ABSTRACT

While most low-rise buildings suffered little structural damage under typhoons, many experienced roof covering failures, and especially lost a large number of roof tiles. A detailed wind tunnel tests were carried out at Tongji University to acquire the wind loads on clay and concrete roof tiles. Test data were fed into a finite element model (FEM) of a roof structure that includes the tiles, the backing materials, and the roof truss. The FEM analysis were compared with the performance of tile roofs under simulated typhoon impact through one-of-a-kind Wall of Wind (WoW) apparatus. The analysis results show that the material defects or improper construction practices are the key factors to induce the roof tiles’ failure and the staggered setting of concrete tiles would help develop an interlocking mechanism between the tiles and increase their resistance to typhoon.

KEYWORDS: TILE ROOF, WIND TUNNEL TEST, TYPHOON, WIND PRESSURE, FEM ANALYSIS

Introduction

In the past few years, typhoons (hurricanes) have caused a direct economic loss of up to tens of billions of dollars in the world for each year. The investigation of the wind-induced disaster shows that more than half of total losses are related to the damage of low-rise buildings. While most houses suffered little structural damage, many experienced roof covering failures, and especially lost a large number of roof tiles. It is important to clarify the wind force acting on roof tiles, not only for the safe of the tile roofs but also for prevention of secondary damage caused by flying roof tiles in strong wind.

In the early studies on this subject, Hazelwood (1980,1981), Kramer and Gerhardt (1983), Amano et al. (1988), Gerhardt et al. (1990) and Bienkiewicz and Sun (1992, 1997) studied the characteristics of wind pressures on the loose-laid roof tiles through the wind tunnel tests. Kawair and Nishimura (2003) took field measurements to assess uplift force on hip roof tiles in natural wind. Huang et al. (2009) carried out a detailed experimental study for full-scale clay and concrete roof tiles with adhesive-set and mortar-set attachments through one-of-a-kind Wall of Wind (WoW) apparatus, and some important conclusions were obtained.

As the pressure points were less and just two wind directions were tested in the WoW tests, a detailed wind tunnel test is carried out at Tongji University to acquire the wind loads
on tile roofs. Test data are then fed into a finite element model (FEM) of a roof structure that includes the tiles, the backing materials, and the roof truss. The FEM provided an accurate tool for the analysis of the entire roof system.

**Wind Tunnel Tests**

The tests of the clay and concrete tile roof were conducted in the TJ-2 Boundary Layer Wind Tunnel of Tongji University. TJ-2 wind tunnel has a testing section of 3m in width, 2.5m in height and 15m in length with wind velocity ranging from 0.5m/s to 68m/s. The models were made of perspex at a geometric scale of 1/5 (Figure 1). In order to measure the simultaneous pressures on the field and ridge tiles, 357 taps and 379 taps were drilled on the clay and concrete tiles roof, respectively (Figure 2). There are 25 wind angles (β) were conducted as following: 0°, 10°, 15°, 20°, 30°, 40°, 45°, 50°, 60°, 70°, 75°, 80°, 90°, 100°, 105°, 110°, 120°, 130°, 135°, 140°, 150°, 160°, 165°, 170°, and 180°. A boundary layer flow over open terrain was simulated in the wind tunnel, whose turbulence intensities $I_u$ at the top of the roofs are about 14% (Figure 3).
Data for each test were recorded for a duration of 1 min at a sampling rate of 312.5 Hz. The pressure coefficient at the \(i\)th tap is estimated as follows:

\[
C_{p_i} = \frac{P_i - P_{\infty}}{0.5 \rho U^2}
\]  

(1)

where \(P_i\) is the pressure at the \(i\)th tap; \(P_{\infty}\) is the static pressure of the Pitot tube; \(\rho\) is the air density; and \(U\) is the mean wind speed at the top of the roof. As an example, the mean and rms pressure coefficient contours of the caly tile roof in 0° direction are plotted in Figure 4. The results show that the rms pressure coefficients are high at the eave on the windward side of the roof.

FEM Modeling and Analysis

**Material Modeling of Clay and Concrete tiles**

Elastic (Young’s) modulus of the tiles is an important material property in their FEM simulation. Coupon tests of clay and concrete tiles were carried out in the laboratory of Florida International University in accordance with ASTM Standard E111-04 (2005), which covers procedures to determine the elastic modulus of concrete and clay tiles. Figure 5a shows a strip of a concrete tile under axial compression in the lab, with a mounted strain gage. The elastic modulus \(E_s\) can be calculated, as
\[ E_s = \frac{\sigma}{\varepsilon} = \frac{P}{A_s} \varepsilon \]  

where \( \sigma \) is the axial stress, \( P \) is the axial compressive force, \( A_s \) is the cross-sectional area of the strip of tile, and \( \varepsilon \) is the axial strain measured on the tile. Figure 5b shows the measured axial stress-strain response curve for two samples of concrete tiles, leading to an average elastic modulus of 2.1x10^4 MPa (3.0x10^6 psi) for concrete tiles. Similar tests on samples of clay tiles led to an average elastic modulus of 1.4x10^4 MPa (2.0x10^6 psi) for clay tiles.

