Wind-driven Rain Study for the Governor's Road Project

Dundas, Ontario

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SUMMARY AND MAIN FINDINGS

This report on the study of wind-driven rain action on the Governor's Road Project in Hamilton, Ontario provides the following information:

- wetting patterns for the Governor's Road Project building without cornice protection;
- wetting patterns for the Governor's Road Project building with cornice protection; and
- a cornice effectiveness evaluation.

A three-dimensional numerical model of the project building geometry, and the wind and rain conditions were designed using commercial computational fluid dynamics software, FLUENT 4.3 (Users Guide, 1996). The building model was numerically tested in atmospheric turbulent boundary layer flow conditions for one dominant wind direction. Figure 1a shows the three-dimensional, AutoCAD-generated model geometry.

A design probability distribution of gradient wind speed and direction and rainfall intensity had been previously developed for two sites in Ontario (Ottawa and London) on the basis of full-scale meteorological records from these areas. These data have been used to infer the dominant wind direction and intensity as well as rainfall conditions at the site of the Governor's Road Project. The wind flow field around the building has been numerically simulated (computational fluid dynamics or CFD) and followed by the calculation of raindrop trajectories and their impact with the building façade. The rain flow impacting the building envelope has been determined for different zones of the main façade and wetting patterns have been determined for two situations: a building without cornice protection and a building with cornice protection. The wetting results for the two situations have been compared and the cornice effectiveness has been assessed.

The highlights and main findings of this study are as follows.

Wind climate

- The directional characteristics associated with the wind and rain climate model are shown in figures 2a and 2b for the Ottawa and London locations, respectively. It can be seen that southerly and easterly directions are the most important with respect to wind-driven rain conditions. The southerly direction is perpendicular to the main façade of the Governor's Road project building and, therefore, has been considered as the main case study.

- Based on the same wind–rain characteristics for Ottawa and London, the 10-year return period conditions at the Governor's Road Project site were approximately determined as an hourly 10 m height wind speed of 10.4 m/s together with a rainfall intensity of 11 mm/hour.

Wetting patterns

- Wetting patterns on the building façade have been predicted and are expressed as local intensity factors:

$$LIF_j = \frac{R_j}{R_o} = \frac{\text{rainfall rate [mm/hr] through a facade zone "j"}}{\text{undisturbed rainfall rate [mm/hr]}}$$

Figure 3 presents the local intensity factors (LIFs) without cornice protection.

- The two cases (with and without cornice) are compared in Figure 4 in which the cornice effectiveness factors (Fj) are defined as:

$$F_j = \frac{\text{LIFj (without cornice)}}{\text{LIFj (with cornice)}}$$

- A summary of the predicted wetting patterns with and without cornice is shown in Table 1.

DETAILS OF THE STUDY

Project Name: The Governor's Road Project

Project Location: Hamilton, Ontario, Canada

Project Dimensions: The project consists of a low rise, symmetrical building.

