitigation of the built environment, the inclusion of resilient systems will become a higher priority.

According to NOAA, climate changes are expected, and the trends are for more frequent and more intense weather events. Resilient design can be a matter of understanding how a building is affected and can respond to change over its useful life.

An example tool to begin to address these future risks is WeatherShift™. It allows for a design “stress test” using a range of plausible futures.[14] This kind of future analysis can be used to see if the risks change over time, for better or worse, depending on the conditions.

RESILIENCE AND ADAPTABILITY IN ROOF DESIGN

Resilient roof systems are designed to weather the storm and help maintain interior conditions for a level of comfort and/or use. The characteristics of a resilient roof system include wind resistance, impact resistance, surface characteristics and color, insulation, energy generation (e.g., solar rooftops), and daylighting.[15]

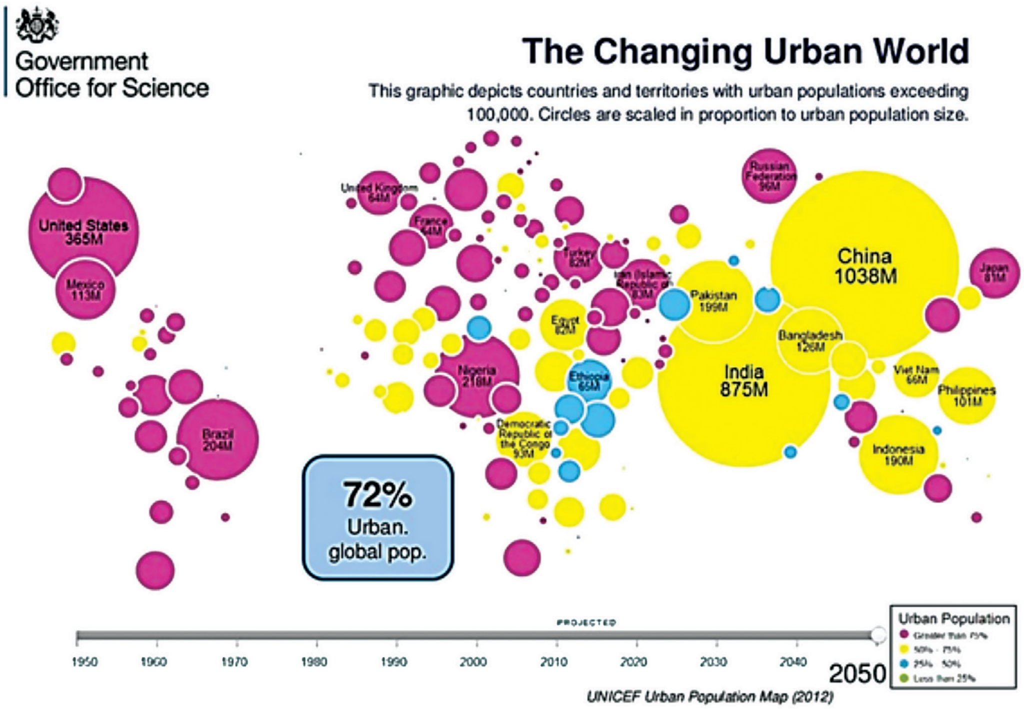


Figure 8 – Graphic showing the urban population of countries and territories. Source: https://www.unicef.org/sowc2012/urbanmap/.

