A Flight over a Roof Landscape: Impact of 40 Years of Roof Research on Roof Practices in Belgium

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ABSTRACT

Systematic roof research in Belgium started in the seventies, when much attention went to low-sloped assemblies. At that time a wide choice of sections was offered. The number of failure cases however peaked. A performance-based approach, narrowing the choice to one and the application of polymer modified bitumen brought the failure count down.

When insulating cathedralized sloped roofs became current practice, moisture complaints jumped up again. So, research moved to these. At that time, manufacturers forwarded the ventilation paradigm. Although research proved that air-tightness and a compact build-up guaranteed better moisture tolerance, application had to struggle with much unbelief.

Finally, the nineties saw the metal roof reappearing. Again, the move to insulated assemblies increased the number of failures. Also now, the importance of an air barrier and ventilation ineffectiveness for avoiding moisture problems was highlighted, a result opposing the paradigm that ventilation withdraws risks. But the market hesitated once more.

INTRODUCTION

Roofs are the most vulnerable part of the envelope. The bending moments, induced by the loads, result in stresses which imply the usage of materials with high tensile strength for the load bearing parts. At the same time, the bending moments demand sections stiff enough to withstand deflection. In Belgium, stack effect mostly tries to push inside air through the roof to the outside. Temperature extremes, experienced by roofs, are harsher than those felt by the façade, resulting in larger thermal movements and faster degradation. UV-attack harms durability more than it does for façade walls. Rain hits a roof surface even when wind velocity is zero. In low-sloped roofs with vapor-tight membrane, built-in moisture can only dry to the inside. Thermal bridging at roof edges is difficult to avoid, while light-weight roofs may show bad acoustical performance.

Those have all been reasons to make roofs the subject of long-lasting research programs. That research mainly evolved in two directions: 1) materials for roofing felts and roof covers and 2) roof assemblies. In the U.S., signs of interest in roof assemblies are first seen in the nineteen thirties, when Teesdale and Rowley both studied interstitial condensation in insulated enclosures and concluded that roofs are well off with a vapor retarder below the insulation and ventilation in the attic above (Teesdale, 1937)(Rowley, 1939). Around the same period, Krischer published a paper on the basics of moisture transfer in Germany (Krischer, 1938). The interest in how to construct trouble-free roofs grew after the Second World War. In the early fifties, Egner and Schäcke commented on how to calculate water vapor diffusion in building assemblies (Egner, 1950)(Schäcke, 1953). The methodology they proposed was completed by Glaser for the special case of cold storage buildings (Glaser 1958)(Glaser, 1958)(Glaser, 1959). The restriction to cold storages was quickly set aside and the method got used to evaluate façade and roof sections on moisture failure risk, a step that gave birth to what today is called the vapor barrier phobia of the late nineteen sixties and early nineteen seventies. Examples of that are found in the book of Seiffert (Seiffert, 1967) and the chapters on 'Building envelopes' in the older versions of the ASHRAE Handbooks of Fundamen-

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sections (Vos et al, 1974)(Hens, 1978). At the same time, methods based on the Devries model for combined heat and moisture transport were developed to further refine evaluation (Devries, 1958)(Van der Kooy, 1974)(Nielsen, 1974). Also more and more experimental work on roofs was published, showing the impact of the assembly on temperature gradients and moisture tolerance (Künzel et al, 1964)(Künzel, 1966)(Plonski, 1971) (Berthier, 1972) (Miettunen, 1974).

Air transport in roofs was out of consideration in most of the references just mentioned. However, in 1974, Orr commented on the problem of air ingress in the cold Canadian climate (Orr, 1974). The year before, Latta published a report on walls, windows and roofs for the Canadian climate, which draws air transport in the center of concern (Latta, 1973). Later, more and more evidence was gained that air ingress was in fact a very important player in the degradation of roof performance. One had to wait until 1980 before a calculation method was published allowing quantification of the air flow through envelope assemblies (Kronvall, 1982).

THE PERFORMANCE EVALUATION SCHEME

CLIMATE

a January mean of some 3°C and a July mean of 18°C, although humid in terms of relative humidity, the annual mean touching 80%. Mean annual precipitation passes 800 mm, while in winter solar radiation falls below the long wave losses. That combination of moderate temperatures, high relative humidity and a negative balance between solar radiation and long wave losses in winter makes horizontal and inclined surfaces very sensitive to under cooling.

