The Elusive Roof Edge Pressure Coefficient

By John B. Hickman

Introduction

When I was in graduate school, I marveled at the arcane thesis topics listed daily in the campus newspaper. Among the memorable ones were "The Fenestration of 3rd Grade Classrooms," "The Rectal Temperature of Hibernating American Black Bears" or my own "Measuring the Stiffness of Thin Fibers and Films." The narrowness of these topics came to mind while preparing this talk on "The Elusive Roof Edge Pressure Coefficient." Although this paper cannot possibly be as intriguing as the hibernating bears, it does contain some interesting insights into roof edge design parameters. As a manufacturer of roof edge devices, we at Hickman understandably have a passion for roof edge details. Therefore, the topic is of crucial interest to us and our industry.

Of all roof components, the perimeter has a special status. Wind engineers largely agree that the roof edge detail is the first line of defense for any low slope roof in severe weather. Johnston and Eastman remarked after viewing the damage from Hugo, "On almost all buildings we looked at, the storm first got a grip on the roof at the roof's edge... Once the storm loosened the roof at the edge, there was little the attachment system in the field of the roof could do to hold the system in place."[1] As important as the roof edge is, few studies in the literature are available to help us with scientific roof edge design for wind effects.

Damage to a building can result from many causes. Fire, earthquake, and wind all take their toll. In most regions, the threat of earthquakes is small, while the threat of fire is ever present and real. Codes of practice have done a marvelous job of reducing fire risk. We have rated doors, wired glass, thick gypsum board, sprinklers, etc. Proper reinforcement of free standing structures achieves protection from earthquakes.

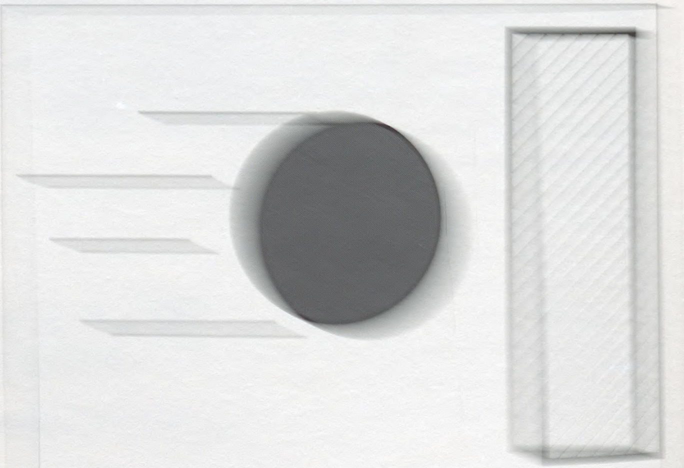
The chief loss from wind storms is usually the water damage to building contents from rain which frequently follows severe wind. Other than fire, water damage can be the most costly disaster likely to impact a building. Roofing is generally tested and rated for resistance to wind uplift. However, we often overlook the highly vulnerable roof edge in roof design, and yet it is said to be involved in 90 percent of roof problems.

This paper reviews some fundamentals of roof perimeter wind design and surveys some best design data available in the field.

Wind Pressure

We derive conversion of wind speed to forces acting on a building from both physical theory and experimental observation. The theory simply says that moving matter has kinetic energy. If you stop moving matter in its tracks, you convert that energy to a force acting upon whatever stopped it. When the matter is molecules of air, we call the force resulting from stopping them "velocity pressure."

Imagine the ball in this illustration as a baseball hurtling toward a wall. Its impact would be a force against that wall. Imagine millions of these balls impacting the wall at once. They would cause millions of times as much force. So it is with molecules of air being stopped by a structure.



What are some tricks the wind plays at the roof perimeter? Among the chief factors which alter strict application of kinetic energy equations are angles of attack, building height, eddy effects and gusts. Of these, the most obvious is the angle of attack. Is the wind normal to the building, or is it blowing obliquely? Perhaps it is parallel to the wall. Pressure forces will depend on the angle of attack. Most studies assume the greatest impact of the wind on a wall occurs when the angle of attack is perpendicular to it. Some methods consider an oblique wind to have the greatest effect.

Another phenomenon is the acceleration of the wind as it blows against a high wall, concentrating as it blows upward and over (or around) the building. This effect can increase the pressure under the edge detail at the roof perimeter much as a boat's mainsail can funnel wind force into a spinnaker. Furthermore, winds have higher speeds aloft than at the surface or at the standard 10-meter level for measuring them. So the height of a building affects design wind forces.