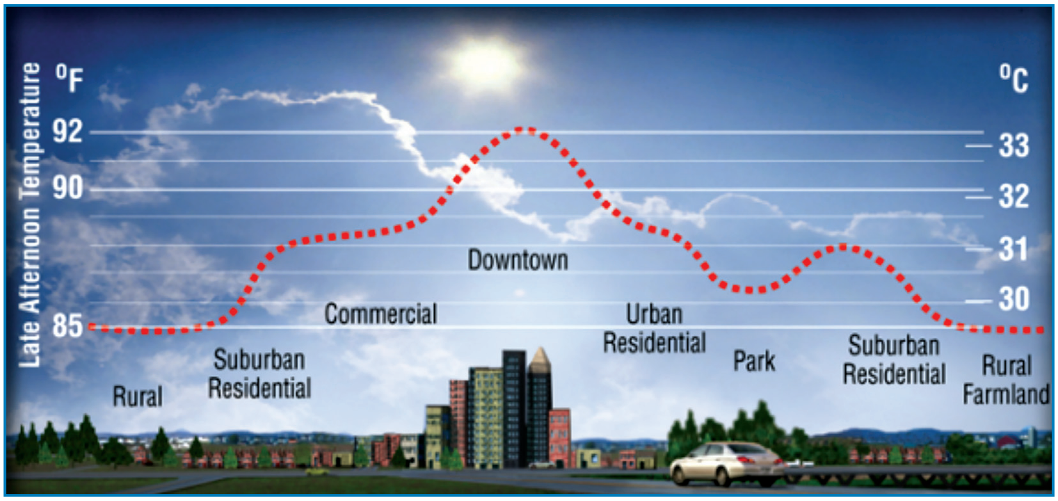
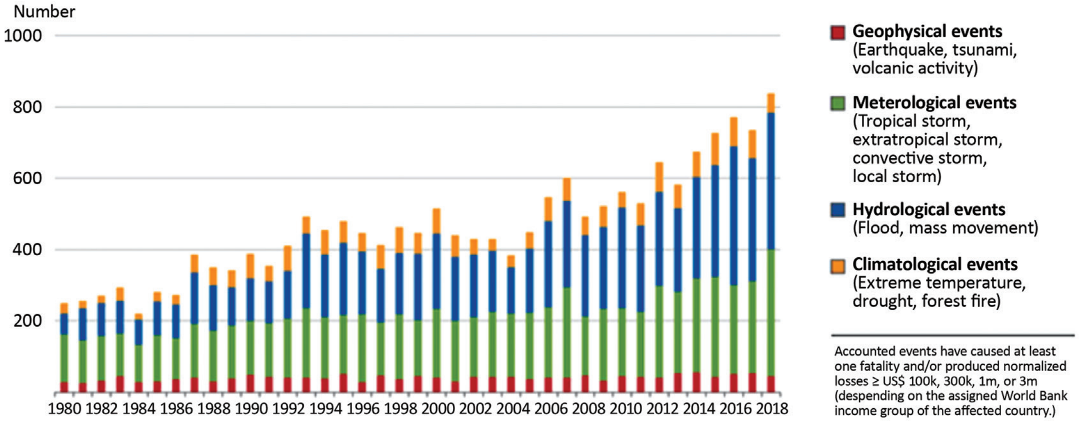


Figure 9 – Graphic showing the UHI effect relative to varying population types. Source: https://heatisland.lbl.gov/coolscience.



Source: © 2019 Munich Re, Geo Risks Research, NatCatSERVICE. As of March 2019.

Figure 10 – Graphic showing the overall increase in the number of extreme weather events. Source: https://www.iii.org/graph-archive/96424.

Wind and Impact Resistance

To weather the storm, the wind and impact resistance of the roof system are of paramount importance. These two characteristics are foremost in the success of a roof system during a significant weather event.

Wind Resistance

Determining the wind loads acting on a roof system is based on requirements contained in the International Building Code and ASCE 7, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*. Wind maps (or other web-based tools that reference these maps) are used to select a location-based wind speed that is used to determine the loads acting on the roof system. While recent building codes have become perhaps more stringent for determining design wind loads for roof systems, the requirements are based on historical data collected over decades. Considering the climatic trends, designing for higher-than-code wind speeds (e.g., +10, +15 mph) will increase the design loads acting on the roof, and subsequently, a roof system with higher capacity will be selected for use. This provides better than code-minimum protection against roof blowoffs and other wind-related failures.

In addition to location-based wind speed, there are a number of variables that are used to determine the loads acting on a roof system. These include the building code in effect and a building's dimensions, exposure, use and occupancy, and type.

The building code enforced at the project location determines which version of ASCE 7 is required. However, not all locations have adopted the most recent codes, and therefore, the use of the most recent version of ASCE 7 may not be required but could be recommended for use. Determining wind loads using the most recent version of ASCE 7 is best practice.

Selecting a higher wind exposure category also increases loads. There are three exposure categories: B, C, and D. Many roof systems are designed using exposure B, which results in the lowest wind loads of the three categories. Selecting a higher exposure category, such as exposure C instead of exposure B, is a more risk-averse selection.

Buildings have different uses and occupancy types. The use and occupancy type determine the specific wind map in the building code and/or ASCE 7 to use for wind load selection criteria. Hospitals, for example, have a higher location-based wind speed requirement than an agricultural building. Selecting a higher-than-code wind speed effectively is placing a higher importance factor on a building.

