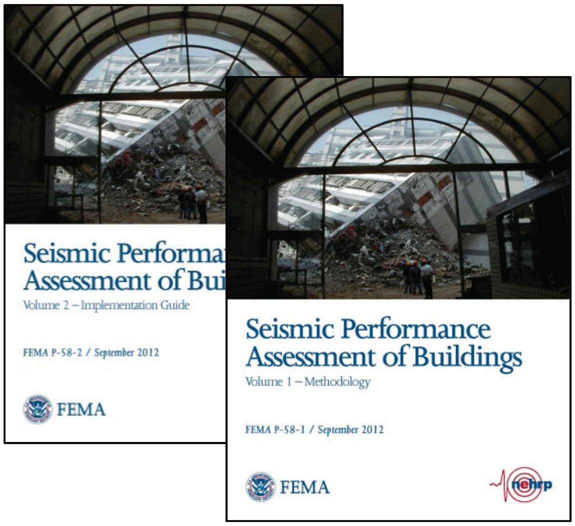


# Background Document

## FEMA P-58/BD-3.9.9

# Fragility of Concrete or Clay Tile Roofing

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## Background Documentation

FEMA P-58 Background Documents are a series of reports documenting the technical background and source information for key aspects of the FEMA P-58 methodology and its implementation. These reports were developed over the course of the 10-year ATC-58/ATC-58-1 Projects funded under FEMA Contracts EMW-2001-RP-0056 and HSFEHQ-06-D-1105.

Background Documents were developed by consultants, serving at various levels within the project hierarchy, reporting the results of: (1) decisions on technical development protocols; (2) focused studies on the development of key aspects of the methodology; (3) documentation of recommended procedures; and (4) collection of available data for the development of structural and nonstructural fragilities. They were initially intended to serve as a record of the technical state-of-knowledge at the time they were produced, and as resources for the development of the eventual project reports. As such, they represent a snapshot in time, and may, or may not, match the technical content, recommended procedures, or data incorporated into the final methodology and its implementation.

This Background Document is intended for the purpose of providing supplemental knowledge to users of the FEMA P-58 methodology. Information contained herein has not been independently verified for accuracy as a stand-alone document, and may have been superseded in its final implementation within the methodology. Specifically in the case of certain nonstructural component fragilities, the NISTIR fragility classification numbering scheme was modified over the course of the project, and the fragility classification number assigned in this document might be different from numbers assigned in the final fragility database. Users of information in this document assume all liability arising from such use.

## Notice



Cover illustration – Primary resource documents for the FEMA P-58 *Seismic Performance Assessment of Buildings, Methodology and Implementation* series of products: FEMA P-58-1, *Volume 1 – Methodology*, and FEMA P-58-2, *Volume 2 – Implementation Guide*.