Wind, streaming up and over the perimeter, can establish eddies. The eddy effect changes the force and direction of the wind pressure. A strong eddy can cause a vacuum at the perimeter. Positive pressure, resulting from air infiltration into the building, can add to the force of this vacuum, increasing the potential for edge blow-off.

We must also consider wind gusts. A wind whose average speed would not cause damage could be dangerous because of short, higher velocity gusts. The current U.S. wind standard is based on "three-second wind gust data" mapped across the country.

Pressure Coefficients

A correction factor handles all of the above factors. We call it the "pressure coefficient." We apply it to the basic kinetic energy equation to predict expected velocity pressure for a given condition. Pressure coefficients are theoretically independent of wind speed. So, having a pressure coefficient that accurately handles a condition, one can predict the pressures experienced for any wind speed by multiplying the theoretical velocity pressure by the applicable pressure coefficient.

Here's the rub! It is hardly clear what the pressure coefficients associated with roof edges should be. A few studies and some standards do suggest values for roof edge pressure coefficients. However, there is little agreement on what these values should be. Part of the problem lies in simply defining what and where the roof perimeter is. Another problem results from the difficulty of conducting experiments. Although we now have data from both wind tunnels and field experiments, each of these studies has its flaws.

To simplify this survey of the literature, we will consider the design of the roof edge near the center and away from corner conditions.

Wind Speeds

We generally obtain wind speeds from wind maps published with standards or guidelines. Two factors must be considered when using a wind speed map: Annual Probability ("Recurrence Interval") and Averaging Method. These have a significant impact on the reported wind speeds.

Annual Probability

Annual Probability or Recurrence Interval is the chance that a wind will peak at or above a certain value during any one year. It is the likely number of years between repeats of a given wind speed peak. Most of us have heard of a "Storm of the Century." This is simply trying to say that a storm like "this" comes along at that place only once in a hundred years on the average. The probability is therefore 1/100 (0.01) that such an event will happen during any one year. Wind maps are generally published as 50-year or 100-year Recurrence Interval maps. That is, maps with annual probabilities of 0.02 or 0.01. Given the probability of a wind event, we can calculate the likelihood of it occurring in any given span of years from statistical equations.

Conversion Factors for
MRI other than 50 Years
V=85-100, Continental USA

Mean Recurrence Interval (MRI)	Conversion Factor
200 years	1.14
100 years	1.07
50 years	1

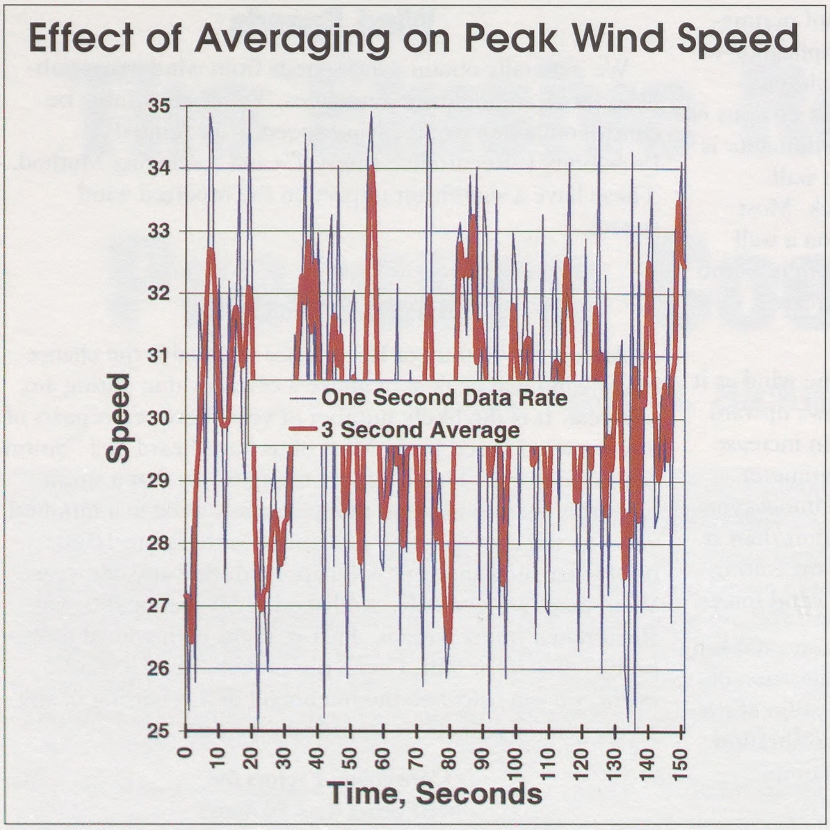
To convert from a longer Recurrence Interval, simply divide the velocity from the longer interval by the conversion factor.[2]

