FIELD EXPERIMENTS FOR WIND LOADING ON METAL EDGE FLASHINGS

WEI WANG, JAMES R. McDONALD and HUI JIANG
Texas Tech University
Lubbock, Texas

The purpose of the study is to obtain full-scale measurements of wind pressures on typical edge flashings and copings. This paper reports results of pressure measurements on four typical edge flashing profiles. The pressures are expressed in terms of pressure coefficients C_p. Values of mean, peak maximum, peak minimum and root-mean square are calculated from the 15-minute time history records. This paper reports the measured pressures on the edge flashing profiles. The largest mean and minimum peak C_p's occur when the wind is blowing normal to the wall, except near the wall corners. The shape of the flashing profile strongly influences the magnitude of the surface pressures.

INTRODUCTION

Failures of metal edge flashings in Hurricane Hugo and Andrew as well as previous storms revealed their vulnerability to extreme wind and suggested the need for a full-scale research effort to better understand wind loading on these roofing components.[1,2,3] Neither the ASCE 7-93 national wind load standard nor the three model building codes (SBC, UBC and BOCA) prescribe wind loads on metal edge flashings or copings. Guidelines for wind design of metal edge flashings and copings are limited and currently inadequate.[4,5,6] Notable guidelines include publications by Factory Mutual Engineering Corp. (FMEC)[7] and Single Ply Roofing Institute (SPRI).[8] *The NRCA Roofing and Waterproofing Manual—Third Edition* includes metal edge flashing and coping details, but it does not address cleat fastening and the wind-resistance capabilities of the details.

Following Hurricane Hugo, NRCA requested a research proposal from the Institute for Disaster Research (IDR) at Texas Tech University (TTU) to obtain full-scale measurements of wind pressures on metal edge flashings and copings. However, funds for the project were not secured until a consortium of roofing industry organizations and manufacturers was formed in 1994. The formation of the consortium was facilitated by the Roofing Committee on Wind Issues (RICOWI). The purpose of the study is to obtain full-scale measurements of wind pressure on typical edge flashings and copings. The flashings and copings are installed on a rotatable building at the Wind Engineering Research Field Laboratory (WERFL) in Lubbock, Texas. Pressure measurements and wind speed data are taken in the natural boundary layer wind in flat open terrain. A second objective of the study is to take the measured pressures and perform a finite element analysis on the flashings and copings to calculate stresses, deformations and fastener loads as a function of wind speed. The information gained will be of value in updating guidelines for design of flashings and copings. The scope of this paper is limited to a discussion of wind pressures on four different flashing profiles. Wind pressure measurements in the form of nondimensional pressure coefficients are presented for flashings of different sizes and shapes. The influence of wind direction and flashing location on wind pressure are presented as results of the study.

EXPERIMENTAL PLAN

Installation

The full-scale experiment was conducted at the Texas Tech University (TTU) Wind Engineering Research Field Laboratory (WERFL). The facility, which is located in flat, open terrain (Exposure C), consists of a 30 ft. x 45 ft. (9.1 m x 13.7 m) rotatable building with a 13-ft. (4 m) roof height and a 160-ft. (49 m) meteorological tower. (See Reference 10 details of the test facility). Figure 1 shows the building with metal edge flashings installed.

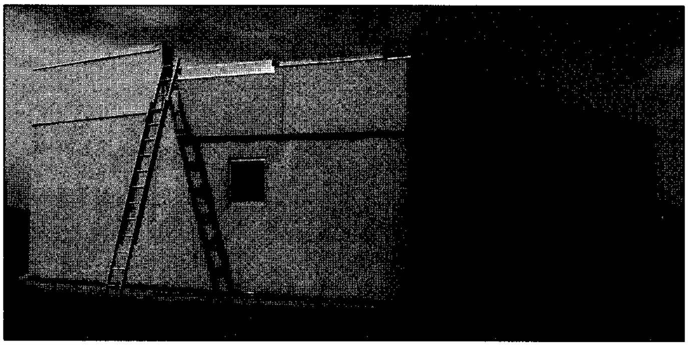

Figure 1. WERFL test building with flashings installed on plywood panels.