# Fragility of Concrete or Clay Tile Roofing

**Keith Porter (04/21/2009)**

**Table 1. Summary results**

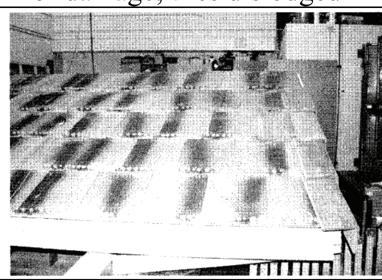
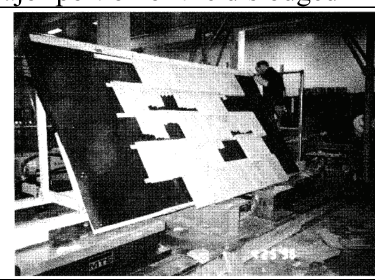
| | | |
|---|---|---|
| **Fragility, damage measures, and consequences for** | | |
| Component category: | B3011.010, Concrete or clay flat or mission roof tile, unknown inst<br>B3011.011, Concrete tiles, compliant with UBC94<br>B3011.012, Clay tiles, compliant with UBC94<br>B3011.013, Ditto, not compliant with UBC 94 | |
| Basic composition: | Roof with pitch between 5/12 and 24/12, concrete flat or S-shaped mission tiles, or clay one-piece S-tile or 2-piece clay mission tile roof | |
| Units: | Whole roof | |
| Demand parameter: | Peak horizontal acceleration of the roof | |
| Num. of damage states: | 2 | |
| Damage states are: | ☒ ordered; ☐ mutually exclusive; ☐ simultaneous | |
| Author and date: | K Porter 21 Apr 2009 | |
| **Damage states, fragilities, and consequences** | | |
| | **DS1** | **DS2** |
| Description: | Minor damage; tiles dislodged | Major portion of tile dislodged |
| Illustration: |  |  |
| Median (θ) All, UBC94:<br>Clay, UBC94:<br>Concrete, UBC94: | 1.6g<br>1.8g<br>1.5g | 2.0g<br>2.2g<br>1.9g |
| Data dispersion ($\beta_d$)[(1)]:<br>All:<br>Clay:<br>Concrete: | <br>0.20<br>0.20<br>0.28 | <br>0.23<br>0.20<br>0.28 |
| Uncertainty $\beta_u$ | 0.25: uniform loading protocol, fairly homogeneous specimens | |
| Total $\beta$: All, UBC94:<br>Clay, UBC94:<br>Concrete, UBC94: | 0.30<br>0.30<br>0.40 | 0.35<br>0.30<br>0.40 |
| Probability[(1)]: | | |
| Correlation: | | |
| Repairs required: | Reinstall few dislodged tiles | Replace roof |
| Possible consequences: | | |
| Repair cost (Y/N/?): | Y | Y |
| Death, injury (Y/N/?): | N | Y |
| Inoperative (Y/N/?): | N | N |
| Red tagging (Y/N/?) | N | Possible “area unsafe” tag |
| Comments: clay DS2: $\beta$ same as DS1, not method C. $\theta$ by judgment. $\beta_d$ = 0.20 as lower bound. | | |

**Table 2. Summary supporting information**

Literature summary. ***Xiao and Yun (1998)*** performed 24 full-scale laboratory tests of concrete and clay tile roofs, subjecting the specimens to monoaxial cyclic loading of 2.5 Hz in incrementally increasing amplitudes up to 1.6g. Six tests each were performed of: 12x17-in concrete flat tiles installed on a 5x8-ft roof; concrete mission tiles; clay 1-piece S tiles; and 2-piece clay mission tiles. See Figure 1 for specimen dimensions. In each batch of six, three values of roof pitch were examined, once in the ridge-parallel direction, once in the ridge-perpendicular direction. The loading protocol is illustrated in Figure 2. Test results are tabulated in Figure 3 (specimen numbers added here for convenience). DS1 and DS2 are illustrated above, from test results.

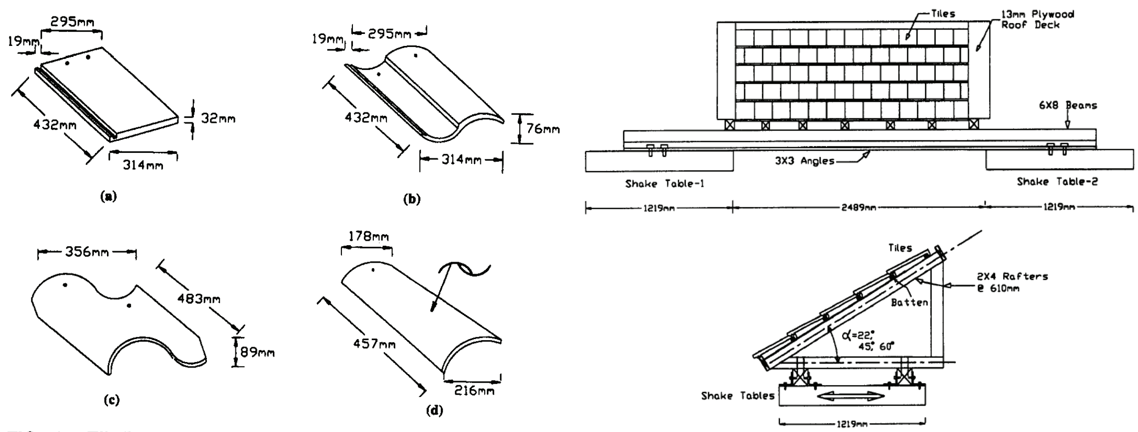



**FIG. 1. Tile Types and Dimensions Used in Tests: (a) Concrete Flat Tile; (b) Concrete Mission Tile; (c) One-Piece Clay S-Tile; (d) Two-Piece Clay Mission Tile**

