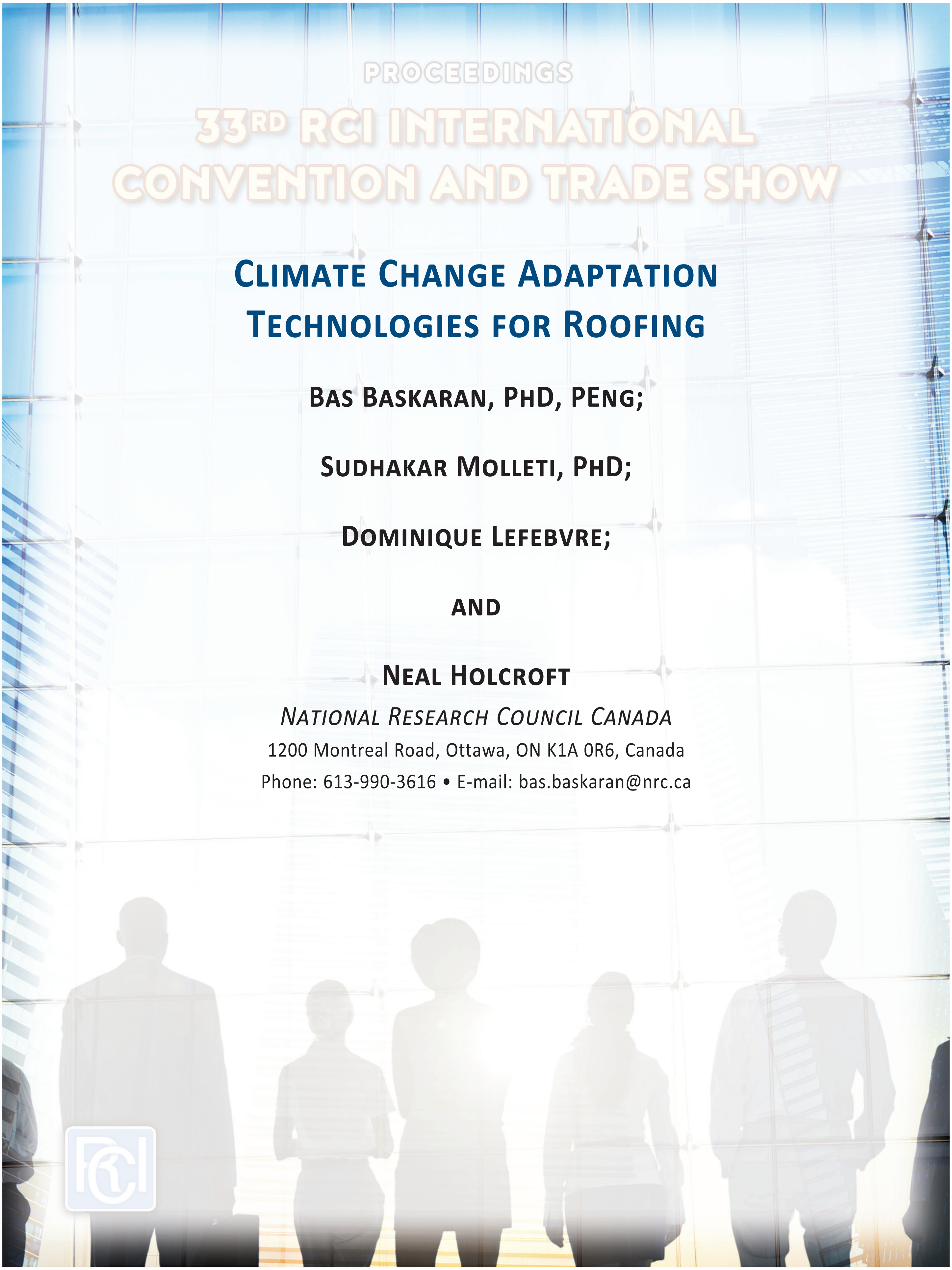

PROCEEDINGS

33RD RCI INTERNATIONAL CONVENTION AND TRADE SHOW

CLIMATE CHANGE ADAPTATION TECHNOLOGIES FOR ROOFING

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ABSTRACT

Wind climate adaptation of building envelopes depends on three key factors: design, evaluation, and installation. A National Research Council of Canada (NRC) project proposes a three-step approach for climate adaptation of commercial roofs. To discuss this endeavor, 45 North American roofing professionals met at the NRC in Ottawa, Canada, on December 15, 2016. The consultation was divided into the following three areas of focus: design loads, resistance, and installation techniques. The three main aims of the consultation were to determine the following for each focus area: consensus on the current state of practice, identification of the knowledge gaps, and formulation of research and development (R&D) needs. The speakers will present the overall project and discuss outcomes from the industry consultation.

SPEAKERS

"BAS" BASKARAN, PHD, PENG — NATIONAL RESEARCH COUNCIL CANADA

DR. BASKARAN is a group leader at the National Research Council Canada. As a professional engineer, he is a member of RICOWI, RCI, ASCE, SPRI, ICBEST, and CIB technical committees. He is a research advisor to various task groups of the National Building Code of Canada and is a member of the wind load committee of the American Society of Civil Engineers. He has authored and/or coauthored over 200 research articles and received over 25 awards, including the Frank Lander Award from the CRCA and the Carl Cash Award from ASTM. Dr. Baskaran was recognized by Her Majesty Queen Elizabeth II with the Diamond Jubilee medal for his contribution to fellow Canadians.

DOMINIQUE LEFEBVRE — NATIONAL RESEARCH COUNCIL CANADA

DOMINIQUE LEFEBVRE is a research associate at the National Research Council Canada. Her research area focuses on the development of tools and techniques for climate adaptation of commercial roofs. At present, she is working on client-driven projects on advanced insulations, roofing materials, and systems. She represents NRC at the ASTM C16–Thermal Insulation and CAN/ULC-S700A–Thermal Insulation Materials and Systems committees. She received her master's degree in chemical engineering from the University of Ottawa.

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CLIMATE CHANGE ADAPTATION TECHNOLOGIES FOR ROOFING

"We cannot direct the wind, but we can adjust the sails." — Dolly Parton

ABSTRACT

To address the effects of climate change on Canadian infrastructure, the National Research Council Canada (NRC) has undertaken a major project entitled "Climate Resilient Buildings and Core Public Infrastructure." One of the objectives of this project is to enhance the longevity of building envelopes such that they can adapt to climate change. Climate adaptation of building envelopes depends mainly on three key factors: design, evaluation, and installation. Toward developing climate adaptation technologies and tools for roofing, this paper presents a three-step approach that will be described below.

