DRIFT SNOW LOADS ON MULTILEVEL ROOFS

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ABSTRACT

In terms of number of collapses and dollar losses in the U.S., triangular drifts on multilevel roofs are the most important roof snow loads. An analysis of approximately 350 drift load case histories, gathered primarily from practicing engineers and insurance companies, is presented. The drift height is shown to be a function of the elevation difference between the upper and lower roofs, the lengths of the upper and lower roofs perpendicular to the change in roof elevation and the ground snow load. Corresponding values for the drift slope and density are also established. The measured case history drift parameters are compared with drift provisions in presently used load standards and building codes (ANSI, NBCC, ISO, MBMA). It is shown that code provisions which are based in part on the windward length of the upper roof provide better estimates.

INTRODUCTION

Snow loads are a consideration in the structural design of almost all building roof systems in the United States and Canada. The importance of establishing appropriate design snow loads, especially for cases where drifting is possible, becomes evident when records of roof collapse are examined. O'Rourke et al. (1982) have reported that in the United States during the period 1974-78, snow loads accounted for approximately 55% of all roof losses. Of these snow related structural losses, approximately 75% are due to drifting at roof elevation changes.

The natural processes and factors which contribute to the formation of drifts at roof elevation changes are complex and not easily quantified. Templin and Schriever (1982) have provided a qualitative explanation for the accumulation of snow on multilevel flat roofs. Actual drift configurations vary depending on the specific building geometry and the local storm conditions, but some common patterns can be understood by applying basic principles of fluid mechanics. A commonly encountered example of drift formation is the triangular drift shown on the right side of Figure 1. When wind blows from left to right, snow is scoured off the upper roof where wind speeds are higher and deposited in the aerodynamic shade on the lower roof. If a large amount of snow is available for drift formation, that is, if there is a large upper roof area and there is a large quantity of snow either falling or already on the upper roof, these drifts can become quite large. In some cases, the top of the drift extends to the elevation of the upper roof.

Another example of drift formation is shown on the left side of Figure 1. In this case, snow from the lower roof or possibly the ground, is blown towards the change in roof elevation and deposited near the wall. A vortex usually forms near the upwind side of the elevation change that prevents the drift from extending all of the way to the wall.

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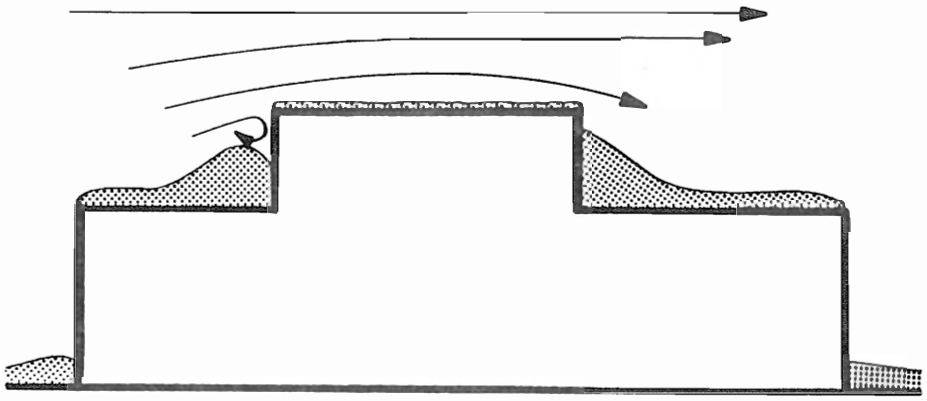

Figure 1. Drift Formation on Multilevel Roof

At the present time, there are a number of procedures (ANSI (1982), ISO (1981), MBMA (1981), and NBCC (1970)) in use for predicting drift loads on multilevel roofs. However, no one procedure has become universally accepted.

It is the purpose of this paper to systematically examine a large, newly established database of actual drift case histories so that a better understanding of the factors affecting drift formation on multilevel roofs can be obtained. Statistical methods are used to analyze the database which includes measured drift parameters, building geometry, and local climatological data. Relationships between the parameters are examined and a new empirical model for predicting drift load profiles is proposed.

DATABASE

The snowdrift case histories analyzed herein are from a variety of sources. These sources include the technical literature, failure reports prepared by practicing engineers, and failure investigations conducted by insurance companies and state agencies. This new database consists of approximately 350 case histories for structures located in the United States and Canada. A majority of the case histories are from the winters of 1977-78 and 1978-79. Forty-three percent of the case histories involve structural failure; either full collapse, partial collapse, or excessive deflection. Of the case histories involving structural failure, approximately seventy-five percent occurred either along the New England coast during the 1977-78 winter or in the Illinois/ Wisconsin area during the 1978-79 winter.

More than 30 different parameters were used to quantify each case history. Information on the buildings includes the site's longitude and latitude, building size, shape, orientation and exposure, and roof thermal properties. Weather conditions were characterized by the average and fastest mile wind speed and direction, while the ground snow was characterized by its depth and density. The roof snow was characterized by the upper roof snow depth and density, and lower roof snow depth, density, and characteristic drift dimensions. A listing of the database and a more complete description of the parameters are found in Speck (1984).