The "type" of building relates to whether or not a building will be pressurized during a high-wind event. Buildings are designed to be enclosed, partially enclosed, partially open, or open. Many roof systems are designed as "enclosed" buildings, which anticipate little to no internal pressurization. This could be very appropriate for new construction where the windows, doors, and large openings have also been designed to resist high winds. Conversely, for reroofing projects, the openings in the building enclosure may not have high-wind capacity. Determining a roof's wind loads based on "partially enclosed" is very rational if it is predicted that windows and doors will be displaced during a wind event. "Partially exposed" will result in higher wind loads and, again, the selection of a higher-wind-capacity roof system.

Edge Metal and Perimeter Restraints

From decades of post-high-wind-event investigations, the roofing industry knows that most wind-related damage begins at the perimeters and corners. Enhancing the edge metal details with thicker metal, higher fastener density, and proper nailer securement can increase the wind resistance of a roof's perimeter. For example, using 22-gauge metal instead of 24-gauge metal and installing fasteners 8 in. apart rather than 12 in. apart can provide cost-effective protection for long-term performance. Using edge metal components that are tested and rated per ANSI/SPRI ES-1 (which is required by building codes) can assist designers with selection of edge metal with appropriate capacity.

In addition to a well-designed perimeter edge or parapet, a "peel restraint bar" can be installed as a secondary measure. The bar can be a continuous piece of metal (e.g., a termination bar) located two to three feet from a building's perimeter. The bar is installed above the membrane, fastened directly to the structure, then covered with a membrane to keep it weathertight. Edge restraint can be an effective preventative measure for new construction, and it can be implemented on existing roofs as well.

Impact

Depending on the circumstances of any individual weather event, the term "impact resistance" can mean resistance against impacts caused by hail, debris, or displaced rooftop equipment. Impact resistance most often requires a system approach. For example, testing by Bhawalkar, Yang, and Taylor[16] showed an adhered fleeceback membrane over an adhered high-density polyisocyanurate (polyiso) cover board over mechanically attached rigid polyiso insulation can provide a high level of impact resistance when these materials are used in combination.

The tests used 2-in.-diameter ice balls and followed a similar procedure to that of FM 4473, *Specification Test Method for Impact Resistance of Rigid Roofing Materials by Impacting with Freezer Ice Balls*. The test did not consider different types of reinforcement. The testing had a number of more generalized conclusions.

- The use of a cover board improves impact resistance.
- The use of adhered membranes and adhered cover boards instead of fasteners and plates located directly under the membrane improves impact resistance.
- Consider the use of thicker membranes.
- Consider the use of fleeceback membranes.
- Consider the use of a long-lasting membrane.

Impact resistance is critical throughout the entire service life of the roof system, especially when considering the resilience of the roof. The tests used in the Bhawalkar, Yang, and Taylor study and throughout the roofing industry use new materials when determining impact resistance of systems. However, a more recent study[17] was performed using aged TPO membranes, 2-in.-diameter ice balls, and a procedure nearly the same as FM 4473.

TPO membranes were aged using variations of accelerated-aging conditions to simulate different equivalent ages. Accelerated aging was done prior to testing for impact resistance. The testing showed that different roof designs have varying resistance to impact. Regardless of the age of membrane used, the referenced work determined that impact resistance is a system characteristic.

In hail-prone regions, an appropriate

cover board is essential for a resilient roof system. The use of plywood in place of a traditional cover board along with an 80-mil-thick adhered fleeceback single-ply membrane is often necessary to achieve the Very Severe Hail rating that is required for buildings insured by FM Global in much of the center of the U.S. Where large hail is anticipated, pavers above the roof membrane can be used to protect the roof system. Pavers may be added to an existing roof provided the structural capacity is adequate to carry the additional weight.

Although often overlooked, rooftop equipment such as exhaust vents and HVAC units can be overturned and displaced large distances during high winds. Displacing a rooftop unit can severely damage a roof system.

Preventing displacement of rooftop units during weather events is a resilience measure. If roof damage from a storm allows significant amounts of water to enter a building, habitability and use may be compromised, potentially rendering a building unusable and thus no longer resilient. Fasteners and tethers can be added to equipment at any time, not just during new construction or reroofing.

Resilient Incentives and Tools

The Resilient Design Rating System (RELi) provides a framework for evaluation of resilient design and encourages hazard preparedness and mitigation of risk. Existing documents, such as ASCE 7 and the Single Ply Roofing Institute's (SPRI's) ES-1[18] (which is used to determine the capacity of a roof's metal edge system) can be used as tools to achieve success in resilient design. Using the most recent versions of these guidelines when local code has adopted an earlier version will often result in a roof system with a higher wind-uplift capacity. Furthering resilient design efforts includes using risk-averse choices during the determination of a roof's wind loads.

