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Full-scale study of wind loads on roof tiles and felt underlay and comparisons with design data

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Abstract. Wind pressure data have been collected on the tiled roof of a full-scale test house at Silsoe in the UK. The tiled roof was of conventional UK construction with a batten-space and bitumen-felt underlay beneath the interlocking concrete tiles. Pressures were monitored on the outer surface of selected tiles, at several locations within the batten-space, and beneath the underlay. Data were collected both with and without ventilator tiles installed on the roof. Little information appears to exist on the share of wind load between tiles and underlays which creates uncertainty in the design of both components. The present study has found that for the critical design case of maximum uplifts it would be appropriate to assign 85% of the net roof load to the tiles and 15% to the underlay when an internal pressure coefficient of -0.3 is used, and to assign 60% to the tiles and 50% to the underlay when an internal pressure coefficient of +0.2 is assumed (an element of design conservatism is inherent in the apparent 110% net loading indicated by the latter pair of percentage values). These findings indicate that compared with loads implied by BS 6399-2, UK design loads for underlay are currently conservative by 25% whilst tile loads are unconservative by around 20% in ridge and general regions and by around 45% in edge regions on average over roof slopes of 15°-60°.

Keywords: felt; house; permeable-cladding; slates; tiles; twin-skin; pressures; roofs; underlay; UK construction; wind-loads.

1. Introduction

Conventional UK house-roof construction comprises external roof tiles or slates mounted on timber battens that are nailed over an underlay material that is draped over timber rafters.

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Uncertainty exists over the sharing of wind uplift loads between the underlay and the tiles. This uncertainty needs to be resolved in order to rationalise the design of both the underlay and the tiles. However, very little information appears to be available to assist with determining the proportion of load resisted by each of the two roof-covering layers.

Full-scale wind pressure measurements were made at the former Silsoe Research Institute in 1998 on the tiled roof of a test house (Freathy, *et al*. 2000). Thirty-two pressure tappings were installed over the external surfaces of the tiles, within the batten-space, and beneath the underlay, and several hundreds of records were collected over approximately 120° range of wind directions.

As these measurements appear to be unique, the source data have been retrieved from archives and selected results have been analysed to assess the load sharing between the tiles and the underlay. Whilst load share will depend on the relative permeability of the two layers of cladding, these data relate to a highly representative house-roof construction in the UK and the tests assessed two cases, one where ventilator tiles were included and one where they were not.

2. Test house and experimentation

The test house (Fig. 1) measured 4 m long by 3.15 m wide (3.77 m over the eaves) by 3.5 m eaves height by 4.6 m ridge height, and had a 30° duo-pitched roof. Although relatively small in plan area, the house provided a real test roof with representative edge details which was considered important as it is in edge zones that tile failures are most prevalent.

The house had a steel frame with plywood cladding to the walls and a single access door. The roof was of conventional construction, comprising timber rafters, bitumen Type 1F underlay, timber battens, and Redland Regent ‘Bold Roll’ interlocking concrete tiles. The batten gauge was 345 mm which gave a nominal headlap of 75 mm. The tiles were fixed mechanically to the roof using nails.

The test house was erected on a flat concrete base on the test site at Silsoe. The house was orientated such that the ridge line was aligned approximately NW-SE. Winds from the SW through to N approached the house over a clear ‘open country’ fetch which extended over more than 600 m.

All roof pressure-tappings were located within one-quarter of the roof. This was on the SW-facing slope (that visible in Fig. 1), between the span-wise centreline and the NW gable verge, as shown in Fig. 2.

Fig. 1 Test house at Silsoe (viewed from south, looking north)

The pressures monitored, and the pressure coefficients computed were:

- external at the centre of 21 of the roof tiles (Taps 10-30) - C_{pe};
- batten-space at 9 positions (Taps 1-9) - C_{pb};
- 'internal' at 2 locations beneath the underlay (Taps 31-32) - C_{pi}.

Measurements were made with:

- two tile ventilators (each with a free area of 10,000 mm^2) installed on the instrumented roof face – these were located at the position of Tap 4 and at the equivalent position on the other half of the instrumented roof slope as can be seen in Fig. 1, but they ventilated into the batten-space, not through the underlay (ventilated batten-space case);
- a uniform covering of tiles over the roof (unventilated batten-space case apart from natural leakage through the tiles).

Slotted vents were present at the eaves and ridge which ventilated into the internal loft space throughout both the above test cases.

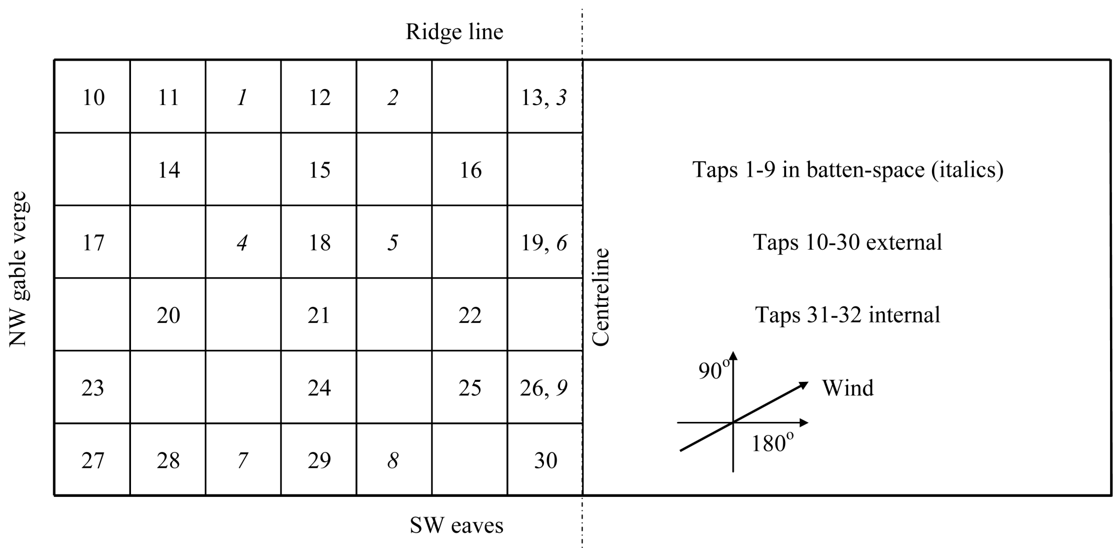

Fig. 2 Plan view of instrumented area of duo-pitched roof

3. Instrumentation

The pressure tappings in each tile comprised a rigid brass tube bonded in a pre-drilled hole so as to be flush with the external surface of the tile. Flexible plastic tubing connected each tap to a ± 1.25 kPa solid-state pressure transducer. Each plastic pipe contained a Y-connector which housed a ceramic plug that allowed rainwater entering through the tapping to drain from the pipework. All tappings were monitored simultaneously under computer control which operated solenoid-switched valves to achieve a zeroing and calibration period at the start and end of each run. All pressures were measured against a reference static pressure sensed by a calibrated probe mounted at the ridge height of the building on a reference mast positioned 12 m upstream of the test house. A reference ultrasonic anemometer and directional pitot tube were mounted on the same mast also at the ridge height of the building. The directional pitot tube provided a dynamic calibration signal and the anemometer provided a record of the approach wind speed and direction.