The drifts were divided into two general shapes according to the previously discussed accumulation patterns; that is, a triangular shape in which the maximum snow depth is at the wall (drift shape #1) and a quadralateral shape in which the maximum snow depth is located at some distance from the wall (drift shape #2). The drift geometry in most case histories was quantified only by the total length and height of the drift. Hence, a consideration of non-linear drift profiles was not possible.

As mentioned previously, the case histories were obtained from a variety of sources. Occasionally, the original case history reports did not contain all of the information needed for this study. In these situations, the case histories were supplemented with other available records. For example, if case histories lacked local wind conditions or actual ground snow loads, values from the nearest first order weather station were used. Another piece of data that was often not included in the original case histories was the lower roof uniform snow depth, H_b, in Figure 2. For these cases, the relationship $H_b = 0.048\ P_g$ was used, which corresponds closely to an assumed snow density of 12 pcf (193 Kg/m^3) and the ANSI (1982) conversion factor for normal exposed structures.

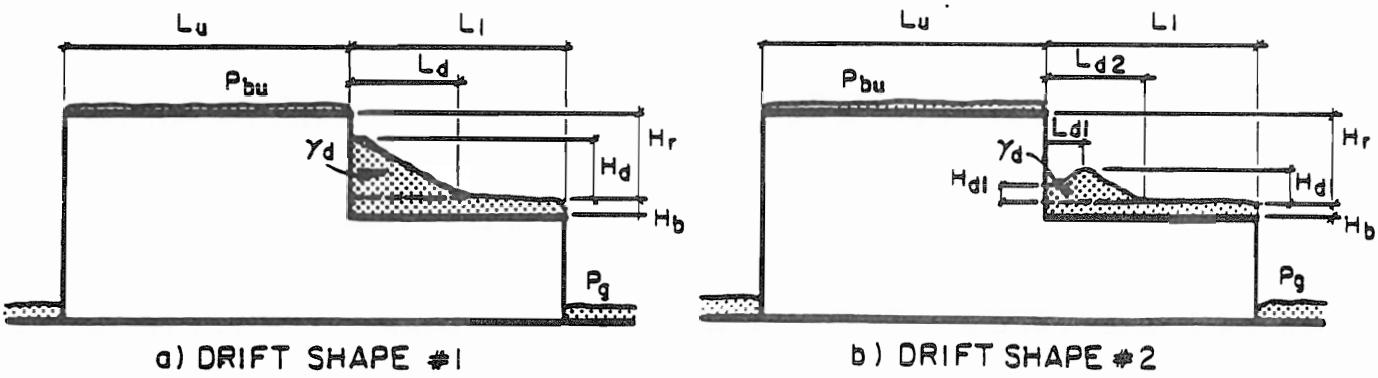

Figure 2. Drift Characteristics and Building Geometry

Figure 2 and Table 1 summarize the important ground and roof load parameters in the database. Figure 2a defines the parameters for the case histories with drift shape #1, while Figure 2b applies to drift shape #2. Table 2 presents the number of cases as well as the mean value and coefficient of variation for these parameters.

DRIFT SHAPES

There are a number of factors that could influence which of the two general drift shapes forms. Wind direction, wind speed, snow moisture, thermal and geometric characteristics of the building, and the amount of snow available for drifting are possible factors. For example, a heated building tends to melt snow adjacent to its walls and over time, drift shape #2 might result. An examination of the database shows that drift shape #1 is the more common drift configuration. Approximately 80% of the drifts correspond to this profile. Also, loads associated with drift shape #1 are generally much larger than those for drift shape #2. Only 8% of drift shape #2 have peak loads $P_d = H_d\ \gamma_d$ greater than 20 psf (0.96 KN/m^2), while 77% of drift shape #1 have peak loads greater than 20 psf.

Since drift shape #1 occurs more often and is more important in terms of magnitude of load, this paper focuses on the characteristics of drift shape #1. It is possible that drift shape #2 is simply an early form of drift shape #1, with drift shape #1 resulting as more snow accumulates.

EMPIRICAL RELATION FOR DRIFT LOADS

Drift Height

In order to design a structural system to safely resist drift loads, an engineer has to know both the magnitude and location of the loading profile. An empirical model which predicts the drift height, length, and density is developed herein for drift shape #1. It

Table 1 Summary of Statistics for Selected Parameters

DRIFT SHAPE NO. 1					DRIFT SHAPE NO. 2				
Parameter	Units*	Mean	Coeff. Variation	No. Cases	Parameter	Units	Mean	Coeff. Variation	No. Cases
L_u	ft	171.7	103%	227	L_u	ft	88.0	70%	59
L_ℓ	ft	85.1	142%	218	L_ℓ	ft	60.0	145%	59
H_r	ft	7.84	59%	255	H_r	ft	5.89	86%	59
Pg	psf	14.80	69%	231	P_g	psf	6.83	72%	58
H_b	ft	0.83	103%	255	H_b	ft	0.26	99%	59
P_{bu}	psf	2.86	122%	241	P_{bu}	psf	3.06	147%	34
P_d	psf	57.78	82%	169	P_d	psf	20.11	185%	50
γ_d	pcf	15.61	36%	169	γ_d	pcf	12.82	31%	50
H_d	ft	4.15	69%	255	H_d	ft	1.41	127%	59
L_d	ft	13.69	73%	198	$H_{d\ell}$	ft	0.65	171%	56
					L_{d2}	ft	11.34	106%	58
					L_{d1}	ft	2.92	99%	59