ROOF TYPES EVALUATED

Over a period of 35 years that started in 1972, four classes of roofs were critically tested, modeled and evaluated:

- Low-sloped roofs
- Attics
- Tiled and slated cathedral ceilings
- Metal roofs

Table 1. Performance Array for Building Components

Topic	Performances	
Structure	Strength	Safety against rupture
	Stiffness	Acceptable deflection
Heat and mass	Air tightness	Air permeance Ventilation and wind washing Buoyancy flow
	Thermal insulation	Clear roof U-value Whole roof U-factor (included thermal bridging)
	Transient response	Temperature damping Dynamic thermal resistance Admittance
	Moisture tolerance	Built-in moisture Rain Hygroscopic moisture Interstitial condensation Surface condensation
	Thermal bridging	Temperature factor
Sound	Sound insulation	Airborne Contact
Service life	Physical attack	Hygrothermal dilatation Frost UV-radiation
	Biological attack	Mold

LOW-SLOPED ROOFS

Typology

When the program started in 1972, three types of low-sloped roofs were used: (1) compact (also called warm roofs), (2) ventilated (also called cold roofs) and (3) protected membrane. The three were further subdivided into heavy-weight, medium weight and lightweight, depending on the type of load bearing deck used: on site cast concrete or prefabricated concrete elements for heavy weight, aerated concrete elements for medium weight and corrugated metal sheet or timber beams with a particle board or plywood floor for light-weight (Figure 1).

A technical note by the Belgian Building Research Institute, published in 1963, discussed for the first time thermal insulation of low-sloped roofs (BBRI, 1963). As the thermal transmittance is impacted by the insulation thickness only, the note advanced the seven heavy weight low-sloped compact roof assemblies of Figure 2 as being of equal value. The word ‘screed’ in that figure relates to an additional light-weight concrete layer, poured on top of the load-bearing deck or the

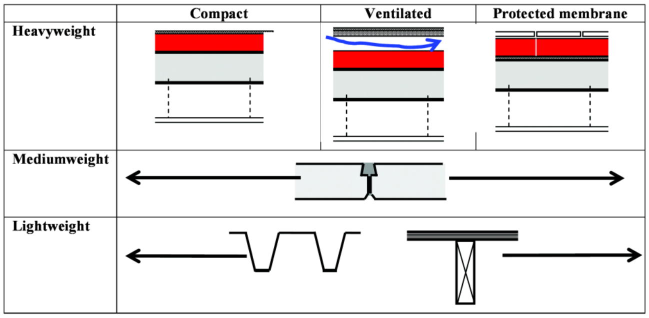

Figure 1 *General array of low-sloped roof solutions. The location of the insulation layer is not repeated in the medium weight and lightweight drawings. The arrows in the medium weight row means that such deck may be used in compact, ventilated and protected membrane assemblies. In the lightweight row, the arrow to the left indicates that metal and timber decks are in theory usable for compact, ventilated and protected membrane assemblies.*

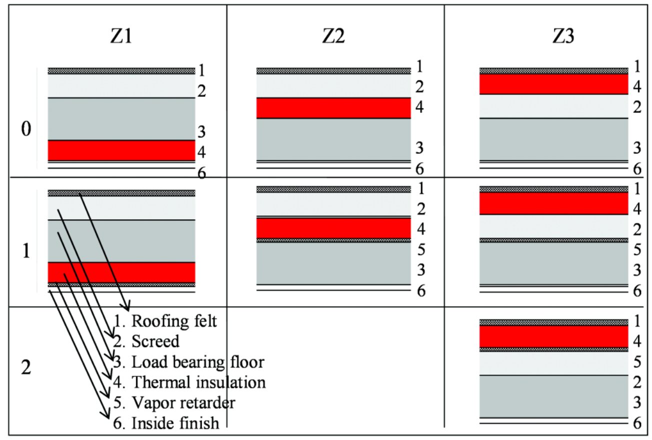

Figure 2 *Array of possible compact heavy weight low-sloped roof assemblies as described in BBRI (1963).*