**Figure 1. Concrete and clay roof tiles and roof specimens tested by Xiao and Yun (1998).**

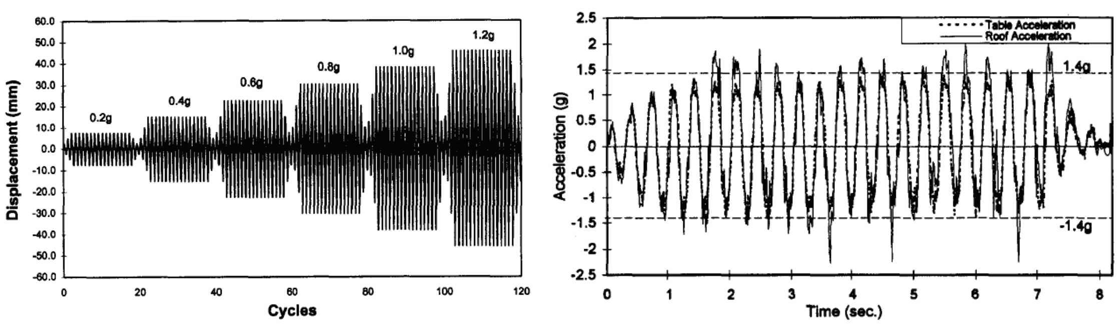



**Figure 2. Excitation of tiled-roof specimens in shake-table tests by Xiao and Yun (1998).**

**TABLE 1. Summary of Test Parameters and Results**

| Roof slope (%) (1) | Pitch (2) | Direction of shaking (3) | Maximum roof acceleration tested ($g$) (4) | Observed performance (5) | Ultimate acceleration, $a_u$ ($g$) (6) |
|---|---|---|---|---|---|
| (*a*) Concrete flat tile | | | | | |
| 42 | 5/12 | Perpendicular | 1.6 | No damage | $1.4 < a_u \leq 1.6$ |
| | | Parallel | 1.6 | Tile slipped only. | |
| 100 | 12/12 | Perpendicular | 1.4 | One tile slipped and fell. | $1.2 < a_u \leq 1.4$ |
| | | Parallel | 1.4 | No damage | |
| 200 | 24/12 | Perpendicular | 1.6 | Tiles fractured. | $1.4 < a_u \leq 1.6$ |
| | | Parallel | 1.4 | No damage | |
| (*b*) Concrete mission tile | | | | | |
| 42 | 5/12 | Perpendicular | 1.6 | No damage | $1.2 < a_u \leq 1.4$ |
| | | Parallel | 1.4 | Tiles slipped. | |
| 100 | 12/12 | Perpendicular | 1.4 | No damage | $a_u > 1.4$ |
| | | Parallel | 1.4 | No damage | |
| 200 | 24/12 | Perpendicular | 1.4 | One tile fractured. | $1.2 < a_u \leq 1.4$ |
| | | Parallel | 1.4 | Edge tiles fell. | |
| (*c*) Clay one-piece S-tile | | | | | |
| 42 | 5/12 | Perpendicular | 1.2 | No damage | $a_u > 1.2$ |
| | | Parallel | 1.4 | No damage | |
| 100 | 12/12 | Perpendicular | 1.4 | No damage | $a_u > 1.4$ |
| | | Parallel | 1.4 | No damage | |
| 200 | 24/12 | Perpendicular | 1.6 | No damage | $a_u > 1.4$ |
| | | Parallel | 1.4 | No damage | |
| (*d*) Clay two-piece mission tile | | | | | |
| 42 | 5/12 | Perpendicular | 1.2 | No damage | $a_u > 1.2$ |
| | | Parallel | 1.4 | No damage | |
| 100 | 12/12 | Perpendicular | 1.4 | No damage | $a_u > 1.4$ |
| | | Parallel | 1.4 | No damage | |
| 200 | 24/12 | Perpendicular | 1.4 | No damage | $1.4 < a_u \leq 1.6$ |
| | | Parallel | 1.6 | One bird-stop block fell. | |