INTRODUCTION

The United Nations' Intergovernmental Panel on Climate Change (IPCC, 2007) referred to two significant terms:

- Mitigation, which is aimed at reducing emissions to minimize global warming or "avoid the unmanageable," and
- Adaptation, which is "managing the unavoidable."

Mitigation efforts are clearly important in terms of slowing the rate of climate change. Given that the climate system has already changed, an adaptation approach acknowledges that there will be a need to develop adaptive strategies for buildings to ensure that they can withstand, absorb, and recover from the stresses of unavoidable climatic events. The IPCC has reported that the warming of the world's climate system is "unequivocal," as evidenced by increases in atmospheric and ocean water temperatures, as well as widespread melting of polar ice caps.

In Canada, the impetus for renewed attention to climate-resilient design came with the release of a report on mitigating the impacts of severe weather by the Office of the Auditor General of Canada (Office of the Auditor General of Canada, 2016). The auditor general's report identified several omissions in the National Building Code of Canada (NBCC) relating to climate trends with potential impacts on buildings and structures for decades to come. So, to address the effects of climate change on Canadian infrastructure, the NRC has undertaken a major project entitled "Climate-Resilient Buildings and Core Public Infrastructure" as a collaborative project. The objective of this project is to develop tools for resilient design and rehabilitation to ensure that existing and future climate change and extreme weather events are addressed.

Resilience in the context of roofs refers to the ability of a roof to continue to function as intended in the face of environmental stresses imposed now and in the foreseeable future. The international roofing community is addressing the concept of climate-resilient roofs as a way of addressing unavoidable climatic events (International Committee on Roofing Materials and Systems). Throughout a roof's lifetime, the probabilities of extreme weather events are not likely to remain the same; and therefore, historical weather data no longer provide a reliable map for future building code requirements. Insurance Australia Group (IAG, 2002) calculated that a 25% increase in peak gusts causes a 650% increase in building damage. New resilient strategies are thus needed to ensure the durability of roofing systems.

Due to climate change, there will be uncertainties in the wind patterns, which have the potential to adversely affect wind pressures on roof assemblies. The windstorms might have greater speed, longer storm duration, and/or increased frequency of occurrence. These uncertain factors present greater wind resistance demand on roof assemblies. Similarly, there is uncertainty concerning the wind performance of the roof system, which is caused by a variety of factors, including roof covering material deficiencies, inadequate uplift-resistance test methods, design deficiencies, and workmanship deficiencies. To avoid damage caused by windstorms that may be stronger, of longer duration, and/or more frequent due to climate change, it is recommended that a variety of actions be taken to achieve greater reliability in the wind resistance of roofing systems than is now commonplace.

Under this project, several working groups, including NRC Construction, are focused on developing tools and techniques for existing and new buildings, as well as codification material for the adaptation of building envelopes. The following three-step approach is proposed.

1. Dialogue with the industry to migrate from its current state of practice of Allowable Stress Design (ASD) to the practice of codified Load-Resistance Factor Design (LRFD).
2. Fill the existing knowledge gap in the quantification of the resistance factors for various building envelope components and materials.
3. Develop a resiliency vs. risk mitigation approach to achieve climate adaptation for building envelopes.

ASD VS. LRFD

Structural engineers apply the LRFD for main wind force resistance systems such as columns and beams. However, the building envelope community (BEC) for the most part applies ASD for the design of building envelope/claddings/skin, which means that there is an inconsistency in the design of buildings.

Figure 1 numerically illustrates the ASD for a typical low-slope commercial roof wind design. For this low-rise building, the rooftop is divided into three wind zones per the NBCC (NBCC, 2015) or ASCE 7 – 2010 and wind uplift loads are calculated. In this example, it is assumed that the design loads are 100, 75, and 50 psf for the corner, edge, and field of the roof, respectively. To satisfy this design requirement, the roofing system suppliers perform laboratory evaluation by constructing roof mock-ups with the associated components and testing the systems—under either static test protocol (FM 4474) or dynamic test protocol (CSA A123.21). The outcome of the lab experiments provides a sustained wind uplift pressure for the constructed system. If the sustained ratings from a dynamic testing are 165, 120, and 90 psf for the corner, edge, and field of the mock-ups, respectively, they are divided by the experimental factor of 1.5 to obtain system resistances of 110, 80, and 60 psf, respectively. Since the system resistance/capacity is higher than the design requirements, these systems with the associated components and installation procedures can meet the building code requirement.

However, in the case of the static testing, a safety factor of 2.0 is used. Normally, only the field of the roof is tested, and prescriptive enhancements are made for the edge and corner zones, making it easier for installation practicality. However, the applicability of the enhancements to satisfy the code requirements remains a question.

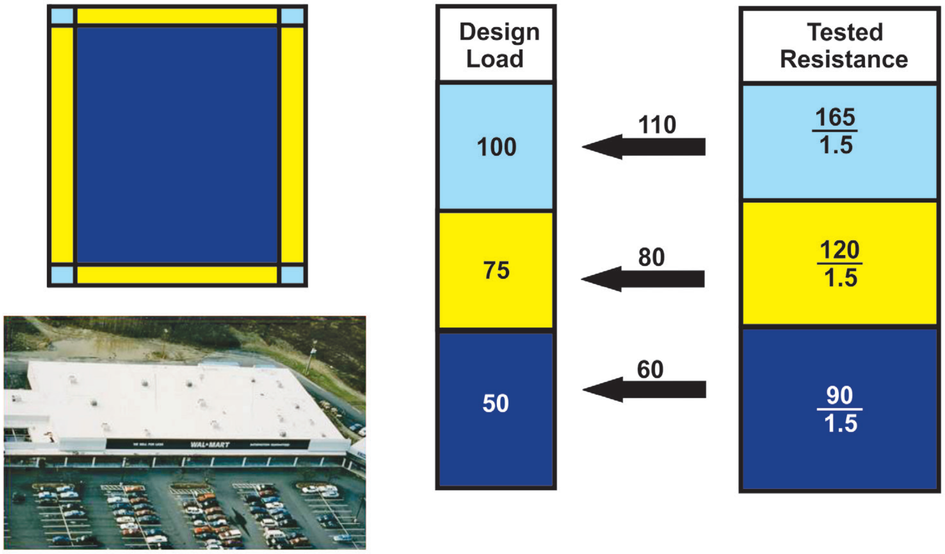

Figure 1 – Classical load vs. resistance design approach for climatic loads.

