A SUMMARY OF EXPERIMENTAL STUDIES ON SEISMIC PERFORMANCE OF CONCRETE AND CLAY ROOFING TILES

TILE ROOFING INSTITUTE

By the
University of Southern California
Structural Engineering Research Study

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Following California's devastating Northridge earthquake, measuring 6.7 on the Richter Scale, some concerns arose regarding the safety and resilience of concrete and clay roofing tile in a severe earthquake. Among the structures damaged in the quake were several homes and commercial buildings with tile roofs. While structural engineers who reviewed the site reported back that architectural flaws and improper installation were at fault in virtually all instances, still no formal testing or results existed on how tile withstands an earthquake.

The National Tile Roofing Manufacturers Association (NTRMA), an organization dedicated to assisting in building code language development pertaining to rooftiles nationwide, decided that a formal study needed to be conducted in order to determine whether or not concrete and clay tile, when installed according to Uniform Building Code, were safe in the event of a major earthquake. Enlisting Assistant Professor Yan Xiao, Ph.D., P.E., of the University of Southern California to conduct the studies, the NTRMA supplied four of the most commonly used types of tile, all materials necessary to properly install the tile according to code, and roofing experts to assure proper installation.

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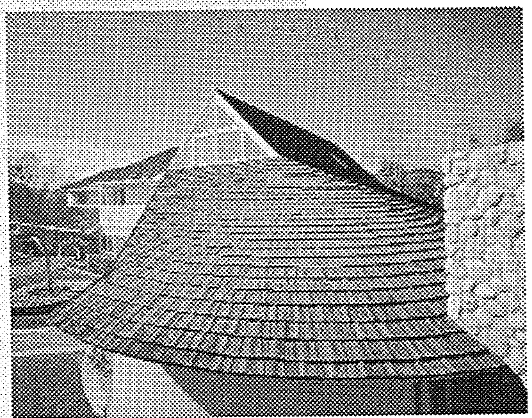
After extensive testing of various types of tiles under gradually escalating simulated earthquake conditions, Dr. Xiao's research determined that concrete and clay tile, when installed according to current code, cannot only withstand the seismic load required by UBC for building materials, it, in fact, was capable of handling a simulated earthquake almost double the strength of the Northridge quake. It was at that point that Dr. Xiao stopped testing due to limitations of the testing equipment, not due to the tile's performance, so it is unknown the exact limit to the seismic load that tile can resist.



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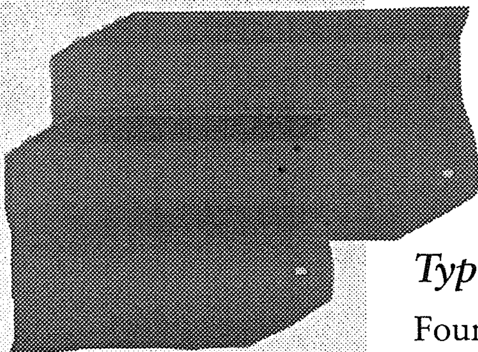
With their attractive architectural appearance, durability, fire resistance and livability, concrete and clay tiles are widely used for residential and commercial roofs. In Southern California, where earthquakes are prevalent, concrete and clay tiles comprise over eighty percent of the new construction market. However, the January 1994 Northridge earthquake produced doubts within the engineering and construction community regarding these roofs because many tile roof systems failed during the earthquake's intensive shaking. Although reconnaissance studies indicated that many factors such as construction age and poor workmanship contributed to the failure, the fundamental question of whether tile roofs constructed to the current standard could sustain a major earthquake, remained unanswered.

A systematic study including dynamic analysis and testing of concrete and clay tile roofing was conducted at the University of Southern California under a research contract with the National Tile Roofing Manufacturers Association, Inc. (NTRMA). The objectives were to assess the performance criteria of tile roofs designed and constructed to current UBC standards, to evaluate failure modes of different types of tiles and to provide directions for future improvement.