4. Illustrative results from measurements

Mean pressure coefficients recorded on the external surface of the tiles at Tap 11 are shown in Fig. 3, those recorded within the batten-space at Tap 1 are shown in Fig. 4, and those within the internal volume of the test house beneath the underlay are shown in Fig. 5. In each case, some 150 records were collected. Each record contained 9000 samples collected at approximately 4.2 samples/s and so represents a 36-minute recording period. Each record was processed as three 12-minute sub-records. Thus, some 450 points are plotted with respect to mean wind direction in Figs. 3-5.

From Fig. 3, the most onerous external suction for Tap 11 is given by a mean pressure coefficient of $C_{pe} = -1.0$ to -1.1 and occurs for a wind direction of approximately 175° (where 180° is parallel to the ridge line). The most onerous external suction for Taps 23 and 27 is given by a mean coefficient of -1.2 and occurs for the same wind direction. Although these are mean pressure coefficients, they agree very closely with the pseudo-steady pressure coefficients given in BS 6399-Part 2 (BSI 1997), the UK wind loading code, and in Eurocode 1, EN 1991-1-4 (BSI 2005).

The mean internal coefficients C_{pi} vary between approximately zero and nearly -0.4 (Fig. 5), which is also consistent with BS 6399-2 (though no positive internal coefficients were recorded for

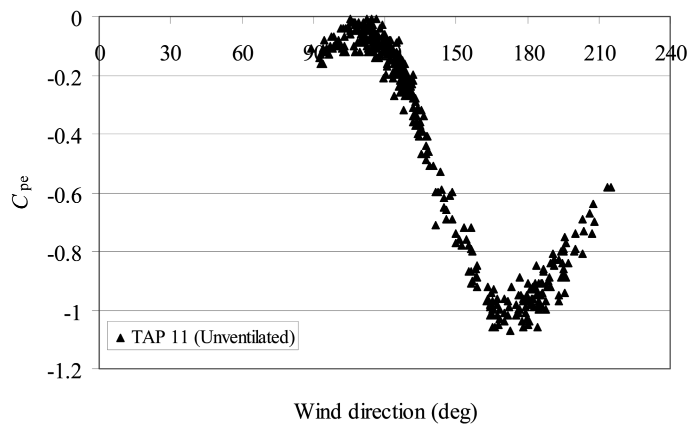

Fig. 3 Mean external pressure coefficients C_{pe} for Tap 11: unventilated batten-space

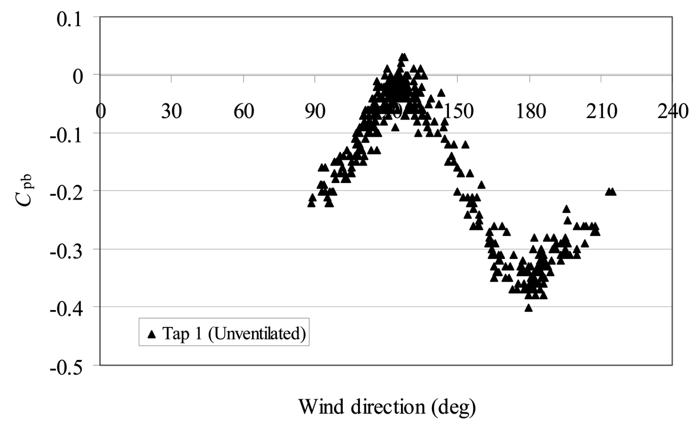

Fig. 4 Mean batten-space pressure coefficients C_{pb} for Tap 1: unventilated batten-space

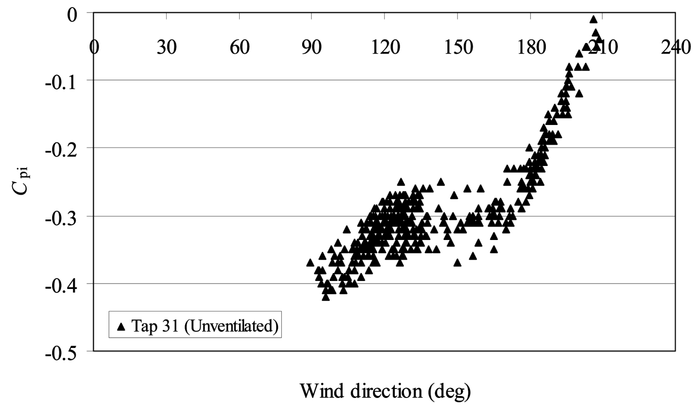

Fig. 5 Mean internal pressure coefficients C_{pi} for Tap 31: unventilated batten-space

the wind directions monitored in the experiments). These values result from the leakiness of the roof and walls, and the external pressures developed over them which vary with wind direction.

The batten-space coefficients C_{pb} (Fig. 4) had a similar range to that of the C_{pi} values, but exhibited a different relationship with wind direction. The C_{pb} coefficients would be determined primarily by the leakiness of the tiles and the external pressures over the roof, and to a small extent by the internal pressure because of the relatively low permeability of the underlay; the leakiness of the walls and the external wall pressures, whilst strongly influencing the internal pressure would have little influence on the batten-space pressure.

5. Load-sharing analyses and discussion of results

5.1. Mean pressure analysis

A least-squares line fit was made to the mean pressure coefficient data for individual tapping locations such as those shown in Figs. 3-5.