**Figure 3. Xiao and Yun (1998) test results**

| | |
|---|---|
| Number of specimens: | 24 |
| Construction quality: | □ exceeds ☒ meets □ does not meet requirements of: UBC94 |
| Seismic installation conditions: | UBC94: Tile installed on deck of solid sheathing, with 1 layer of heavy-duty felt. The fasteners shall be corrosion-resistant nails long enough to penetrate into the sheathing 19 mm (3/4 in.) or through the thickness of the sheathing, whichever is less. Attaching wire for clay or concrete tile shall not be smaller than 2.11 mm (0.083 in.) in diameter. One fastener per tile is required for roof slope greater than 2.5 units vertical per 12 units horizontal (21% slope) to less than 3 units vertical per 12 units horizontal (3/12 or 25% slope). Two fasteners are essentially needed for roof slope 25% (3/12 pitch) and over, however, only one fastener on slopes of 58.3% (7/12 pitch) or less is required for tiles with installed weight exceeding 36.6 kg/ $m^2$ (7.5 lb/sq ft) having a width no greater than 406 mm (16 in.). For flat tiles without vertical laps, two fasteners are required for all slopes. The tiles shall be overlapped for a minimum length of 76.2 mm (3 in).<br><br>Tiles with anchor lugs (UBC Table 15-0-2). Horizontal wood strip battens are required for roof slopes over 7 units vertical per 12 units horizontal (58.3% slope). If no batten is provided, one fastener per tile is required. The similar requirements as described above are applied to the types of fasteners. If battens are installed, no fastener is required for slopes greater than 3/12 to less than 5/12 (33.3-41.7% slopes). One fastener each tile for every other row is specified for slopes equal to or greater than 5/12 to less than 12/12 (41.7- 100% slopes). One fastener per tile is needed for roof slopes greater than 12/12 (100%) to less than 24/12 (200%). All perimeter tiles require one fastener. The perimeter fastening areas include three tile courses but not less than 914 mm (36 in.) from either side of hips or ridges and edges of eaves and gable rakes. In addition to the ordinary "field" tiles, edge tiles as well as bird-stop blocks are typically used in practice, and they all must be fastened properly. |
| Loading protocols applied: | See Figure 2: displacement (left-hand figure) was imposed to the supporting structure, and acceleration of the roof at the center of the roof panel was observed via one tridirectional accelerometer installed on the top surface of the tile at the center of the roof panel. |
| Method for observing demand: | Excitation was imposed on USC shake table |
| Method for observing damage: | In-person observation with videotape backup. |

**Table 3. Table of test results**

| Specimen | DS1 | | DS2 | | DS3 | | Comment |
|---|---|---|---|---|---|---|---|
| | Data type: B | | Data type: B | | Data type: | | |
| | ***demand*** | ***f*** | ***demand*** | ***f*** | ***demand*** | ***f*** | |
| 1 | 1.6 | 0 | 1.6 | 0 | | | Concrete flat |
| 2 | 1.6 | 1 | 1.6 | 0 | | | |
| 3 | 1.4 | 1 | 1.4 | 0 | | | |
| 4 | 1.4 | 0 | 1.4 | 0 | | | |
| 5 | 1.6 | 1 | 1.6 | 1 | | | |
| 6 | 1.4 | 0 | 1.4 | 0 | | | |
| 7 | 1.6 | 0 | 1.6 | 0 | | | Concrete S |
| 8 | 1.4 | 1 | 1.4 | 0 | | | |
| 9 | 1.4 | 0 | 1.4 | 0 | | | |
| 10 | 1.4 | 0 | 1.4 | 0 | | | |
| 11 | 1.4 | 1 | 1.4 | 0 | | | |
| 12 | 1.4 | 1 | 1.4 | 1 | | | |
| 13 | 1.2 | 0 | 1.2 | 0 | | | Clay 1-piece |
| 14 | 1.4 | 0 | 1.4 | 0 | | | |
| 15 | 1.4 | 0 | 1.4 | 0 | | | |
| 16 | 1.4 | 0 | 1.4 | 0 | | | |
| 17 | 1.6 | 0 | 1.6 | 0 | | | |
| 18 | 1.4 | 0 | 1.4 | 0 | | | |
| 19 | 1.2 | 0 | 1.2 | 0 | | | Clay 2-piece |
| 20 | 1.4 | 0 | 1.4 | 0 | | | |
| 21 | 1.4 | 0 | 1.4 | 0 | | | |
| 22 | 1.4 | 0 | 1.4 | 0 | | | |
| 23 | 1.4 | 0 | 1.4 | 0 | | | |
| 24 | 1.6 | 1 | 1.6 | 0 | | | |