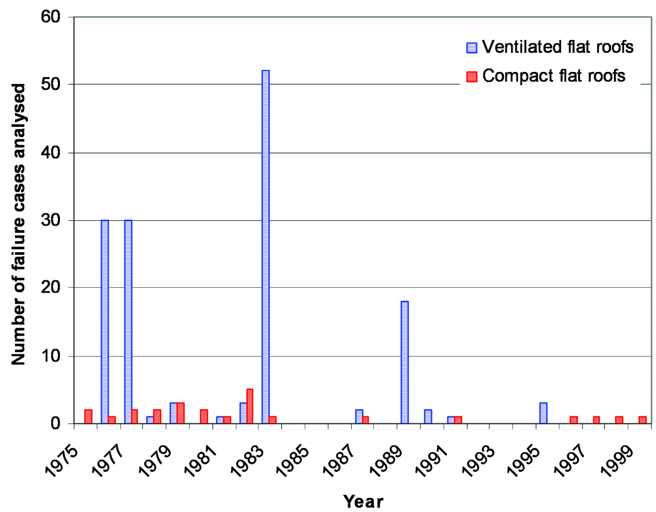

Figure 3 *Low-sloped roof failure cases over the years.*

insulation, for creating the slope necessary to allow drainage of the roof surface.

Failure Cases Investigated

Between 1975 and 1999, on demand of the owner, the designer, the contractor or a court expert, 170 severe low-sloped roof failure cases were thoroughly investigated and critically analyzed by the Laboratory of Building Physics, K.U.Leuven, Belgium (Anon, 1975-1999)(Hens, 1982)(Anon, 2003). Of these 170, 146 concerned ventilated low-sloped roofs and 24 compact low-sloped roofs. No protected membrane roof was on the list. The distribution over the years is shown in Figure 3. The three large packages of ventilated roof cases belonged to social estates where numerous dwellings had problems. The number of cases clearly diminishes as time progresses and no ventilated roof failure cases were investigated after 1995. Figure 4 lists the causes of failure in terms of percentages, while Table 2 gives the absolute numbers. As some failure cases had several causes, the sum of the causes passes the number of cases. The table and the figure show that in the moderate, humid Belgian climate, ventilated low-sloped roofs are clearly more prone to interstitial condensation than compact low-sloped roofs are.

Also interesting is to look to the inside climate for the cases, where interstitial condensation caused the problems. In Belgium, four indoor climate classes (ICC) are handled, see Figure 5. The variable determining the ICC is the weekly mean inside partial water vapor pressure excess, given as a function of the weekly mean outside air temperature. Definition of the borderlines between the four classes is based on measured data in numerous buildings, among them dwellings, schools, offices, swimming pools and industries, and on considerations about interstitial condensation by water vapor diffusion. In ICC 1, interstitial condensation is absent. The borderline between ICC 2 and ICC 3 coincides with the vapor pressure excess needed to get accumulation of condensate in a well insulated, north-oriented wall with vapor-tight exterior cladding and no vapor retarder at the inside. The borderline between ICC 3 and ICC 4 reflects the excess needed to get accumulation of condensate in a well insulated low-sloped roof without vapor barrier. ICC 4 is found in buildings with high water vapor release such as swimming pools and some industrial complexes.

Of the 82 ventilated roofs with interstitial condensation problems, 80 belonged to indoor climate class 1, 2 or 3 buildings, among them numerous dwellings, while only 2 belonged to indoor climate class 4 buildings, in the case being swimming pools. One of these roofs just collapsed the night before the enquiry started. Of the 7 compact roofs, showing intersti-