Simulation Dates: February 1998

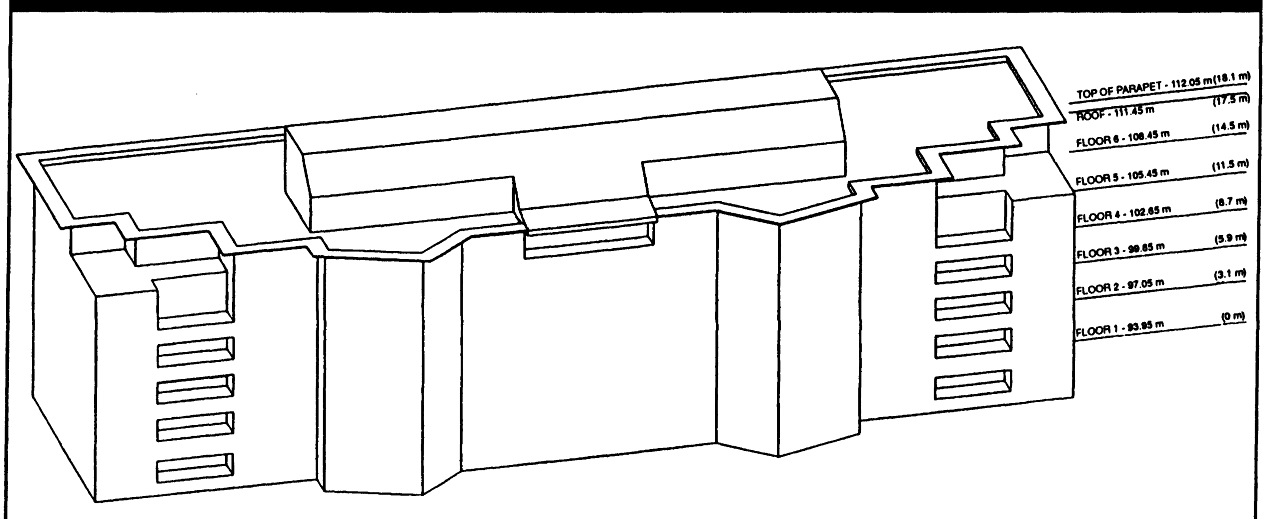
Preliminary Reporting: March 5, 1998

Report Scope and Format: The results presented in this report rely on parallel studies of:

- the full-scale wind climate in order to determine the strength and directionality of the wind and the undisturbed rainfall intensity; and
- computational fluid dynamics (CFD) simulations to determine the aerodynamic and raindrop trajectories data relevant to this project.

The combination of these two studies provides predictions of rain wetting on the building façade.

Figure 1a
3D AutoCad model



1. THE WIND–RAIN CLIMATE FOR HAMILTON

- The joint wind–rain climate model for the Governor's Road Project site in Hamilton has been inferred from previous studies (Skerlj et al., 1995) for two sites in Ontario: London and Ottawa. (See figures 2a and 2b.)

- The climatic data for the two sites are well correlated and indicate prevalence of the wind/rain from two main directions: south and east. Based on the Governor's Project site orientation, the southerly wind/rain direction, which is perpendicular to the main façade of the building, has been considered relevant and has been employed in the present study.

- Based on the same previous studies (Skerlj et al., 1995) the hourly mean wind speed at 10 m height corresponding to undisturbed rainfall intensity R_O = 11 mm/hour was 10.4 m/s. The wind speed and rainfall intensity correspond to a 10-year return period.

- A suburban exposure has been assumed corresponding to a power law coefficient of $a = 0.22$. A constant wind turbulence intensity has been assumed below 50 m height: I_u= 17% .

Figure 2a
Wind-rain roses for all hours and rainy hours, London

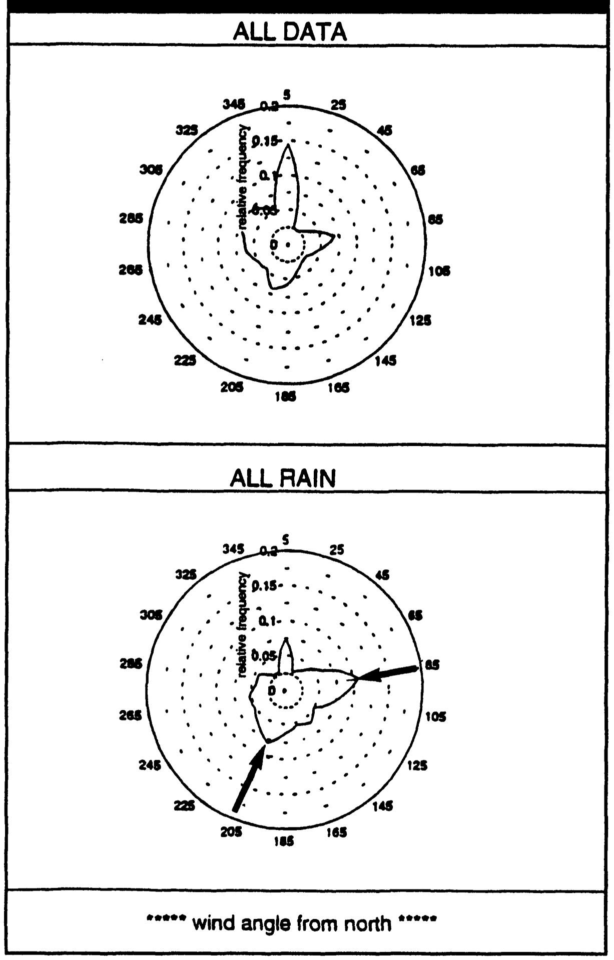
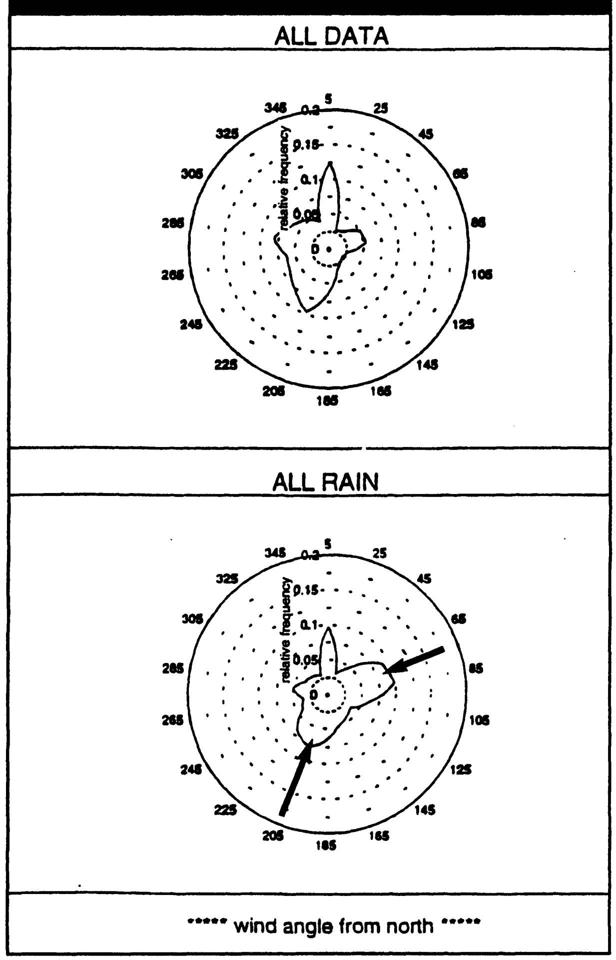