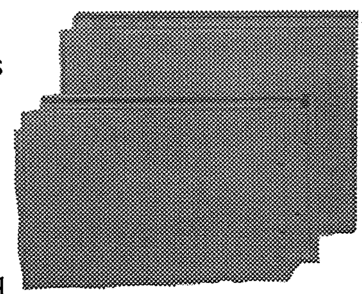
Although no engineered design process is required for the construction of concrete or clay tile roofs, the current UBC does provide minimum requirements for tile, dependent on the different tile types and slope of the roof. Solid sheathing for the roof decks, corrosion-resistant nails or screws of a specified size and quantity, minimum-sized attaching wire and any necessary battens are all considered part of the requirements to roof according to code.

The study sought to assess the seismic demand for roofing tiles by considering them as nonstructural components, despite the fact that current code does not require such practice. Based on these requirements and the resulting formula developed by the study's authors, the tile roofs could be subjected to a lateral acceleration of 0.8 g, or a force equal to 80% of the tile's weight. The remaining question was whether the roof tiles, installed properly following current code requirements, could sustain the simulated seismic activity required by the UBC, and if so, what were its seismic limitations.



Types of Tiles Tested

Four types of tiles, two each of concrete and clay, were chosen for study from commercially available roofing tiles manufactured by NTRMA members. All tile specimens are high pressure extruded products or fired clay conforming to UBC standards. These tile profiles represent the full spectrum of commercially available tiles, although they might vary slightly based upon manufacturer. Breakage tests were conducted on the selected samples to confirm that they conformed to the production specifications for strength.



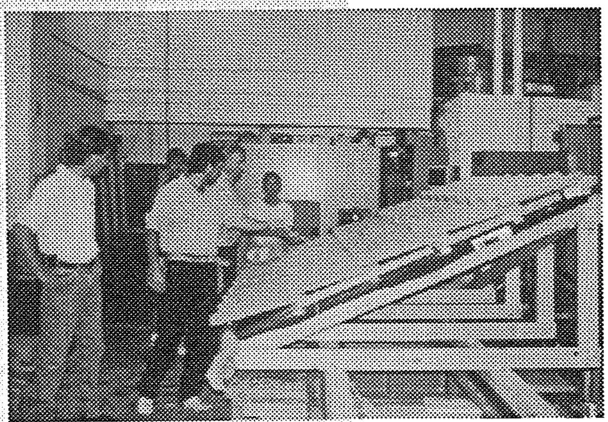
USC Dual-Shaking-Table System

At the USC structural laboratory, dynamic tests were conducted on both unit tiles and full scale tile roofs using the Dual-Shaking-Table system. Each table was capable of simulating seismic activity up to an earthquake of 1.4 - 2.0 g.

Unit Tile Testing

To assess the performance and seismic demand on a tile unit and the fasteners under a stand-alone condition, the authors designed a simple jig for testing tile units, which consisted of two or three individual tiles, a two-foot square of waterproof underlayment and 15/32 in. plywood deck found in typical new building construction. The tile unit was fixed on a steel frame connected to the top of the shaking table. The angle of the frame was adjustable for studying the tile unit performance at different slopes, to better replicate the wide variety of architectural styles.

Full Scale Model Roof Panel Testing



In order to study the performance of concrete or clay tile roofs at different slopes and shaking directions, 24 full-scale tile roofs were tested. These tests were made possible by using the dual-shaking-table system in synchronized mode. The testing included shaking the model tile roofs at different slopes in directions perpendicular and parallel to the roofs, to more accurately simulate the erratic movement of an earthquake.