WeatherShift™ is a software tool that allows a designer to run a "design stress test" using a range of plausible futures, including increased wind speeds, storms, and hail stones. This kind of future analysis can provide valuable information about long-term durability to see if risks change over time.

Water Control

The International Building and Plumbing Codes dictate roof drainage requirements. While these code requirements are based on the 100-year hourly rainfall rate, they do not account for the impact that volume of water may have on the storm drains and the surface permeability of surrounding communities.

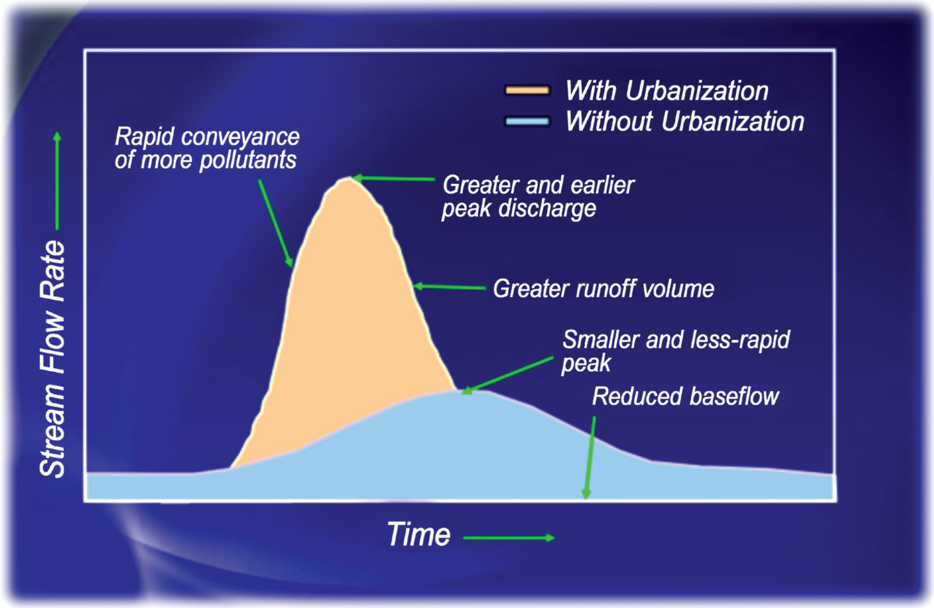


Figure 11 – Peak discharge and runoff volume relative to time in urban and rural areas. Image courtesy of NC APWA Innovations in Water Resources and Stormwater Management.

As storms increase in intensity, many urban areas are challenged to manage the sudden volume of precipitation. Storm and sewer drains are combined in many cities, and intense storms can overwhelm urban drainage systems, resulting in localized flooding and uncontrolled sewage discharge.

Many cities are contending with the sudden peak discharge of stormwater, as illustrated by the orange plot in *Figure 11*. As urban areas are dominated by impervious surfaces such as roads, sidewalks, parking lots, and rooftops, a large volume of water rapidly enters the storm drains. In rural areas, we see the intensity of the runoff volume is significantly decreased, as shown in blue. Water is released more slowly as it filters through the natural landscape.

During periods of heavy rainfall, the capacity of a combined sewer may be exceeded. When this occurs, regulators are often designed to let the excess flow, which is a mixture of stormwater and sanitary wastes, discharge into the rivers and creeks. Release of this excess flow is necessary to prevent flooding in homes, basements, businesses, and streets. However, this overflow can contain material which contributes to high bacteria levels in the receiving waters and can negatively impact the health of the water and wildlife. A more resilient approach would be to control the runoff volume during storms to match the capacity of the sewer system and avoid release of excess flow while taking into consideration the amount of hard and permeable surfaces.

Green and Blue Roofs

Green roofs, also known as vegetative roofs, are a proven way to reduce the amount of water runoff from low-slope roofs and delay the time at which runoff occurs, resulting in decreased stress on sewer systems at peak flow periods. Green Roofs for Healthy Cities reports that green roofs can retain 70% to 90% of the precipitation that falls on them during the summer, and between 25% to 40% during the winter,[19] meaning green roofs could significantly reduce the volume of stormwater discharge from roofs following a heavy rain event.

A blue roof is explicitly designed to capture and slowly release rainwater over a period of time, in order to reduce the peak runoff intensity and volume and enhance stormwater management capabilities of the roof.

Water can be temporarily held in a detention layer beneath the green roof and hardscape elements; restricted by weirs at roof drain inlets; collected into trays for evaporation; and/or captured and stored in a cistern for reuse to supplement irrigation, toilet flushing, cooling tower needs, and water features. A building's structural capacity should be evaluated and enhanced if necessary.