By differencing the external and internal pressures, a non-dimensionalised measure of the overall roof load can be determined at any external tapping location for any wind direction for which data are available:

$$\text{overall load } \alpha (C_{pe} - C_{pi}).$$

By differencing the external and batten-space pressure, a non-dimensionalised measure of the load on the tile can be determined for any wind direction for which data are available:

$$\text{tile load } \alpha (C_{pe} - C_{pb}).$$

By differencing the batten-space pressure and the internal pressure, a non-dimensionalised measure of the load on the underlay can be determined for any wind direction for which data are available:

$$\text{underlay load } \alpha (C_{pb} - C_{pi}).$$

The proportion of the net or overall roof load acting on the tile and on the underlay can be found from:

$$\text{proportion of load on tile} = (C_{pe} - C_{pb})/(C_{pe} - C_{pi});$$

$$\text{proportion of load on underlay} = (C_{pb} - C_{pi})/(C_{pe} - C_{pi}).$$

These calculations have been made using the least-squares line-fit data for selected external tappings (C_{pe}) and then extracting the calculated values for each 5° increment of wind direction. The percentage of load on a tile varies with wind direction (because the external, batten-space, and internal pressures vary independently with wind direction) and between tapping locations (because the pressures vary differently with wind direction at different locations). Consequently and unsurprisingly, the percentage of load on a tile is not a single value.

The results of the percentage of load acting on the tile are plotted in Figs. 6-8. They have been plotted in the manner shown (against net roof load) so as to reveal the percentage of load on the tile when the overall roof load is greatest, as this is when damage is most likely to occur. For each selected external tapping, the closest batten-space tapping has been selected to obtain the differential pressure coefficient across the tile by differencing the coefficients. For Tap 14, the average of the values from the equi-distant Taps 1 and 4 was used.

For the unventilated batten-space (Fig. 6), the percentage of load on the tiles when the net load on the tile reaches its maximum varies between 50% and 85%, but is 85% when the net load is at an overall maximum. The peak tile loads arise when the local external suction peaks, i.e., they arise at a wind direction of approximately 160° -175° (see, for example, Fig. 3).

For the ventilated batten-space, the percentage of load on a tile is reduced just very slightly, though the data are fewer for this case (Fig. 7). This suggests that the ventilators did not add significantly to the leakiness of the roof.

If the calculations are re-run but with the measured internal coefficients replaced by a constant value of $C_{pi}=+0.2$ (the positive C_{pi} value prescribed by BS 6399-2 (BSI 1997) for enclosed buildings), and it is assumed that the underlay is impermeable (i.e. there is no flow through the underlay which would transfer some of the positive internal pressure through to the batten-space), then the percentage of load on a tile is reduced to 50-55% (Fig. 8). In practice, the proportion of load on a tile is likely to be higher as underlay has finite permeability. The peak loads again arise when the external suction peaks, which is at a wind direction of 160° -175°. It would be highly desirable to undertake further such measurements but with a positive internal pressure operating beneath the underlay which could be achieved by creating a dominant opening in the windward wall of the test house.

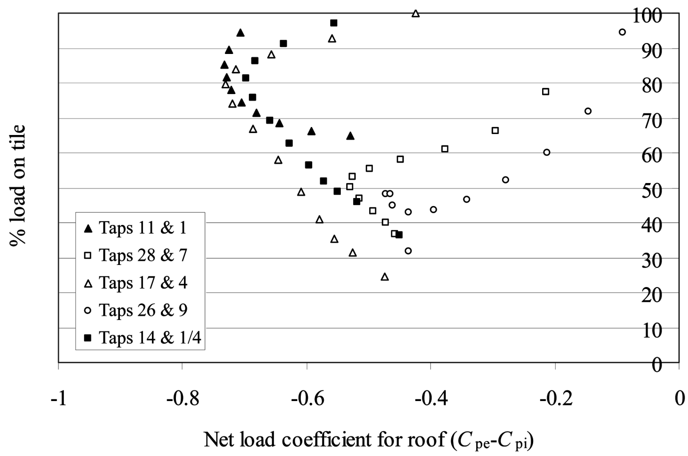

Fig. 6 Percentage load on tile for selected tiles against net roof load: unventilated batten-space

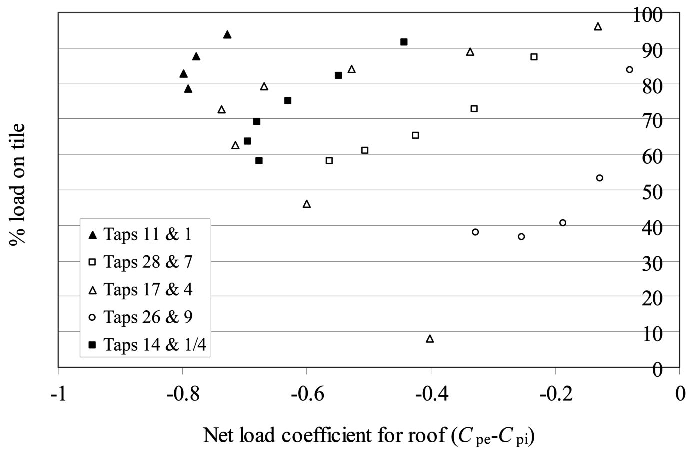

Fig. 7 Percentage load on tile for selected tiles against net roof load: ventilated batten-space

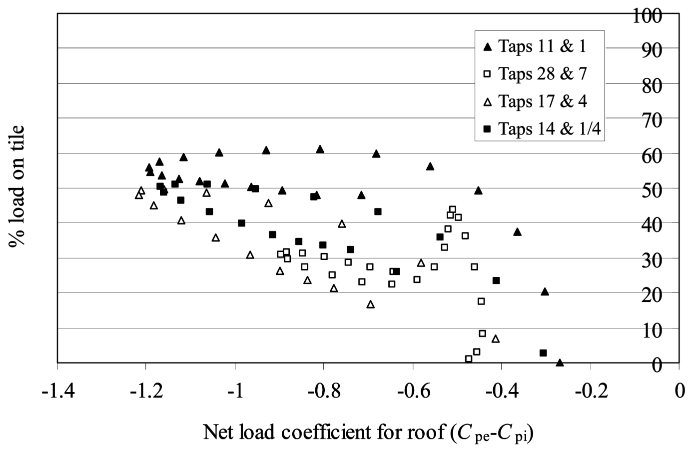

Fig. 8 Percentage load on tile for selected tiles against net roof load: unventilated batten-space with internal pressure numerically set to C_{pi} = +0.2 and zero-porosity assumed for underlay

The proportion of uplift load carried by the tiles can exceed 100% of the net roof load. This arises whenever the internal pressure is lower than the batten-space pressure and a positive pressure then applies to the underlay. From the measurements, this arises only when the net loads are relatively small and has not been included in Figs. 6-8 to aid clarity. Similarly, the proportion of load on the underlay can exceed 100% but from the measurements this arises only when the net loads are very small and positive (i.e. downwards-acting). This, however, raises the question of the suitability of describing tile and underlay loads as proportions of the net roof load.