Vertical and horizontal plywood panels were installed along the roof edge to accommodate the edge flashings and the plastic tubing attached to the pressure taps. The panels are hinged along the roof edge to allow the vertical panel to swing outward and give access to the plastic tubing behind the panel. An EPDM membrane was placed over the plywood panels on the roof to simulate a common single-ply roof system installation. The membrane was sealed to the flashings and at its other edge on the roof.

Pressure taps are installed in the outside surface of the flashings as close together as practical to give the pressure distribution over the flashing profile. Taps were also placed directly in the plywood panels to measure the pressure behind the flashing (internal pressure) and the pressure on the roof and wall near the flashings. Figure 2(a) shows taps in the outer surface of the flashing; Figure 2(b) shows taps in the wall. The top two taps in the wall measure internal pressure behind the flashing after the flashing is installed.

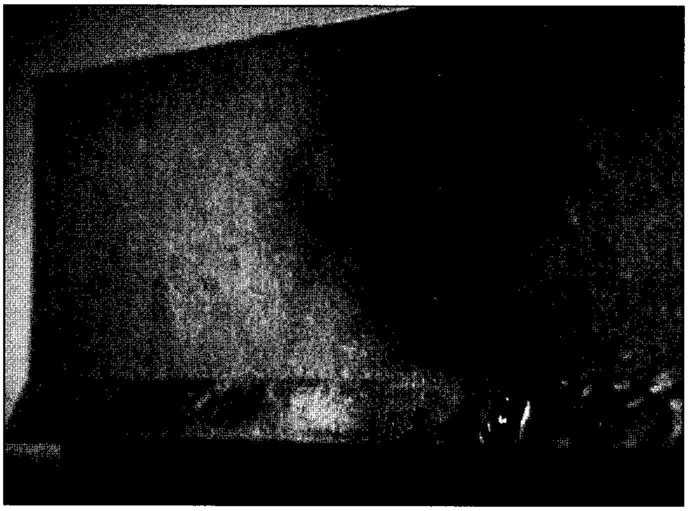

Figure 2a. Pressure taps installed on flashing surface and in wall. Pressure taps Flashing "A" at the corner.

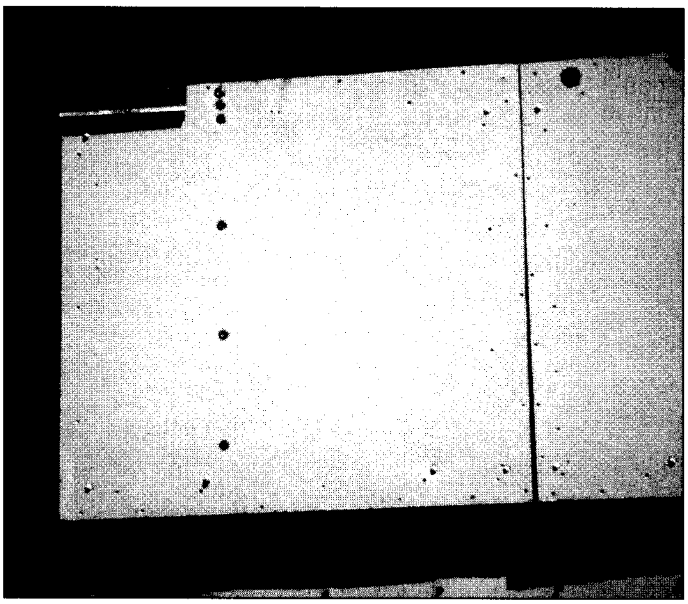

Figure 2b. Pressure taps installed on flashing surface and in wall. Pressure taps in wall.

Flashing Details

Four flashing shapes designated "A", "B", "C" and "D", and two coping shapes designated "A" and "B" were installed on the test building as shown in Figure 3. Flashing "A" and Coping "A" were also installed at building corners. Discussion on the copings study is not included in this paper. The angle of attack of the wind is also defined in Figure 3.