Projects seeking sustainability accreditations such as the USGBC's Leadership in Energy and Environmental Design (LEED) rating system, Green Globes, or Living Building Challenge may leverage green roofs for points. Owners may also consider incorporating green roofs to enhance amenity space. However, the hardscape (pavers, wood decks) and swimming pools often included in amenity space can significantly reduce the square footage of the green roof elements and its stormwater management capabilities.

Hybrid assemblies that incorporate green and blue roof elements can be a powerful combination of detention and retention to address stormwater management, and they have been reported to reduce runoff peak intensity and overall runoff volume by nearly 50%.[20] These hybrid assemblies can control the amount of weight being added to a roofing assembly, while increasing the rainwater storage capacity.

Buildings with blue and/or green roofs contribute to the resilience of the communities by slowing runoff. They have the potential to enhance the resilience, adaptability, and sustainability of the building when water is captured and reused.

Resilient Incentives and Tools

In 2009, Toronto was the first city in North America to pass a green roof law. Today, many other cities have followed suit, including New York City; Washington, DC; Chicago; Denver; Portland; and San Francisco. These cities have legislation in place, often to address two concerns: stormwater runoff, and UHI effect (which will be discussed in the next section). Stormwater management measures can include permeable pavement, cisterns, and green and blue roofs.

Programs such as RELi provide a holistic approach to resilient design of roof systems, incentivizing adaptive design considerations and implementation to address extreme rain and weather events. This includes credits for rainwater harvesting, and specifically notes underutilized water-harvesting opportunities such as roofs and paved areas. Harvesting rainwater from the roof for drinking water during emergencies through incorporation of roof membranes that comply with NSF International Certification P151 could also contribute to points under the RELi program.

In light of the increased intensity, duration, and frequency of storms, RELi incentivizes users to go beyond the 100-year storm used in the code-minimum design approach. Additional credits are provided for projects that harvest and store rainwater to cover emergency operations, including toilet flushing and mechanical equipment.

RELi also incentivizes the use of green roofs in a variety of resilient aspects, including stormwater management, reduction of the UHI effect, community garden space, habitat restoration, and food production, including habitats for bees, free-range chickens, and aquaponics.

Additionally, there are publicly available tools, including the Naturally Resilient Communities,[21] which provide nature-based solutions to address flooding, including green roof resources.

Energy Efficiency

Electrical power outages lead to a loss of building heat or air conditioning, which can reduce or prevent functional habitability and business operations in affected buildings. The impact of power outages becomes even more significant in urban areas when considering thermal safety and passive survivability during emergencies, given that annual mean temperatures can be up to 5°F warmer than their surroundings in urban areas, and up to 22°F warmer in the evening due to the UHI effect.[22]

From a low-slope roof design perspective, continuous air barriers, continuous insulation, and cool roof membranes can help reduce energy loss and heat gain during power outages, thereby making a building more resilient.

Air Barriers and Roof Membranes

Since 2012, the International Energy Conservation Code (IECC) has required a continuous air barrier, which is defined as a "combination of interconnected materials, assemblies, and sealed joints and components which together minimize air leakage into or out of the building envelope." The ultimate goal of airtightness is whole-building performance and energy efficiency. To help accomplish that goal, the IECC specifies aspects of air barrier design and installation for continuity across joints, penetrations, and assemblies.

The roof can be an integral part of the energy efficiency of a building, especially when the roof-to-wall ratio is high. The roof assembly becomes an important element of the continuous air barrier, as it is one of the six sides to any building, and a necessary component of an airtight structure.

Providing continuity of the air barrier across the roof system could mean the roof membrane is utilized as the air barrier, which can be effective if properly designed and detailed, or could include a dedicated air barrier at the topside of the roof deck. An air barrier at the deck level is a primary means of mitigating air intrusion by preventing air from reaching the insulation layer, possibly reducing the effective R-value, and increasing the condensation potential.

When considering resilience in terms of maintaining internal temperatures during power outages, attachment of the roof membrane can play an important role. Energy efficiency is enhanced when the roof membrane is adhered rather than secured with fasteners. Membrane fasteners and plates create a thermal bridge, allowing heat to flow through each fastener, which is what the roof insulation is intended to prevent. Adhering the roof membrane reduces the heat flow by reducing fluttering that draws air into the roof system. This, in turn, reduces the external to internal temperature differential. An adhered roof membrane also prevents air intrusion, or the flow of interior air passing into the roof system, which can happen when a mechanically attached roof membrane flutters or billows with the wind.[23]

Energy efficiency will help with thermal safety and passive survivability during emergencies when grid or stored power reserves are not available. Continuity of the air barrier across the roof system and adhering the roof membrane both contribute to energy efficiency. Cool roof membranes can also contribute to these efforts and lower the UHI effect.

