What are the effects of wind on tile roofs?

Following are the results of wind tunnel studies showing the wind pressure distribution on pitched roofs and around individual tiles

***Editor's note:** The following is an excerpt from a paper titled, "Wind Effects on Tiled Roofs—Wind Safety and Ventilation." Written by Carl Kramer and Hans J. Gerhardt, with WSP Consulting Engineers, Germany, it was presented at the 1991 International Symposium of Roofing Technology.*

The following article describes the wind pressure field on pitched (steep-slope) roofs and the wind loading mechanism for wind permeable surfaces. Results of extensive wind tunnel studies concerning the wind pressure distribution on pitched roofs and around individual tiles are presented.

The influence of the tile design (i.e., leading edge radius, permeability of overlap) and the use of an underlay on the batten space pressure, and therefore, on the net wind loads for common tile shapes, are given.

Introduction

Wind loading data available for building surfaces are usually based on wind tunnel tests with simple building models having smooth and wind impermeable surfaces. In Europe, however, most pitched roofs are covered with tiles as outer, weather-protecting surfaces.

The wind load on the surface elements, such as tiles or slates, corresponds to the difference of external pressure and underelement pressure. The latter depends on the external pressure distribution of the roof, the wind permeability of the surface and on the possibility of pressure equilibration underneath the permeable surface. Therefore, the element wind load may differ significantly from the load derived from the external pressure distribution alone.

Wind loading mechanism

The wind load acting on an element of a wind permeable roof surface is due to the difference of the pressures on the upper side and on the bottom side of the element surface.[1]

The external pressure distribution depends on the building flow field and on the local element flow field. The internal pressure is governed by the external pressure and by the pressure equilibration process through the surface permeability and along the air space between the tiled surface and the wind impermeable layer (underlay or building wall).

The former process leads to what may be termed as "tile resistance;" the latter leads to an underelement resistance. Large permeabilities will lead to low tile resistance and large batten spaces to low underelement resistance.

There are two limiting cases of practical importance:[2]

1. Pavers or insulation boards put on a flat (low-slope) and smooth roof surface will have very high underelement resistance and relatively small tile resistance.

2. Tiled surfaces on pitched roofs will experience relatively large tile resistance and very low underelement resistance.

In Case 1, the underelement pressure distribution will be similar to the external pressure distribution, thus leading to relatively small net wind loads. In Case 2, the underelement pressure will be nearly constant. The net wind load for single tiles will be relatively large in the wind critical areas of high external suction.

Figure 1 gives a schematic drawing of the two limiting cases considered. Whereas for the case of pavers or insulation boards, the external flow field is not influenced by the pavers due to their smooth upper surface, the external pres-

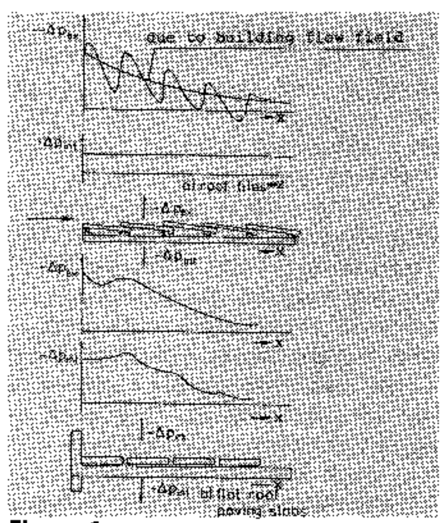

Figure 1

sures acting on tiles (in a zone of attached flow) consist of a superposition of the pressure distributions due to the building flow field and the element flow field.

The local flow field is important for the wind safety of tiles and slates. For the situation considered in Figure 1, the stagnation zones at the overlapping gaps will lead to relatively large internal pressures. In addition, the flow acceleration around the windward edges of the tiles leads to a suction peak resulting in a strong tilting moment. It should be noted that fundamental aerodynamic considerations concerning optimum tile shapes may lead to an increase in wind safety of tiled roof surfaces.