* 1 ft = 0.305 m
1 psf = 47.9 N/m^2
1 pcf = 16.1 Kg/m^3

uses as input parameters, values which would be known to the engineer during the design phase.

The process of determining an empirical relation began by performing simple correlation analyses between each of the potential input parameters and certain drift load characteristics. The drift load characteristics chosen were the drift height, H_d, the cross-sectional area of the drift, $H_dL_d/2$, and the peak drift load, $Pd(=H_d\gamma_d)$. Only those items which an engineer would likely know during the design phase were considered a potential input parameters. For example, because of this practicality criteria, ground snow load was chosen, instead of ground snow height, as a potential input parameter.

Overall, the length of the upper roof and the roof elevation difference were the input parameters which had the most influence on drift size. In addition, the simple correlation analyses indicated that some parameters such as building depth, i.e. the building plan dimension parallel to the change in roof elevation, did not show significant correlation with drift size. Such items were eliminated from further consideration as potential input parameters.

After using simple correlation analyses to narrow the list of potential input parameters, multiple linear regression was used to establish a precise relationship for the drift height. The criteria used to establish the final set of input parameters was that a parameter would not enter the relationship unless the change in the coefficient of multiple determination was significant at the 90% level.

In order to model correctly drift loads of importance for structural design, the multiple regression relationship for drift height H_d given in equation (1) was based on case histories where the peak drift load was greater than or equal to 30 psf (1.44 kN/m^2)

$$H_d = 1.22\ \ell n(L_u) + 1.51\ \ell n(H_r) + 1.03\ \ell n(P_g + 10) + 0.36\ \ell n(L_\ell) - 9.28 \qquad (1)$$

In equation (1) the lengths (H_d, L_u, H_r, L_ℓ) are in units of feet while the ground snow load P_g has units of psf.

The drift heights predicted by equation (1) were compared with actual values for all of the case histories and are plotted in Figure 3. The slope of the least squares straight line through these points and the origin is 1.006 and the standard error of the estimate is 1.72 feet (0.52 m). Thus, equation (1), which was based on a dataset containing drift loads greater than 30 psf (1.44 kN/m^2), appears to also be fairly accurate at lower load levels.

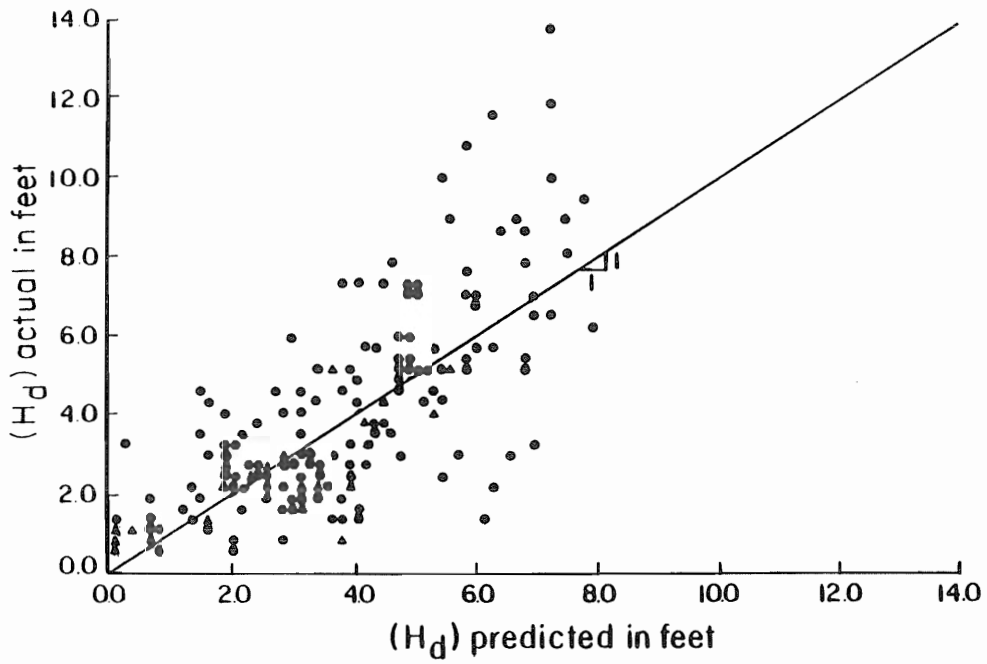

Figure 3. Actual Drift Height vs. Value Predicted by Eqn. (1)