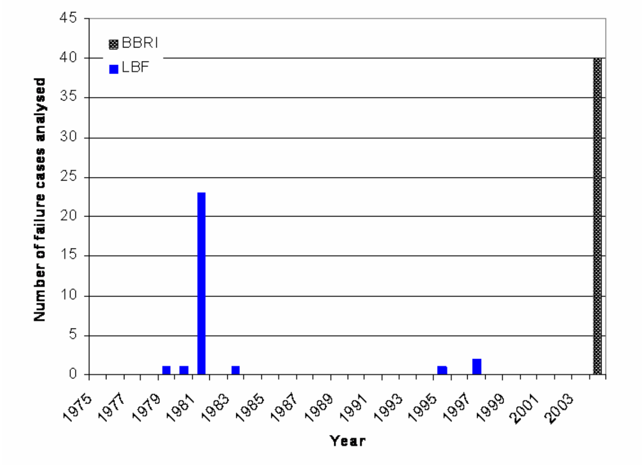

Figure 4

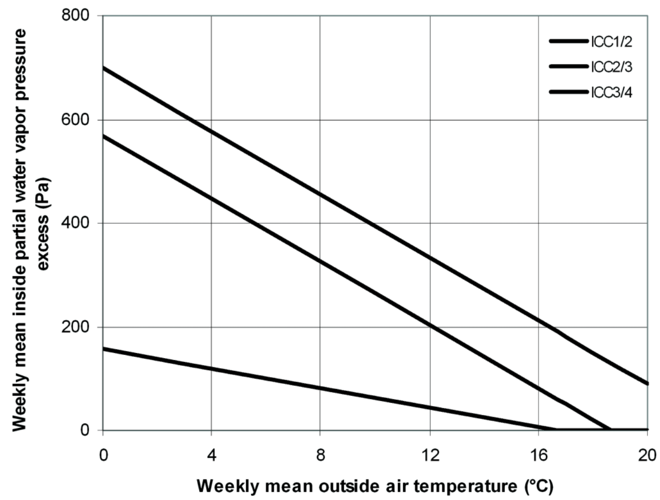

Figure 5

Table 2. Ventilated and Compact Low-Slope Roofs, Failure Causes in Absolute Numbers

Causes	Ventilated Low-Sloped Roofs	Compact Low-Sloped Roofs
Built-in moisture	20	5
Interstitial condensation	82	7
Rain penetration	8	9
Other	32	12

Research Conducted

Ventilated Low-Sloped Roofs.

sensitive? Several facts were found to be responsible for that (Anon, 1982)(Hens, 1987):

1. Ventilation is not a fact but rather a random phenomenon as stack flow can hardly develop in a horizontal air layer, while the effects of wind depend on the orientation of the air in- and outlets. As during the cold season in Belgium wind comes mainly from the south west or the north east, roofs with the air in- and outlets on a south east to north west line experience under-pressurization instead of ventilation. Things are even worse with ventilation pipes on the roof (Figure 6). Then under-pressurization is permanent with the ventilated air space acting as a suction volume on top of the building. That way humid inside air is entrained into the roof space through leaks in the ceiling, promoting interstitial condensation rather than decreasing the risk.
2. During clear nights, when sky radiation cools down the non insulated top-floor of a ventilated low-sloped roof to temperatures below the dew-point of the outside air entering the roof space, ventilation may become a cause of condensation itself. Especially in a moderately cool climate as the Belgian one, that phenomenon is critical, as temperature changes from 6 to 12 °C down to -2 to 5°C induce quite large drops in vapor saturation pressure.
3. Ventilation may cause wind washing through and under the insulation.
4. Removing built-in moisture through ventilation is an extremely slow process, even for a roof with the in- and outlets on a south west to north east line. Avoiding condensation of built-in moisture coming from a wet deck or a wet top floor support against and in the top-floor demands a percentage of air in- and outlets far beyond the acceptable value of 0.2% of the roof surface. A wetted top

floor in turn only dries in summer! The only workable solution therefore is to combine an air and vapor barrier on top of the deck with air-dry top-floor supports and an air-dry top-floor.

5. Architects heard for decennia that ventilated low-sloped roofs are a risk-free construction. They got so convinced of that paradigm that proposing such solution was no longer a matter of designing a correct assembly but of ventilation only, what so ever the assembly was.

Compact Low-Sloped Roof. As said, the technical note of 1963, published by the Belgian Building research Institute, advanced the seven heavy weight compact roof assemblies of Figure 2 as being of equal value. A few years before, Glaser published his calculation method for interstitial condensation. Yet, as soon as an evaluation method exists, the problem covered climbs higher on the list of considerations. This was particularly true for interstitial condensation in compact low-sloped roof assemblies, looking to the cool climate of Belgium, where the roofing membrane functioned as vapor-tight layer at the wrong side of the thermal insulation. Hence a vapor barrier somewhere at the warm side of that insulation, in the case being the inside, became a kind of obligatory measure. That eliminated three of the seven sections.

But, are things that simple? Looking closer to reality, not only interstitial condensation, but also built-in moisture appeared to be a problem. Table 3 gives some built-in moisture data for Belgium, measured on site just before the membrane was installed.