Pressure distribution

Wind loading codes and standards provide information concerning time averaged pressures on flat and pitched roofs. Usually, the design pressure coefficients given depend only on the roof pitch angle. The influence of the varying flow displacement due to different relative building dimensions is usually not considered.

In an early parametric study,[3] the pressure distribution on flat and pitched roofs was measured for various length/width (l/w) and height/width (h/w) ratios. The investigation was conducted in smooth wind tunnel flow. However, the results of this study are in agreement with pressure measurements of the authors conducted in a wind flow corresponding to open country exposure.[5-6]

For low pitched roofs (about 3-in-12), the highest external suction occurs for yawing flow (α = 45). The pressure distribution on the windward side of the roof corresponds to the well-known pressure distribution on a flat roof with conical vortices centered at the windward corner. Time averaged, local pressure coefficients may be as high as $C_p = -4$.

The conical vortices will decrease in strength with increasing roof pitch angle. For medium pitched roofs (about 7-in-12), the critical flow situation occurs for wind direction perpendicular to the ridge (α = 0). A vortex with its axis parallel to the ridge is formed leading to a zone of high negative pressure underneath the separation bubble. Pressure coefficients for major parts of the roof may reach values of $C_p = -1.2$. The flow reattaches near the ridge. Typical time averaged pressure coefficients for the ridge area are $C_p = -0.5$.

Though the negative pressures are higher near the eaves as compared to the ridge area, the critical uplift area is near the ridge. Here, the element flow field superimposed on the building flow field leads to critical loadings.

For coding purposes, the pressure distributions measured in wind tunnel tests have to be simplified. Usually, the roof area is divided into three regions;[4,5] corner, edge and middle. For each region, the time averaged pressure coefficient is assumed to be constant. The influence of the building geometry is taken into account by the parameters relative length (l/w) and relative height (h/w). It should be noted that for low pitched roofs, the pressure coefficients in the edge and middle regions may be significantly higher than for flat roofs.

Net wind load

As stated above, the net wind load acting on a tile corresponds to the difference between external and underelement pressure. The underelement pressure for a tiled roof is the batten space pressure. The external pressure on roofs, as given in codes of practice and standards, is representative for the external local wind load on a tiled roof only if the flow is not attached to the roof.

For regions where the wind flow is attached to the roof surface, the element flow field may alter the local flow field on a roof significantly. A typical result of a detailed study is given in Figure 2.

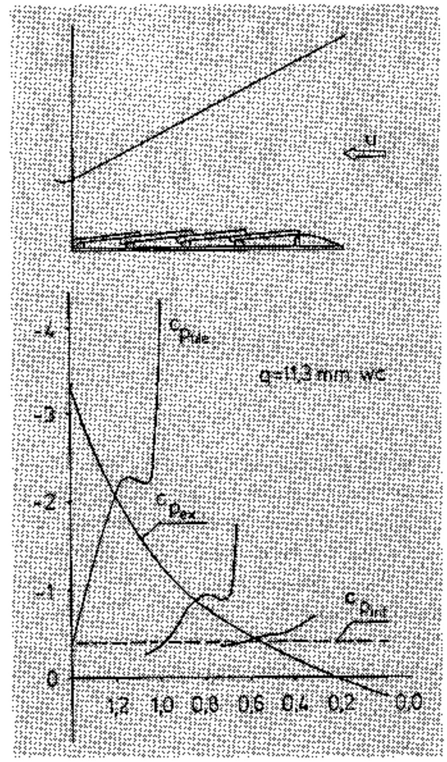

Figure 2

A section of a typical covering for pitched roofs was fitted to the floor of the wind tunnel test section. The test specimen included rafters, battens and tiles. The test section floor may be considered as a wind impermeable underlay or a wind impermeable thermal insulation layer.

The test section roof was adjusted to produce a longitudinal pressure gradient typical for the ridge region of a steep roof (about 10-in-12) and wind direction perpendicular to the ridge. Figure 2 gives the distribution of the external pressure due to the building flow field ($C_{p\,ex}$) to which the local pressure distribution due to the element flow field ($C_{p\,tile}$) is superimposed. As expected, the batten space pressure ($C_{p\,int}$) is uniform. For the case considered, the underelement flow resistance is much smaller than the tile flow resistance (see "Pressure Distribution on Pitched Roofs").