5.2. Instantaneous-pressure analysis

Selected data records have been processed to generate 'instantaneous' (0.23 s increment) computations of the load proportion resisted by a tile. Run 122 was chosen for the ventilated batten-space case; it had a mean wind dynamic pressure of 18.5 Pa, and a mean wind direction of 169.3°.

Run 232 was chosen for the unventilated batten-space case; it had a mean wind dynamic pressure of 40.6 Pa and a mean wind direction of 175°. These runs were chosen as they had mean wind directions close to those for which the local external mean suctions peaked (see, for example, Fig. 3).

Firstly, however, Fig. 9 gives an illustration of the uniformity of the batten-space pressures for the ventilated batten-space case (Run 122). It shows instantaneous values of the difference in pressure, in Pa, between Taps 1 and 9 (the two batten-space taps which are furthest apart) plotted against the free-stream wind dynamic pressure. The plot is for the ventilated batten-space case. It is apparent that there is a large degree of pressure-equalisation taking place as the pressure difference is consistently less than ±6 Pa, even for a dynamic pressure of 60 Pa, and that the pressure difference is invariant with wind dynamic pressure. Fig. 10 shows the equivalent plot for the unventilated batten-space case (Run 232). This run had a higher mean wind dynamic pressure than did Run 122 but the pressure difference between Taps 1 and 9 remains generally below ±10 Pa, and is again invariant with wind dynamic pressure. These plots suggest that the batten thickness is sufficient to create open areas in the batten-space that are sufficiently large to allow batten-space pressures to

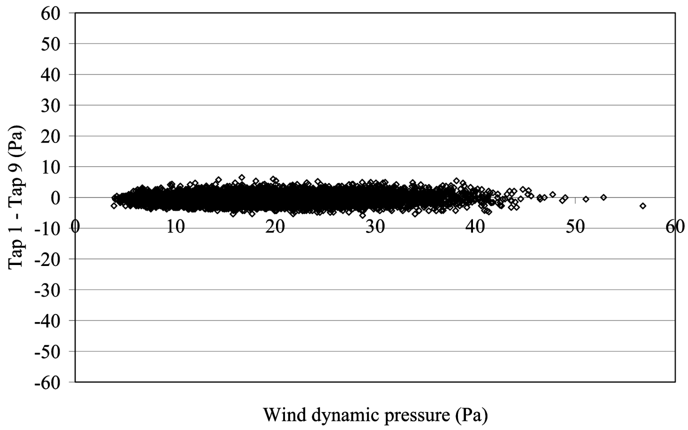

Fig. 9 Difference in batten-space pressure between Taps 1 and 9 plotted against wind dynamic pressure: ventilated batten-space (Run 122)

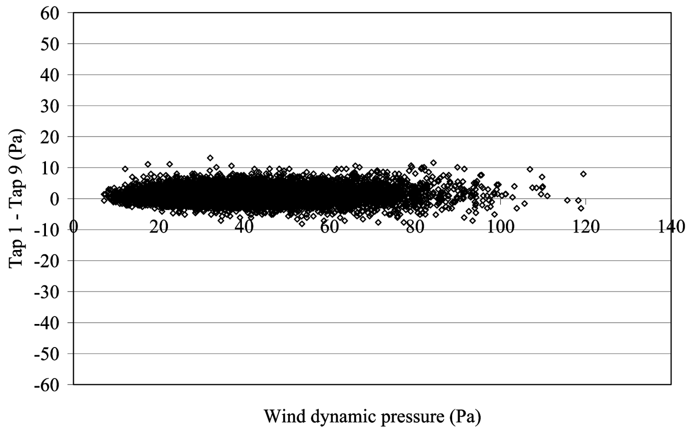

Fig. 10 Difference in batten-space pressure between Taps 1 and 9 plotted against wind dynamic pressure: unventilated batten-space (Run 232)

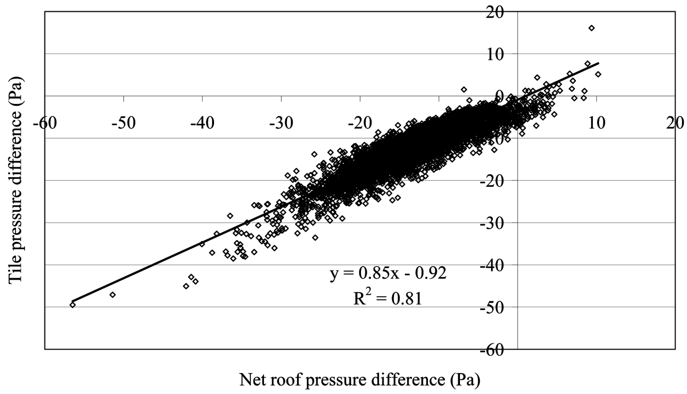

Fig. 11 Tile pressure difference (Taps 11 and 1) against net roof pressure difference (Tap 11 and internal): ventilated batten-space

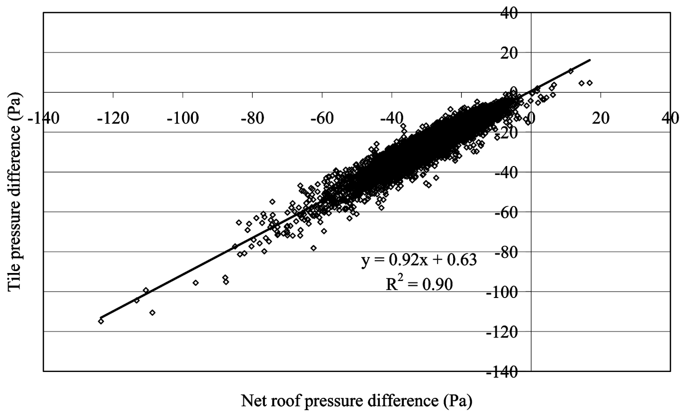

Fig. 12 Tile pressure difference (Taps 11 and 1) against net roof pressure difference (Tap 11 and internal): unventilated batten-space

equalise fairly effectively over the roof area to a value that depends on wind direction as indicated in Fig. 4. This in turn suggests that leakage paths through the roof perimeter, the tiles, and the underlay are small in comparison to those through the batten-space.