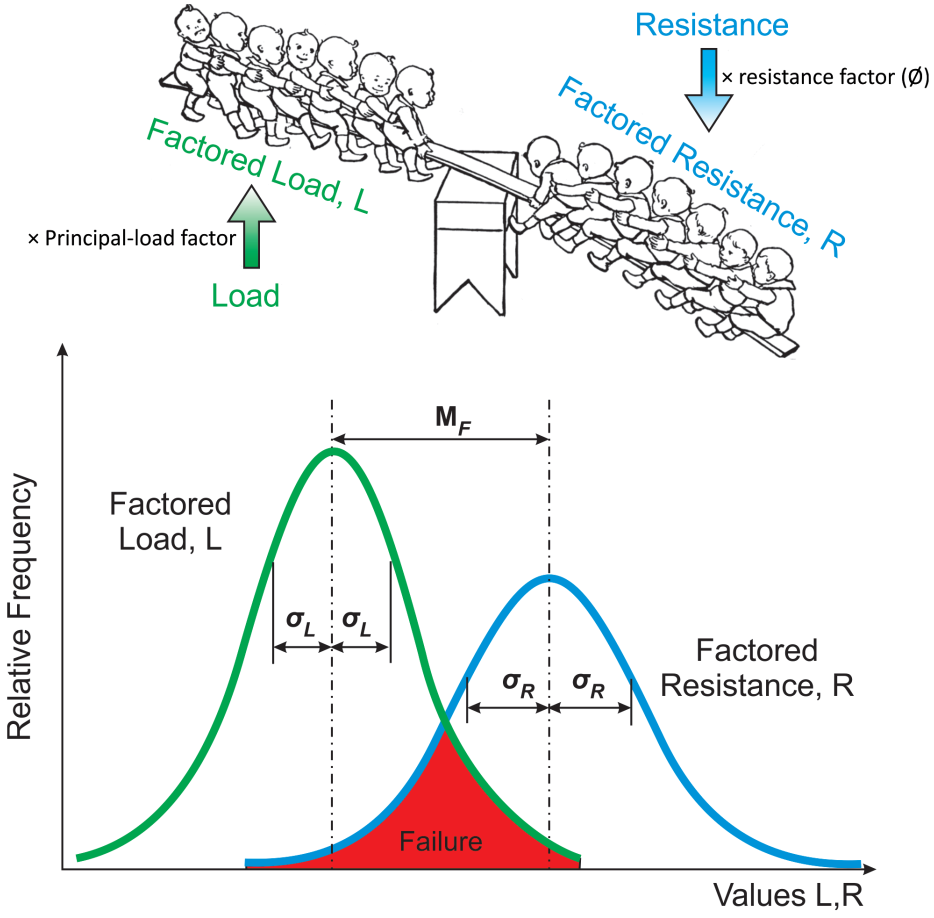

Figure 2 – Load resistance factor design approach for climatic loads.

Figure 2 shows the LRFD approach where the risk involved in the design load is adjusted by a load factor to account for the uncertainties in the climatic load determination, and the system capacity is adjusted by a resistance factor to account for variability in the material properties, uncertainties in the resistance predications, and others. It should be noted that the load factor for wind is greater than 1.0; it is 1.4 for NBCC (2015) and 1.2 for the ASCE 7-2010, whereas the resistance factor is less than 1.0. More importantly, there is no consistency in the specification of the resistance factors for various building envelope components such as walls, roofs, windows, and other claddings, which represents another missing element in the NBCC and ASCE. NBCC (2015) provides the following language for the resistance factor in part 4.1.3.2. - Division B:

> k) nominal resistance, R, of a member, connection or structure, is based on the geometry and on the specified properties of the structural materials,
> l) resistance factor, □, means a factor applied to a specified material property or to the resistance of a member, connection, or structure, and that, for the limit state under consideration, takes into account the variability of dimensions and material properties, workmanship, type of failure, and uncertainty in the prediction of resistance, and
> m) factored resistance, □, R, means the product of nominal resistance and the applicable resistance factor.

In the case of the window and curtainwall industry, there is a consistent approach in the development of resistance factors such that they can be used for reliability-based designs. However, the adaptation of resistance factors is still under development for other building envelope industries, such as roofing (both residential and commercial), concrete masonry units (CMU), brick cladding, and exterior insulated finish systems (EIFS). The metal roof industry led the LRFD approach by developing resistance factors as per the *Design Guide for Standing Seam Roof Panels* (CF00-1, 2000).

A NOVEL APPROACH TO DEVELOP SYSTEM RESISTANCE FACTORS

Taking the wind uplift performance of a roof assembly as an example, a scientific approach is ongoing at the NRC to develop a reliability-based resistance factor. *Figure 3* shows the critical components of a commercial mechanically attached membrane roof and the wind-induced forces. They can be divided as follows:

- Components (membrane, insulation, and deck) are subjected to either tensile or compressive forces.
- Interface (membrane seam, membrane and insulation, fastener, and deck) are subjected to either tensile, shear, or peel forces, depending on the interface location or a combination of the three.
- Systems (mock-ups) are comprised of the assemblage of components and interfaces, and they are subjected to the wind uplift forces.

In developing the resistance factor, the approach should consider all of the above scenarios for interactions and corresponding uncertainties.

Figure 4 shows an example of the probability-based resistance for the major components of a roof system—namely waterproofing component (membrane), thermal barrier (insulation), structural support (deck), and the whole system. In this distribution, it is expected that the mean resistance of the system could be represented by the lowest resistance of the three components. This is justified by the fact that the system is considered failed if any one of the components fails. This justification aligns well with the "weakest link" concept as described in Baskaran et al. (2009). Such developed factored resistance distributions are suitable for the LRFD.

Figure 5 shows a typical probability characteristic of a mod-bit membrane subjected to tear forces. For this exercise, over 100 samples of the mod-bit membranes were tested in accordance with ASTM D5147/D5147M - 14, *Standard Test Methods for*

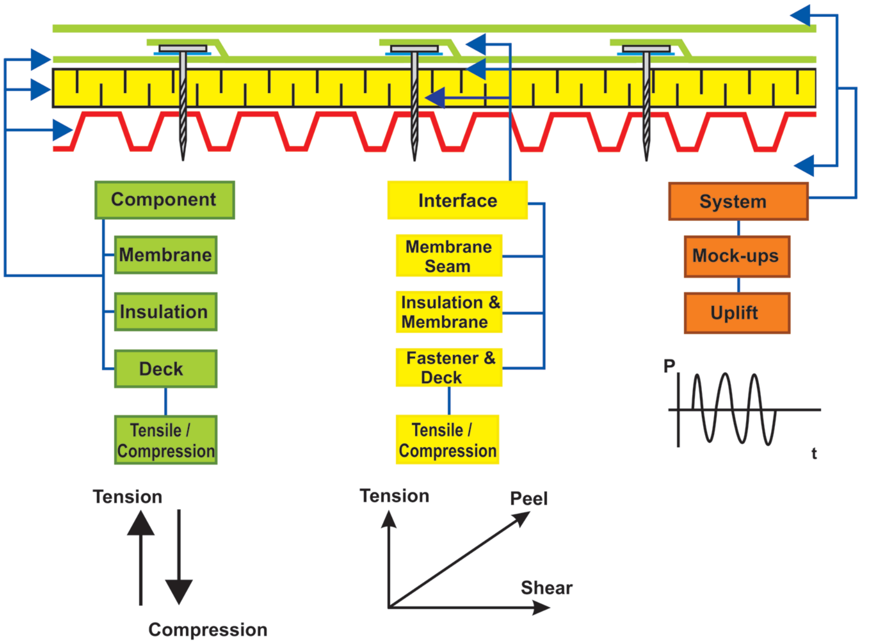

Figure 3 – Component vs. interface vs. system approach for resistance factor development.