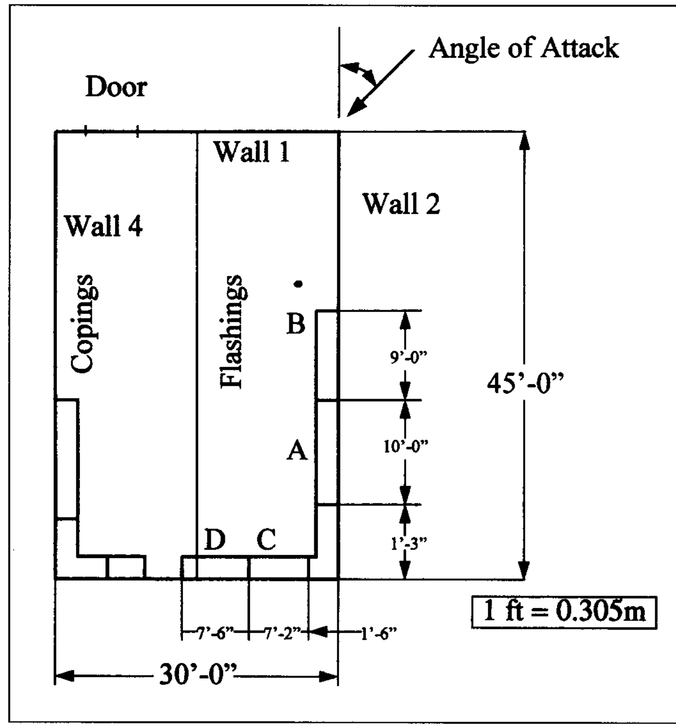

Figure 3. Plan view on metal edge flashing and coping installations on WERFL test building.

Dimensions of the flashings are shown in Figure 4. Flashings "A" and "B" have the same shape and dimensions. Flashings "A" and "D" have cleats; Flashings "B" and "C" do not. Flashings "A" and "B" are fabricated of 24-gage (0.7 mm) galvanized steel; Flashing "C" is 26-gage (0.6 mm) galvanized steel. Flashing "D" is made of 0.050-in. (1.3 mm) mill finished aluminum. All cleats are 22-gage (0.9 mm) galvanized steel. The horizontal flashing flanges are fastened to the roof panels with two rows of nails spaced at 6-in. (150 mm) on center and staggered; the cleats are fastened with nails at 12-in. (300 mm) on center.

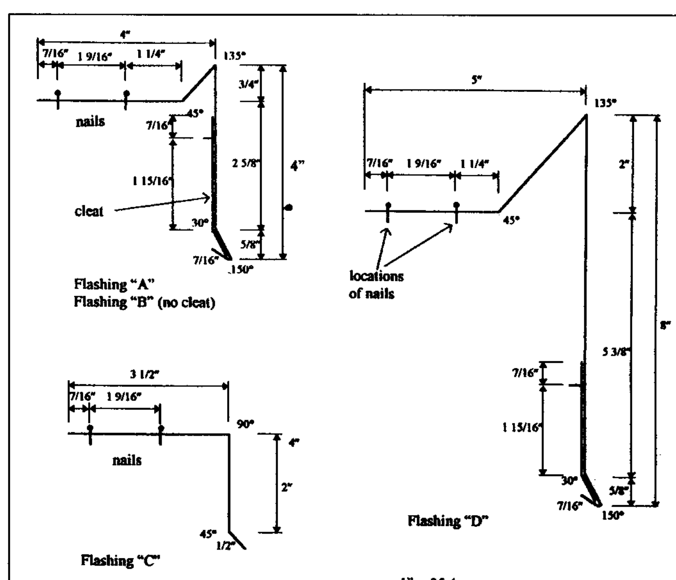

Figure 4. Dimensions of metal edge flashings.

Experimental Data

Wind pressure measurements were taken at different wind angles of attack. Previous experience and preliminary wind-tunnel studies[9] suggested the following angles of attack for the flashings:

Flashing "A": 90°, 135°, 270°
Flashing "B": 90°, 135°, 270°
Flashing "C": 0°, 135°, 180°
Flashing "D": 0°, 135°, 180°
Flashing "A" at the corner: 90°, 135°, 180°, 270°

These angles of attack represent winds blowing toward the flashing and normal to it, away from the flashing, but normal to it and at 45°, called a quartering wind. During periods of strong winds, the test building was rotated to the desired angle of attack. The data acquisition system was then manually triggered to obtain a data run. The collected data is designated as Mode 28, which identifies the configuration of the data acquisition system and marks the data for archiving purposes. Wind pressures were measured at a sampling frequency of 30 Hz; wind speed was measured with a three-cup anemometer at 13-ft. (4.0 m) above ground (roof level) at a sampling rate of 10 Hz. A description of the instrumentation system and the data acquisition system can be found in Levitan and Mehta.[10,11]

