

Simplified Prediction of Driving Rain on Buildings

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1. INTRODUCTION

Moisture is the most important natural agent responsible for deterioration of the building enclosure. The amount of water deposited on the above-grade building envelope by driving rain is generally larger than any other source, including condensation, in almost all cases. Rain deposition can result in staining, leakage, dimensional change, freeze-thaw damage, leaching, efflorescence, and biological deterioration. Water penetration of the cladding can cause similar problems within a wall. Vapour diffusion can also move water that penetrates or is stored in the cladding inward where it can cause serious wetting of framing, sheathing, etc. (Straube et al 1998a).

Despite the importance of driving rain to building performance, there is a lack of quantitative data relating to the magnitude, duration, and frequency of rain deposition of on buildings. This data is especially important for use as input to those hourly hygrothermal building enclosure simulation packages such as WUFI (Kuenzel et al, 1997), that can properly model rain absorption. Complex CFD modelling packages which require detailed input of building and site geometry are not practical for most situations in design offices.

This paper develops a simplified method of predicting rain deposition on buildings using hourly weather record data. The existing literature is reviewed and driving rain field measurements, both in the free wind and deposition on a test house at the University of Waterloo are reported.

2. DRIVING RAIN

Driving rain can be defined as the amount of rain that passes through a vertical plane in the atmosphere. All but the largest drops will reach their terminal velocity within about 20 m (Beard 1976) of beginning their fall, i.e., for building applications it can be assumed that the drops are at terminal velocity. Similarly the horizontal velocity of the drops will equal that of the wind within a short distance. The fraction of falling rain that will pass through a vertical plane is therefore:

$$r_v = r_h \cdot \frac{V}{V_t} \quad (1)$$

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where, r_v is rate of rain passing through a vertical plane, i.e. driving rain (mm/m²/h or l/m²/h), and

V is the average wind velocity (m/s).

The mass of individual raindrops is sufficiently small that falling drops will respond to wind gusts that last for longer than about several seconds. Because the wind speed decreases significantly as the ground is approached, the trajectory of a drop will be curved. Very close to the ground (where the velocity changes quickly with height), at sharp changes in topography (e.g. hill tops), and around buildings, the momentum of a drop will cause its velocity components to vary from that of the wind.

Lacy (1965) proposed a simple equation relating wind speed and rainfall intensity to driving rain :

$$r_v = 0.208 \cdot V \cdot r_h = \text{DRF} \cdot V \cdot r_h \quad (2)$$

where, r_v is the rate of rain passing through a vertical plane (l/m²/h),

V is the average wind velocity (m/s), and

r_h is the average rainfall rate on the ground (mm/m²/h).

The proportionality constant in Equation 2 relating rain on a vertical plane (driving rain) to rain on horizontal plane (falling rain) is defined here as the driving rain factor (DRF). From equation 1 it can be seen that the DRF defined in equation 2 is just:

$$\text{DRF} = \frac{1}{V_t} \quad (3)$$

The terminal velocity of raindrops, from laboratory studies and doppler radar measurements can be predicted. Equation 4, developed by Dingle and Lee (1972) is accurate to $\pm 2.5\%$:

$$V_t(\varnothing) = -.166033 + 4.91844 \cdot \varnothing - .888016 \cdot \varnothing^2 + .054888 \cdot \varnothing^3 \leq 9.20 \quad (4)$$

where, $V_t(\varnothing)$ is the terminal velocity of a raindrop in still air [m/s].

It is generally agreed that raindrop size can be approximated as a function of rainfall intensity. This belief is supported by the field measurements of Best (1950), Laws and Parsons (1943) and Marshall and Palmer (1948) with each research group developing their own relationship (Markowitz 1976). The general conclusion is that the nature of the distribution clearly varies not only with rainfall intensity but also with the type of storm, the cloud height, etc. Best (1950) estimated the cumulative probability distribution of raindrop diameter as a function of rainfall intensity as:

$$F(\varnothing) = 1 - \exp\left\{-\left(\frac{\varnothing}{1.30 \cdot r_h^{0.232}}\right)^{2.245}\right\} \quad (5)$$

where, $F(\emptyset)$ is the cumulative probability distribution of drop diameters for a given rainfall intensity

\emptyset is the equivalent spherical raindrop diameter, and

r_h is the rainfall rate or intensity on a horizontal plane ($\text{mm}/\text{m}^2/\text{h}$).