Averaging Methods

The method used to average wind data has a profound impact on the results. You may have heard of studies in which the peak wind speeds or peak forces were phenomenally high. Often such results are simply the random "noise" which can appear in any experiment. This simulation graph shows the difference between measuring peaks and measuring averages. While the peak of the values measured at one second intervals is 35.0, the peak of the running average over three seconds is only 34.

Wind Tunnel Data

The most widely accepted studies have used small scale models in wind tunnels. While such studies are adequate for examining the macro effects of wind pressure on buildings, the "grid" used is too coarse for measuring the micro



effects at the perimeter. Some studies have used full-size models of the roof edge, but boundary effects in restricted wind tunnels have cast doubts on these results as well.

Jack Cermak at Colorado State University has done extensive work with 1:400 scale models[3]. The problem is the scaled size of the pressure taps with respect to the relative sizes of roof edge devices. If a roof edge tap had been used at 1:400 scale, a 1/8″ pressure tap would scale to approximately four feet in diameter—much wider than most edge details used in common practice. If smaller taps were to be used to correct this scaling problem, air viscosity would affect results and would render bad data.

There are studies using full scale models in large wind tunnels, but having a wind tunnel large enough to simulate a real-life building adequately is difficult. Wind tunnel studies have also used 1:100 and even 1:60 scale models, but the scaling problem still adversely influences the results.

Design Guidelines and Standards

American National Standards Institute (ANSI), Factory Mutual Research Corporation (FMRC), the British Standards Institute (BSI), and SPRI (formerly Single Ply Roofing Institute) all have wind design methods covering roof perimeters.

ANSI

ANSI, with the American Society of Civil Engineers (ASCE), established the first comprehensive U.S. wind design standard as part of ANSI/ASCE 7-88, "Minimum Design Loads for Buildings and Other Structures."[4] This document was revised as ASCE 7-93[5] in 1994, but the wind design provisions in that document were unchanged from 7-88. These documents provided design factors for all kinds of structures. They compiled and presented a wind map of the United States based on "Fastest Mile" 50-year recurrence wind speed data collected over many years from weather stations throughout the country. At a point on the map reading, say 60 mph, we would interpret that as a location expecting to experience a peak gust lasting one minute (the time needed for the wind to travel one mile) once every 50 years. A point on the map reading 120 mph would be expected to experience a 120 mph peak gust lasting 30 seconds within a 50-year period.

ANSI Design Pressure Coefficients are based on tributary area, which is the surface area of a component acted upon by the wind. Thus, a fascia ten feet long and one foot high would have a tributary area of 10 square feet. ANSI/ASCE 7-88 gives the vertical roof edge pressure coefficient for tributary areas less than 10 square feet as -2.6 for structures 60 feet or lower and -2.5 for higher

The edge detail on this roof failed, resulting in membrane failure at the perimeter during Hurricane Hugo.

buildings. The horizontal coefficient is -2.5 for higher buildings, but not defined for lower ones. We have assumed the wall corner coefficient of -2.0 for lower buildings in this survey.

In 1996, ASCE 7-95[6] was published with wind design methods totally revised. Since fastest mile data are no longer recorded by the National Weather Service (NWS), wind speed data for this revision were based on three second gust data rather than fastest mile. Return interval is still 50 years. Examination of the wind histories of various reporting stations revealed that some gradients used in previous maps apparently were caused by random error, so the map is now greatly simplified. The vertical perimeter pressure coefficient for ASCE 7-95 is -1.8 for buildings 60 feet or under and -2.3 for higher buildings. ASCE 7-95 is unclear about the horizontal coefficients. If one again assumes the wall corner coefficients, it would appear that -1.3 and -1.8 are the values for lower and higher buildings, respectively.

FMRC

Factory Mutual Research Corporation publishes FMRC Loss Prevention Data Sheet 1-49, "Perimeter Flashing".[7] FM 1-49 shows an outward pressure coefficient of -1.0 and an upward pressure coefficient of -2.0. However, current approval standards[8] require an outward (horizontal) coefficient of -1.5. The Basic Wind Speed map used by FMRC is based on a 100-year recurrence interval. We presume it uses "Fastest Mile" wind speeds, but FMRC is unclear on this point. FMRC recommended pressure coefficients can be adjusted to the 50-year interval of the current standard using a factor from the MRI table above.