Fig. 11 shows the instantaneous pressure, in Pa, between Taps 11 and 1 (i.e. the tile load) plotted against the instantaneous net roof pressure between Tap 11 and the internal pressure, for the ventilated batten-space case. The 9000 instantaneous data points fall along a clearly discernible line, the least-squares, linear line-fit to which has a slope of 0.85, indicating the same 85% of load being resisted by the tile as was revealed by the mean pressure coefficient analysis. Fig. 12 shows the equivalent plot for the unventilated batten-space case. This demonstrates a still closer fit to a straight line indicating 92% of the net roof load being carried by the tile.

Fig. 13 shows the equivalent plot but for Tap 26 adjacent to the roof centreline, for the ventilated batten-space case. Here the instantaneous analysis indicates 73% of the load is resisted by the tile, which is significantly higher than the 40% estimate obtained from the mean coefficient analysis when the net load attains its peak value, but it is within the range of values for all net loads (see Fig. 7). Fig. 14 shows the equivalent plot for the unventilated batten-space case. This again demonstrates a good fit to a least-squares straight line indicating 79% of the load to be carried by the tile.

Equivalent plots for the underlay reveal, unsurprisingly, the complementary (i.e. remaining) component of the net roof load to act on the underlay.

5.3. Physical reasoning

For a conventionally-tiled roof with battens and an impermeable, flexible underlay there will be relatively unrestricted flow paths through the batten-space volume in the direction parallel to the battens because the battens create clear air channels; provided the internal pressure is lower than the batten-space pressure the underlay drape will also provide clear air paths in the perpendicular direction parallel to the rafters. If the underlay is relatively well-sealed, and so too are the edges around a roof face, then the permeable tiles uniformly distributed over the roof will constitute the dominant leakage to the batten-space, and the batten-space pressure will tend to an area-average of the external pressure distribution over the roof face ($C_{pb} \approx C_{pe,avg}$). This means that the underlay loading will be relatively uniform over its area and equal to the difference between the average

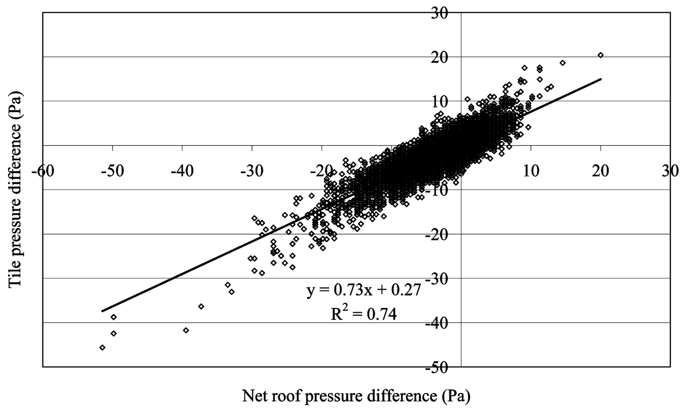

Fig. 13 Tile pressure difference (Taps 26 and 9) against net roof pressure difference (Tap 26 and internal): ventilated batten-space

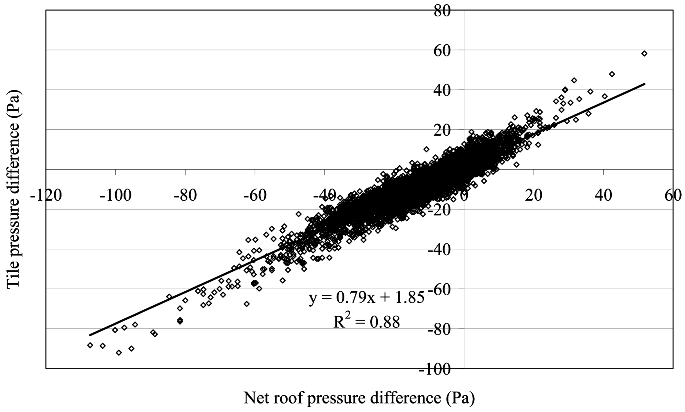

Fig. 14 Tile pressure difference (Taps 26 and 9) against net roof pressure difference (Tap 26 and internal): unventilated batten-space

external pressure (developed in the batten-space) and the internal pressure ($C_{pe,avg} - C_{pi}$). The loading on the tiles, however, will on average over all the tiles be zero, ranging from a maximum uplift on the tiles experiencing the highest external suctions ($C_{pe,min} - C_{pe,avg}$) to a maximum downward load on those experiencing the least negative (or positive) external pressure ($C_{pe,max} - C_{pe,avg}$). On this basis, there is little merit therefore in referring to percentages of load acting on tiles as the percentages are likely to vary widely in magnitude and in sign. The present study supports this physical reasoning insomuch as it has been shown that the batten-space pressure varies little over the roof face, and introducing two tile ventilators altered batten-space pressures very little. If the internal pressure is higher than the batten-space pressure then the underlay will tend to be lifted up against the underside of the battens and restrict batten-space flows in the direction parallel to the rafters, although there will still be clear air paths in the perpendicular direction. This may lead to greater variations in batten-space pressures than were found in the present experiments although comparison of Figs. 4 and 5 reveal that for the maximum suction wind direction of around 180° the batten-space pressure was more negative than was the internal pressure (and so the underlay would tend to be lifted and seal against the battens). Some tiles, including those featured in these tests have a profiled underside which does not seal against the top face of the batten; such tiles will allow some airflow parallel to the rafter even if the underlay is lifted and seals against the underside of the batten. Further measurements with a positive internal pressure would be desirable to resolve this specific question.

More tightly sealed tiles or slates than those tested would be expected to attract a larger proportion of the load than has been found here. Wet slates, for example, may seal fairly effectively; if combined with a leaky underlay, the batten-space pressure would be expected to tend to the internal pressure and the entire roof load would act on the tiles (again being greatest where the external suctions were greatest) and no load would act on the underlay.