A single free-standing driving gauge has been mounted 3.5 m above grade and 10 m upwind of the UW test house. More than 1000 15-minute periods during which it was raining were collected and analysed. The DRF factors were calculated, using both equations 2 (e.g., directly) and using equations 3 through 5, for the 147 periods during which the average wind direction was within 30° of perpendicular. To adjust for wind direction the cosine of the average wind angle off perpendicular during each period was used. Table 1 presents these results.

Table 1 Comparison of Measured DRF and Calculated DRF

Intensity Category (mm/h)	Median Intensity (mm/hr)	Median Drop Diameter (mm)	Measured DRF	Calculated DRF using eqn 3-5
< 1	0.37	0.88	0.272	0.286
1 - 2.99	1.80	1.27	0.220	0.211
3 - 4.99	3.60	1.49	0.188	0.186
> 5	10.26	1.90	0.136	0.158

Considering the nature of the experimental results and the imperfect equations for raindrop diameter distribution, the agreement between the DRF calculated using Equations 3-5 is seen to be good. Using a constant DRF value of 0.20 or 0.22 will obviously result in significant errors for all rainfall intensities other than 1-3 mm/h (the most commonly occurring rainfall intensity). The inaccuracy of the large raindrop category was predicted based on the rate of change of windspeed with height. The curved trajectory of large raindrops near the ground begins to have an effect at average windspeeds at a height of our gauge. A taller gauge would be required to demonstrate the accuracy of the equations for higher rainfall rates (and hence larger raindrop sizes).

Recent field studies and a literature review (Straube and Burnett) 1997 have found that the value for the DRF ranges between 0.20 to 0.25 for average conditions but varies considerably for different rainfall intensities and rain storm types (from more than 0.5 for drizzle to 0.1 for intense cloudbursts).

3. WIND AND RAIN AROUND BUILDINGS

When wind encounters a building, stream lines and pressure gradients form around it. While it is clear that driving rain is re-directed by these streams of air, accounting for this effect is difficult.

As the wind encounters a building, stream lines and pressure gradients form around the building. While it is clear that driving rain is re-directed by these streams of air, accounting for this effect is difficult. Recently, some researchers have pursued a computational fluid dynamics (CFD) approach (Choi 1994, Karagiozis 1995) while others have begun wind tunnel modelling (Inculet et al 1994) to help predict driving rain deposition on buildings. While promising research directions, these methods are too time consuming and project specific for practical use in developing hourly rain loads for hygrothermal computer models.

Since the method proposed here is intended as a simplified approach, we have introduced a linear factor, the rain admittance factor (RAF). This factor transforms driving rain at some horizontal distance (i.e. outside of the region disturbed by the building) to deposited rain on the building. The RAF accounts for the effect of the building on driving rain in the unobstructed wind and is believed to be a factor of the building's aerodynamics and the angle of attack of the wind. It is also likely that the RAF is a function of raindrop diameter and wind speed. The terminology has been chosen to be consistent with the wind engineering factor, aerodynamic admittance.

In his studies of driving rain on buildings, Lacy also suggested that it might be possible to predict rain deposition on a building surface by applying a factor to the driving-rain intensity. The RAF is this factor. To predict driving rain deposition on the vertical face of a building an extension of Equation 2 (driving rain in the free wind) can be written:

$$r_{bv} = \text{RAF} \cdot \text{DRF}(r_h) \cdot \cos(\theta) \cdot V(h) \cdot r_h = \text{RAF} \cdot \cos(\theta) \cdot r_v \quad (6)$$

where r_{bv} is the rain deposition rate on a vertical building surface ($l/m^2/h$),

$V(h)$ is the wind speed at the height of interest, h ,

θ is the angle between the normal to the wall and the wind direction, and

RAF is the rain admittance function; $\text{RAF} = r_{bv} \div (r_v \cdot \cos(\theta))$.

The RAF can often be calculated from the literature if information regarding windspeed and direction are provided. Unfortunately, the literature contains only a few references to simultaneous measurements of driving rain in the environment and driving-rain deposition on a building.

