PREDICTION OF WEATHERING EFFECTS ON CONCRETE BUILDINGS USING COMPUTATIONAL METHODS

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Abstract

This paper derives from work currently being undertaken at Oxford Brookes University, School of Architecture, Post Graduate Research School. It concentrates on buildings that use concrete as their external surface. The aim of the work is to develop a computer model that will predict the manner in which concrete surfaces weather.

The model will be based on the hypothesis that concrete weathers irregularly, because driving rain, which forms runoff, distributes impurities unevenly over building facades. The amount and speed of rain and the geometry of the building are critical factors that determine the run-off and the manner in which dirt deposits are distributed on the concrete surface.

The main variables that are taken into consideration in the model are driving rain, absorption capacity of the material, and the accumulation of dirt on the surface (pollution). The model is based on Finite Element Techniques and converts water run-off to weathering characteristics.

It is possible that this initial experimental model might be developed to a high level of sophistication and that it might be used by building designers to predict and optimise the weathering characteristics of their buildings at the design stage.

The Problem Of Weathering Effects On Buildings

The alteration of a building's appearance as a result of exposure to atmospheric and environmental conditions is collectively termed weathering. These conditions induce visual and compositional changes within and on the surface of building materials. These can be of physical, chemical or biological nature and may have a favorable or unfavorable impact upon the appearance and physical state of a building. Most of the factors which induce weathering, i.e. climate, environment, adjacent materials, soiling, organic growths, may be taken into consideration during the design process and can, to some extent, be anticipated, controlled and used as positive elements in design.

Computer Aided Design (C.A.D) packages allow designers to design and model a building in two or three dimensions. These packages can be used both as a basis for architectural and construction design and for analysis purposes (structural, quantity or environmental analysis). At present there is no computer package for the prediction of weathering effects on buildings. Such a package, which could be used in conjunction with an existing designing package, is being proposed to assess weathering of concrete surfaces.

At the preliminary stages of design, important decisions are made concerning the orientation and geometry of a building and the materials used. These decisions have an important influence on the weathering of a building, and general design guidance would be helpful at this stage. Later in the design process more detailed information relating to the weathering of specific areas or features of the building might permit the optimisation of building details to reduce the effects of weathering.

A Predictive Model For Weathering

In order for the proposed model to be of greatest practical application, it should be able to fulfil certain tasks. It should recognise the effects that different materials have upon weathering as well as the influence of the building's geometry upon weathering. It should also be able to calculate the amount of driving rain hitting the building when the information provided consists of the amount of rain falling in the area and the dimensions of the building. It should be able to calculate the rain distribution upon the building's facade, when the geometrical features of the building and the direction and amount of driving rain are specified, and the amounts of water absorbed into the material's surface. Finally, it should calculate the amounts of water running off the surface.

Following conventional computational methodologies, the structure of the model might be comprised of three parts.

a. A mechanism for developing a three dimensional model of the building, using a suitable adapted software package.

b. An analytical engine where data describing the topography of the building or parts of the building are combined with input data concerning the materials and the environment. Through calculations, the nature of likely weathering effects on the modelled surfaces is determined.

c. A visualisation of the weathered facade, based upon rendered techniques applied to the original model.

Objectives Of This Research

This research is interested in the *engine* part (b) of the model described above. Previous research suggests that water movement on building facades is the main variable in causing weathering (Beijer 1980, Hawes 1986, El Shimi et.al. 1979, Hall et.al 1982). Therefore water movement can form the basis of analysis. Associated factors include wind patterns, pollution rates and the different qualities of materials.

The data needed for the development of a model for predicting weathering can be divided into three categories.

1. Data concerning the dimensions, geometry and orientation of the building.
2. Data concerning the technology and the materials used.
3. Data describing the environment where the building will be built, i.e. amount of rain falling in the area, direction and speed of wind and the pollution rates.

The Weathering Of Concrete Buildings

Concrete buildings are strongly associated with 'uneven' weathering, which becomes noticeable over a relatively short time, i.e., less than ten years in a wet climate. This can be due to bad detailing and design but is mainly due to the material's properties and its reaction to the environment. The majority of concrete's weathering problems are related to the presence of water which reacts with the constituents of the material and also redistributes any impurities present on its surface, creating tide marks and stains.

Rainwater runoff is usually the main cause of unevenness of soiling on buildings' facades. When driving rain impinges on a building facade, a part of the water gets absorbed into the building material and the rest forms rain run-off. This runoff acts as a cleaning agent for the upper parts of the building. As it moves across the facade it acts as a carrier of dirt particles from the higher which accumulate on the lower parts of the building. At the point where rain runoff stops, soiling stains are created.