![Tile strip under axial compression](a) Tile strip under axial compression  
![Axial Stress-Strain Response](b) Axial Stress-Strain Response

Figure 5: Elastic modulus test of concrete tiles

<table>
<thead>
<tr>
<th>Table 1: Material Properties of Various Components of the Roof System</th>
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<td>Component</td>
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<tr>
<td>Elastic Modulus (psi)</td>
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<tr>
<td>Poisson’s Ratio</td>
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<td>Mass Density (lb/in^3)</td>
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**Modeling of Single Tile System**

There are currently two main attachment methods for clay and concrete tiles: adhesive-set (foam) and mortar-set. The interface between the roof tiles and the plywood deck, i.e., the backing materials (foam or mortar), poses the most challenging issues for finite element modeling. For accurate modeling of the tiles and the interface, a series of laboratory experiments on single tiles system were carried out at Florida International University. The mechanical uplift and displacement data were used to calibrate the stiffness coefficients of the equivalent nonlinear springs, which were applied to simulate the interface in the finite element modeling.

**(1) Single Ridge Tile**

Figure 6 shows the test set up for single clay ridge tiles with mortar-set placed on three field tiles that were in turn mechanically attached to a 13 mm (0.5 in.) plywood deck. The figure also shows the positions of potentiometers (Points A–D), where the displacements of the system were measured, and the load-deflection curves. The stiffness of the interface (equivalent spring) was then calculated based on the difference of the load-deflection response at the center point of the tile (Point A) and the average of the responses at the edges of the tile (Points C and D), i.e., \( A-(C+D)/2 \).
The clay ridge tiles, as well as the plywood deck, were discretized using elastic shell (Shell63) elements. The ridge tile was meshed using 216 shell elements with 18 and 12 equal divisions in the longitudinal and transverse directions, respectively. All elements were restrained along the longitudinal axis, and the plywood board was affixed at the corners using pin supports. The attachment interface was modeled using nonlinear spring (Combin39) elements, whose nonlinear stiffness coefficients used in the model for mortar-set are shown in Figure 6. The load was applied at the center of the tile to simulate the mechanical uplift tests. Comparison of the ANSYS model simulation and the test results indicate good agreement.

For the single ridge tile with adhesive-set (foam), similar process was carried out. Details are provided in Mirmiran et al. (2007).

(2) Single Field Tile

The single clay field tile was attached with adhesive-set (foam) to a deck underlayment, and a 13 mm plywood decking (Figure 7). The displacements at the locations of potentiometers (Points 1~4) were measured. The clay field tile was meshed using 288 elements with 18 and 16 equal divisions in the longitudinal and transverse direction, respectively. The constants for the equivalent springs at the adhesive interface were calibrated using the load-deflection test data, leading to the nonlinear spring parameters.
Modeling of Entire Tiles Roof

The finite element models were expanded to the entire roof system, consisting of the field and ridge tiles, the backing materials, the roof deck, and the roof truss (Figure 8). The model was used to determine the internal forces that develop in the attachment systems of roof tiles under high wind speeds during a hurricane. The spring constants for the interface elements used in the single ridge and tiles system (see Figures 6 and 7) were applied to the entire tiles roof.

The wind loads obtained in the wind tunnel tests were applied to the models to carry out the finite element analysis. The analysis results were compared with the performance of tile roofs under simulated typhoon impact through one-of-a-kind Wall of Wind (WoW) apparatus. Figure 8 shows the ANSYS model for the clay and concrete tile roofs with adhesive-set or mortar-set subjected to a 53.64 m/s (120 mph) wind speed.

Figure 9 shows the contours of vertical displacement on clay and concrete tile roofs with mortar-set at wind speed of 53.64 m/s in 0° and 50° wind directions, respectively. The vertical displacement in the edge of the roof is at its largest, which shows that the wind loads on the roof edge are large and the connection there between the tiles and the roof deck is weakly.

The failure of the tiles is mainly due to the breakage at the interface. Therefore, for a tile to remain intact, the internal forces of the equivalent springs (simulating the interface) should be within the range of their respective load-deflection curves. Figure 10 shows the shear stresses on clay and concrete tile roofs with mortar-set at wind speed of 53.64 m/s in
50° wind direction, respectively. The FE analysis shows that the loads developed in the attachment systems (adhesive-set and mortar-set) of both clay and concrete tiles are well below the uplift capacity measured in the load tests. It was therefore concluded that such tile roofs, if constructed properly and according to the code, should not suffer any failure under a strong Category 3 hurricane (wind speed is less than 120 mph). Any such failures in the field may therefore be attributed to material defects or improper construction practices, as suggested in the MAT reports (FEMA, 2005).

Figure 9: Vertical displacements on tile roofs at wind speed of 53.64 m/s

(a) Clay tiles with mortar-set in 0° direction   (b) Concrete tiles with mortar-set in 0° direction

(c) Clay tiles with mortar-set in 50° direction  (d) Concrete tiles with mortar-set in 50° direction

Figure 10: Shear stresses on tile roofs at wind speed of 53.64 m/s in 50° direction

(a) Clay tiles with mortar-set   (b) Concrete tiles with mortar-set
It was noted that concrete field tiles were installed in a staggered pattern, while the clay field tiles were installed in tandem. The staggered pattern of concrete filed tiles helps form an interlocking system to resist the wind pressure. Therefore, the vertical displacement and the largest internal force of the springs for the concrete tiles roof are less than those of the clay tiles roof (see Figures 9 and 10). This is perhaps one of the reasons why concrete tile roof with mortar-set was the only model that did not fail at 53.64 m/s wind speed in the Wall of Wind tests.

Conclusions

The results of finite element analysis show that the material defects or improper construction practices are the key factors to induce the roof tiles’ failure. The wind loads on the roof edge are large and the connection there between the tiles and the roof deck is weakly.

This study also points out the effect of tile setting pattern on the uplift capacity of the roof, suggesting that staggered setting of tiles would help develop an interlocking mechanism between the tiles and increase their resistance to typhoon.

The model developed in this study can be used for further analysis of various tile roof systems under dynamic and impact loading.

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References