Figure 2b
Wind-rain roses for all hours and rainy hours, Ottawa



2. GEOMETRY, TOPOLOGY AND MESH GENERATION

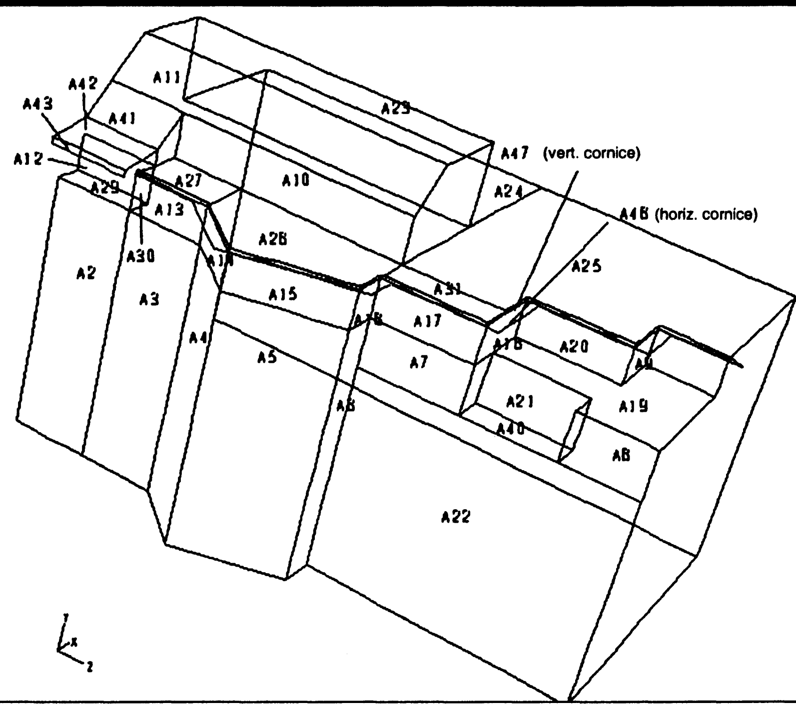
Geometry

- The three-dimensional geometry has been generated in AutoCAD 13 based on architectural drawings. The architectural geometry has been simplified eliminating any architectural details of little aerodynamic significance.
- The AutoCAD-generated, building geometry is shown in Figure 1a.