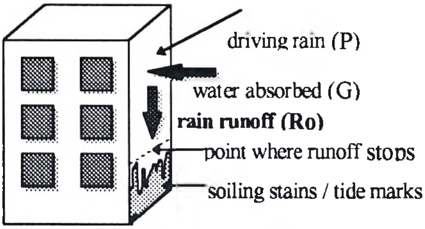

Figure 1: Mechanisms of weathering

Each building material has a different absorption capacity which is expressed by a *water absorption coefficient (A)* defined by C.I.B (Conseil International du Batiment pour la Recherche)(1977). This absorption coefficient is an important factor which influences the extent to which the building facade becomes soiled, because it determines if and how soon rain runoff occurs and how far down the facade it will manage to reach. The less porous a building material is (low water absorption coefficient), the faster rain runoff occurs and vice versa.

Absorption coefficients vary between different materials from 0 (zero), i.e. glass and metal, to 300-600 gr/m sec$^{1.5}$, i.e. ordinary brick. When the value of the absorption coefficient is under 10 gr/m sec$^{1.5}$, rain runoff commonly reaches all the way to the ground level, thus cleaning the whole surface of the building facade. Concrete, however, has an absorption coefficient varying from 10 to 40 gr/m sec$^{1.5}$, which means that it has a tendency to create runoff quite quickly. However, where the amount of rainfall is greater on the top of the facade than on the lower region (as is normally the case), runoff may not reach the ground level. Therefore the surface is not evenly cleaned and unsightly stains are formed where the rain runoff stops (Beijer 1980, pp. 21-24, Hawes 1986, p.10).

An Analytical Engine To The Predictive Model

A suitable calculation technique is required to calculate the flow of water on each part of the modelled surface. Finite Element Methods are often used by engineers for structural analysis. The basis of these methods is that the body or structure, in our case the building facade, is represented by an assembly of subdivisions called *finite elements*. The facade is thus divided into smaller areas, connected at certain points, called nodes or nodal points. Instead of solving the problem for the entire body of the facade, it is solved for each constituent (Desai et.al. 1972, p.3, Pickard 1986, p.50) where the complexity of the problem is much smaller and thus easier to resolve. After carrying out calculations within each finite element, the information is joined together to form the general picture of the facade. Going from part to whole should make it possible to predict the weathering patterns on the whole facade more accurately.

Choice of finite elements' dimensions and shapes relate to the size of facade, the variety of materials used and geometry of the building. The relationships between neighbouring finite elements may also be determined according to the materials and the geometry of each finite element. The properties of the materials, i.e. absorption capacity and texture, influence the relationship between neighbouring finite elements.

Once a building is modelled and the model divided into finite elements, a calculation procedure can be instigated, beginning with the theoretical exposure of the building to the environment. The most important elements influencing the weathering of a surface are rain, wind and pollution. Pollution will be given a rate with reference to a scale, e.g. 0-10, where 0 refers to a non-polluted area while 10 refers to a very polluted area. The amount of rain falling on the area in a certain period of time must be known (Met. office, mm or inches) in order to calculate the amount of rain falling on the building. Then the distribution of the water on the building's surface is determined and the amount of water absorbed by the surface material calculated. When these two tasks are executed, it will be possible to calculate the amount of rain run-off on the building surface.