The downward pressure loadings on tiles are of little or no wind-loading design consequence. Of greatest consequence to both tiles and underlay are maximum uplifts as this is when failures are most likely to occur. Since wind loading is most effectively covered by codes that provide external and internal pressure coefficients, only total net roof loads can be estimated, and so identifying percentages of load acting on tiles and underlay then does have relevance, and so is pursued further in this discussion.

The internal pressure within a non-partitioned, enclosed building is a uniform value which depends on the porosities of the faces of the building and external pressures. If the building is partitioned, however, and the porosities of external walls are not uniform, internal pressures will vary between the partitioned sub-volumes. For UK houses which generally have horizontal, insulated ceilings to upstairs rooms and cold loft-spaces, the ceilings are required increasingly to be less leaky to combat problems of condensation-formation in cold loft-spaces. The internal pressure in the lofts of such houses will consequently be little affected by wall pressures and porosities and more governed by roof pressures and porosities alone. Loft pressures are highly likely therefore to differ from the internal pressures defined in wind loading codes. For shallow-pitched roofs (below about 30°) of at least 2-stories, external pressures will tend to be entirely negative and so the internal pressure in the roof space will probably remain negative for all wind directions. This will reduce the net uplift wind loads on the roof but will tend to increase the proportion of the load carried by the tiles. The ceiling would then become more severely loaded (upwards) whenever the room internal pressure became positive.

5.4. Existing design information and other studies

In the UK, the design of roof tiles, slates and underlay against wind loading is not covered by BS

6399-2 (BSI 1997) but by a dedicated code BS 5534 (BSI 2003) for slating and tiling, which also considers underlay. For wind loading of underlay, BS 5534 assumes 67% of the net roof load obtained using internal and external pressure coefficients from BS 6399-2 is carried by the underlay. BS 5534 does not assume, however, that the complementary 33% of the net roof load is carried by the tiles or slates but instead adopts a different design approach that uses pressure difference coefficients contained in BS 5534 instead of pressure coefficients from BS 6399-2. This is discussed further in the following section.

Eurocode 1 – Part 1.4 – Wind actions, EN 1991-1-4 (BSI 2005) considers pressures on walls and roofs with more than one skin (Sec. 7.2.10 thereof), although the content may be adapted by National Annexes. For cases where the batten-space is less than 100 mm deep and the perimeter to the batten-space volume is sealed, EN 1991-1-4 states in Note 2:

"As a first approximation the following recommended rules may be applied:

- For walls and roofs with an impermeable inside skin and a permeable outside skin with approximately uniformly distributed openings, the wind force on the on the outside skin may be calculated from $c_{p,\mathrm{net}} = ⅔\, c_{pe}$ for overpressure and $c_{p,\mathrm{net}} = ⅓\, c_{pe}$ for underpressure. The wind force on the inside skin may be calculated from $c_{p,\mathrm{net}} = c_{pe} - c_{pi}$."

Underpressure refers to external suctions, so for this case the above rule is equivalent to assigning the batten-space pressure coefficient to two-thirds of the external pressure coefficient in considering loadings on the outer permeable skin (i.e. the tiles). Note that the outer permeable skin loading is given here as one-third of the *external* pressure coefficient c_{pe}, not of the net coefficient. However, for the design of the inner impermeable skin, (i.e. the 'impermeable' underlay), the loading is given as the total net roof load (because the skin is treated as impermeable). EN 1991-1-4 does not cover the case where the perimeter to the batten-space volume is not sealed, nor does it cover the case where both skins are permeable. Interestingly, in the following Sec 7.3 of EN 1991-1-4 concerning canopy roofs for which net pressure coefficients, $c_{p,\mathrm{net}}$, are given, canopies with double skins are considered: "the impermeable skin and its fixings should be calculated with $c_{p,\mathrm{net}}$ and the permeable skin and its fixings with $⅓\, c_{p,\mathrm{net}}$." Note here that the loading on the permeable skin is given as one-third of the *net* pressure coefficient, rather than of the external coefficient.

A study related to the present investigation has been conducted by Parmentier, *et al.* (2001) at the Belgian Building Research Institute in Limelette who constructed a test house (10 m long, 5 m wide, 3.7 m eaves height, 5.2 m ridge height) with a 30° duo-pitched roof on a rotating base in a field. The roof had a batten-space overclad with tiles. External and batten-space pressures were measured. Numerous measurement difficulties were encountered that constrained the acquisition of good quality data. However, the findings revealed that batten-space pressures were very small (i.e. very close to zero), even in the vicinity of high external suctions, indicating that the assumption within the Belgian Standard NBN B 03-002-1 (1988) and Eurocode 1 for wind actions (BSI 2005) that $C_{bp} = C_{pe}$ is unjustified and unsafe in relation to tile design, and over-conservative in relation to underlay design.

Another study has been conducted by Geurts (2000) in the Netherlands which was started in 1992 and was reported in a brief Conference paper in 2000. Full-scale measurements were undertaken on 'low-rise housing' with roofs comprising cement tiles on wooden battens over a 'stiff under roof' layer. 'Pressure equalisation factors' C_{eq} were computed from the measurements which are applied as multiplicative factors to local external pressure coefficients in the Netherlands Code NEN 6702; values of 0.3 - 0.5 were reported for inclined tiled roofs, the higher values applying in the higher external suction zones. This would appear largely to have the effect of increasing the EN 1991-1-4 factor of one-third applied to the external pressure coefficient to obtain the loading on the outer permeable skin of a twin-skin wall or roof subjected to external suctions, although the internal pressure coefficient is also included in the relevant design equation in NEN 6702. However, interpretations of, and comparisons with these findings are constrained as no details are given of roof geometry, tapping locations, and external or internal pressure coefficients.

Commercial-in-confidence testing has been conducted at BRE (Breeze 2006) on small-scale, low-rise, duo-pitched models of 22.5° roof slope with fibre-cement slates and different underlays (including air-permeable) covering the roofs. The models, measuring approximately 2 m by 2 m on plan, 0.45 m eaves height and 0.85 m ridge height, were tested at the end of the BRE wind tunnel. Leeward roof slopes only were monitored, and these only for winds perpendicular to the ridge. Although reported external pressure coefficients were very small (between −0.05 and −0.2), meaning no high external suctions were monitored, the proportion of load on the underlays was found to vary between 10% and 70% depending on underlay type, roof location, and roof ventilation. Averaged over the roof face, the load proportion on the underlays was found to vary between 29% and 50%, i.e., between 50% and 71% of the load was carried by the fibre-cement slates, which is broadly in line with the present findings.