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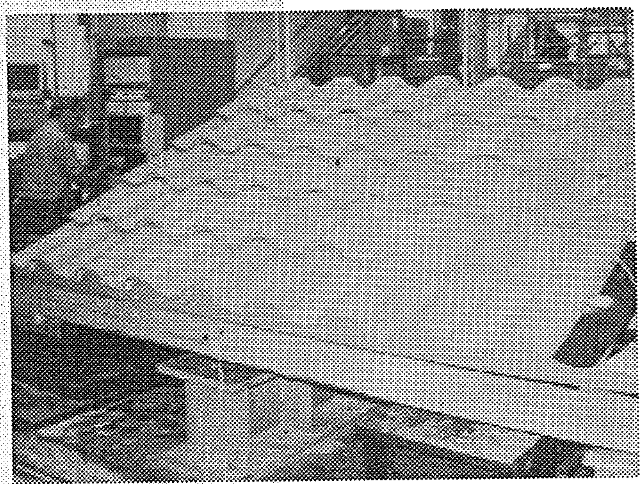
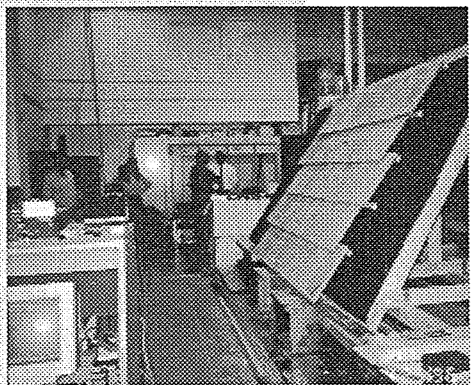
Accuracy and consistency were top priority in testing the roof panels. Professional roof installers strictly followed current UBC requirements, and the same model roof was used for each of the four types of tiles. The rafters were installed first on top of the cross beams and then the plywood roof deck was nailed onto the rafters. A waterproof underlayment sheet was installed over the solid plywood roof deck.

Since the requirements for installation vary dependent on the pitch of the roof, profile and whether or not the tile is concrete or clay, different guidelines were followed for each of the panels. For concrete tiles, horizontal battens with a cross section of 3/4 in. thick and 1.5 in. wide were installed onto the underlayment. For a slope of 5/12 (42%), only the tiles along the two sides were nailed; field tiles were not nailed. At a 12/12 (200%) slope, the tiles were nailed at every other row. Besides nailing, the tiles were laid with their lugs attached onto the battens along the rows and their sides interlocked with adjacent tiles in the same row.

Clay tiles were laid directly on the underlayment and fastened to the deck. For the 5/12 (42%) slope, these tiles were fastened only with nails. For slopes at 12/12 (100%) and 24/12 (200%), the tiles were fastened with both nails and nose clips. Birdstops were also installed for all cases. For two-piece Mission tiles, the pan sections and the cover sections were both fastened with nails.



Initial testing was set to determine whether or not tile could satisfy the UBC's requirement of being able to withstand 0.8 g of acceleration. Within the working range of the Dual-Shaking-Table, a fixed frequency of 2.5 Hz was determined to satisfy the requirements. If the roof assembly successfully sustained this initial peak acceleration level, then the frequency was adjusted to shakings corresponding to 1.4 g and 1.6 g. Tiles were subjected to gradual acceleration of the shaking, with a brief stop typically induced at the end of each step to examine the tiles and their fasteners.



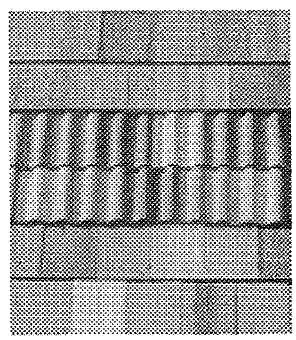
Full scale tile roof panel tests were successfully conducted in all cases.

Tile Units

The tile units were subjected to horizontal vibrations perpendicular to the rows, while the full scale model roof panels were subjected to horizontal shakings in both perpendicular and parallel directions. For tile units tested with an acceleration as high as 2.0 g the only failure was observed for the clay one-piece S-tile unit. At an input acceleration of 2.0 g, which is more than double the current code value, a nail was pulled out and the tile fell.