**Table 4. Quality tests**

| Quality test | DS1 | DS2 | DS3 |
|---|---|---|---|
| Passes Lilliefors goodness of fit test? (Type A only) | NA | NA | |
| Are θ and $\beta$ within 20% of past results? If not discuss. | NA | NA | |
| Are $0.2 \le \beta \le 0.6$? If not discuss. | Y | Y | |
| Discussion | | | |

**Table 5. Extrapolation to other detailed conditions and to average conditions**

| Condition (describe) | From tests? | DS1 | | DS2 | | DS3 | |
|---|---|---|---|---|---|---|---|
| | | $\theta$ | $\beta$ | $\theta$ | $\beta$ | $\theta$ | $\beta$ |
| Best: 2 nails/tile or 1 nail/ tile and tiles < 4 psf | N | 2.4 | 0.5 | 3.0 | 0.5 | | |
| Roof > 2000 sf, compliant with UBC94 | N | 1.6 | 0.6 | 2.0 | 0.6 | | |
| Worst: Not compliant with UBC 94 | N | 0.4 | 0.5 | 0.5 | 0.5 | | |
| Average: unknown compliance | N | 0.8 | 0.6 | 1.0 | 0.6 | | |

Basis for extrapolation. What factors affect $\theta$ and $\beta$? The authors suggest that tile weight and number of fasteners per tile (0, 1, or 2) potentially affect roof tile capacity. Slope also seems to matter: tile slip appears to more likely with shallow to moderate slopes ($\leq$ 12/12), tile fracture for steep slope (24/12), seemingly because horizontal motion causes tiles on steep roofs to flap. Greater median capacity might be expected from lower tile weight or more fasteners per tile (say 2 nails/tile or < 4 psf and 1 nail/tile); assume 1.5x median capacity in such case, and 0.25x median capacity for noncompliant roof. It also seems reasonable that a large roof requiring multiple installation crews would have greater variability $\beta$, as would a roof with significantly different conditions than those tested. For roof whose compliance with UBC94 is unknown, say ½ compliant capacity (i.e., closer to noncompliant than compliant).

Krawinkler considers loading protocol possibly extreme, especially if failures were related to low-cycle fatigue, which would tend to produce a low estimate of $\theta$. Alternatively, laboratory test specimen may be of superior construction quality relative to roofs in the wild, which would tend to produce an overly high estimate of $\theta$. Perhaps these two effects counteract each other.

"From tests" means that the tests reported here are believed to represent this condition level