A large number of data records were collected for metal edge Flashing "A", "C", "D" and "A" at the corner for the angles of attack listed above. Since Flashing "B" was the same as Flashing "A", except for the cleat, pressure readings were not taken on that profile. The pressure records were then validated to assure high quality of the data. The time histories of wind pressure, wind speed and wind direction were tested for stationarity, which means the records are independent of sampling time. Nonstationary records were eliminated from further data analysis. Turbulence intensity and roughness length were calculated for each data run. Table 1 lists the records that remained after quality assurance procedures were complete. Wind speed and wind direction are averaged over the 15-minute length of each record. Turbulence intensity, which is a measure of the gustiness of the wind is given by:

	Record Number	Mean Angle Attack (deg.)	Mean Wind Speed	Turbulence Intensity	Flashing
1	M28N390	88.6	18.9	0.21	for "A" & "A" @ corner
2	M28N391	98.5	17.6	0.29	
3	M28N392	95.7	19.3	0.22	
4	M28N393	88.3	18.5	0.21	
5	M28N435	139.5	15.1	0.26	
6	M28N437	132.8	14.8	0.25	
7	M28N438	135.5	14.7	0.24	
8	M28N484	266.6	17.5	0.20	
9	M28N489	265.4	18.2	0.21	
10	M28N494	276	15.4	0.24	
11	M28N506	80.3	19.3	0.20	
12	M28N507	88.7	18.9	0.20	
13	M28N532	269.7	18.6	0.22	
14	M28N540	269.5	19.0	0.20	
15	M28N542	274.2	19.4	0.20	
16	M28N730	185.0	15.4	0.19	for "C" & "D"
17	M28N732	180.1	14.9	0.19	
18	M28N734	88.9	15.6	0.20	
19	M28N751	92.1	23.2	0.17	
20	M28N752	93.4	22.2	0.21	
21	M28N753	2.8	25.6	0.19	
22	M28N754	7.8	24.3	0.20	
23	M28N757	6.1	25.0	0.19	
24	M28N759	175.8	23.0	0.17	
25	M28N762	177.1	21.1	0.16	
26	M28N786	158.2	20.8	0.18	for "C", "D" & "A" @ corner
27	M28N788	154.1	20.1	0.18	
28	M28N791	155.7	21.7	0.17	
29	M28N797	184.0	18.8	0.16	
30	M28N799	187.8	16.7	0.20	
31	M28N800	186.8	16.4	0.17	
Note: Because the pressure coefficients are dimensionless, they are also applicable to higher design wind speeds.					

Table 1. *Validated data for metal edge flashing study.*

$$I = \frac{S}{V} \quad (1)$$

where

S is the standard deviation (rms) of the time series of wind speed, mph (m/s);

V is the 15-minute mean wind speed, mph (m/s).

Roughness length is a measure of the upstream, terrain characteristics for a given mean wind direction. It is one of the parameters that define the wind speed profile.

DATA ANALYSIS

The measured wind pressures are converted to dimensionless pressure coefficients by the equation:

$$C_p = \frac{P - P_0}{\frac{1}{2} p V^2} \quad (2)$$

where

P is the pressure at a particular tap location, psf (Pa)

P_0 is the reference atmospheric pressure, psf (Pa)

p is the mass density of air, slugs/ft^3 (kg/m^3), and

V is the 15-minute mean wind speed at roof height, mph (m/s).

Sign convention for C_p: positive pressure pushes toward a surface and negative pressure pulls away from a surface.

Pressure-Time Histories

Two typical 15-minute pressure-time histories for Flashing "C" (180° angle of attack) are shown in Figure 5. One trace is the surface pressure coefficient and the other is the internal pressure behind the flashing. The pressure coefficients (C_p) on the external surface are negative indicating a suction. The C_p on the internal surface is positive indicating a push toward the surface of the flashing. The external suction pressure is larger than the internal pressure, but they both act in the same sense attempting to push the vertical face of the flashing outward. There is more fluctuation in the external pressure than in the internal pressure, as expected.