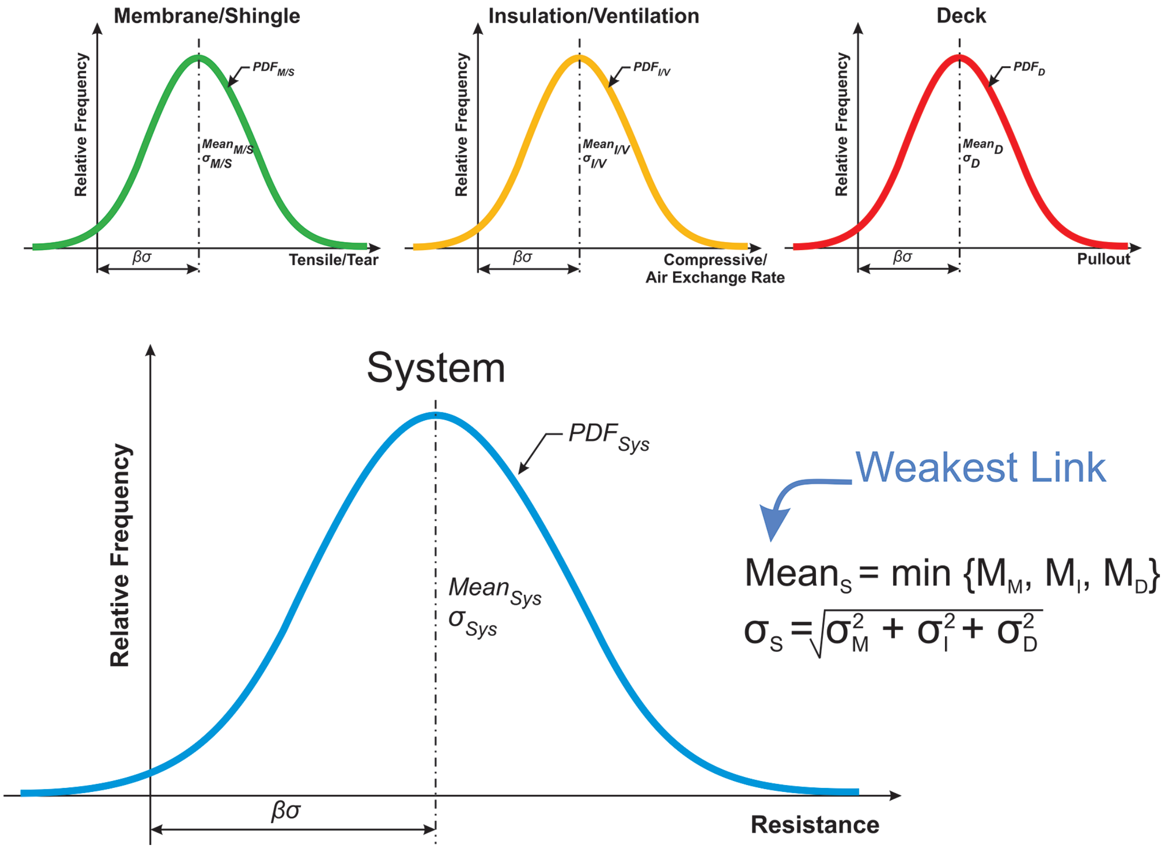

Figure 4 – Generalized resistance factor development for commercial roofs.

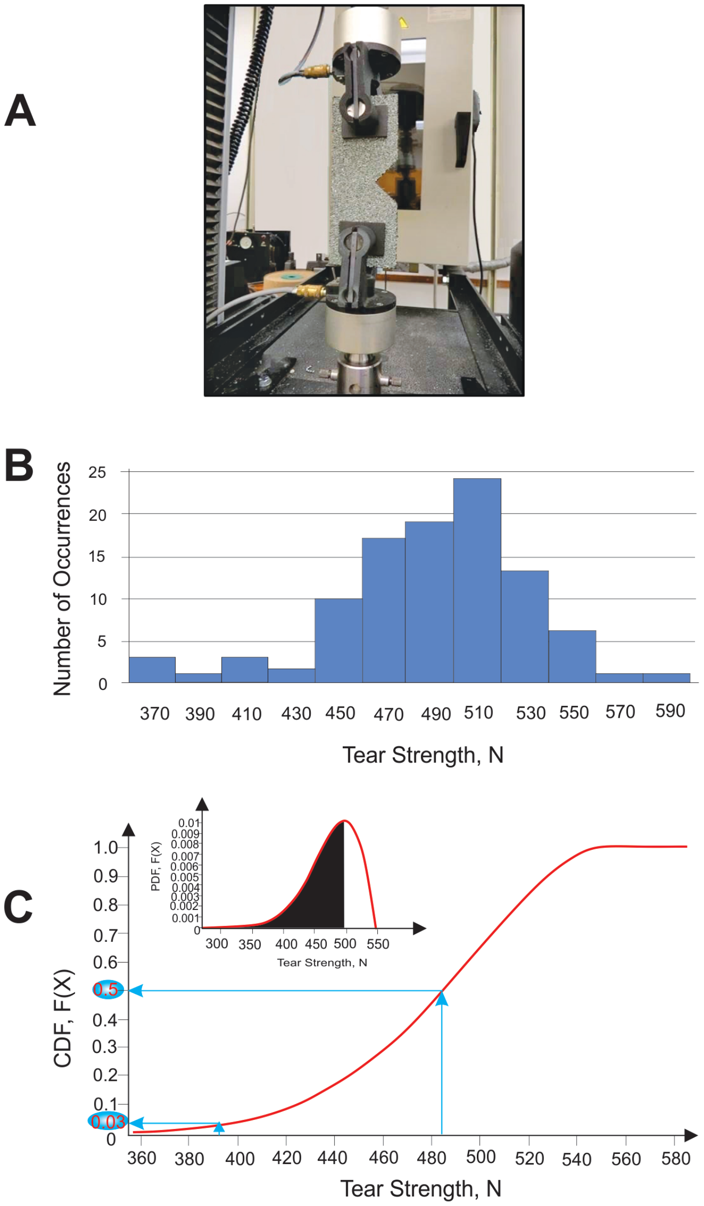

Figure 5 – Probability characteristics of a modified-bitumen membrane subjected to tear force.