Topology and Mesh

- The building geometry has been divided in topological surfaces (wall zones). These surfaces are later used to determine the amount of water impacting the building. Each surface (zone) "j" has an area Aj.
- The wall zones are shown in Figure 1b for half the building. As the building presents one symmetry axis, only half the geometry has been employed for the numerical simulations.
- Both the topology and numerical grid generation emphasize the area adjacent to the cornice zone (the upper part of the building façade). The cornice itself is constituted in two main parts: the canopy above the balcony 1 (left-hand side in Figure 1b) and the rest of the cornice all along the building façade.
- An unstructured, tetrahedral grid with approximately 80,000 cells (before refinement) and average skewness of 0.3 has been employed. A detail of the unstructured grid is presented in Figure 1c for the area adjacent to the cornice zone.

Figure 1b
CFD topology and wall zones



Model

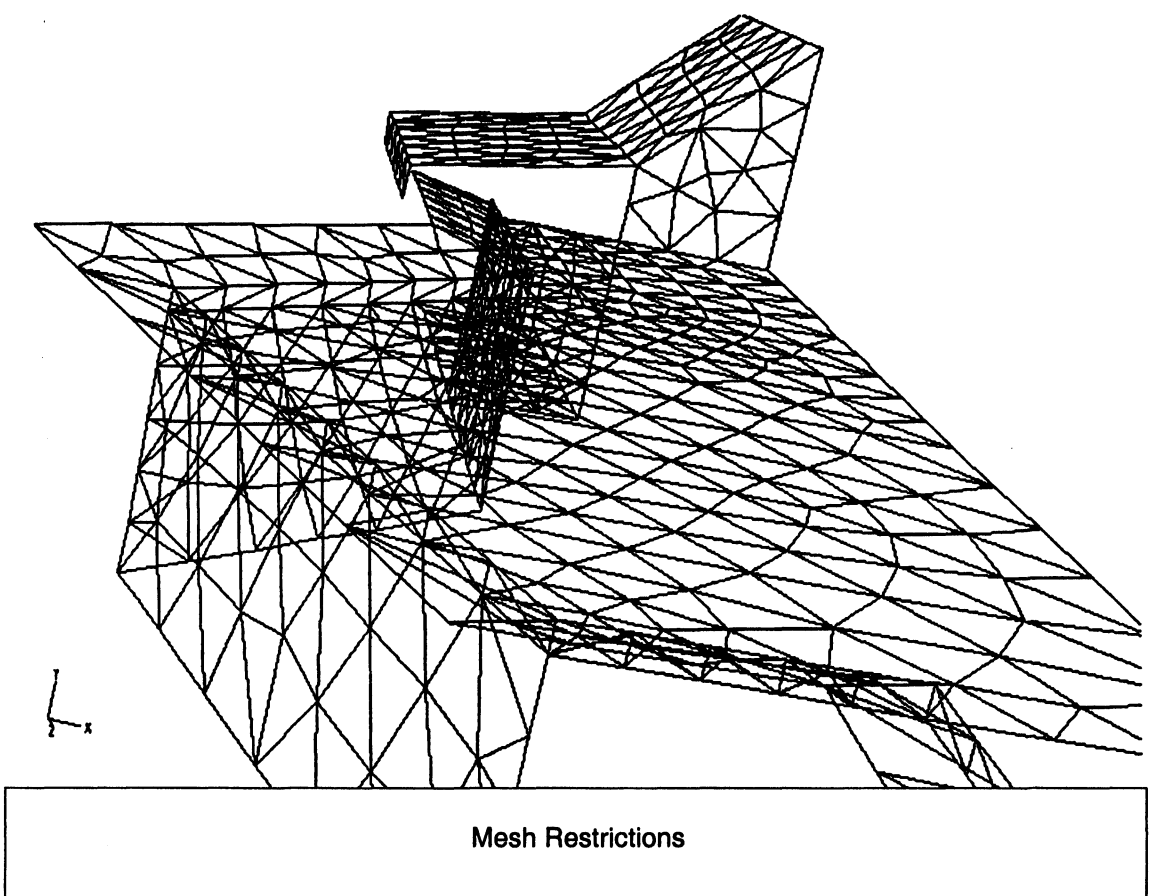
3. BOUNDARY CONDITIONS

- Velocity inlet boundary conditions have been employed as upstream conditions. A power law velocity profile (a = 0.22) with a 10 m height velocity of 10.4 m/s and average turbulence intensity 17% has been adopted based on previous studies (Skerlj et al., 1995) and the Governor's Road Project exposure.