Cool Roofs and Urban Heat Island Effects

The code provides minimum roof reflectance and emittance requirements for roof membrane selection in climate zones 1, 2, and 3. Known as cool roof membranes, those with higher reflectance and emittance requirements reflect the sun's energy, lower the internal temperature rise, and reduce air conditioning loads in the summer. Each of these contributes to energy efficiency.

Beyond reflective roof membranes, there are ongoing efforts to develop membranes that can actively cool a roof's surface. Reflective roofs radiate heat back into the sky during the night, lowering the roof's surface temperature to below that of the surrounding air. An Australian team at the University of Technology, Sydney, has shown that it is possible to lower a roof temperature significantly below ambient temperatures during the day as well, as shown in *Figure 12*.

The team's experimental roof materials have been shown to radiate back more heat than they absorb from the sun. While this work is still in the research phase, it is a good example of how building enclosure technology could adapt to changing climate needs. As the severity of the UHI effect increases, this adaptation to a roof membrane could positively contribute to UHI reduction.

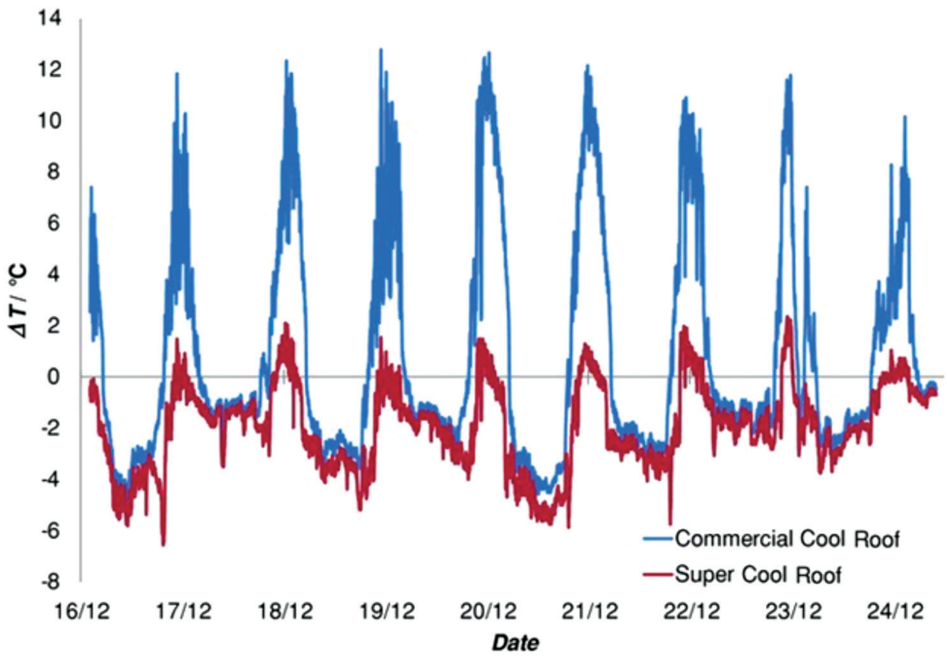


***Figure 12 – Impact of super cool roof materials on roof temperatures. Image courtesy of A. R. Gentle and G. B. Smith, in* A Subambient Open Roof Surface under the Mid-Summer Sun.**

Insulation

The IECC has multiple compliance paths, including prescriptive requirements contained within, or performance modeling requirements of ASHRAE 90.1, Appendix G. When LEED compliance is desired, modeling is performed to comply with Appendix G in ASHRAE 90.1. When an existing building is reroofed, the prescriptive path is most often followed to determine the amount of insulation to use.

Insulation can be specified to go beyond code requirements. From a resilience point of view, the right amount of effective insulation can help reduce the amount of energy a building uses and can help keep a building habitable for longer when there is no power.

Compliance with the 2018 code requirements to install insulation in two layers with staggered and offset joints helps reduce thermal loss through gaps and enhances thermal efficiency. Code does not currently include provisions for thermal bridging as it relates to the attachment of the roof. However, recent research into the overall thermal impact of the fasteners (at a rate of 1/sq. ft.) that penetrate roof insulation has found the effective R-value can be reduced by up to 29% when the insulation is mechanically attached.[24] Reducing overall fastener density reduces the thermal loss, which improves the effective R-value.