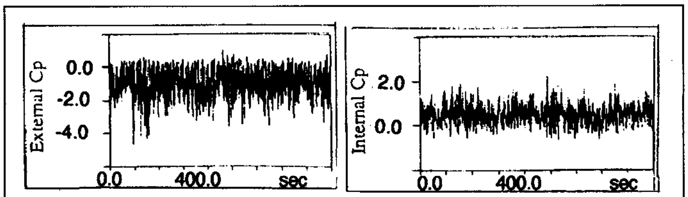

Figure 5. Typical external and internal time histories for Flashing "C" (Record: M28N762, θ = 177°).

Mean Pressure on Flashing: Wind Blowing toward Flashing

Figure 6 shows the mean C_p distributions on metal edge flashings when the wind blows toward the flashings. The intended angle of attack for Flashing "A" was 90° and for Flashings "C" and "D" 180°. The mean C_p values in Figure 6 are average values of several records for runs with the same angle of attack. The average angle of attack θ is given for each flashing in Table 1.

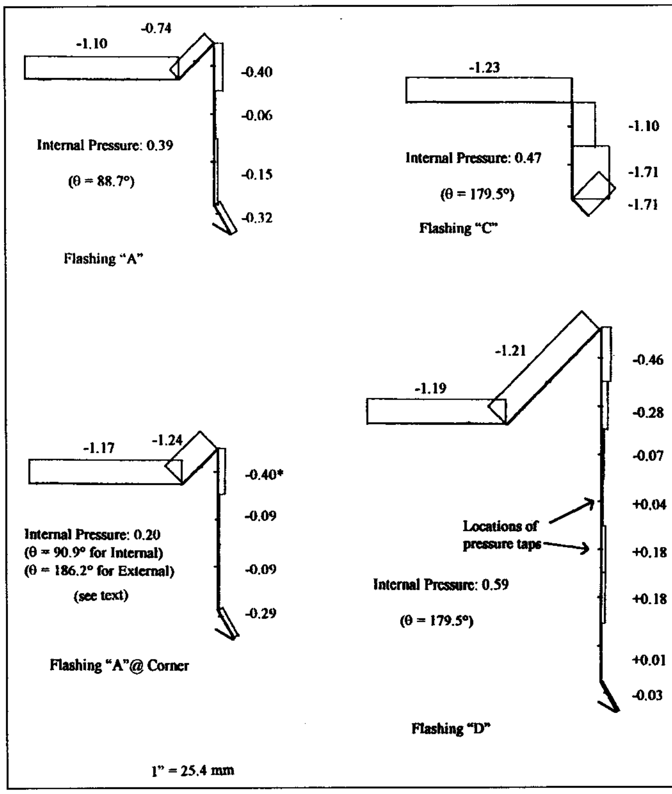

Figure 6. Mean C_p distribution on the outer face of flashings for windward wind.

With the wind blowing essentially normal to the flashings, the pressures are essentially uniform along the length of the flashings. The pressure taps measure the pressure variation over the various segments of the flashing profile. Flashing "C" has outward acting surface pressures significantly larger than those on Flashings "A" and "D". The larger pressures are not due to the location of flashing along the wall, because Flashing "C" is located between "A" at the corner and "D" along the wall. The mean pressure differences are attributed to the shape and size of the flashings. The gravel stop portion of the flashing could also have an influence, since the mean C_p's on the vertical face of the flashings near the gravel stop in "A" and "D" have almost identical values. Since Flashing "C" does not have a gravel stop, the flow separation takes a different form at "C" than at the others. The pressure differences between Flashing "C" and others demonstrate the significance of profile size and shape on wind pressures. All pressures on the outer face of the profiles are outward or upward acting, except for the vertical flange of Flashing "D", which has regions of inward and outward acting pressure. The pressures on top of all of the horizontal flanges are about the same magnitude and act upward. Profile pressures on Flashing "B" were not measured because its profile is the same as Flashing "A".

Mean Pressure on Flashings: Quartering Wind

Figure 7 shows the mean C_p distributions on Flashings "C", "D" and "A" at the corner for a near quartering wind angle. The quartering wind produces higher pressures on Flashing "A" at the corner than the wind normal to the flashing surface (compare Figures 6 and 7). Otherwise, the pressures caused by normal wind on the other flashing profiles are higher than the quartering wind. This observation suggests that, except near the corner, design pressures can be based on a normal wind blowing toward the flashing.