BSI

British Standards Institute (BSI) wind design standard BS 6399[9] requires a pressure coefficient of -1.15 for a wind perpendicular to a wall and as high as -1.4 when the wind is 30° from perpendicular. We therefore use the worst case of -1.4 as the BSI design criterion when applying it to roof edge design. Strictly speaking, the BSI coefficients are derived for rooftop pressures. Nevertheless, BSI does state that these may be used for cladding (or, presumably, fascias, etc.) BSI uses a one-hour average peak wind speed map, but speeds used for design can be corrected by equations which account for gusts. Special calculations are needed to correct these coefficients for comparison with 3-second gust values.

SPRI

SPRI (an association of membrane roofing & components manufacturers) has published a roof edge wind design guide[10]. Pressure coefficients for this Guide were obtained by reviewing the sources surveyed in this paper. The pressure coefficients used are -2.0 for uplift and -1.6 for horizontal force. These values must be corrected for 3-second gust values.

Full Scale Roof Perimeter Studies

Studies of full scale roof edge details have been conducted at Georgia Tech Research Institute (GTRI), Texas Tech University (TTU), and National Research Council of Canada (NRCC). Each had a unique experimental approach.

Experience also gives us at least a guideline on results since roof edge manufacturers keep track of the field performance of their products. Failures are examined and causes established. Manufacturers report that, using design values reported in the literature, their roof edge products perform at least as well as the design standards anticipate. Although these are anecdotal data, they do attest to the reasonableness of conventional design wisdom.

TTU

Texas Tech University (TTU) maintains a Wind Engineering Research Field Laboratory (WERFL) near its campus in Lubbock, Texas. This laboratory is an instrumented 30 by 45 foot test building, having a wall height of 13 feet with a low slope roof. The building can be rotated to present a test face to the prevailing wind at any desired angle of attack. A consortium of interested companies and organizations facilitated by the Roofing Industry Committee on Wind Issues (RICOWI) supported studies of common styles of fascias and copings. They mounted samples of common roof edge devices on the roof perimeter of the WERFL.

In this study, pressures were recorded over 15 minute periods at 30 readings per second. Results in this study had a remarkable dependence on the size and shape of the roof edge device. This suggests that spoiling of wind flow over protrusions such as the drip-edge of the fascia may have an effect beyond any expected from other studies. Force was greatest on gravel stops from a windward direction, while copings showed the greatest forces when the wind was parallel to the wall. Also, the coping showed negative pressure coefficients on all three faces, outside, top and roof-side. These coping results suggest that infiltration from the ends of the coping may have exaggerated the internal forces, thus inflating the pressure coefficients.

Results of the TTU study are summarized in the table on page 14.

NRCC

The National Research Council of Canada (NRCC) has done two studies of interest here in its large wind tunnel in Ottawa.[11] The tunnel has a 30 foot by 30 foot cross-section which allows large scale models to be evaluated. As part of wind tunnel studies performed on membrane roofing, edge details matching some of those used at TTU were instrumented. The results showed worst-case pressure coefficients between -0.9 and -2.1 on the windward side. Pressure taps for these studies were located within a few inches (6.5″

Summary of Peak Pressure Coefficients Measured at WERFL

Wind Direction	Horizontal Pressure Coefficient		Vertical Pressure Coefficient	
	Fascia	Coping	Fascia	Coping
Windward	-1.9	-0.9	-1.6	-0.5
Quartering	-1.3	-1.1	-2.6	-0.8
Parallel	NA	-1.2	NA	-0.9
Leeward	-0.8	-0.8	-0.7	-1.5

to 12.5″) of the corners, so corner turbulence effects might have biased these results. The data rate for these studies was 500 Hz with peak values picked from a 60-second run.

GTRI

In 1990, my company, The W. P. Hickman Company, joined with MM Systems Company to conduct the first full-size edge detail study at Georgia Tech Research Institute (GTRI) in Atlanta. The GTRI wind tunnel has been used for both aeronautical and industrial wind design. Automobile and sports equipment performance have been among the more interesting industrial applications.

The GTRI wind tunnel has a specimen space 30″ x 43″ x 90″. For our studies, a six-inch coping with legs approximately four inches was secured to a 12-inch high wall. The peak pressure coefficients measured were approximately 1.6 on top and -1.4 on the face or back leg.