In most cases, the value of RAF calculated from the literature is less than 1.0, and for low-rise, rectangular buildings the value near the center can be assumed to be about 0.3. Sandin (1988, 1991) reported values of 0.3 (near the lower centre) to 1.0 (upper corners) in studies of driving rain on low-rise rectangular buildings. Lacy (1965) reported values of 0.3 for the middle, and about 0.5 for the corner of a low-rise wall over a wide range of wind speeds and rainfall intensities. Henriques (1992) measured an RAF value of 0.6 on the centreline of a low-rise building, but the gauge was mounted near the top of the partially-obstructed building at an unreported height above the free-wind gauge. Flori (1992) found a RAF value of almost 0.6 and, more importantly, reported increasing values of the RAF factor (up to 1.2) as the wind angle changed from normal to the wall to parallel to the wall.

These values of RAF have been calculated from driving rain measured at the same height in the free wind for low-rise (less than 10m) buildings. Higher up a tall building, the driving rain intensity will be higher because wind speeds increase with height according to a power law. Lacy's measurements near the top corner of a highly-exposed ten-storey apartment building suggest a RAF value of 1.0. However, the amount of rain received as close as one meter from the edge of the building appeared to be greater. Schwarz (1973) measured driving rain deposition on an 18-story building for a seven-month period. The RAF for these measurements was approximately 0.5 at the 10 m height.

Windspeed increases with height following a power law distribution. Extrapolating windspeed data higher up the tall building studied by Schwarz (using the appropriate power law as is common in structural load calculations), one can calculate the RAF for other heights on the building from his data. The calculated RAF for the ninth and sixteenth storeys was no different than that for the third story at 10 m above grade. The RAF calculated for the upper corners of the building, however, ranged from 0.9 to 1.0. These results (RAF = 0.3 to 0.5 for the centre of a building and RAF = 0.9 to 1.0 for the corners) match Sandin's and our own results for a low-rise building. An important implication of these results is that driving rain deposition increases with height at the same rate as wind speed. The RAF also appears to be scale-independent, probably in a similar way as mean wind pressures gradients can be scaled for buildings of the same geometry.

Based on the windspeed variable in Equation (2), the upper portions of a 30 storey (78 m) apartment building would be exposed to almost twice the amount of rain wetting as a two-storey (5 m) house. When the sheltering effect of neighbouring houses and roof overhangs are taken into consideration, the rain on the low-rise building would be expected to be substantially less.

When results from the literature reviewed above, our own measurements, and computer modelling (e.g. Karagiozis 1995) are evaluated in terms of DRF and RAF there is a

reasonable agreement of results. Figure 1 summarises this data. The figure shows that the amount of driving rain deposited on a building is usually less than the amount in the free wind ($RAF < 1$), although there may be small areas near the upper corners of the building where the RAF occasionally exceeds 1.0.

Peaked roofs and overhangs redirect airflow and can thereby have a significant effect on rain deposition (regardless of the building size). For example, adding a 1.5 m wide canopy to a multi-storey building will result in a lower RAF value and can, in theory, be an effective and economical means of improving rain control (see also Inculet 1994).

Note that all of the measurements reported above are averaged over several rain events, or even over several years. The RAF is likely to vary with the wind speed and rain drop diameters of the individual storm. Much work remains to be done.