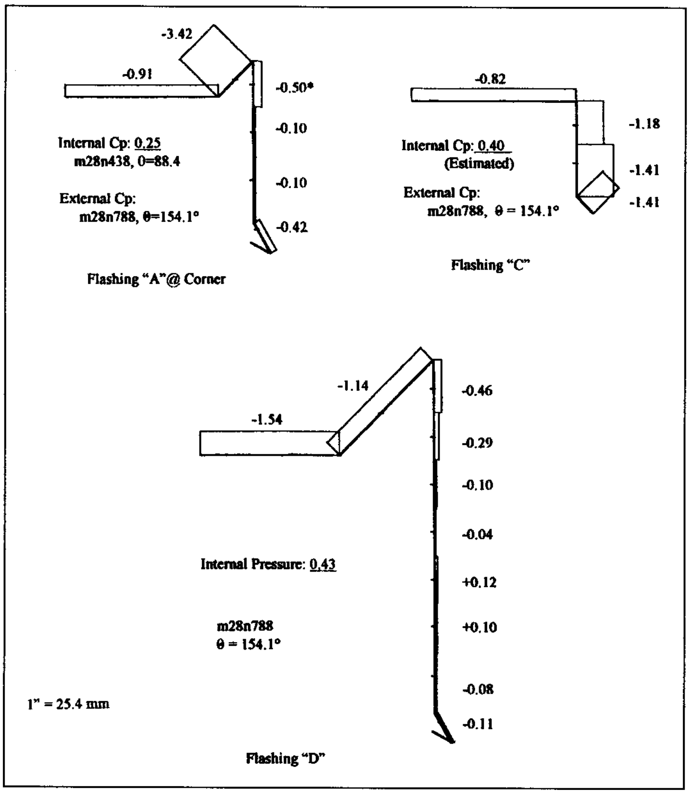

Figure 7. Mean C_p distribution on the outer face of flashings for quartering wind.

Minimum Pressure on Flashing: Wind Blowing toward Flashing

The minimum peak pressure coefficients (minimum C_p) on the outside surface of the flashings are shown in Figure 8. These are the minimum (largest negative value) C_p found in each 15-minute data record. The minimum C_p's do not occur simultaneously, so the plots do not represent an instantaneous loading condition over the surface of a flashing. The duration of each pressure is $1/60$ second. The largest minimum C_p's are found on Flashing "A" at the corner and Flashing "C".

Minimum Pressure on Flashings: Quartering Wind

The minimum peak pressure coefficient (minimum C_p) for a quartering wind are shown in Figure 9. The minimum C_p's on the vertical face of Flashing "C" are much larger than those at corresponding locations on the other flashings. A suction value of -10.8 occurs for an instant on the gravel stop of Flashing "A" at the corner.

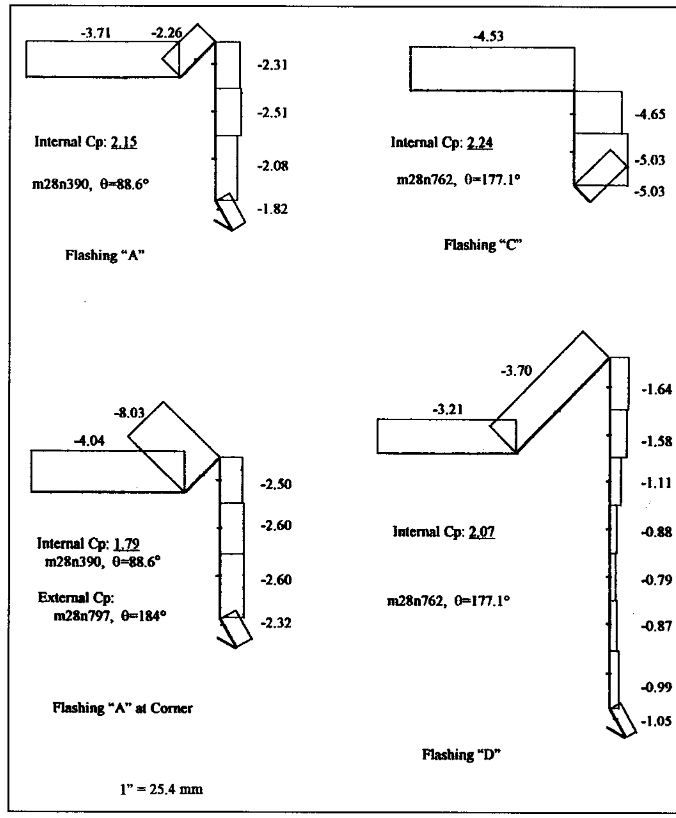

Figure 8. Minimum C_p distribution on the outer face of flashings for windward wind.