To improve the effective R-value of the roof system and balance system cost, the bottom layer of insulation can be mechanically attached, and the upper layers of insulation and the membrane can be adhered. The building will use less energy and will provide a more habitable environment for a longer period of time when there is no power with a more effective thermal control layer.

Vacuum-insulated panels, which offer a significant increase in the R-value per inch as shown in *Figure 13*, are available but not yet widely used. Incorporation of these panels could be a valuable solution for existing buildings that face height limitations to comply with today's code requirements for R-value.

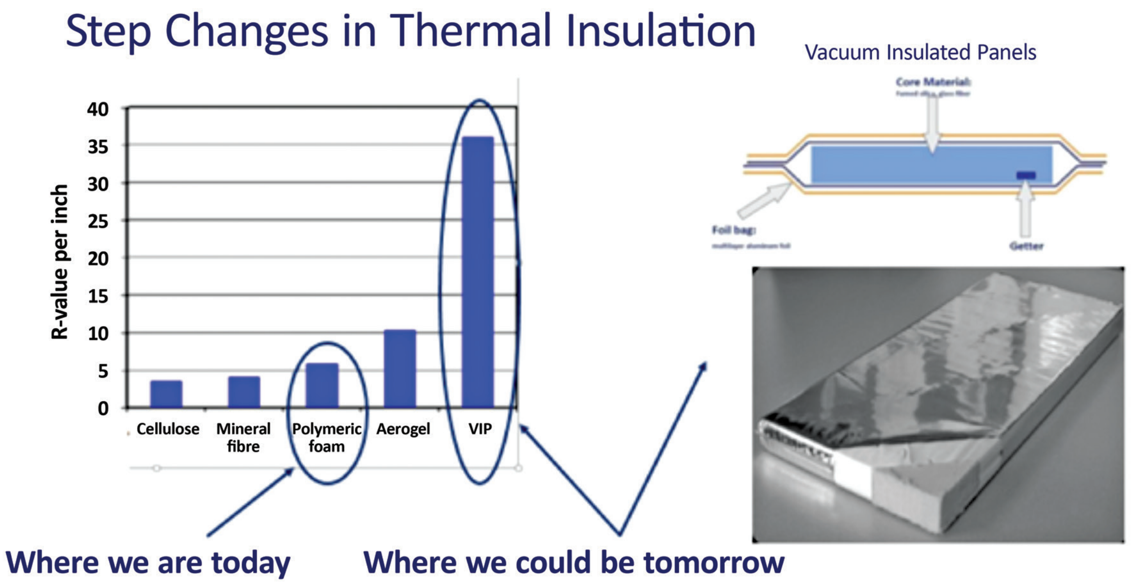


Figure 13 – R-value of vacuum-insulated panels compared to conventional insulation. Image courtesy of Oak Ridge National Laboratory.

Resilient Incentives and Tools

Programs such as LEED v4 and RELi incentivize more resilient design by providing points for reduced energy demand through efficiency and conservation methods above and beyond the code and ASHRAE 90.1 2010 baseline requirements. Incorporation of airtightness strategies, cool roof membranes, and effective thermal control layers are necessary to achieve these goals.

Through the daily evaporation and transpiration cycles, plants are able to cool cities during hot summer months and reduce the UHI effect. The light absorbed by vegetation would otherwise be converted into heat energy. National Research Council of Canada (NRC) estimates that a green roof can reduce air conditioning use in a building by as much as 75%.[25] Additionally, green roofs can reduce rooftop temperatures by 30°F–40°F when compared with conventional roofs, and can reduce city-wide ambient temperatures by up to 5°F.[26,27] This might not sound like a consequential reduction, yet this significantly reduces the heat mortality risk of the urban population.[28]

Consequently, many cities have included green roofs, solar arrays, and cool roof membranes into their local ordinances to reduce the UHI effect. The LEED Pilot Credits on Resilient Design include mitigation measures to address extreme heat, and RELi provides points for reduced site environmental impacts on the UHI effect, both of which could include implementation of a cool roof membrane and/or green roof for a more resilient building.

Incorporation of cool reflective coatings on hardscape areas of green roofs or hybrid assemblies could also contribute to the reduction of the UHI effect, while creating rooftop community space as shown in *Figure 14*. In LEED v4, the Sustainable Sites credit related to UHI includes the roof as well as the hardscape and vegetation at grade in the calculation for surface reflectivity.