Full Scale Tile Roof Panels

Full scale tile roof panel tests were successfully conducted in all cases. At 42% slope (5/12 pitch) and with acceleration as high as 1.6 g, the battens appeared to properly prevent the falling of the unfastened tiles during perpendicular shaking. The roof also performed successfully in parallel direction when the peak acceleration was below 1.4 g. During parallel shaking with a peak acceleration of 1.6 g, the unfastened tiles started to move along the rows. The edge tiles appeared to be effective in restraining the dislocation of the unfastened tile rows, despite some of the edge tiles distorting slightly.



At a 100% slope (12/12 pitch) where the tiles were fastened at alternate rows, the roof performed very well when subjected to perpendicular shaking until the peak acceleration increased to 1.4 g and one unfastened tile near the end of the second row from the top slipped and fell. During parallel shaking of the same roof panel, no tiles were dislocated or fell, although several moved slightly after shaking at a peak acceleration of 1.4 g.

The 200% (24/12) pitch roof exhibited excellent performance in both perpendicular and parallel directions, with no damage observed even when the roof panel was subjected to a peak acceleration as high as 1.4 g. Extra shaking at 1.6 g took the tiles to their performance limit, with tile fractures observed.

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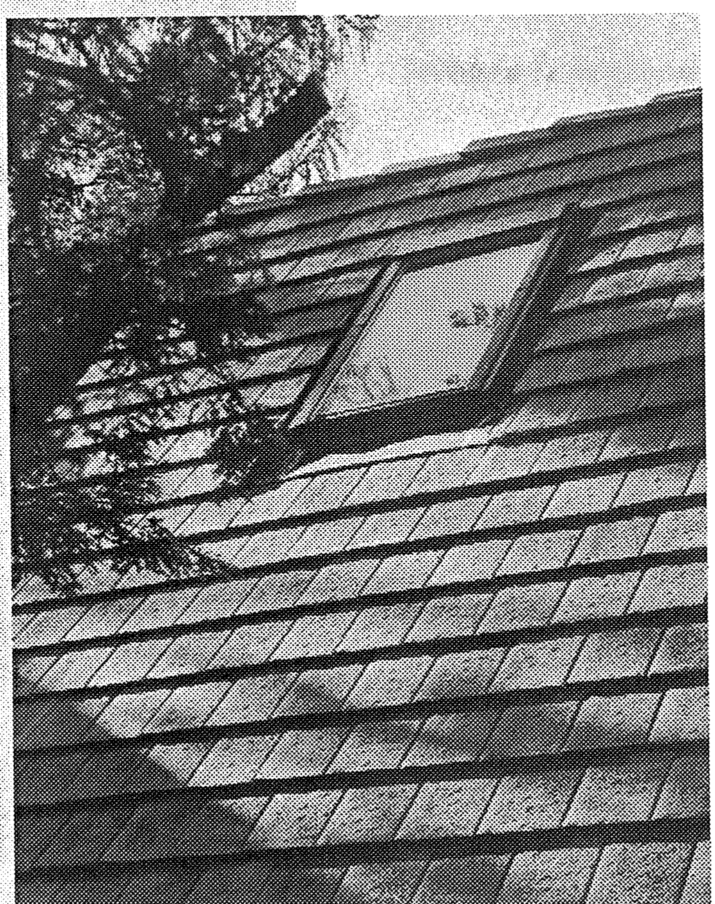
The concrete mission tile roofs performed similarly as the flat tile roofs, with most unfastened field tiles slipping during parallel shaking at 42% slope (5/12 pitch) and 1.4 g acceleration, no sign of damage or dislocation for the 100% slope (12/12 pitch) for shaking in either perpendicular or parallel directions up to 1.4 g, and only one top-row tile fracturing and falling down during perpendicular shaking for fastened tiles at 200% slope (24/12 pitch) up to1.4 g.