Further-on, air-tightness, thermal transient response, temperature loading, rain tightness and others are also performance criteria to consider. Clearly, a more systematic analysis of the overall performance of the seven heavy-weight assemblies of Figure 2 was needed. Results:

1. In general, air tightness is not a problem with heavy-weight compact assemblies as the bituminous roofing acts as an effective air barrier. Only when vents perforate the roofing, continuous air paths may be created from indoors to outdoors, on condition however that all layers below should be air permeable. This is quite unlikely with a concrete or prefabricated load bearing deck.
2. Assemblies Z10 and Z11, with the thermal insulation under the load bearing deck, combine a too low thermal admittance with large temperature swings in deck and screed, resulting in uncontrolled thermal movement and crack formation in the supporting walls. Built-in moisture can dry-out in Z10 but is trapped in Z11. There, in summer, part of it diffuses through the insulation and condenses on top of the vapor barrier.
3. Assemblies Z20 and Z21, with the thermal insulation between screed and load bearing deck, show a much better transient response. Anyhow, the screed still is subjected to high daily and annual temperature variations. That demands parceling by perimeter joints and joints in between. This was mostly not done, giving rise to spontaneous joint formation and membrane cracking. Also built-in moisture in the screed can hardly dry in both assemblies. In fact, in winter, the screed becomes the interstitial condensation zone, halting drying completely, while in summer the built-in moisture diffuses downwards to condense in the insulation layer and on the deck or the vapor barrier. Next winter, that condensate moves back to the screed. Anyhow, Z20 still experiences some slow drying in summer through the deck but Z21 does not.
4. Assemblies Z30 and Z31, with the thermal insulation directly under the membrane, are doing very well from a thermal transient response and temperature loading point of view. They anyhow have one negative point: the membrane experiences a heavier temperature load. But, built-in moisture in the screed poses problems again. In winter, part of it diffuses upwards to condense in the insulation and below the membrane. In summer diffusion changes direction, pushing that condensate back into the screed. In assembly Z30, that process is accompanied with some drying (Figure 7). In section Z31, it goes on without any drying.
5. Assembly Z32, finally, with the thermal insulation directly under the membrane and a vapor barrier directly below the insulation, is the only one that does well for all

Table 3. Built-In Moisture in Compact Low-Sloped Roofs, Measured Values

Roof	Layer	Built-In Moisture, kg/m^3	Capillary Moisture Content, kg/m^3
Apartment building	Screed, lightweight concrete	117	105
Office building	Thermal insulation (expended perlite board)	42	>70
Hospital	Screed, normal concrete Concrete Top-layer	 38 154	120
Dwelling	Screed, lightweight concrete	126	105
Apartment building	Screed, lightweight concrete	38/153/93 Three samples	

Figure 6

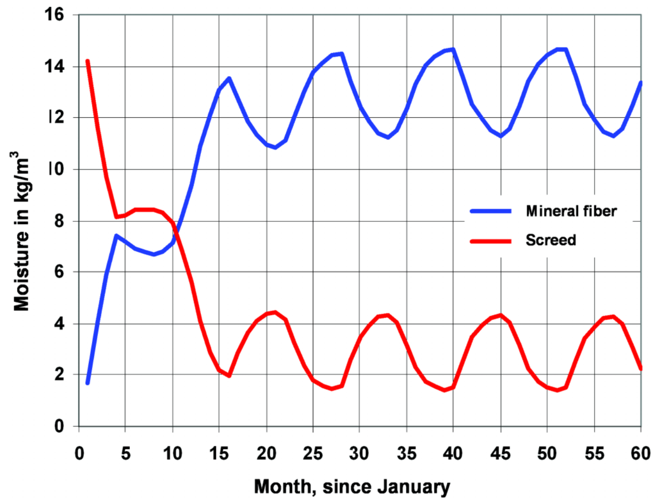

Figure 7 *Compact roof with section Z30, built-in moisture moving between the thermal insulation and the lightweight concrete screed, slow drying of the screed (calculated with Match®).*

performance criteria: excellent thermal transient response, deck and screed well protected from temperature swings, built-in moisture migrating to the inside without harm for the insulation.

What with interstitial condensation in the seven assemblies? In the three without vapor barrier, application in indoor climate class 4 buildings results in an annual accumulation of condensate, which is not acceptable. In indoor climate class 3 buildings, Z10 appears critical but only in case a vapor permeable insulation and an internal lining with low vapor resistance is used. For the four with vapor barrier, interstitial condensation is not an issue, except for Z11, where mounting a continuous vapor barrier from below is such a difficult task that bad workmanship appears the rule rather than the exception.