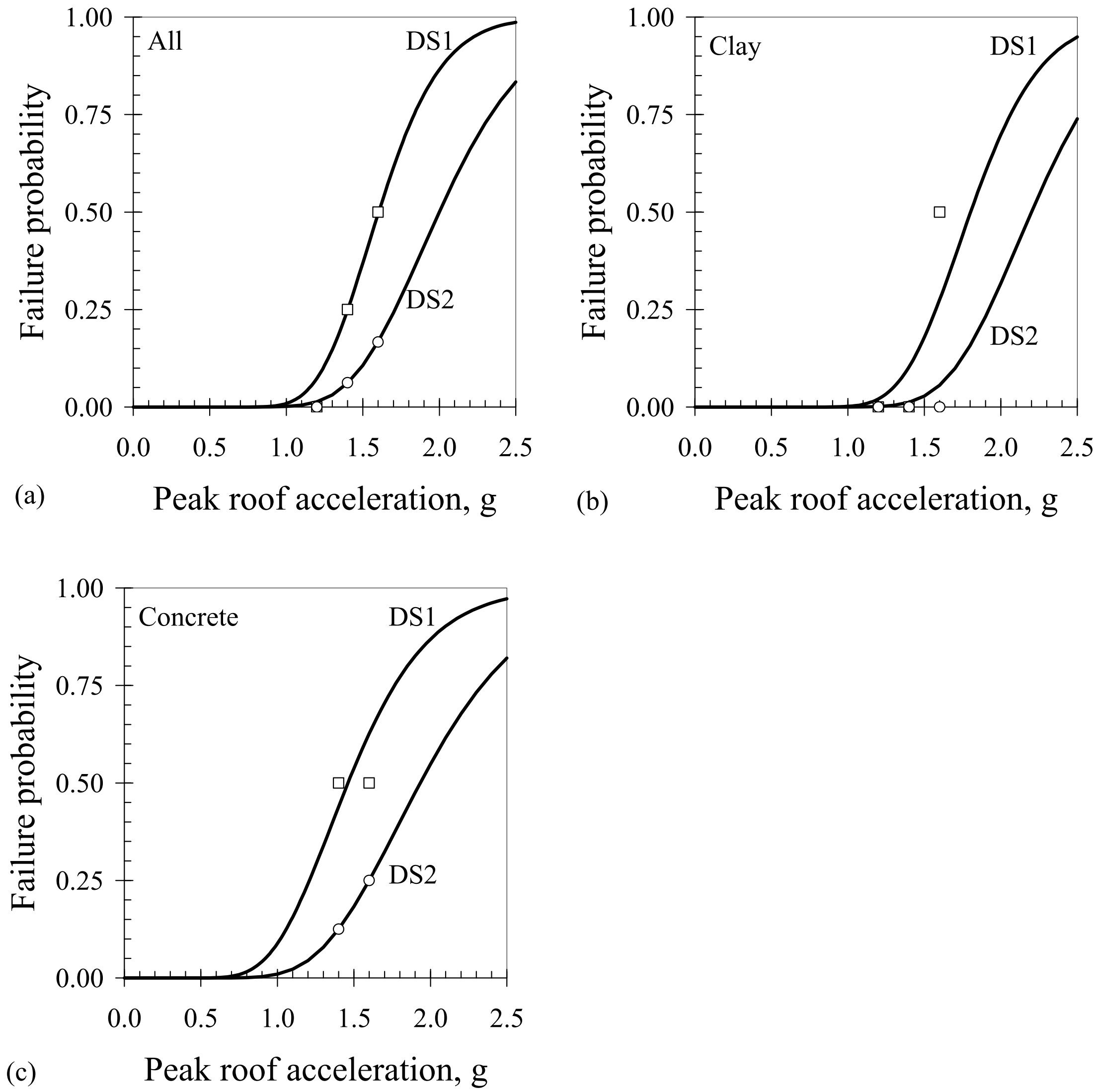



**Figure 4.** Proposed fragility functions for tile roof (a) concrete or clay, (b) clay only, and (c) concrete only. Smooth curves reflect θ and *β* before rounding θ to 2 sig figs and *β* to nearest 0.05.

## REFERENCES CITED


Xiao, Y. and H.W Yun, 1998. Dynamic testing of full-scale concr ete and clay tile roof models. *ASCE Journal of Structural Engineering*, 124 (5), May 1998, 482-489


**Revision history**

| | | |
|---|---|---|
| 1.0 | 21 Aug 2008 | Initial release |
| 2.0 | 20 Feb 2009 | Add clay mission tiles |
| 3.0 | 21 Apr 2009 | Add $\beta_u$, change DP plot labels |