6. Implications for BS 5534: Code of practice for slating and tiling

Equation 20 of BS 5534 (BSI 2003) assigns 67% of the net roof load to act on the underlay, the loads being based on pressure coefficients from BS 6399-2 (BSI 1997). However, BS 5534 does not assume that the proportion of the net roof load not carried by the underlay is carried by the tiles but instead, for apparently historical reasons, calculates tile loads by a different method that uses pressure difference coefficients, C_{pt}; this is considered further in the last part of the ensuing discussion.

The indications from the present mean-pressure analysis are that the proportion of load carried by the tiles ranges between 85% for $C_{pi} \approx -0.3$ and a little over 50% for $C_{pi} = +0.2$ (for convenience this latter proportion will be assumed here to be 60% which may or may not be conservative). Consequently, 15% to a little under 50% of the load is then carried by the underlay – taking the maximum proportion of load on the underlay as 50% is therefore indicated to be conservative. The 50% underlay load proportion arises when the internal coefficient is taken as $C_{pi} = +0.2$ and it is assumed that the underlay is impermeable. The maximum load on a tile will be the greater of the two values given by: 85% of the net load when the internal coefficient is negative and 60% (which may or may not be conservative) of the net load when $C_{pi} = +0.2$.

From BS 6399-2 (BSI 1997), the maximum external pressure coefficient for a duo-pitched roof is −1.6 which applies for a pitch of 15°, and -1.2 which applies for a pitch of 30° or above (values of -2.6 and -1.7 respectively apply for mono-pitched roofs of these slopes).

Taking $C_{pe} = -1.6$, and $C_{pi} = -0.3$ (the negative C_{pi} value prescribed by BS 6399-2 for enclosed buildings), then the pressure on the tiles assuming an 85% share is:

$$0.85\ (-1.6 + 0.3)\ q_s = 1.11\ q_s \text{ where } q_s \text{ is the design wind pressure,}$$

and the pressure on the underlay is then:

$$0.15\ (-1.6 + 0.3)\ q_s = 0.20\ q_s.$$

Taking $C_{pe} = -1.6$, and $C_{pi} = +0.2$ (the positive C_{pi} value prescribed by BS 6399-2 for enclosed buildings), and assuming this results in 60% of the load being resisted by the tiles, then the pressure on the tiles is:

$$0.6\ (-1.6 - 0.2)\ q_s = 1.08\ q_s$$

and the pressure on the underlay (conservatively assumed to be impermeable) is:

$$0.5\ (-1.6 - 0.2)\ q_s = 0.9\ q_s.$$

Thus the maximum tile pressure is similar in both cases, but is slightly larger for the case of the negative internal coefficient value. It would be larger still for a negative internal coefficient of C_{pi} = -0.2 or -0.1. This raises the query of whether it would be better to incorporate a transition rather than a step-change in the load-sharing percentages with respect to negative and positive C_{pi} values. The underlay pressure is greatest, by a large margin, for the positive internal coefficient value (assuming all the positive internal pressure is resisted by the underlay).

For the same values of $C_{pe} = -1.6$ and $C_{pi} = +0.2$, the current guidelines in BS 5534 give 1.2 q_s for the underlay pressure (Equation 20 of BS 5534) and 0.7 q_s for the pressure on single-lap tiles on underlay (Equation 11 of BS 5534).

Thus in the highest suction regions of a shallow-pitched roof, the present findings together with the pressure coefficient data in BS 6399-2 indicate a reduced design pressure for underlays given by a factor of:

$$0.9/1.2 = 0.75, \text{ i.e. a reduction of } 25\%$$

and an increased design pressure for tiles given by a factor of:

$$1.11/0.7 = 1.60, \text{ i.e. an increase of } 60\%.$$

Note, however, that the factors will be different in relation to mono-pitched roofs as the external coefficients are then more severe ($C_{pe} = -2.6$ instead of $C_{pe} = -1.6$).

The indications from the 'instantaneous' pressure difference analysis for selected runs are that it is necessary to consider not less than 85% of load to be resisted by the tile, and that indeed the design case should arguably be 100%. For underlay, the load proportion is in the range 10%-30% depending on roof location and wind direction. This would lead to a greater reduction in the design pressure for underlay than the 25% indicated above, although this ignores the circumstance of a positive internal pressure.

BS 5534 (Equation 19 thereof) calculates loads on slates or tiles with sealed laps in a manner consistent with that used to calculate underlay loads insomuch as it is based on BS 6399-2 pressure coefficients, but such roof coverings are extremely rare. For air-permeable tile coverings, however, BS 5534 calculates loads not as might rationally be expected as the complementary 33% to the 67 % underlay proportion of the net roof load obtained using BS 6399-2 pressure coefficients, but by a different method (see Equations 11-18 of BS 5534). The method uses pressure difference coefficients, C_{pt}, for different roof zones (general and local), air permeability factors, D, for slates and tiles, and roof substrate shielding factors, S, for underlay or board sarking. Loads are calculated using different equations depending on whether or not the roof covering overhangs the verge or eaves by more than 50 mm. This makes comparisons between the BS 5534 loads on air-permeable tiles and those indicated by the present analysis rather more cumbersome.

A simple numerical comparison has been undertaken for general, ridge, and edge zones of duo-pitched roofs with slopes of 15°-60°, taking values of C_{pi} = +0.2, D = 3.48 (single-lap tiles) and S = 1 (underlay or board sarking present). Values of C_{pt} were taken from Table 6 of BS 5534 and C_{pe} values were taken from Table 10 of BS 6399-2. The comparisons are shown in Table 1. Comparing the load predictions from Equation 11 of BS 5534 (for non-overhanging roof coverings) with the complementary 33% of the net roof loads obtained using BS 6399-2 pressure coefficients and