An analogous analysis for medium weight compact low-sloped roofs with aerated concrete deck learns that built-in moisture is even more critical there. Fresh aerated concrete contains up to 320 kg water per m^3. Air-dry, the hygroscopic moisture content is 25 to 30 kg/m^3. The difference, 290 to 295 kg/m^3, must dry out without causing problems. This is only possible if the underside is left untreated, meaning that a vapor retarder there is not an option. Thus, such roof is excluded in ICC4, except if one turns it into a Z32 assembly by adding a thick enough insulation layer on top, under the membrane, with a vapor barrier directly below.

Light-weight low-sloped roofs finally appear less problematic from a built-in moisture point of view but more sensitive to air outflow when vents perforate the roofing felt and to interstitial condensation, reason why an air and vapor retarder below the insulation is needed in any case.

Protected Membrane Roofs. Although no failure cases were included in the set discussed, much research was devoted to new dense mineral fiber boards and XPS/concrete composites for use in protected membrane roofs. The mineral fiber boards functioned well from a hygrothermal point of view, on condition that their underside was vapor-tightened with a bituminous layer added during manufacturing and the low slope roof surface well drained. If not, the boards could turn extremely wet by rain water that accumulated on the roofing felt, diffused into the boards and condensed there. The system failed because of excessive erosion of the mineral fiber surface (Hens et al, 1986). The XPS/concrete tiles with the capillary concrete layer on top of the XPS accumulated too much moisture by interstitial condensation of the moisture sucked by the concrete in the XPS to be usable.

Is it possible to design a moisture tolerant ventilated low-sloped roof? The answer is yes, if a sum of conditions are met: a perfect air and vapor retarder on the deck, the insulation perfectly mounted and protected by a wind barrier, air-dry top-floor supports that do not act as thermal bridges and an air-dry top-floor, that carries the roofing felt, in a frost resisting material with high enough thermal resistance. Even than, not only the investment but also failure risk remains higher than when a compact low-sloped roof is used. In the early nineties, a new technical note was therefore published by the Belgian Building Research Institute, excluding ventilated roofs definitely from the list of accepted low-sloped roof solutions in the moderate but humid climate of Belgium (BBRI, 1992). That same technical note also reduced the seven compact assemblies and the companion medium weight and low weight assemblies that figured in the old 1963 note to a single one: Z32.

TILED AND SLATED CATHEDRAL CEILING ROOFS

Typology

through the usage of venting tiles and ridge elements. Quickly a third request was added: insertion of a vapor retarder below the insulation. This was done by promoting mineral fiber blankets with vapor retarding facing as product for cathedral ceiling insulation.

Failure Cases Investigated

Between 1975 and 1999, 29 failure cases were investigated by the Laboratory of Building Physics, of which 23 belonged to the same social estate of 45 dwellings (Figure 8). The real number of failure cases in Belgium of course ranked much higher. The Belgian Building Research Institute for

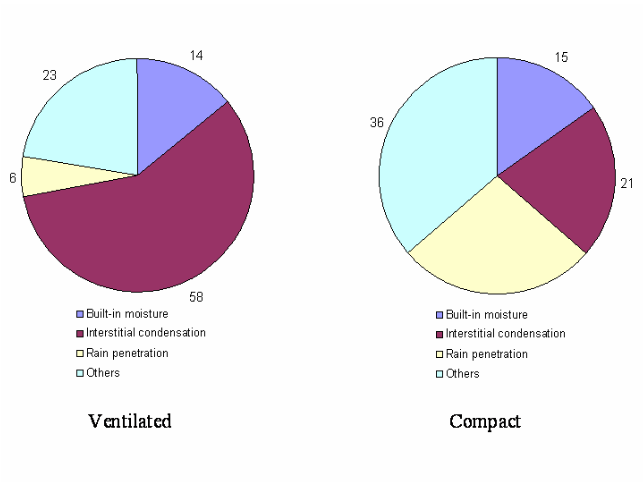

Figure 8

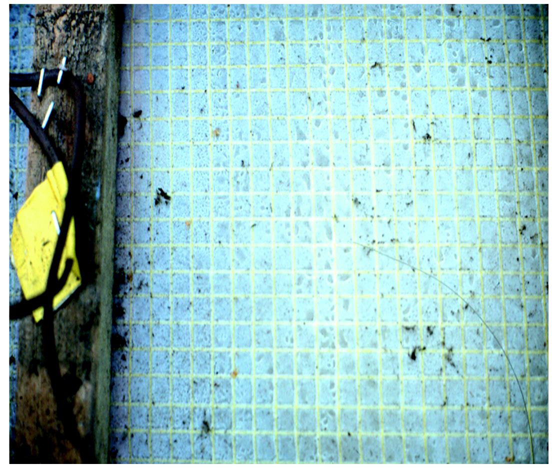

Figure 9 *Droplet deposit by interstitial condensation below a vapor retarding plastic foil underlay in the ventilated reference roof section.*