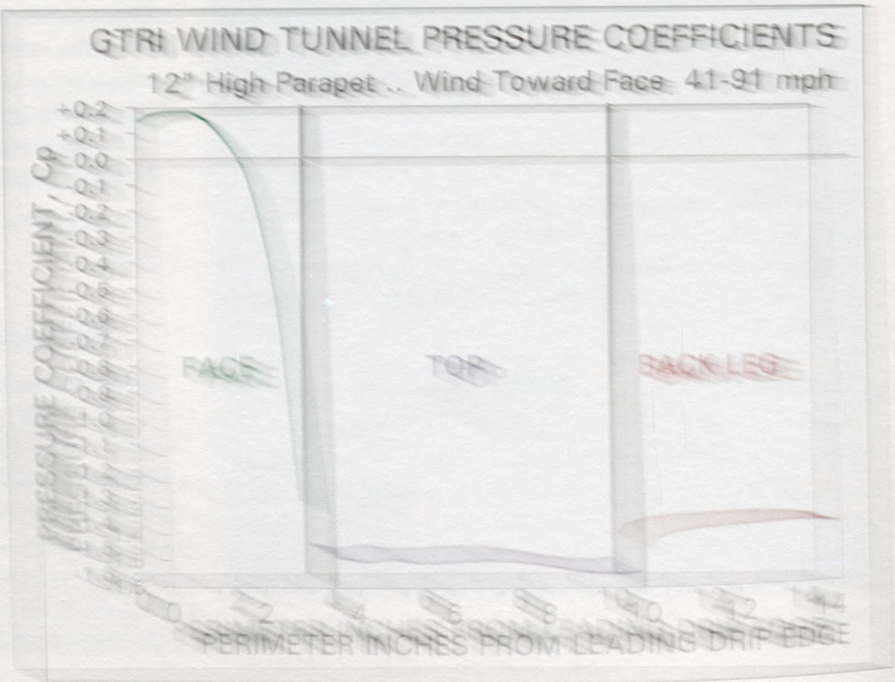
Summary

Out of this babble, it would seem that there may be no agreement on the appropriate pressure coefficients one should use for roof edge design. However, to compare them, we must take into account the wind averaging method assumed with each standard, studies and guides presented. As we saw above, the peak wind speed (or peak pressure coefficient observed) will depend on the averaging time. Not averaging the data will usually show some very high isolated peaks. Wind data averaged over a long period will show lower peaks. The peaks will be higher for shorter averaging times. A definitive answer to how long the average should be would probably require a dynamic model of the structure to determine how long a gust would need to last to have a damaging impact on the structure.

At one time, the National Weather Service (NWS) reported "Fastest Mile" wind speeds. However, because of the characteristics of the instrumentation now used at NWS stations, the measurements are now approximately three-second peak gusts. Since this is now the U.S. standard for reporting wind speeds, it is appropriate to reduce the pressure coefficients surveyed here to that level. Fortunately, we can develop multipliers based primarily on statistical studies.[12] The values used for correction can be derived from the chart on page 155 of ANSI 7-95.

BSI needs a special adjustment factor because the BSI wind velocities, although based on one-hour averages, are corrected for gusts. The correction factor for BSI was derived assuming 10-meter height, 100 km from the sea and the area of an element of the edge detail of 10 sq. meters or less.

Applying appropriate conversion factors to the pressure coefficients surveyed in this article shows that they are in remarkable agreement. FM 1-49 may actually be a bit low, and TTU and NRCC values appear high. Others are within a few tenths of each other. The tables on page 15 show the comparisons of the various pressure coefficients before and after applying the corrections.



Comparison of Reported Roof-Edge Pressure Coefficients for buildings less than 60 feet tall

	Reported Coefficients		Averaging Method	Adjustment Factor	Corrected Coefficients	
Source	Horizontal	Vertical			Horizontal	Vertical
ANSI/ASCE 7-88 (7-93)	-2.0	-2.6	Fastest mile	0.68	-1.4	-1.8
ANSI/ASCE 7-95	-1.4	-1.8	3 second gust	1.00	-1.4	-1.8
BSI 6399	-1.4	-1.4	1 hour adjusted	1.17	-1.6	-1.6
FM 1-49	-1.5	-2.0	Fastest mile?	0.78	-1.2	-1.6
NRCC	-2.1	NA	1 second	1.03	-2.2	NA
GTRI	-1.4	-1.6	1 second avg.	1.03	-1.4	-1.7
SPRI	-1.6	-2.0	3 second gust	1.00	-1.6	-2.0
TTU Field Study	-1.9	-2.6	3 second gust	1.00	-1.9	-2.6
Least Coefficient	-1.4	-1.4			-1.2	-1.6
Greatest Coefficient	-2.0	-2.6			-2.2	-2.6