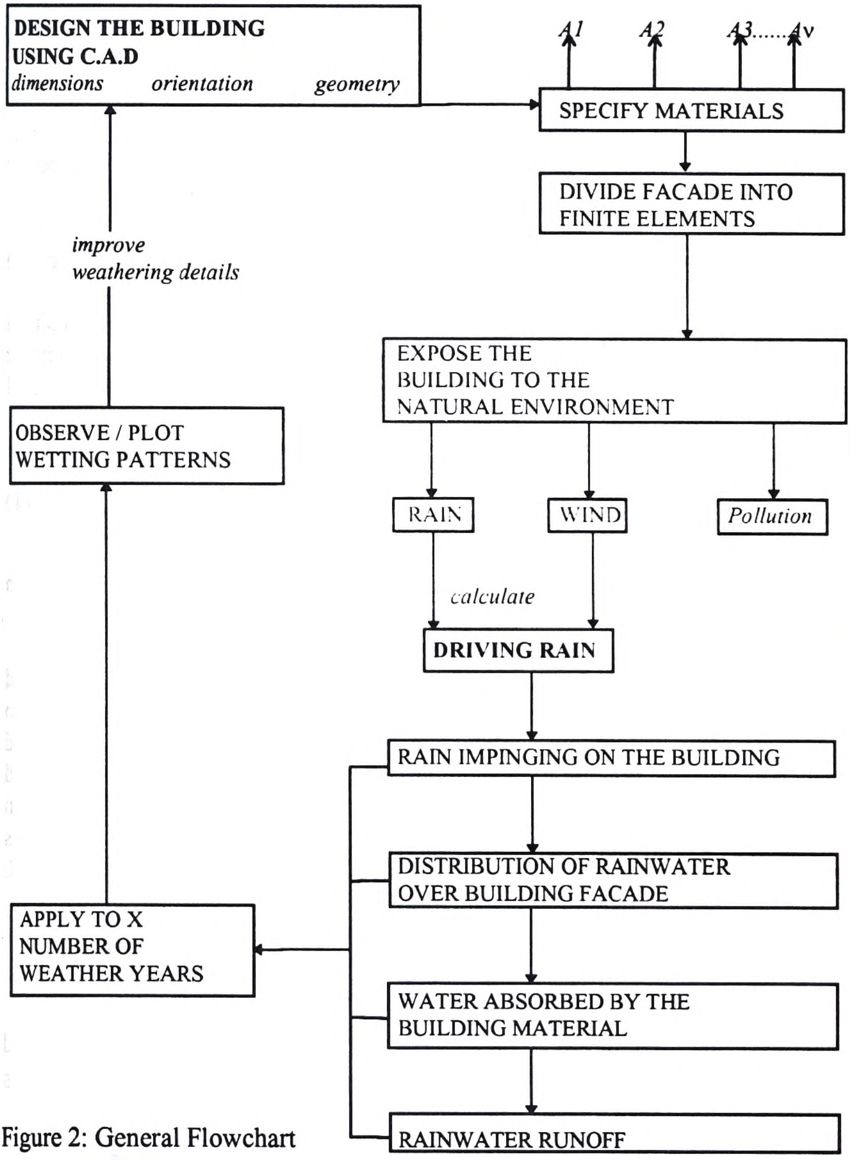

Figure 2: General Flowchart

A number of standard weather years is applied to the building in order to observe the different patterns and passages possibly followed by the water. The total amount of water running over each finite element of the building is calculated as well as the total amount of water absorbed at each of the building's elements. A reference to soiling data will be finally made so that soiling indices may be produced (Figure 2: General flow chart).

Development Of The Predictive Weathering Model

The aim of this part of the model is to calculate the amount of rain runoff which is created on the building facade at every level and eventually to find out how far down the building facade this runoff goes and at which point it stops.

The initial stages of the development of the model involve four distinctive stages:

A. Calculation of the total amount of driving rain P_{vtotal} impinging on the vertical surfaces

The amounts of rain precipitation are usually measured through water deposition on horizontal surfaces. Lacy (1977) first established a relationship between the rate of water deposition on vertical walls and water deposition on horizontal surfaces which refers to quantified amounts

$$\mathbf{R_v = \frac{2}{9} V\, R_h^{8/9}} \qquad (1)$$

where **R** is the *rate* of rainfall expressed in mm/h, **V** is wind speed expressed in m/sec and **v**, **h** stand for vertical and horizontal surfaces respectively.

The formula which is used in this stage of the model derives from a study carried out by Zhu et.al (1995) for the area of Montreal, Canada, where quantification of driving rain exposure on vertical surfaces was attempted. The data used included hourly rain precipitation and hourly mean wind speed and was collected over the period of thirty years. The method used was based on Lacy's equation (1) and on the notion that the impingement of driving rain on a vertical surface is not always from a direction normal to a wall but over an azimuth sector of 180 degrees. So the total amount of driving rain impinging on a vertical surface is:

$$P_{vtotal} = \frac{2}{9} \sum_{\theta=-90}^{+90} V_\theta \left(\frac{P_{h\theta}}{t_\theta}\right)^{8/9} \cos\theta \bullet t_\theta \qquad (2)$$

where θ is wind direction of angle θ to the normal to the wall, $\mathbf{V_\theta}$ is wind speed of this direction (m/sec), $\mathbf{P_{h_\theta}}$ is precipitation (mm) on horizontal surface and $\mathbf{t_\theta}$ is hours of simultaneous rain from direction θ.

Data needed: Angle of the wind & orientation of wall
Wind speed (m/sec)
Precipitation (mm)
Duration of rainfall (hours)

B. Distribution of rain over the building facade (Beijer 1977) e.g. height 20 meters

The driving rain impinging on a building's facade is not evenly distributed over the surface. The amount of rain hitting each part of the building's surface varies according to factors such as air currents, surrounding environment and dimensions of the building. For the purpose of the model an assumption is made that only the dimensions of the building influence rainfall distribution because the other factors would make the problem very difficult to solve at this initial, experimental stage .