Table 1 Comparison of tile load factors from BS 5534 and BS 6399-2

Roof pitch (deg)	Tile load Eq. (11) F_t/q_sA_t			Sealed-lap tile load Eq. (19) F_t/q_sA_t			33% Tile load Eq. (19) $0.33F_t/q_sA_t$			60% Tile load Eq. (19) $0.6F_t/q_sA$			Tile load ratio Eq. (11) 33% Tile load			Tile load ratio Eq. (11) 60% Tile load		
	General	Ridge	Edge	General	Ridge	Edge	General	Ridge	Edge	General	Ridge	Edge	General	Ridge	Edge	General	Ridge	Edge
15	-0.49	-0.52	-0.70	-0.8	-1.5	-1.8	-0.26	-0.50	-0.59	-0.48	-0.90	-1.08	1.85	1.05	1.17	1.02	0.58	0.64
20	-0.42	-0.49	-0.63	-0.8	-1.4	-1.7	-0.26	-0.46	-0.56	-0.48	-0.84	-1.02	1.58	1.05	1.12	0.87	0.58	0.61
25	-0.38	-0.49	-0.56	-0.8	-1.2	-1.5	-0.26	-0.40	-0.50	-0.48	-0.72	-0.90	1.45	1.23	1.12	0.80	0.68	0.62
30	-0.38	-0.49	-0.49	-0.8	-1.1	-1.4	-0.26	-0.36	-0.46	-0.48	-0.66	-0.84	1.45	1.34	1.05	0.80	0.74	0.58
35	-0.38	-0.45	-0.45	-0.8	-0.9	-1.4	-0.26	-0.30	-0.46	-0.48	-0.54	-0.84	1.45	1.52	0.98	0.80	0.84	0.54
40	-0.38	-0.45	-0.45	-0.8	-0.8	-1.4	-0.26	-0.26	-0.46	-0.48	-0.48	-0.84	1.45	1.71	0.98	0.80	0.94	0.54
45	-0.38	-0.45	-0.45	-0.8	-0.8	-1.4	-0.26	-0.26	-0.46	-0.48	-0.48	-0.84	1.45	1.71	0.98	0.80	0.94	0.54
50	-0.38	-0.45	-0.45	-0.8	-0.8	-1.4	-0.26	-0.26	-0.46	-0.48	-0.48	-0.84	1.45	1.71	0.98	0.80	0.94	0.54
55	-0.38	-0.45	-0.45	-0.9	-0.9	-1.4	-0.30	-0.30	-0.46	-0.54	-0.54	-0.84	1.29	1.52	0.98	0.71	0.84	0.54
60	-0.38	-0.45	-0.45	-0.9	-1.0	-1.4	-0.30	-0.33	-0.46	-0.54	-0.60	-0.84	1.29	1.37	0.98	0.71	0.75	0.54
												Avgs	1.47	1.42	1.03	0.81	0.78	0.57

Equation 19 of BS 5534 reveals that Equation 11 gives very similar values for edge zones, but values that are 51% greater at the ridge and 78% greater in general zones. However, when C_{pi} = +0.2 it has been found here that tiles carry nearer to a 60% than to a 33% share of the load based on BS 6399-2 pressure coefficients (i.e. that tile loads are a factor of approximately 60/33 = 1.8 higher than those indicated by a 33% share). The present findings thus indicate that compared with the loadings implied by the pressure coefficients in BS 6399-2, BS 5534 under-estimates loads on ridge tiles and general zones by around 20% and loads on eaves/verges tiles by 43% on average over roof pitches from 15^o to 60^o (Table 1). It is of note that tile failures are most prominent in edge zones.

7. Conclusions

From the mean pressure analysis undertaken for four selected tiles on the test house, up to 85% of the net roof load is carried by a tile when the net load reaches a peak value (i.e. when damage is most likely to occur). Providing ventilation to the batten-space by means of tile ventilators reduces the percentage of net load carried by tiles only very marginally.

However, the distribution of load between tiles and underlays is dependent upon the internal pressure. This was consistently negative in the test house. Numerically replacing the measured negative internal pressure coefficients with a constant value of C_{pi} = +0.2 and combining this with the measured batten-space and external pressures reduces the percentage of load carried by a tile to 50-55% if it is assumed the underlay is impermeable and all the internal pressure is resisted by the underlay. In practice underlay has finite permeability, and the percentage of load carried by a tile would consequently be greater than 50 - 55%, assumed here to amount to 60%, although this is a speculated figure. Similarly, the present study indicates that the load share on underlay may conservatively be taken as 50% with C_{pi}=+0.2. The numerical substitution of C_{pi}=+0.2 into the load-share analysis tacitly assumes that for such a circumstance the physical mechanisms concerned are unaltered from those that prevailed in the experiments. It may be that under such circumstances the underlay seals against the underside of the battens and so restricts batten-space flows parallel to the rafters which may lead to greater gradients of batten-space pressure, although in the experiments the batten-space mean pressure was often lower than the internal pressure and so the underlay would have tended to be lifted in the experiments in some areas at least. It would be highly desirable to undertake further such measurements but with a positive internal pressure prevailing beneath the underlay to investigate this condition specifically.

As ceilings become better sealed, the internal pressure within rooms will have little influence on the roof-space pressure which will be determined by the porosity of the roof and the external roof pressures. For shallow-pitched roofs (below about 30^o) of 2-storey houses, the pressure coefficient in the roof space is likely to be negative for all wind directions. Should a positive internal pressure arise (which tends to occur only when there is a dominant opening in the windward wall) in upstairs rooms with well-sealed ceilings there will consequently be increased uplift loads on the ceilings.

The instantaneous pressure analysis indicates a very similar, but generally slightly still greater proportion of load is carried by the tiles. Regression-fits to the instantaneous data indicate around 90-95% for an edge tile with an unventilated batten-space, or 85% for the same tile with a ventilated batten-space; and approximately 80% for a mid-roof tile with an unventilated batten-space, or approximately 75% for the same tile with a ventilated batten-space. The load proportion on the underlay is the complementary proportion and so is in the range 10%-30%. Individual instantaneous values can, however, indicate higher percentages than these for both tiles and underlay.

BS 5534 currently assigns 67% of the net roof load to the underlay. Taking the most severe external pressure coefficient of −1.6 for duo-pitched roofs of 15^o slope or greater, and taking C_{pi} = +0.2 (both as prescribed by BS 6399-2), the present findings from the mean pressure coefficient analysis would result in design pressures for underlays being reduced by 25%. For tiles, design pressures would be increased by up to 85%. Importantly, the present analysis indicates that BS 5534 currently under-estimates tile loads by some 20% in ridge and general regions and by some 45% in edge zones – these being the zones where wind damage to tiles is most prevalent.

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