- Wall boundary conditions have been used for the ground and various zones on the building envelope.

- Pressure outlet boundary conditions were used as outflow conditions, and symmetry boundary conditions have been adopted for the building and computational domain symmetry plane, running parallel with the wind direction.

Figure 1c
Detail of the unstructured grid for the cornice adjacent zones



4. MODELLING OF WIND AND RAIN

Overall Approach

- The basis of the computational method is the FLUENT commercial CFD package, to which suitable models of rain are added, based on data existing in the literature. Physical models of wind–rain effects on buildings have been previously developed at the Boundary Layer Wind Tunnel Laboratory (BLWTL) (Inculet and Surry, 1995; Hangan, 1998), and the wind tunnel experiments form the basis for the verification.

- The modelling problem consists of calculating the raindrop trajectories in the presence of the airflow around the building. This is a Lagrangian approach and implies assumptions such as low-volume fraction of water in air (<10%) and neglect of particle–particle interaction.

Wind Flow Around Buildings

- The flow field is solved using the Navier-Stokes (N-S) and continuity equations:

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}(u_i u_j) = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\nu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \text{ (N-S);}$$

$$\frac{\partial u_i}{\partial x_j} = 0 \text{ (continuity)} \qquad (1)$$

A $k-\varepsilon$ and Reynolds stress turbulence model with wall functions are employed for the Eulerian (fluid phase) flow.

Generally, both experimental and CFD simulations show typical wind flow patterns around buildings such as frontal base vortex, separation, reattachment and vortex shedding. The particles (especially the light ones) have the tendency to follow the streamlines. Figure 5 presents a detail of the wind flow (arrows) and typical raindrop trajectories for the cornice zone of the Governor's Road Project.

Wind-driven Rain

- The raindrops are considered spherical of diameter d and density P_p. Their terminal velocity is expressed based on the equilibrium between gravity and aerodynamic drag (Stokes formula) on the particle (2). The particle size distribution can be expressed by a Gaussian model (3).

$$V_T = \frac{d^2}{18\nu}\left(\frac{P_p - P}{P}\right)g \qquad (2)$$

where P and ν are the air density and kinematic viscosity

$$M_d = \exp[-(\frac{d}{\bar{d}})^n]$$

= the mass fraction of droplets larger than d
where: (3)

$\bar{d} = bR_o^p$ is a mean diameter, n is a spread parameter (n = 2.25 for raindrops) and $R_o[\frac{mm}{hr}]$ is the undisturbed rainfall intensity.

Raindrop trajectories are determined based on a force balance (Lagrangian reference) between the aerodynamic drag (F_D) and the gravitational force on the particle (Hangan, 1998).

$$\rho_p\frac{\partial u_p}{\partial t} = F_D(u_i - u_p) + g(\rho_p - \rho) \qquad (4)$$

where u_i and u_p are the air and particle velocities, $F_D = \frac{18\nu\rho}{d_p^2} * \frac{C_D * Re}{24}$ is the aerodynamic drag (Stokes law), $Re = \frac{d_p}{\nu}\sqrt{\Sigma(u_i - u_p)^2}$ the particle Reynolds number (Lagrangian) and $C_D = a_1 + \frac{a_2}{Re} + \frac{a_3}{Re^2}$ is the drag coefficient (Morsi-Alexander law).

- The turbulent dispersion of droplets has been taken into consideration for the CFD simulations.

5. THE ESTIMATION OF WETTING ON THE BUILDING FAÇADE

Overall Approach

- The droplets are "trapped" on the building zone. Trajectory calculations are performed for all droplet sizes and then the mass flow rate of particles crossing the façade (ϕ_j) and the rainfall intensity on every zone (of area A_j) are calculated $R_j = \frac{3600*\phi_j}{A_j} [\frac{mm}{hr}]$.
- Local intensity factors (LIFs) are afterward estimated by relating the rainfall intensity on each building zone to the undisturbed rainfall intensity: $LIFj = \frac{Ri}{Ro}$.
- The results are analyzed for the two cases, without cornice and with cornice in terms of local intensity factors (LIF).

Wetting Patterns Without Cornice

- The LIFs indicate that the areas likely to be affected without the cornice (LIF>1, Figure 3) are in the wake of the mechanical penthouse (LIF = 4.3) the frontal and inclined walls of the same mechanical block (LIFs = 1.6 and 1.5 respectively), the balcony 1 back wall (left side, LIF = 1.9) and the upper wall zone (immediate below the cornice, LIF = 1.1).