Drift Length

Once the drift height has been established, one must determine the drift length in order to fully describe the drift profile. Most building codes and load standards use a direct relationship between drift length and drift height. Analysis of the actual drift profiles in this study shows that there is, in fact, a good relationship between these two parameters. Drift length is plotted versus drift height in Figure 4 for the 101 cases in which both measurements were available. The correlation coefficient for this plot is 0.804 and the slope of the regression line is 0.228, or 1:4.4. Various subsets of data were also tested. For example, when drift length was plotted versus drift height for those cases with a total peak load greater than 30 psf, a correlation coefficient of 0.881 and a slope of 0.253, or 1:4.0, was obtained. For all of the subsets tested, correlation coefficients generally exceeded 0.80 and average slopes ranged between 1:3.6 and 1:6.9 (Speck, 1984).

Some generalizations can be drawn from the analysis of the drift profile slopes. For the typical case where the lower roof is long enough so as not to influence drift length ($L_\ell \geq 5(H_r+H_b)$), and where the total drift height is less than the difference in roof

elevation (H_r-$H_d \leq 6$ in.), drift slopes closely approximate 1:4. Drift slopes averaging about 1:5 or 1:6 are more common when the drift height is about equal to the roof elevation difference or when the total peak load is less than 30 psf. When there is a continuous supply of snow available for drift accumulation, it appears that the normal drift profile fills and additional snow ends up at the toe of the drift resulting in a flatter slope.

These findings are consistent with those of Finney (1939) and Tabler (1975), who have studied the process of drifting using wind tunnels and topographical catchments, respectively. Finney found that for vertical embankments with drifting to the top of the embankment, drift length was equal to 6.5 times the embankment height on downwind facing steps for heights between two and ten feet (0.61 and 3.05 m). Tabler found that drift length converged to a value close to 6.5 times the embankment height, but that flatter slopes were common for small embankment heights. In both studies, it was found that there was little accumulation on an embankment downslope of 1:6. It appears therefore that if a snowdrift fills an elevation difference with a slope of about 1:6, the profile is sufficiently streamlined so that additional drifting does not occur. For the common cases on multilevel roofs, though, where normal profiles are not full, where wind direction is random, and where total peak loads are greater than 30 psf (1.44 kN/m^2), the snow tends to accumulate at a 1:4 height to length ratio.

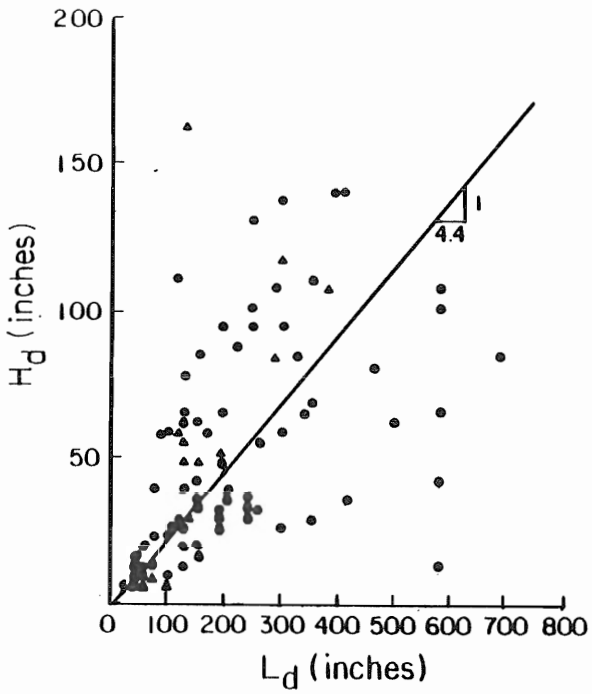

Figure 4. Scattergram of Drift Height H_d vs. Drift Length L_d

Drift Density

The density of drifted snow is needed in order to convert a drift shape profile into a drift load profile. For the 169 cases in the drift load database for which density was available, the mean density was 15.6 pcf (215 kg/m3) with a standard deviation of 5.7 pcf (91.8 kg/m^3). A histogram of the drift density data is shown in Figure 5. There is no doubt that much of the scatter in Figure 5 is due to the natural variability of snow densities. However, some of the scatter might also be due to the fact that the density measurements were made by a number of different individuals. Items such as sample location, time of sample measurement after initial deposition, and sampling technique could not be standardized because the case histories were obtained, after the fact, from a number of sources. Note that Figure 5 suggests that the commonly used rules-of-thumb that

10 inches of freshly fallen snow corresponds to one inch of water (snow density equal 6.24 pcf or 100 kg/m^3), or that one inch of "old" snow corresponds to a load of one pound per square foot (snow density equals 12 pcf or 193 kg/m^3) are unconservative for drifts.