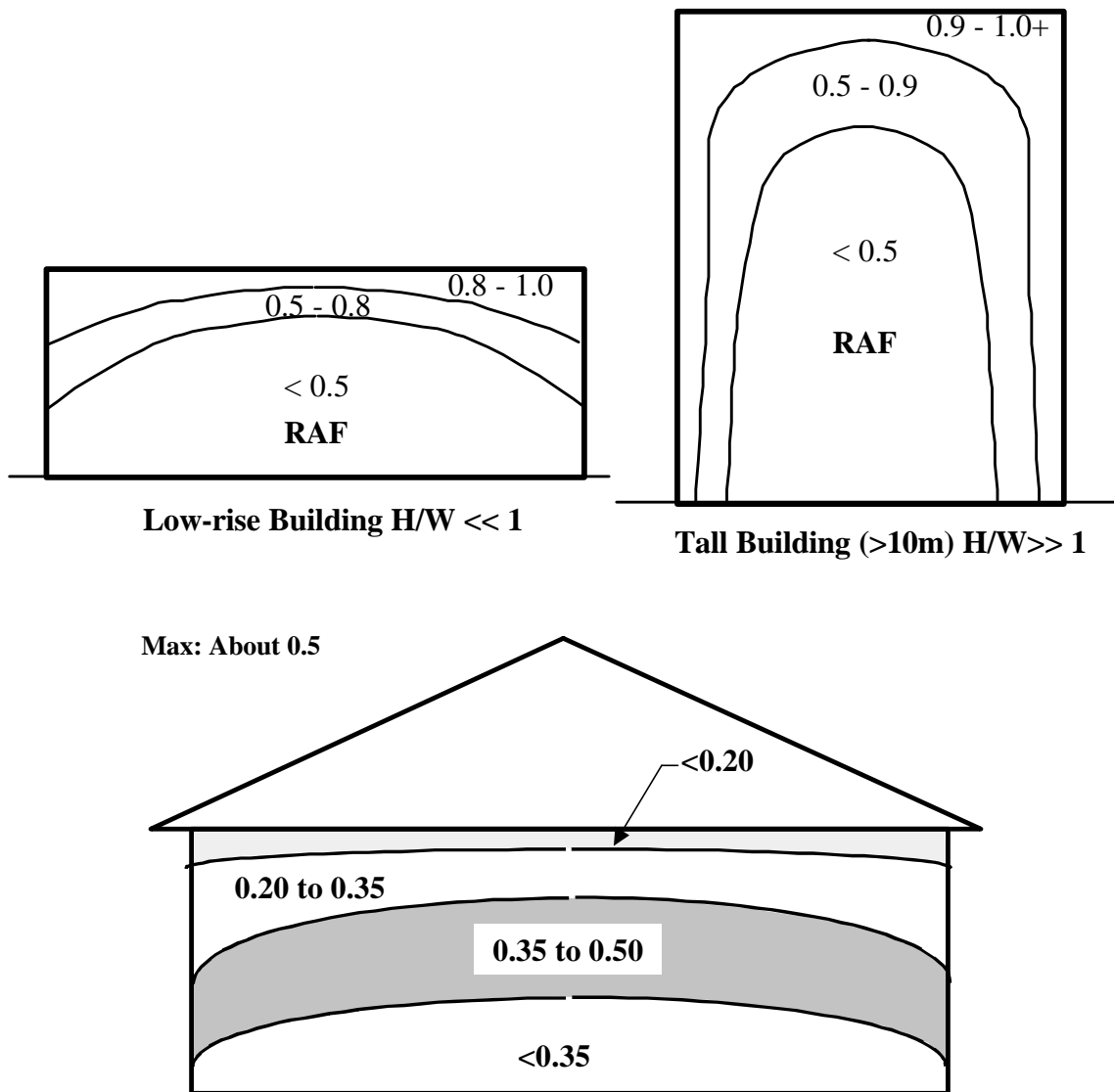


Figure 1 Typical Measured Rain Admittance Factors for Simple Buildings

4. CONCLUSIONS

Driving rain can be an important moisture load for building enclosures, especially those with absorbent claddings and leaks. Computer models are now available that can predict the hygrothermal condition within enclosures. Such models require hourly driving rain data but practical limitations exclude present CFD models from design offices.

An equation of the form:

$$r_{bv} = \text{RAF} \cdot \text{DRF}(r_h) \cdot \cos(\theta) \cdot V(h) \cdot r_h$$

is suggested as a simple means of predicting driving rain deposition on a building face from hourly weather records of wind speed, direction and rainfall. The value for the Driving Rain Factor ($\text{DRF}=1/V_t$) can be calculated quite precisely from rainfall and windspeed data using:

$$V_t(\emptyset) = -.166033 + 4.91844 \cdot \emptyset - .888016 \cdot \emptyset^2 + .054888 \cdot \emptyset^3 \leq 9.20$$

$$\text{and } F(\emptyset) = 1 - \exp\left\{-\left(\frac{\emptyset}{1.30 \cdot r_h^{0.232}}\right)^{2.245}\right\}$$

used to calculate the median drop diameter from the rainfall intensity at every hourly interval.

In lieu of this detailed calculation, a DRF of between 0.20 and 0.25 can be chosen (as Lacy 1965, Kuenzel 1994 and Frank 1973 have).

The value for the Rain Admittance Factor is less well known, although a range of 0.3 to 1.0 appears to cover many situations. It is important to note that the RAF need not change for tall buildings but that the increase of windspeed, V , with height *must* be taken into account.

Most of the theoretical and analytical work presented below is described in far greater depth and detail in (Straube 1998b). Several other field studies are presently underway or complete.

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