Comparison of Reported Roof-Edge Pressure Coefficients for buildings more than 60 feet tall

	Reported Coefficients		Averaging Method	Adjustment Factor	Corrected Coefficients	
Source	Horizontal	Vertical			Horizontal	Vertical
ANSI/ASCE 7-88 (7-93)	-2.5	-2.5	Fastest mile	0.68	-1.7	-1.7
ANSI/ASCE 7-95	-1.8	-2.3	3 second gust	1.00	-1.8	-2.3
BSI 6399	-1.4	-1.4	1 hour adjusted	1.17	-1.6	-1.6
FM 1-49	-1.5	-2.0	Fastest mile?	0.78	-1.2	-1.6
NRCC	-2.1	NA	1 second	1.03	-2.2	NA
GTRI	-1.4	1.6	1 second avg.	1.03	-1.4	-1.7
SPRI	-1.6	-2.0	3 second gust	1.00	-1.6	-2.0
TTU Field Study	-1.9	-2.6	3 second gust	1.00	-1.9	-2.6
Least Coefficient	-1.4	-1.4			-1.2	-1.6
Greatest Coefficient	-2.5	-2.6			-2.2	-2.6

Conversion Factor Calculations

Wind Averaging

The corrections for adjustment can be found on page 155 of ANSI 7-95. Because wind pressure varies as the square of the wind speed, the pressure coefficients are adjusted by multiplying by the square of these factors to get the Pressure Coefficient Conversion Factor (PCCF).

Averaging Time	Peak Gust/1 Hour Average	Averaged Peak / 3-Second Gust	Pressure Coefficient Conversion Factor (PCCF)
1 Second	1.57	1.01	1.03
3 Seconds	1.55	1.00	1.00
Fastest Miles (45 Seconds)	1.28	.83	0.68
One Hour	1.00	.65	0.42

BSI Conversion Factor

BSI requires that the basic wind speed (one hour average) be corrected for distance from the sea, gusts, building height, size of the edge element and topography. See Tables 4-6 of BS 6399. The equation is

$$S_{TB}=S_{SC}[1.0+(g_{GUST}S_{TSC})+S_{TP}]$$

In which:

S_{SC} is the "fetch factor" dependent upon distance from the sea, S_{TB} is the Terrain and Building factor, g_{GUST} is a gust peak factor, S_{TSC} is a turbulence factor and S_{TP} is a topographic factor. Assuming an effective building height of 10 meters, a distance greater than 100 km from the sea, and a roof edge element surface of less than five square meters, these factors are as follows:

$S_{SC} = 1.04$

$g_{GUST} = 3.44$

$S_{TSC} = 0.178$

$S_{TP} = 0$ (assumed flat terrain)

Inserting these values into the equation:

$$S_{TB}=1.04 \times [1.0+(3.44 \times 0.178)+0]=1.677$$

Since S_{TB} is a speed adjustment, it must be squared for its effect on the pressure coefficient. Since the Pressure Coefficient Conversion Factor (PCCF) for a one hour average (see table under "Wind Averaging" above) is 0.42, the total correction for BSI data is:

$$\text{Conversion Factor}=S^2_{TB} \times \text{PCCF}=1.677^2 \times 0.42=1.18$$

About The Author

John B. Hickman *is the president and CEO of the W.P. Hickman Co., headquartered in Asheville, N.C. Hickman holds a Master's degree in engineering. He is chairman of SPRI's Edge Detail Task Force and is their delegate to the Edge Detail subcommittee of the Board of Directors of the North Carolina Quality Leadership Foundation (NCQLF) and the North Carolina Alliance for Competitive Technologies. He has served NCQLF as a senior quality examiner. Hickman is also a member of CSI, RCI and NRCA and is a past member of the National Board of Directors of SPRI. Hickman presented this paper to the 12th Annual Convention of RCI in Anaheim in March.*

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Interface
Editorial Calendar

July	Document Competition
August	Maintenance
September	Decks/Substrates/Structural Issues
October	EIFS & Curtain Walls
November	Environmental Issues