Relationships between the density of drifted snow and various other parameters were examined in an attempt to explain some of the variability of the data. For the case histories in the database, it was found that the drift density was not a function of the geographical location of the site. For example, the average density for the eight failure cases in the Northeastern coastal area for which densities were available was 17.2 pcf. This is essentially the same as the 16.8 pcf value for 36 similar cases in the Midwest. One might expect drift densities to increase with ground snow load or drift height. For one case history, Reidy (1978) in which extensive density measurements were made, it was found that density did indeed increase with depth. Also, older drifts at lower depths had markedly higher snow densities for this particular case history. However, for the database as a whole, the correlations between drift density and ground snow load, and drift density and drift height, were not good. That is, the apparent natural variability of snow densities appears to have overshadowed these factors.

Since drift load, P_d, is the product of the drift height, H_d, and the drift density, γ_d, one expects a positive correlation between P_d and γ_d. This is born out by the fact that for total drift loads greater than or equal to 30 psf (1.44 kN/m^2), the average density was 17.4 ± 4.9 pcf (280 ± 79 kg/m^2), while for cases with total peak loads less than 30 psf, the average drift density was 10.4 ± 4.4 pcf (167 ± 71 kg/m^2). In order to model loads of importance to designers, a drift density of 17.4 pcf (780 kg/m^3) is recommended for use.

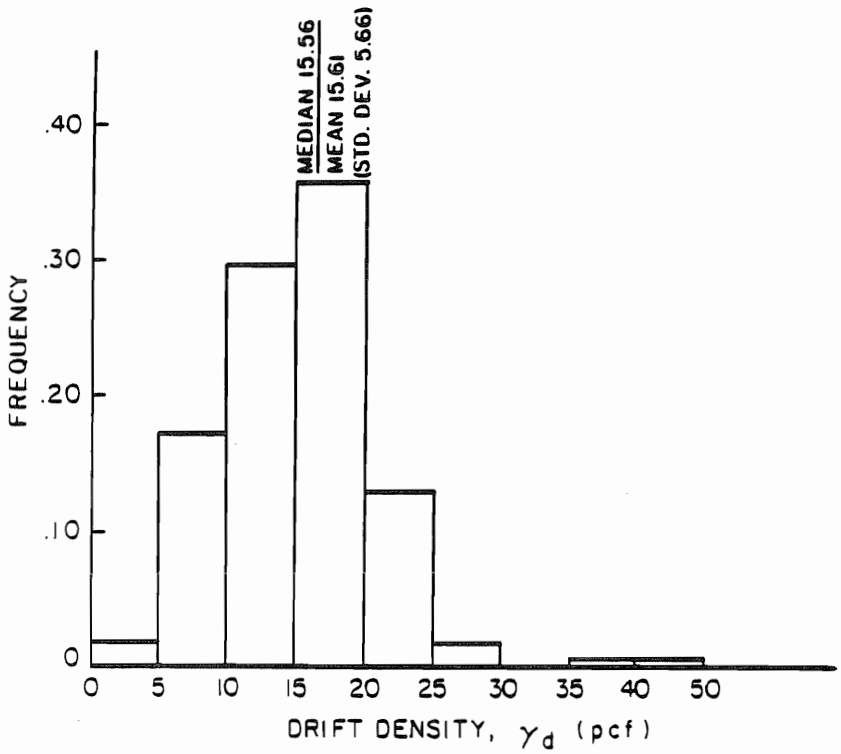

Figure 5. Histogram of Drift Snow Density

ACCURACY OF EMPIRICAL RELATIONSHIP

As proposed herein, the predicted drift load is a function of the ground load, P_g, and the geometry of the multilevel building as characterized by the length of the upper roof, L_u, the length of the lower roof, L_ℓ, and the roof elevation difference, H_r. The drift

height, H_d, is given by equation (1) with an upper bound of H_r. The drift length, L_d, is taken as four times the drift height with an upper bound of L_ℓ. Finally, the drift density is assumed to be 17.4 pcf (280 kg/m^3).