Cornice Effectiveness

- Cornice effectiveness factors (Fj) have been defined as ratios (for every zone "j") between the LIFs without and with cornice: $Fj = \frac{(LIFj) \text{ without cornice}}{(LIFj) \text{ with cornice}}$. These factors are useful in determining the effect of the cornice for every zone: for $F_j>1$ the cornice reduces the rainfall rate on that specific area and for $Fj<1$ the cornice increases the rainfall rate to that specific area.
- These factors should be reviewed along with the LIF factors, as increases or reductions are most significant where LIF values are large. It has been observed that the cornice has a positive effect (reducing the rainfall rate) for the great majority of the building zones. See Figure 4.
- Reduction factors between 1.1 and 2.5 are expected for the main wall zones. The upper wall zones, immediately below the cornice, are well protected (Fj factors between 1.4 and 4.3). The back wall corresponding to balcony 1 (under the canopy, Fj = 20.4) and the terrace (right hand side, Fj = 30.9) are also well protected by the cornice.
- The only increases in rainfall rates due to the cornice occur for the balcony 2 back wall (right hand side, under the terrace, Fj = 0.5 and Fj = 0.8), the mechanical penthouse roof and the floor of the balcony 1 (under the canopy, Fj = 0.4).
- The corresponding LIF values show that the only zone likely to be affected negatively (LIF>1) by the cornice is the floor of balcony 1 for which LIF = 1.11. However, this value is considered to be acceptable in the context of the overall positive effect of the cornice.
- It is underlined that a 10% increase in the LIF coefficient is not significant and is less than the overall quantitative error embedded in the simulation process as a whole.

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Table 1
Rainfall rates (Rj) and local intensity factors (LIF) with and without cornice

GOV5NEW - With cornice				**GOV5 - Without cornice**			
Ro=13.9 mm/hr. U10=10.35m/s				**Ro=11mm/hr. U10=10.35m/s**			
Rj	***LIFj***	**Aj**	**Zone**	**Rj**	***LIFj***	***Fj***	**Obs.**
[mm/hr]	*[~]*	[m^2]	Fig.1	[mm/hr]	*[~]*	*[~]*	
2.72	***0.19***	72.43	A2	5.15	***0.49***	**2.53**	Wall
2.56	***0.18***	70.76	A3	4.43	***0.42***	**2.31**	Wall
2.26	***0.16***	75.5	A4	3.72	***0.36***	**2.20**	Wall
2.50	***0.18***	104.91	A5	2.74	***0.26***	**1.46**	Wall
5.86	***0.42***	17.58	A7	4.59	***0.44***	**1.05**	Cornice wall(low)
10.38	***0.74***	13.28	A8	10.59	***1.01***	**1.36**	Cornice wall(low)
2.53	***0.18***	38.65	A10	16.49	***1.57***	**8.73**	MB front
15.02	***1.07***	63.03	A11	15.26	***1.46***	**1.36**	MB inclined
1.30	***0.09***	10.38	A12	19.87	***1.90***	**20.42**	Balc1 back
3.55	***0.25***	10.68	A14	11.49	***1.10***	**4.32**	Cornice wall
5.14	***0.37***	15.25	A15	9.0800	***0.87***	**2.36**	Cornice wall
2.39	***0.17***	13.63	A17	2.4500	***0.23***	**1.37**	Cornice wall
0.29	***0.02***	18.53	A18	-	-	-	-
1.71	***0.12***	45.83	A19	1.1400	***0.11***	**0.89**	Terrace
0.20	***0.01***	13.2	A20	4.73	***0.45***	**30.91**	Back Terrace
7.61	***0.54***	16.33	A21	4.32	***0.41***	**0.76**	Balc2 back
3.22	***0.23***	198.9	A22	2.61	***0.25***	**1.08**	Wall
5.12	***0.37***	95.85	A23	0.08	***0.01***	**0.02**	MB roof
45.13	***3.23***	172.12	A24	45.02	***4.30***	**1.33**	MB wake
13.99	***1.00***	***225.77***	**A25**	10.47	***1.00***	**1.00**	**Roof-Reference Ro**
1.52	***0.11***	53.21	A26	1.44	***0.14***	**1.26**	Roof
0.10	***0.01***	52.67	A27	0.6800	***0.06***	**8.86**	Roof corner
15.56	***1.11***	7.49	A29	4.9	***0.47***	**0.42**	Balc1 floor
0.39	***0.03***	13.83	A31	-	-	-	-
5.44	***0.39***	9.94	A40	2.09	***0.20***	**0.51**	Balc2 floor
13.79	***0.99***	11.79	A41	-	-	-	Balc1 cornice
11.44	***0.82***	1.89	A43	-	-	-	Balc1 cornice
0.19	0.01	42.89	A46	-	-	-	Cornice
1.29	***0.09***	8.34	A47	-	-	-	Cornice
1.83	***0.13***	42.89	A461				