It is important to note that the batten space pressure is less negative than the average value of the external pressure distribution. This is due to the fact that the predominant permeability of the tiled surface is situated in the stagnation area of the overlap region. In fact, the batten space pressure agrees quite well with the static pressure near the overlaps.

The batten space pressure is determined by the permeability of the tiled surface. The permeability may be specified by a nondimensional permeability factor C_D.[4] The permeability factor is a function of the percentage open area (see Figure 3). Large C_D is equivalent to small permeabilities, and vice versa. In general, concrete tiles have—due to their small manufacturing tolerances—a smaller permeability than clay tiles. In comparison, wind permeable facade elements cover a much wider range of permeabilities.[2]

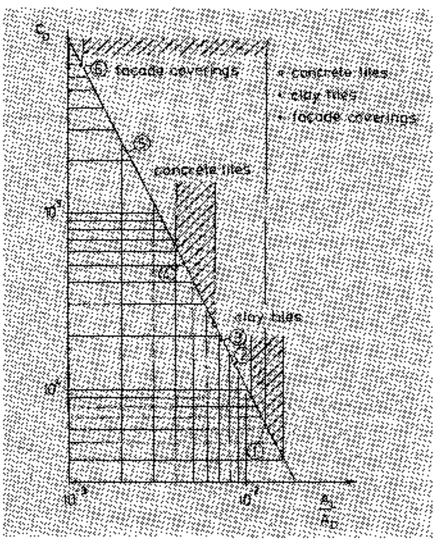

Figure 3

The authors derived a simple model to calculate the batten space pressure corresponding to given external pressure distributions, if the element flow field is neglected. The calculation neglects the influence of the tile shape on the external pressures. The basis for the calculation is the continuity equation; i.e., the volume flow in the batten space and the volume flow discharged to the tiled surface have to be the same.

The external pressure distribution is described by a quadratic function. The resulting integral equation can be solved[6] (see Figure 4). The calculated batten space pressure p_{int} is about 10 percent below the area averaged pressure $\bar{p}_{int}$. Thus, the batten space pressure is close to the area averaged external pressure.

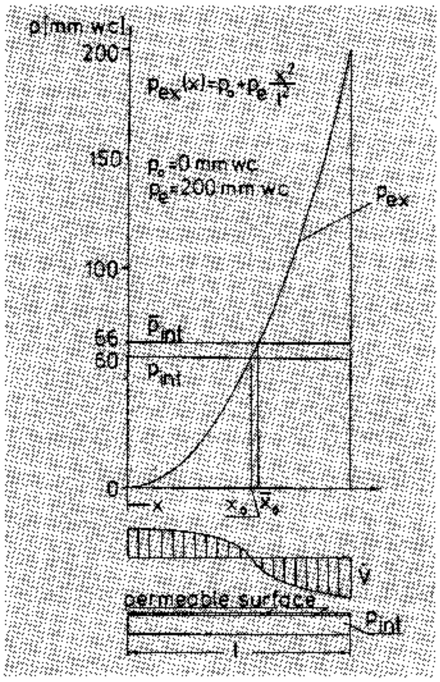

Figure 4

A significant effect on the batten space pressure is, however, due to the change of the building flow field by the element flow field. This effect is most pronounced for flow direction perpendicular to the ridge, since the surface flow field is stagnated at the overlaps of the tiles. For sufficient permeability of the overlap gaps, this flow direction will lead to a remarkable increase in batten space pressure.