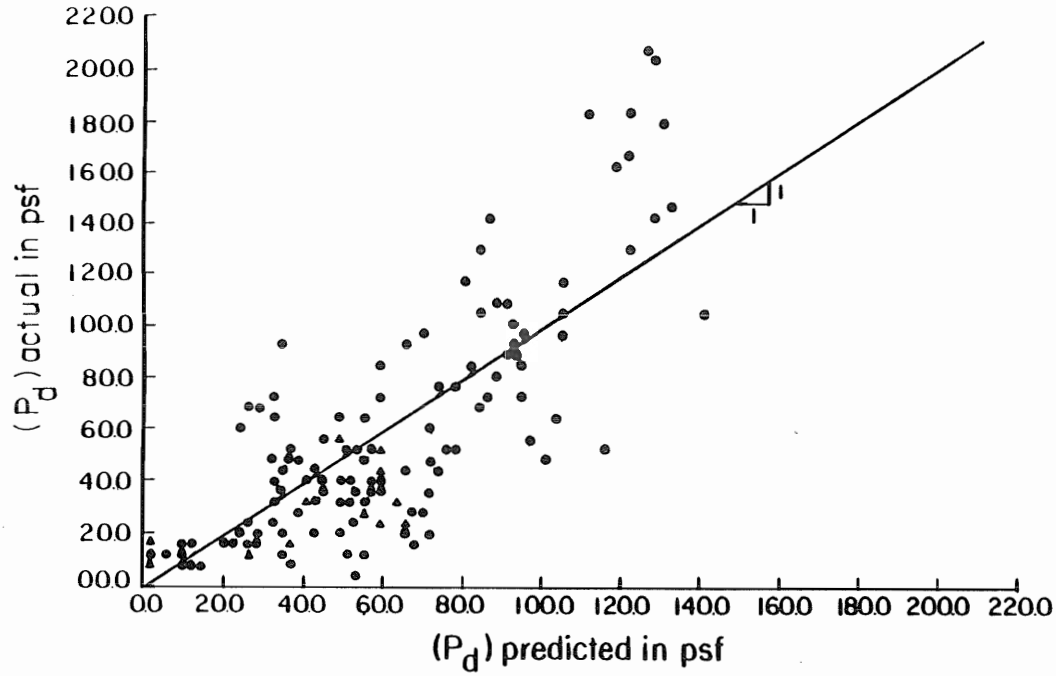

Figure 6. Scattergram of Actual vs. Predicted Peak Drift Load (1 psf = 47.9 N/m^2)

The accuracy of the empirical relationship is illustrated in Figures 6 and 7. Figure 6 is a plot of the measured peak drift load in psf, $P_d(=H_d\gamma_d)$, versus the corresponding value predicted by the empirical procedure. Figure 7 is a plot of the measured total drift volumetric load per unit length paralel to the change in roof elevation in plf, $H_dL_d\gamma_d/2$, versus the corresponding predicted value. The slopes of the least squares regression line are 0.967 and 1.028 for Figures 6 and 7, respectively, while the standard errors of the estimate were 27.7 psf (1.33 kN/m^2) and 518 plf (7.56 kN/m). If one considers only those case histories involving partial collapse or failure, the empirical procedure underestimates these measured values, on average, by about 10%.

Hence, although the empirical procedure overestimates drift loads for some case histories and underestimates them for others, it provides on average fairly accurate estimates of the measured drift loads. It should be noted that values in the drift load database for L_u, L_ℓ, H_r, and P_g were generally less than about 350 feet (107 m), 210 feet (64 m), 12 feet (3.4 m), and 25 psf (1.2 kN/m^2), respectively. Therefore, the empirical procedure developed herein might not be appropriate for situations outside this range of values.

The empirical procedure proposed herein which uses Hr, Lu, L_ℓ, and P_g as input parameters, accounts for only about 50% of the total variation in the actual data. This is evidenced by the scatter in Figures 4, 6 and 7. Although some of the scatter of actual data points about the proposed empirical relation can be explained by the lack of controlled data gathering methods for a large part of the database, it is felt there are other factors which also contribute. These other factors are the threshold wind speed and snow cohesion.

Schmidt (1980) has shown that the most important parameter to be considered when evaluating the horizontal transport of blown snow is the threshold wind speed, that is, the wind speed at which a snow particle initially at rest begins to move. The threshold wind speed is mainly a function of the cohesion of the snow surface.

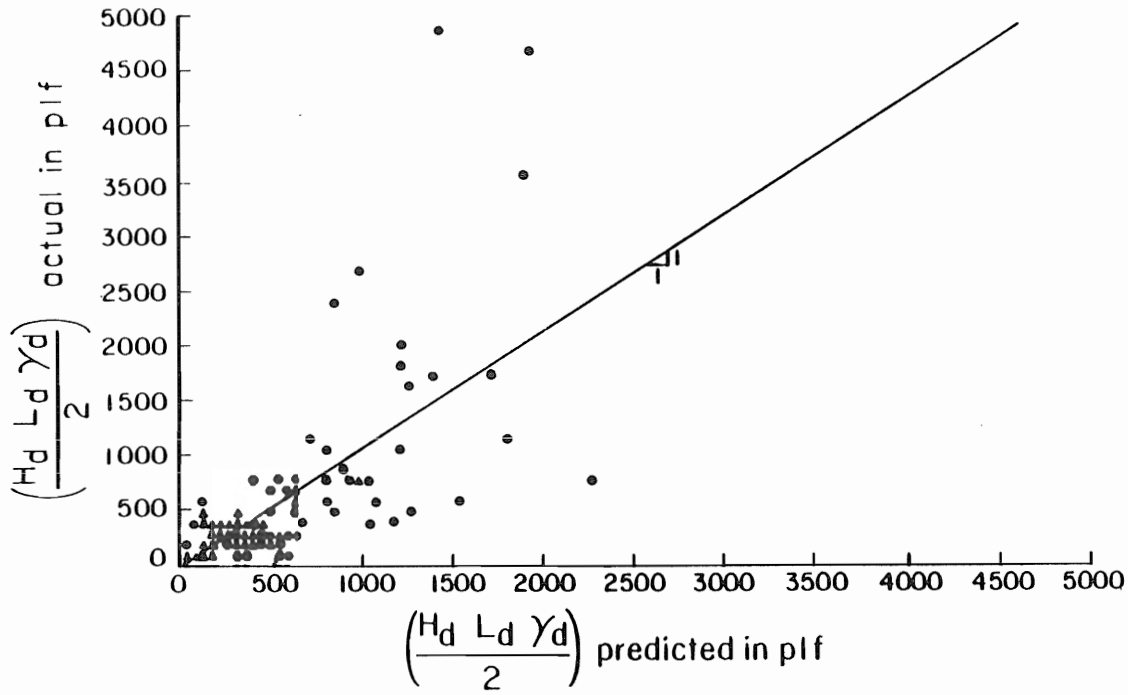

Figure 7. Scattergram of Actual vs. Predicted Volumetric Load Per Unit Length (1 plf = 14.6 N/m)