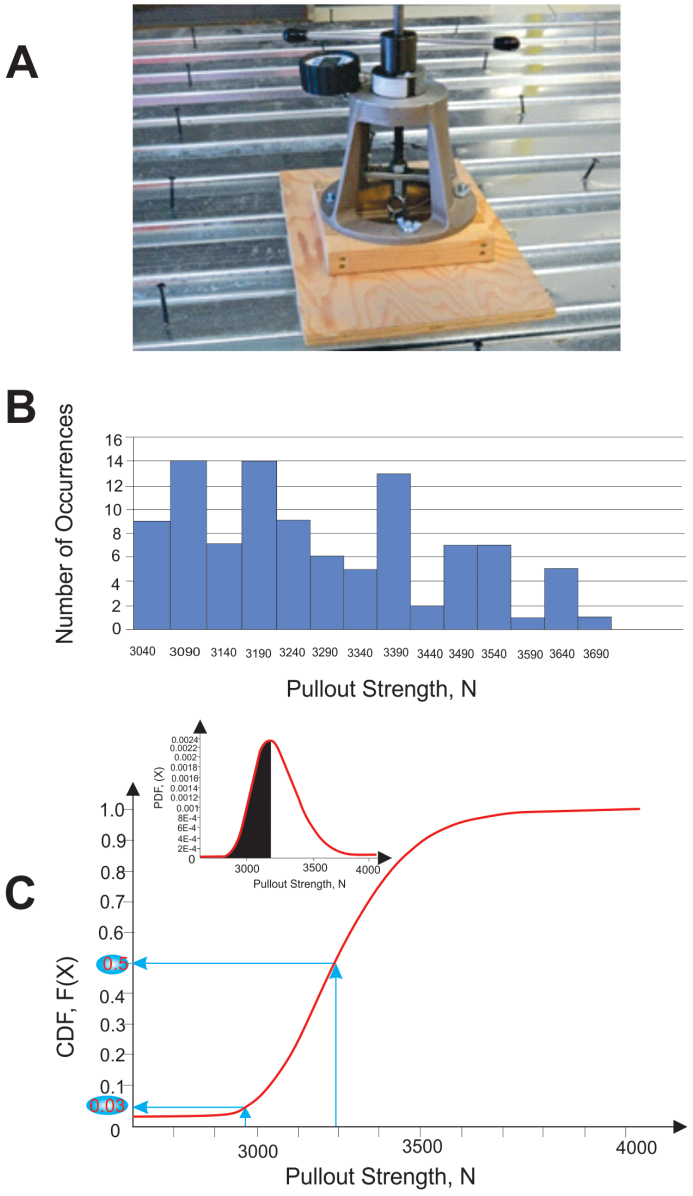

Figure 6 – Probability characteristics of fastener/deck interface subjected to pullout force.

Sampling and Testing Modified Bituminous Sheet Material, shown in *Figure 5A*, to gather a statistically independent data set. A histogram of the number of occurrences for different tear strength is shown in *Figure 5B*. *Figure 5C* shows risk-based information as a cumulative probability density function. For example, a designer can expect a tear resistance of 485N and less with 50% probability, whereas for a tear resistance of 390N and less, the probability reduces to 3%. *Figure 6* shows the fastener/deck interface resistance probability in the same format as that of *Figure 5*. There is 47% probability to expect a fastener resistance between 2800 and 3250N.

Figure 7 shows the probability characteristics of the tested adhesive-applied mod-bit roof systems. All the tested systems were installed by a professional applicator to include the variability in installation, after which the systems were subjected to the dynamic wind load cycle (CSA A123.21-14). Over 40 mock-ups of different material combinations were investigated to develop the parent data set for the probability distribution. *Figure 7B* is the histogram plot of the sustained wind uplift pressures. The majority of the systems had a wind uplift rating ranging from 75 to 135 psf. *Figure 7C* shows both the probability distribution, as well as the cumulative frequency plot. From the plot, the data show that there is 48% probability to expect wind rating between 50 and 100 psf, and there is 70% probability for wind rating between 75 to 140 psf.

CALIBRATION OF SYSTEM RESISTANCE FACTOR FOR MOD-BIT SYSTEMS

This section presents an example of the calibration of a resistance factor for the mod-bit roof assemblies. The ongoing research at the NRC under the SIGDERS consortia will address the other commercial roof assemblies. ASTM D5457-15, *Standard Specification for Computing Reference Resistance of Wood-Based Materials*

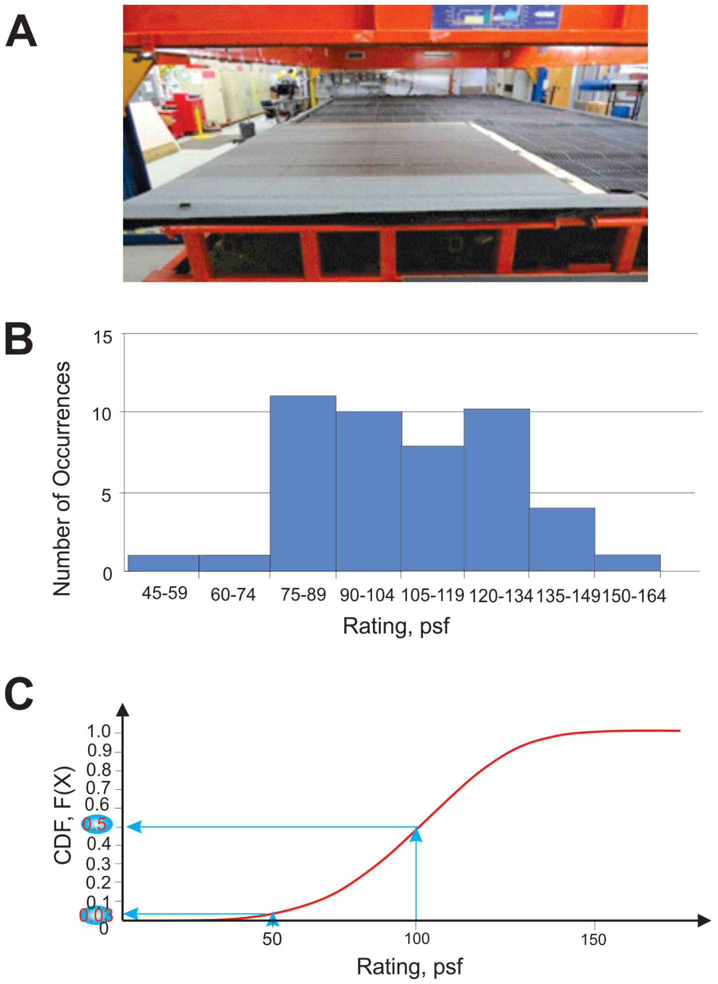

Figure 7 – Probability characteristics of modified-bitumen roof systems subjected to wind uplift pressures.