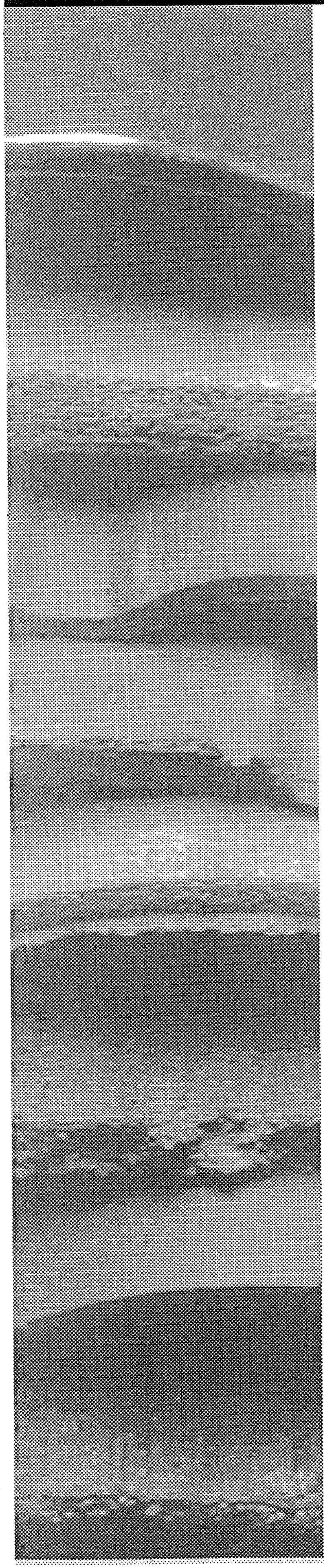
Clay one-piece S-tile and clay two-piece Mission tile roofs performed very well up to peak accelerations of 1.4 g or 1.6 g, with tests being terminated in every case without exhausting the performance limitations. Nose clips for tiles with slopes greater than 100% (12/12 pitch) appeared to be very effective to prevent damage due to pounding from the severe shaking.

In summary, the following trends of performance were observed for concrete tile roofs: 1) Concrete tile roofs were capable of performance limits significantly higher than the design level acceleration of 0.8 g put forth by UBC; 2) Tiles fastened more securely for higher slopes following code requirements, preformed even better than the unfastened tiles; 3) for roofs with slopes lower than 100% (or pitch lower than 12/12), the ultimate performance was determined by the performance of the unfastened field tiles; and 4) the requirement to fasten each tile when the slope exceeds 200% (24/12 pitch) effectively prevented the dislocation of tiles. The performance limit may also depend on the strength of the tiles to resist fracture due to pounding.

Regarding clay tile roofs, the values of ultimate accelerations were the peak accelerations tested in the program. No tile failure was observed throughout. One birdstop block for the one-piece S-tile roof at 200% slope (24/12 pitch) fractured and slipped during a severe perpendicular shaking with peak acceleration of 1.6 g.



Conclusions



The following observations and conclusions were drawn by the USC seismic experts:

1. All of the full scale model tile roofs tested outperformed the 0.8 g acceleration threshold established by current UBC standards and were capable of resisting ultimate accelerations higher than 1 1/2 times this code-required value. The ultimate accelerations that can be sustained by tile roofs depend on the type of tile, roof slope and particularly on the details of attachment. Ultimate acceleration as high as 1.6 g was resisted by tile roofs fastened with nails and steel wire nose clips. For many cases, the ultimate accelerations were not exhausted due to the limitation of the testing apparatus.

2. Where small performance issues were observed, the ultimate performance was dominated by the behavior of unfastened field tiles at roof slopes lower than 100% (pitch lower than 12/12), while the tile strength controlled the performance of the roof when all tiles were fastened at slopes exceeding 200% (24/12 pitch).

3. The concrete tile roofs at a 42% slope (5/12 pitch) developed an ultimate acceleration much higher than the design level acceleration of 0.8 g, even without fasteners for the field tiles.

4. The ultimate performance limits of clay tile roofs were not reached within the testing range of this study when steel wire nose clips were used.

5. **All concrete and clay tile roofs installed according to current UBC standards will meet or exceed specified seismic loading.**