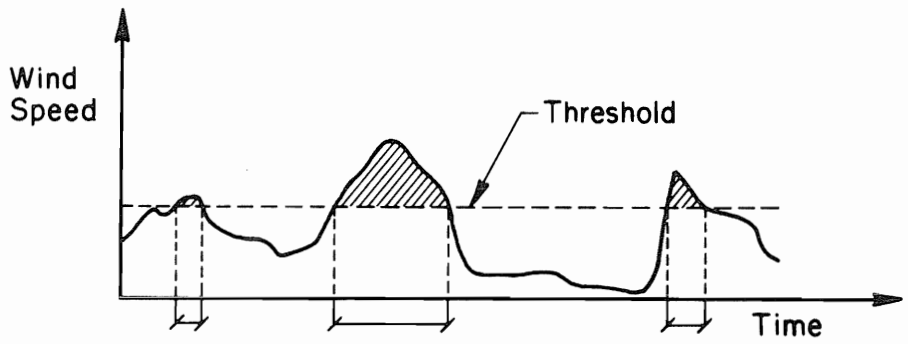

Figure 8. Possible Wind Parameters

In the work presented herein, the wind was characterized by both the average wind speed and the fastest mile speed. The preliminary correlation analysis and the multiple linear regression analysis indicated that these wind parameters did not have a significant effect upon drift size. It is felt that this counter-intuitive result may be due to the manner in which the wind was characterized. A better parameter may be the area under a wind speed vs. time curve as shown in Figure 8 or simply the amount of time the wind speed was above the threshold.

The empirical procedure developer herein provides a relationship between roof geometry and measured ground load, on the one hand, and measured drift loads on the other. It is not intended to provide a concise methodology for estimating a 50-year MRI drift load. This is due to the fact that a combination of wind and snow is necessary to produce drifts. The joint probability of wind and snow must be evaluated and quantified before a procedure for estimating 50 year MRI drift loads is proposed.

COMPARISON WITH EXISTING CODES AND LOAD STANDARDS

In this section, the drift procedures recommended in ANSI (1982), ISO (1981), MBMA (1981) and NBCC (1970) are compared with measured values from the database. The drift procedures recommended in each code are summarized in Table 2. Using the measured ground load as a starting point, the drift height, peak load, and cross sectional area were calculated using each of the four codes and were then compared with the corresponding measured values from the database. For example, Figure 9 is a plot of the actual drift height versus the value predicted by ANSI (1982). The slope of the least squares straight line is 1.50, indicating that, on average, ANSI (1982) underestimates the drift height for cases in the database. A comparison of the drift characteristics using each code is presented in Table 3. Both MBMA (1981) and ISO (1981) provide, on average, good estimates for drift height and cross sectional area as indicated by regression line slopes close to 1.00. However, because of the drift densities recommended by these two codes, unconservative peak loads usually result as indicated by regression line slopes substantially larger than 1.00. Both ANSI (1982) and NBCC (1970) yield, on average, unconservative values for all drift characteristics, due mainly to the arbitrary upper limit placed on the recommended value for H_d. Overall, best agreement is provided by codes that take the upper roof length into account.

Table 2 Summary of Design Code and Load Standard Procedures

	INPUT PARAMETERS				RECOMMENDED EQUATIONS		
	P_g	H_r	L_u	L_ℓ	Drift Height H_d (ft)	Drift Length L_d (ft)	Drift Density γ_d (pcf)
American National Standards Institute ANSI (1982)*	X				$2IP_g/Ce\gamma_d$ $H_d \leq H_r$	$3H_d$ or $4H_d$; $L_d \geq 10$	15 20 25
National Building Code of Canada, NBCC (1970)	X	X			H_r; $(H_r+H_b)\frac{\gamma_d}{P_g} \leq 3$, $H_b = 0.8\frac{P_g}{\gamma_d}$	$2(H_r + H_b)$; $L_d \geq 10$ $L_d \leq 30$	15
Metal Building** Manufacturers Association MBMA (1981)	X		X		$\sqrt{\frac{L_u(0.8\ P_g)}{8\gamma_d}}$; $H_d \leq H_r$	$4H_d$	$.24P_g + 9.0$
International Standard Organization ISO (1981)	X	X	X	X	$\left[\frac{(L_u+L_\ell)}{2(H_r+H_b)} - 0.8\right]\frac{P_g}{\gamma_d}$; $H_d \leq H_r$	$2(H_r+H_b)$ $L_d \geq 16.4$, $L_d \leq 49.2$	12.7