Figure 2c
Close-up view of the building under construction

Figure 3
Local intensity factors (LIF) for building zones without cornice

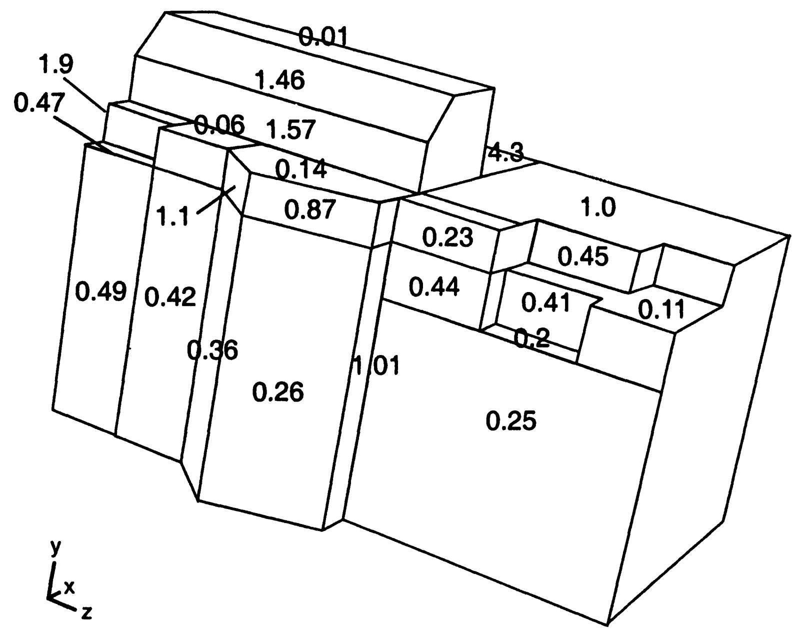

Figure 4
Cornice effectiveness factors

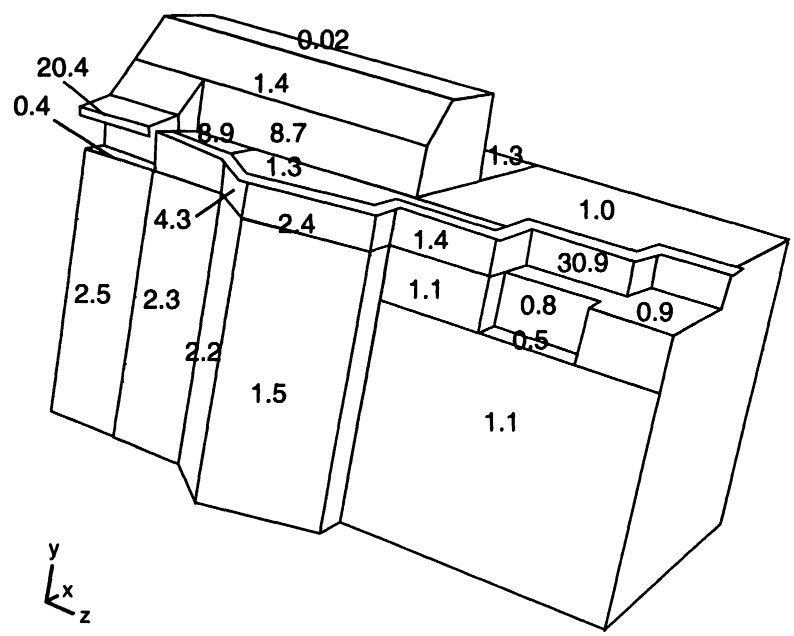

Figure 5
Detail of the wind flow (arrows) and typical raindrop trajectories (continuous lines)