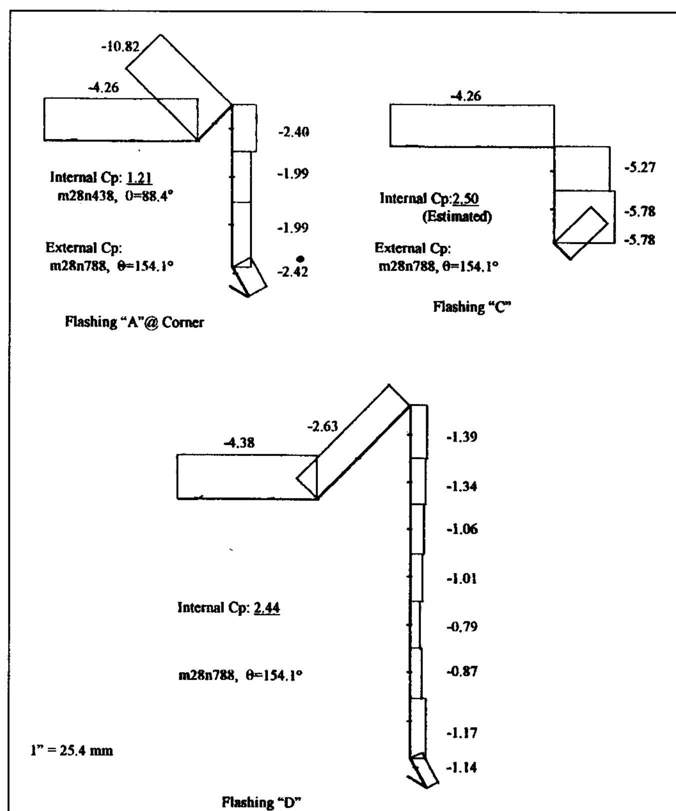

Figure 9. Minimum C_p distribution on the outer face of flashings for quartering wind.

Internal Pressures

Internal pressures are measured behind the flashing with a pressure tap at the face of the plywood wall panel. All pressures behind the flashing are positive, which means they are pushing outward on the flashing. The positive internal pressure acts in the same sense as the negative pressures on the outside surface of the flashing. Although not measured, the internal pressure directly underneath the horizontal flange of the flashing should be the same as behind the vertical flange of the flashing, unless the horizontal flange is sealed to the substrate, thereby preventing pressure from developing underneath this flange. The external and internal pressures for Flashing "A" at the corner were taken at different angles of attack: $\theta = 90.0°$ for internal and $\theta = 186.2°$ for external pressures. In both cases, because of the location of the pressure taps, the normal wind is blowing toward the flashing surfaces.

The mean internal C_P's are slightly higher when wind is blowing toward the flashing surface than when a quartering wind is blowing toward the surface. Flashing "D" has the largest internal pressure. The transducer at the tap measuring internal pressure behind Flashing "C" malfunctioned on some runs. The value is estimated from the results from a nearby tap behind the flashings.

Wind blowing normal to a wall, but away from the flashing produces relatively small negative internal pressures and negative external pressures that tend to cancel each other.

Comparing the mean pressures on Flashing "D" in Figures 6 and 7, the angle of attack within a plus or minus 45° does not seem to make much difference.