* I = importance factor, Ce = exposure factor
Drifting not considered if $H_r/H_b < 0.2$, $P_g \leq 10$ psf

** L_d changes with building depth; γ_d changes with P_g
Drifting not considered if $(H_r - H_b)/H_b < 0.2$

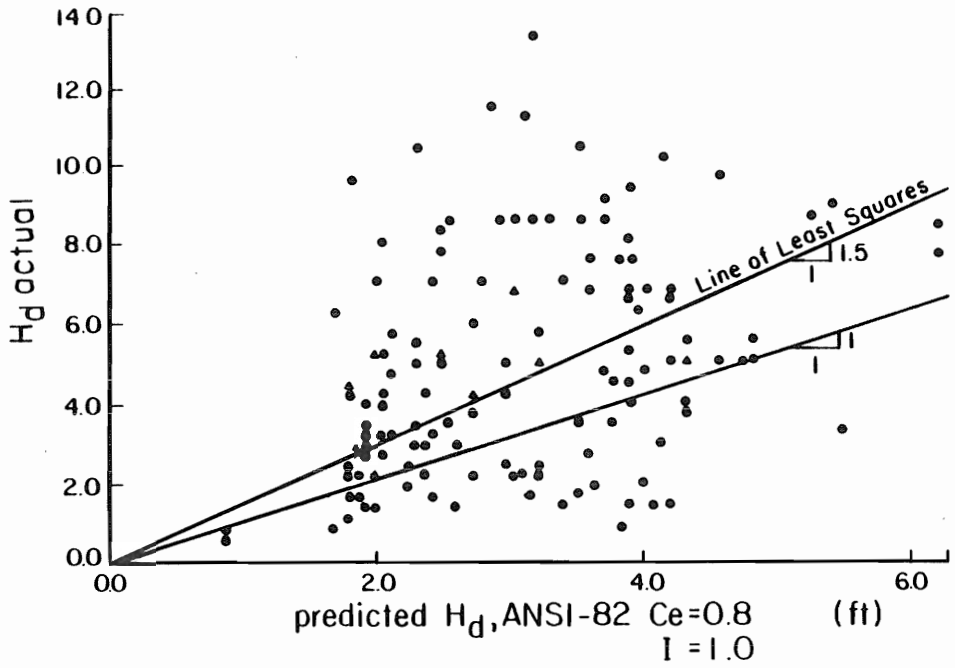

Figure 9. Scattergram of Actual Drift Height vs. Value Predicted by ANSI (1982)

Table 3 Statistics of Actual vs. Predicted Drift Load Parameter

Parameter	Code	Standard Error of Estimate	Slope of Regression Line Through Origin
H_d	MBMA	1.97 ft	1.107
	ANSI*	2.86 ft	1.500
	ISO	2.55 ft	1.023
	NBCC	2.87 ft	1.563
P_d	MBMA	31.5 psf	1.248
	ANSI*	45.6 psf	1.503
	ISO	38.7 psf	1.415
	NBCC	40.8 psf	1.731
$1/2\ H_dL_d$	MBMA	31.9 ft^2	1.065
	ANSI*	56.6 ft^2	1.635
	ISO	39.4 ft^2	0.943
	NBCC	52.2 ft^2	1.419

* I = 1.0; Ce = 0.8
1 ft = 0.305 m
1 psf = 47.9 N/m^2
1 ft^2 = 0.093 m^2

It should be noted that the scatter in the predicted values from each code, as measured by the standard error of the estimate, is larger than that for the empirical procedure presented herein. That is, the proposed empirical relationship provides a better fit to the observed data than any of the codes considered.

SUMMARY AND CONCLUSIONS

Information on snowdrifts from approximately 350 multilevel flat roofed structures, gathered from a variety of sources, has been analyzed herein. The purpose of the analysis was to provide a better understanding of the primary factors affecting snowdrift formation, and their relative importance, so that areas of potential drifting can be recognized and expected magnitudes of load projected.

It was found that the right triangular drift configuration (drift shape #1), with the peak load intensity immediately adjacent to the wall, occurs more often and is more important in terms of load magnitude than the quadralateral drift configuration (drift shape #2). For the triangular shaped drifts, the peak drift height, peak load, and cross sectional area were found to be most influenced by the upper roof length, roof elevation difference, ground snow load, and lower roof length in that order. An empirical equation was developed, utilizing these parameters, to predict the drift height. For drifts of importance to structural design, the typical rise to run ratio was found to be about 1:4 and the average drift density about 17.4 pcf (280 kg/m^3). This information allows one to estimate drift load.

Finally, comparisons were made with presently used design codes and load standards. There tends to be fairly good agreement with the actual drift measurements for codes which use the length of the upper roof as an input parameter. Overall, however, the empirical relationship developed herein provides more accurate estimates than any of the codes considered.

Acknowledgements

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