Rainfall distribution can be measured in three different ways:

1. Empirical methods i.e. rain gauges and wind-tunnel experimentation
2. A computer simulation (which unfortunately does not yet exist)
3. A diagram compiled by Oscar Beijer (1977,1980) where the percentage of driving rain at different heights of the building is set for weak and intensive rain (figure 3). So if the amount of water impinging on a building 20 m high is P_{vtotal}, calculated from (2). then at level 9 it will be 85% of P_{vtotal} This diagram seems to be appropriate to use for the model because although it is quite approximate, it allows a theoretical approach to the problem which method (1) does not.

levels	**intensive rain**
10	100%
9	85%
8	70%
7	50%
6	35%
5	15%
4	10%
3	5%
2	0%
1	0%

% of Driving rain

levels	**weak rain**
10	100%
9	75%
8	55%
7	40%
6	25%
5	15%
4	10%
3	5%
2	0%
1	0%

% of Driving rain

Figure 3: Rainfall Distribution on the building facade

Data needed: P_{vtotal} (1)
Height of the building

According to March (1977) and Choi (1995), there is a differing vertical distribution of rainfall over the building surface which, combined with Beijer's approach (Figure 3),can result in the following rainfall distribution (Figure 4)

intensive rain

	A	*B*	*C*
10	**100%**	**90%**	**100%**
9	**85%**	**75%**	**85%**
8	**70%**	**60%**	**70%**
7	**50%**	**40%**	**50%**
6	**35%**	**25%**	**35%**
5	**15%**	**10%**	**15%**
4	**10%**	**5%**	**10%**
3	**5%**	**0**	**5%**
2	**0**	**0**	**0**
1	**0**	**0**	**0**

% of driving rain

weak rain

	A	*B*	*C*
10	**100%**	**90%**	**100%**
9	**75%**	**65%**	**75%**
8	**55%**	**45%**	**55%**
7	**40%**	**30%**	**40%**
6	**25%**	**15%**	**25%**
5	**15%**	**10%**	**15%**
4	**10%**	**5%**	**10%**
3	**5%**	**0**	**5%**
2	**0**	**0**	**0**
1	**0**	**0**	**0**

% of driving rain

Figure 4: Rainfall Distribution (Beijer 1977, p.71, Marsh 1977, Choi 1995, p.6)

C. Calculate water absorbed at the top of the building until the time of saturation t_s for one rainfall

Assumptions:

1. Porous building material with uniform water content
2. Constant rate of rainfall

According to Hall and Kalimeris (1984) the time t_s for a porous building material to reach surface saturation is:

$$t_s = g\frac{S^2}{\dfrac{P^2_{vtotal}}{t^2}} \tag{3}$$

where **g** is a constant (0.5-0.75), P_{vtotal} is the total amount of rainwater impinging on the vertical surface (calculated by equation 2), and **S** is the sorptivity of the material. Sorptivity **S** is a quantity associated with capillary effects in a material and is the factor that influences horizontal absorption of water in a building material. It is a useful parameter for defining the free water suction of a building material and it was first introduced as a term in hydrology and soil physics. (Gummerson et.al 1980, pp. 102,106, Hall and Yau 1987, p.81).

If equation (3) is applied at level 10 of the building facade of figure 4 the following equations calculate the time to reach saturation for level 10

$$t_{s10} = g \frac{S^2}{P^2_{vtotal}} \tag{4}$$

The water absorbed by the building material until the time of saturation is (Beijer 1977, p.73, Hall et.al, 1984, p.108): :

$$G = S\sqrt{t_s} \tag{5}$$

Data needed: P_{vtotal} (calculated in (1))
Sorptivity (S) of materials

D. Calculate rain runoff

Once the time of saturation for level 10 is calculated it is possible to calculate the rain runoff (RO_{10})created from this level (Hall & Kalimeris 1982, p.110). So:

$$RO_{10} = P_{vtotal} - G_{10} \tag{6}$$

Data needed: P_{vtotal} (1)
G_{10} amount of water absorbed at level 10 (5)

Formulae (3), (5), (6) are applied for all the building facade until the ground level is reached so that the amount of rain runoff is calculated and thus the point where soiling patterns are created is identified. What will vary for each level is the amount of rain water impinging on the surface which varies according to height and width of the building. The amount of runoff from the level above is also added to the amount of water impinging on the surface. For example for (intensive rain) :

$P_{v9} = 85\% \ P_{vtotal} + RO_{10}$
$P_{v8} = 70\% \ P_{vtotal} + RO_9$
$P_{v7} = 50\% \ P_{vtotal} + RO_8$

Validation Of The Model

There are two ways by which the model can be validated. One is by comparing the results with those coming from another similar model, and the other way is by empirically comparing the results of the model with real examples. Since there is no other similar existing model, empirical methods must be adopted to validate it. The model is applied to a number of existing buildings, and the results are compared to the present weathering patterns of the buildings in order to determine the degree of accuracy of the proposed model.

The experimental model described in this paper could be used as the basis for development of a more sophisticated computer program for the prediction of weathering effects on buildings. This program, used in conjunction with an existing Computer Aided Design program, will enable the optimisation of weathering characteristics of buildings at the design stage.

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