CONCLUSIONS

Based on the above observations, it is clear that critical wind pressures on metal edge flashings are a combination of internal pressure pushing from behind the flashing and the suction pressure pulling on the surface of the flashing. The pressure distributions on metal edge flashings depend strongly on the size and shape of the flashings, the locations of the flashings on the building, and the wind angle of attack. More specifically, the following observations can be made:

- The largest mean and minimum peak C_P's occur on flashings when wind is blowing normal to walls, except for flashings near a corner.
- The largest mean and minimum peak C_P's on flashings near a corner are produced by a quartering wind.
- Flashing "C" exhibits the largest mean and minimum peak C_P of all profiles tested.
- Flashing "D" which has a long vertical surface exhibits both outward and inward acting pressures on its outer face.
- Internal pressure is positive (pushes outward) when wind blows toward the flashing and is not sensitive to the wind angle of attack within plus or minus 45° from normal.
- Positive internal pressure and negative external pressure act in the same sense and tend to push the flashings outward from the wall and upward from the roof when the wind is quartering or normal to the wall.
- Negative internal pressure and negative external pressure act in opposite directions and tend to cancel when wind blows away from the wall.
- The cleat does not appear to have an effect on internal or external pressure so long as the uncleated profile is not bent outward by the force of the wind.

The results of this research should be moved into practice at a early date. For example, the pressures on the flashing profiles could be incorporated into the *SPRI Edge Flashing Design Guide.* Results of the finite element analyses will give further guidance on material thickness and fastener pullout resistance requirements.

ACKNOWLEDGMENTS

The generous financial support for this project by the following roofing industry organizations and manufacturers is gratefully acknowledged: American Institute of Architects (AIA), Asphalt Roofing Manufacturers Association (ARMA), Canadian Roofing Contractors Association (CRCA), Cedar Shake and Shingle Bureau (CSSB), Factory Mutual Research Corporation (FMRC), Institute of Roofing and Waterproofing Consultants (IRWC), Metal Era, MM Systems, National Tile Roofing Manufacturers Association (NTRMA), Roof Consultants Institute (RCI), Sheet Metal and Air Conditioning Contractors National Association (SMACNA), Society of Plastics Industry/Polyurethane Foam Contractors Division (SPI/PFCD), Single Ply Roofing Institute (SPRI), and Steel Roofing Manufacturers Association (SRMA).

REFERENCES

1. McDonald, J.R. and T.L. Smith, 1990, Performance of Roofing Systems in Hurricane Hugo, September 22, 1989, *Technical Report,* Institute for Disaster Research, Texas Tech University, Lubbock, Texas.
2. Hogan, L.D., 1992, On the Edge, *RCI Interface,* (Special Edition Hurricane Andrew Issue), pp. 5-8.
3. Smith, T.L., 1994, "Causes of Roof Covering Damage and Failure Modes: Insights Provided by Hurricane Andrew," *Proceedings* of a Symposium, *Hurricanes of 1992,* ASCE, New York, N.Y.
4. Englar, R.J., 1991, Investigation of the Aerodynamics Effects of Wind Loading on Roof Perimeter Coping/Fascia, *Final Letter Report,* Aerospace Laboratory, Georgia Tech Research Institute, Georgia Institute of Technology, Atlanta, Ga.
5. Smith, T.L., 1990, "Hurricane Hugo's Effects on Metal Edge Flashing," *International Journal of Roofing Technology,* Vol. 2, pp. 65-70.
6. Smith, T.L., 1995, "A Review of SPRI's *Wind Design Guide for Edge Systems,"* *Professional Roofing,* June 1995, p. 54.
7. Factory Mutual Engineering Corp., 1985, "Loss Prevention Data 1-49, Perimeter Flashing."
8. SPRI, 1994, *Wind Design Guide for Edge Systems Used with Low-Slope Roofing Systems,* Single Ply Roofing Institute, Wellesley Hills, Mass.
9. McDonald, J.R., P.P. Sarkar, and H. Gupta, 1995, "Wind-Induced Loads on Metal Edge Flashing," *Proceedings of the 9th International Conference on Wind Engineering,* New Delhi, India.
10. Levitan, M.L. and K.C. Mehta, 1992a, "Texas Tech Wind Experiments for Wind Loads Part 1: Building and Pressure Measuring System," *Journal of Wind Engineering and Industrial Aerodynamics,* Vol. 41-44, pp. 1565-1576.

11. Levitan, M.L. and K.C. Mehta, 1992b, "Texas Tech Wind Experiments for Wind Loads Part 2: Meteorological Instrumentation and Terrain Parameters," *Journal of Wind Engineering and Industrial Aerodynamics,* Vol. 41-44, pp. 1577-1588.