Figure 5 shows the element pressure distribution for a concrete tile widely used in Germany for different wind directions. For flow toward the overlap gaps, a suction peak occurs at the leading edge of the tiles. This peak is most pronounced for flow perpendicular to the ridge. The peak, which leads to a large tilting moment around the

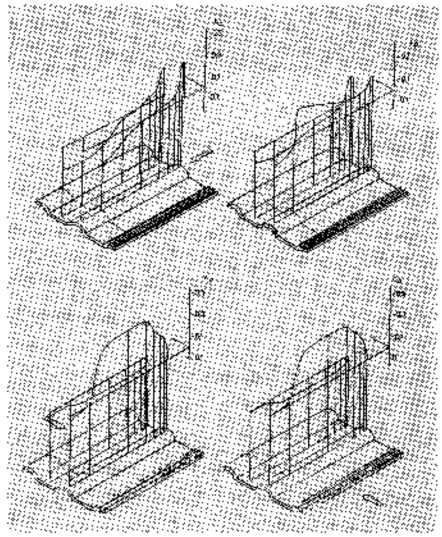
Figure 5

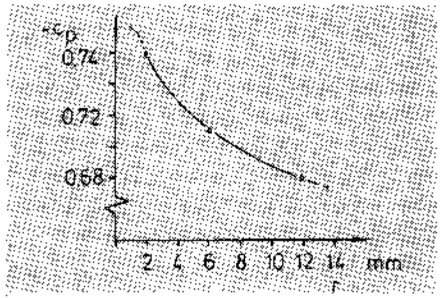

Figure 6

pivoting line, may be decreased by increasing the edge curvature radius (see Figure 6).

Failure mechanism

It has been shown that roof failure on tiled surfaces occurs due to a moment turning the tile upward around the pivoting line on the batten.[7] The turning moment consists of a lifting force and two force couples caused by the external and internal pressure distributions, respectively. This failure mechanism could be observed in wind tunnel tests.

The largest component of the tilting moment is caused by the external pressure distribution, when large suction peaks occur at the leading edge. As may be seen from Figure 5, suction peaks at the leading edge occur only for flow directions more or less perpendicular to the ridge. To lift tiles up sufficiently for failure to occur, the local velocities must be relatively high. Fortunately, high local velocities perpendicular or nearly perpendicular to the ridge occur only in small areas of a pitched roof. From flow visualization studies, those areas have been identified. The size and position of the critical areas depend on the roof pitch angle.

Improving wind safety

The most common methods claimed to improve the wind safety of tile roofs are: nails or clamps; using an underlay; and aerodynamically favorable tile shapes.

The authors have investigated a great number of nails and clamps. Almost all types investigated may be classified as either easy to fit and being of little use, or difficult to handle but improving the wind safety.

Figure 7 gives typical results for a concrete tile widely used in Germany with two common clamps. The speed of the undisturbed flow at eave height, for which failure

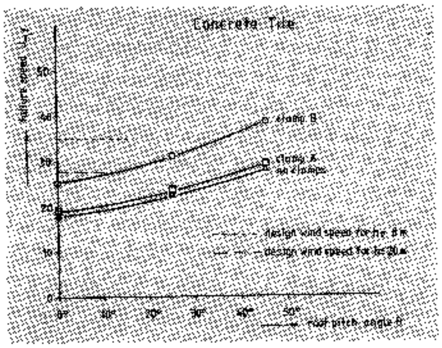

Figure 7

occurred, is plotted versus roof pitch angle. Only clamp B increases the wind safety noticeably. Also included in Figure 7 is the design wind speed according to the German Standard DIN 1055 Part 4 for building heights 8 m (26 feet) and 20 m (66 feet), respectively.

An underlay sealing the batten space against the space underneath the roof will not prevent cladding elements on the windward roof from being lifted up.

Due to the sealing effect of the underlay, the windward side of the batten space is now mainly subjected to the high pressures at the stagnation zones in the overlap regions. Thus, an underlay may in fact increase the batten space pressure on the windward side, and therefore, lead to a decrease in wind safety. However, the pressure equilibration in the gable room is prevented, leading to a much lower net wind load for the leeward roof tiles.

Aerodynamically shaped tiles will prevent the large suction peak at the leading edges. In addition, the permeability at the interlocking gaps perpendicular to the ridge, where suction due to the element flow field occurs (see Figure 5), should be high, at least somewhat higher than the permeability of the overlap gap. This will lead to a decrease in batten space pressure resulting in an improved wind safety. PR

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