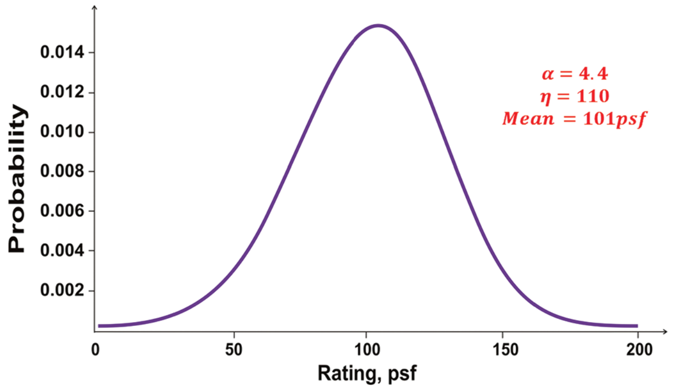

Figure 8 – Weibull probability distribution from experimental data.

and Structural Connections for Load and Resistance Factor Design, describes the resistance factor calculation method for wood-based materials and structural connections for load and resistance factor design (LRFD). This established approach is used in the current study. *Sidebar 1* details the parameters required in calibrating the reference resistance. (See sidebar.)

The procedure described in the sidebar gives a resistance factor of 0.6. In other words, to have 95% reliability, the designer must use 0.6 as the resistance factor, to be multiplied with the rating of the tested assemblies to obtain the wind uplift resistance of adhered mod-bit systems. Therefore, the tested ratings that were discussed in *Figure 1*—namely 165, 120, and 90 psf—should be multiplied by a factor of 0.6 to obtain the factored resistance. Then the calculated factored resistance data should be compared with the factored loads as shown in *Figure 2* to demonstrate compliance as per the LRFD approach.

Following the above procedure, *Figure 9* shows the resistance factor for various percentages of reliability. As expected, the resistance factor decreases as the reliability increases. Any decrease in the resistance factor will result in systems with fewer uncertainties in the material selection, component integration, and installation procedures. The LRFD approach enhances the conventional ASD approach by providing the designer with the reliability-based resistance data. As presented in the above example, the resistance factor is developed based on calibration under controlled laboratory conditions and with materials/components manufactured in controlled factories. As such, the resistance factor and the LRFD exclude installation and workmanship uncertainties in the durability determination of a roof assembly.

INDUSTRY CONSULTATION

To obtain industry feedback on this missing link, a consultation with members of the North American roofing industry was held at the NRC in Ottawa, Canada, on December 15, 2016. There were 45 individuals who participated in the consultation process, with designers and manufacturers of equal representation (45% each) and installers (10%). Also, in the past, NRC participated in fact-finding investigations conducted after major hurricanes (Katrina, Charley, and Ivan) as part of the Roofing Industry Committee on Weather

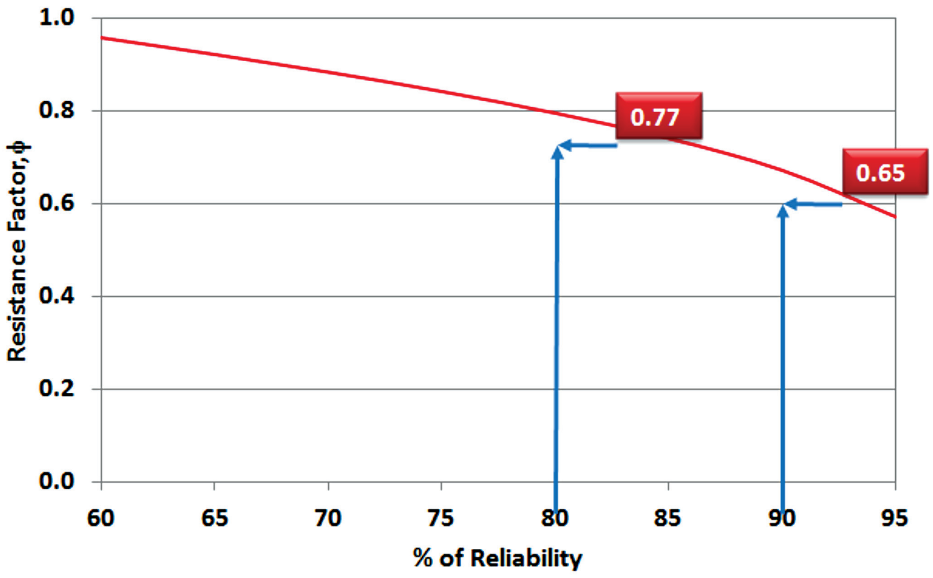

Figure 9 – Ø vs % of Reliability in a modbit system.

Reference resistance,

$$R_n = R_p \times \Omega \times K_R$$

Where:
R_p = Distribution percentile estimate
Ω = Data confidence factor
K_R = Reliability normalization factor

Distribution percentile estimate is calculated as follows:

$$R_p = \eta\,[-\ln(1-p)]^{1/\alpha}$$

Where:
η = Weibull percentile estimate,
p = Percentile of interest expressed as a decimal, and
α = Weibull shape parameter

The coefficient of variation, CV_w, is necessary when determining the data confidence factor, Ω, and the reliability normalization factor, K_R. The CV_w can be estimated from the shape parameter of the Weibull distribution as follows:

$$CV_w \cong \alpha^{-0.92}$$

A step-by-step approach is presented to calculate the system resistance factor, ∅.

Step 1: Forming the Probability Distribution

Over 40 mod-bit systems were tested at the NRC's Dynamic Roofing Facility. The data from *Figure 7B* is inputted to generate Weibull probability distribution (*Figure 8*).

Step 2: Computing the Reliability Parameters

As specified in the ASTM D5457-15, to compute the reference resistance, the following parameters are estimated from *Figure 8*. A confidence level of 95% is assumed for the distribution parameter estimation.