Power Generation

In the face of a power outage, resilient buildings need to provide a functional habitat and passive survivability during emergencies. For long-term survivability, the need for on-site power generation becomes a critical part of the discussion.

If photovoltaic systems (solar arrays) were installed on all of the commercial buildings in the U.S. with roofs over 5,000 sq. ft., they are estimated to provide enough energy to power nearly 60% of the total commercial electricity demand.[29] This effort would reduce the carbon footprint of energy generation and contribute to the resilience of our communities.

While rooftop solar- and wind-generated power installations on commercial and industrial buildings are increasing, they do not provide power to a building in the event that the grid goes down unless they are supplemented with storage. When storage is added, such systems become the basis of microgrids, which often operate at the neighborhood level, contributing to the resilience of the community.

Resilient Incentives and Tools

While the code has largely been silent about sustainable power generation requirements, ASHRAE 90.1 recently incorporated an on-site renewable energy requirement in Appendix G.

Certain states are requiring or incentivizing renewable energy. The state of California now requires all new homes under three stories to incorporate solar power. The incorporation of storage will enhance the resilience of these homes.

LEED Pilot Credits on Resilient Design and RELi both incentivize solar and wind harvesting with energy storage. RELi provides extra points when connected to a neighborhood micro-grid, for contributing to the resilience of the community.

Taking energy generation to the next level, net-zero carbon buildings are highly energy efficient and fully powered from on-site and/or off-site renewable energy sources, providing an additional level of resilience to new and existing buildings. These buildings are inherently resilient in terms of passive survivability during emergencies.

North American cities that have signed the Net-Zero Carbon Buildings Declaration[30] pledging to meet the net-zero carbon standards by 2050 include Montreal, Toronto, Vancouver, Los Angeles, New York City, Portland, San Francisco, Seattle, and Washington, DC.

Additionally, RELi incentivizes net-zero buildings and offers extra points for net-positive or surplus energy production.

Figure 14 – Rooftop playground designed with Streetbond cool reflective coatings.

Daylighting

Resilient design allows buildings to be occupied in the absence of power. While passively maintaining safe temperatures inside the building is necessary, light and ventilation are also important elements to consider.

Passive lighting techniques can include louvers that direct light, tubular daylight devices, clerestories, and skylight. Natural ventilation and passive cooling are often necessary to maintain interior temperatures and contribute to a more resilient building.

Resilient Incentives and Tools

The LEED Pilot Credits on Resilient Design and RELi programs offer points for thermal safety and passive survivability during emergencies, which can be achieved with natural ventilation combined with passive cooling efforts, such as airtightness, cool roof membranes, green roofs, and an effective thermal control layer.

Resilient and Adaptive Design Conclusions

As weather events become more extreme, today's solutions for improving resilience of the built environment may not be sufficient. Compounding the effects of the changing climate is the increasing urban population, which makes resilience an even more critical discussion.

Sustainable choices are available, readily made, and incentivized by programs such as LEED, Living Building Challenge, and Green Globes. Resilience is about investing in our future by anticipating future challenges, designing above-code minimum requirements, providing energy independence, and incorporating considerations that are community minded into design strategies. We can no longer build to currently known challenges but have to consider future unpredictability.

Fortunately, ways to improve the toughness and resilience of today's building are available, whether they are new construction or restorations of existing buildings. To improve the ability to cope with or avoid harmful impacts, and reduce risk and vulnerability, project teams must prioritize incorporation of resilient and adaptable practices in the design of our buildings. Implementation of these design elements can increase initial installation costs and maintenance efforts, but the return on investment can be significant. Resilient and adaptive buildings do require a commitment to provide the best approach with a focus on future impacts and long-term performance.

Examples of available tools to design for future events include very severe hail ratings, better-than-code wind resistance requirements and R-value, design elements that contribute to stormwater management and UHI effect reduction, and incorporation of energy generation and storage, such as rooftop solar and wind power.

Programs such as RELi and LEED Pilot Credits on Resilient Design provide a framework for resilient design considerations. Both include design considerations for building resilience in the wake of earthquake, flood, hurricane, high winds, tornado, wildfire, winter weather, drought, landslide, and tsunami. Business continuity and community resilience are considered and incentivized.

The U.S. Climate Resilience Toolkit[31] provides a framework to discover and document climate hazards, then develop workable solutions to lower climate-related risks. The toolkit includes a catalog of digital tools to help project teams take steps to build resilience. WeatherShift™ is another tool that allows for a design "stress test" using a range of plausible futures, allowing project teams to consider the risks over time.

Again, we can no longer build to currently known challenges but must consider future unpredictability.

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