Weibull shape parameter, $\alpha = 4.45$
Weibull percentile estimate, $\eta = 110.5$
Percentile of interest expressed as a decimal, $p = 0.05$

Step 3: Computing the Reference Resistance

From Table 1 of ASTM D5457-15, the data confidence factor, Ω, is 0.88 and the coefficient of variation is 0.25 when the sample size is 40.

From Table 3, the reliability normalization factor, K_R, is equal to 1.155.

Coefficient of variation,

$$CV_w \cong \alpha^{-0.92} = 4.45^{-0.92} = 0.25$$

Distribution percentile estimate,

$$R_p = \eta\,[-\ln(1-p)]^{1/\alpha} = 110.5\,[-\ln(1-0.05)]^{1/4.45} = 56.67$$

Reference resistance,

$$R_n = R_p \times \Omega \times K_R = 56.67 \times 0.88 \times 1.155 = 58 \text{ psf}$$

Step 4: Calculate the Resistance Factor, Ø for the System

$$\text{Resistance factor, } \emptyset = \frac{\textit{Reference resistance, } R_n}{\textit{Mean tested resistance}}$$

$$\text{Resistance factor, } \emptyset = \frac{58}{101} = 0.6.$$

Sidebar 1.

Issues (RICOWI). RICOWI started a Wind Investigation Program (WIP) with the following objectives:

- To investigate the field performance of roofing assemblies after major wind storms,
- To document roof assembly performance and modes of damage, and
- To report the results for substantial wind speeds.

The key to a successful WIP is to ensure that investigation teams are balanced, unbiased, and trained in wind damage assessment. The teams are typically made up of a roofing manufacturer, a roofing consultant, a university or insurance organization representative, and a manufacturer from another sector of the industry. The unique investigation of RICOWI added a new dimension, substandard workmanship to the classical load vs. resistance LRFD design methodology to account for the uncertainties involved in the building envelope installation procedures.

Figure 10 presents a holistic design approach considering the installation uncertainties as the third dimension. As shown, this holistic approach de-risks the uncertainties by increasing the failure zone. This multifaceted design approach was further discussed during the consultation with members of the roofing industry. The consultation was divided into three themes:

- Design loads
- Resistance
- Installation techniques

The three main aims of the consultation were to determine, for each of the above topics, the following:

- Consensus on the current state of practice
- Identification of the knowledge gaps
- Formulation of R&D needs to fill the identified gaps

The roofing stakeholders discussed the adaptation of the design, resistance, and installation techniques to ensure that roofs are resilient to climatic threats. The consultation process began with three opening presentations to introduce the three topic areas. Afterwards, all stakeholders participated via three think tank sessions. Based on the consultation, the following three major projects were developed for climate-resilient roof systems:

1. Guidelines for Commissioning and Certifying the Resiliency of Roofs Subjected to Extreme Weather Events
2. Codification of Material Properties for Building Adaptation to Climate Change
3. Development of a National Standard for Resilience Mapping of Roofs

The full report is available upon request (Baskaran et al., 2016), and a summary of the industry consultation is presented in *Appendix A. Figure 11* identifies the "sweet spot," which is the point where the load, resistance, and installation considerations are combined for resilient building envelope designs, as per the roofing community consensus.

CONCLUDING REMARKS

This paper differentiated the conventional design practice of ASD from the current LRFD. Moving forward, for the design of climate-resilient roof assemblies—a novel concept that includes the installation and workmanship uncertainties—was proposed. To obtain industry feedback on this missing link, a consultation with members of the North American roofing industry was held. The consultation outcomes validated the proposed inclusive approach to minimize design risk and offer durable roofs throughout their service life.

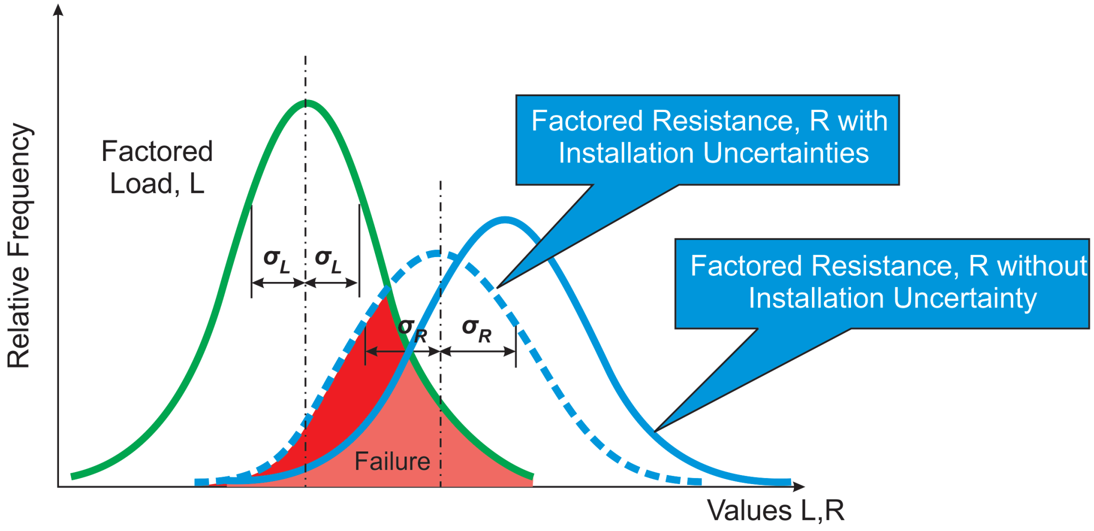

Figure 10 – De-risking the design via load/resistance/installation combination.

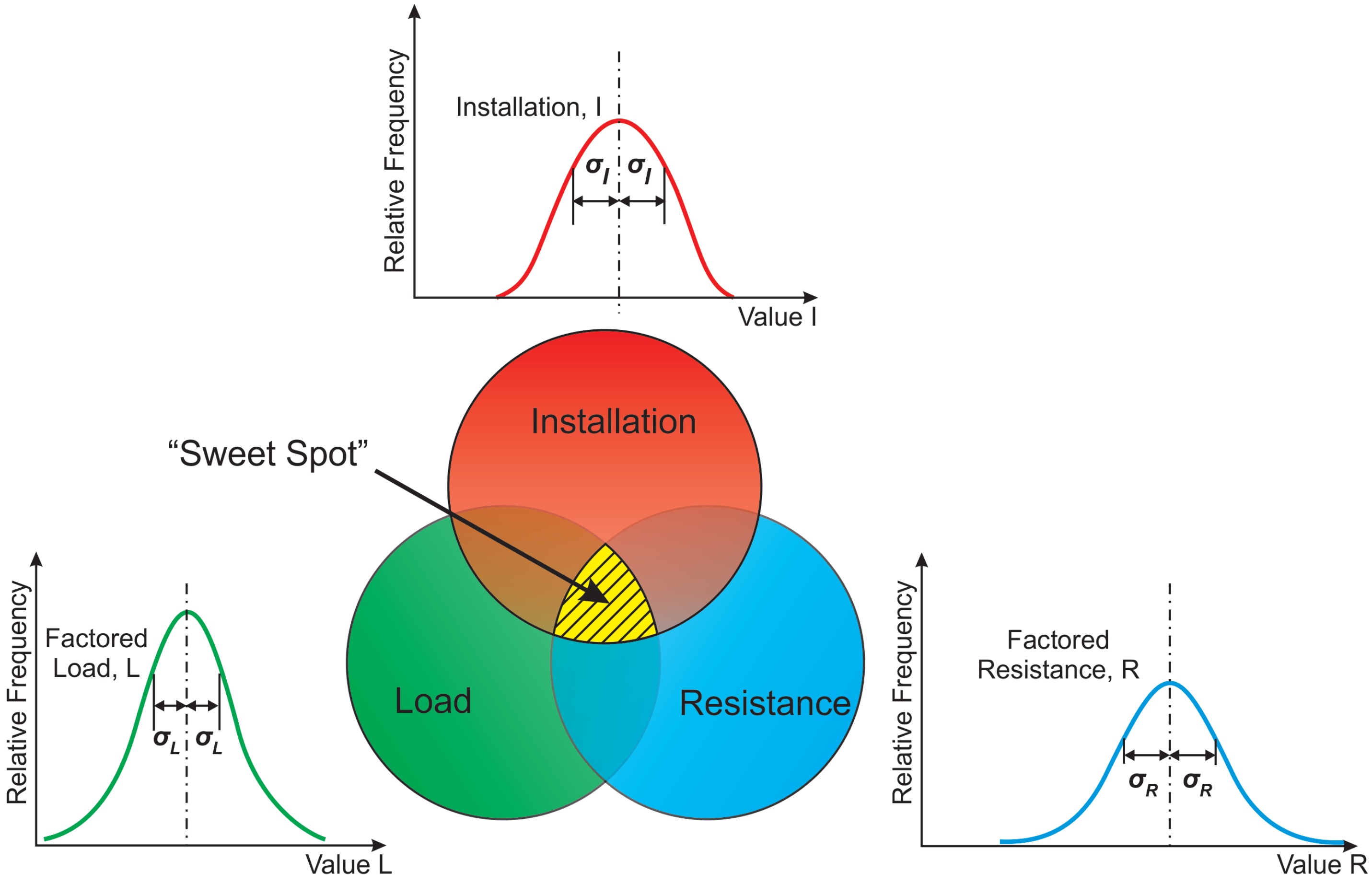

Figure 11 – Proposal for a holistic design approach for building envelope climate change adaptation.

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APPENDIX A: SUMMARY OF THE INDUSTRY CONSULTATION

Design Load

The design load session focused on identifying the required considerations for the adaptation of climatic loads for the design of climate-resilient roofs. A set of questions was provided during the combined session to initiate discussion. The four questions provided are summarized below.

1. Is the use of historical climatic loads (i.e., wind, precipitation, and temperature) suitable for the design of future climate-resilient roofs?
2. How can uncertainties in the magnitude and rate of climate change affect the design of newly built roofs and/or the assessment of existing roofs?
3. What is the current state of practice for the design of climate-resilient roofs against extreme events (i.e., high winds, heavy precipitation, extreme heat/cold waves)?
4. What kind of adaptive strategies can be used for the design of future climate-resilient roofs?

The responses to the questions were divided into three areas: current state of practice, knowledge gaps, and R&D.

Design Loads: Discussion and Conclusions

The current state of practice for design loads is to incorporate greater degrees of conservatism into the design for unknown uncertainties in projected climatic data, which can be variable from one designer to another. The knowledge gaps for the design loads of roofs for the adaptation to climate change include the lack of projected climatic data, the lack of knowledge regarding the uncertainties involved, the lack of guidelines for the design of extreme events, and the lack of adaptive solutions for climate-resilient roof systems. The major R&D needs that were identified include the development of appropriate test protocols for climate-resilient roofs, the testing of roof systems under extreme events, and the development of new load factors for projected climatic data.

Resistance

The resistance session focused on adaptation tools and techniques regarding the resistance of climate-resilient roofs. A series of six questions were provided to the attendees and are summarized below.

1. What are the perceptions regarding performance expectations of roofs among building owners, designers, and system manufacturers?
2. What is the current state of practice for the design of climate-resilient roofs, and what are the perceived impediments to implementing the best available practices?
3. How should the vulnerability of the aging roof stock be tested?
4. What adaptation techniques should be incorporated into new and retrofit roof designs to ensure resiliency, and how will it be evaluated?
5. How should the roofing industry strengthen the existing wind uplift standards and/or design guidelines for added resiliency?
6. What initiatives is your organization undertaking?

The responses to the questions were again divided into three areas: current state of practice, knowledge gaps, and R&D.

Resistance: Discussion and Conclusions

The responses of the stakeholders regarding the current state of practice for roof resistance included following the current codes, standards, and test methods for the design and testing of roofs. The current approaches have been continuously developed and improved. The session highlighted the knowledge gaps related to the unknowns regarding changing climatic conditions, as well as the gaps relating to testing the in-situ and field performance of existing roof systems. The main areas identified for R&D were the improvement of climate and wind maps to account for changing conditions, as well as the development and harmonization of wind tests. Further research on the correlation between laboratory tests and actual field performance was also identified as a need in order to determine the in-situ performance of aged roofing systems.

Installation

The field installation session focused on identifying tools and techniques for the adaptation of installation practices regarding climate change. Five questions were provided and are summarized below.

1. Is there a need to differentiate installation techniques based on the climatic loads?
2. Is there a need for a national certification process?
3. Should NRC facilitate a national mandate to address field installation requirements?
4. What is currently being done to address the quality control of field installations?
5. How should the performance of roof systems be commissioned?

The responses to the questions were again divided into three areas: current state of practice, knowledge gaps, and R&D.

Installation: Discussion and Conclusions

The current state of practice for field installation is through voluntary training, apprentice programs, or manufacturer specifications, which can be variable and are often incomplete. The knowledge gaps for the installation of roofs for the adaptation to climate change include the influence of the environment on the installation quality, the system tolerances for climate changes, training, and regulations. The major R&D needs include system sensitivities to climate changes, development of protocols for proper installation practices, development of advanced roof monitoring strategies, and coordination of laboratory and field testing.