Table 4. Tiled Mono-Pitch Cathedral Ceilings, Reference Sections

From Inside to Outside	
Reference Section 1 Compact	**Reference Section 2 Ventilated**
Inside lining	Inside lining
Air space	Air space
Continuous air and vapor retarder (PE-foil)	
20 cm mineral fiber between wood joists, spaced 0.6 m	8 cm mineral fiber blanket with vapor retarding facing between wood joist, spaced 0.6 m
	Ventilated air space
Capillary, vapor permeable underlay, directly on the insulation	Capillary, vapor permeable underlay
Battens and laths	Battens and laths
Tiles	Tiled deck with venting tiles

example reported 40 complaints after the winter of 2003-2004 (BBRI, 2004). All 29 cases analyzed were struggling with interstitial condensation by advection, the combination of water vapor diffusion and air flow induced water vapor displacement. In theory, 28 of the 29 roofs were built according to the two ventilation planes and vapor retarder below the insulation rationale. In reality, however, ceilings were not airtight, insulation blankets were mounted carelessly leaving marvelous paths for air and water vapor ingress and the underlay was far from air retarding!

Research Conducted

As tiled and slated cathedral ceilings are very popular in residential construction in Belgium and as the industrial interests are high, important research efforts went to that type of roof. Results of these efforts have been published on several occasions (Hens et al, 1996) (Hens et al, 1998) (Janssens et al, 1998) (Hens et al, 1999) (Hens et al, 1999) (Hens et al, 2004) (Houvenaghel et al, 2004).

Two test buildings were constructed, a first for mono-pitch roofs and later-on, a second for duo-pitch roofs. The experimental work in the two buildings formed the kernel of the research, while the models developed had as main goal an understanding and extrapolation of the test data, with risk as the main guiding principle.

In the mono-pitch test building, sixteen different roof sections were evaluated, with as references a compact roof and a two-plane ventilated roof. For the sections see Table 4. The 14 other roofs figured as variants on these two: exchanging the capillary, vapor permeable underlay for a vapor retarding glass-fiber reinforced plastic underlay foil, omitting the air and vapor retarder in the compact roofs, perforating the air and vapor retarder close to the ridge in the compact roofs, using a slated instead of a tiled roof cover. Each roof went through two winters. The inside climate simulated an ICC3/4 situation, representative for small, intensely used dwellings. The performances evaluated were those listed in Table 1.

The results were straight forward. The ventilated reference performed worse than the compact one. In winter its thermal response suffered more from wind washing and air looping around the insulation, while moisture content in the capillary, vapor permeable underlay touched higher values. Droplet formation, however, was not noticed. That changed with the vapor retarding plastic foil as underlay. Then droplets were formed against the underlay (Figure 9), while the

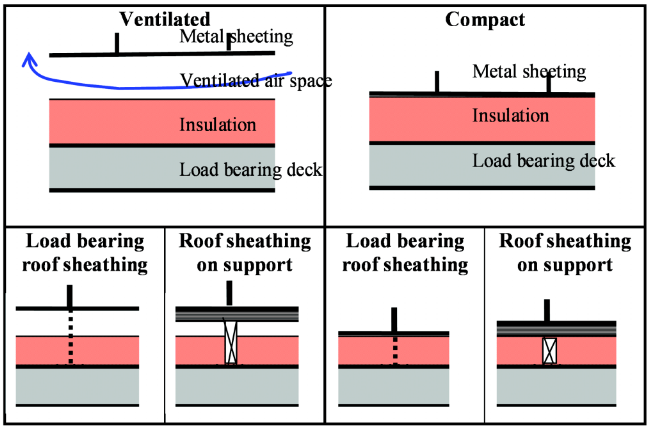

Figure 10 *Array of typical metal roof assemblies.*

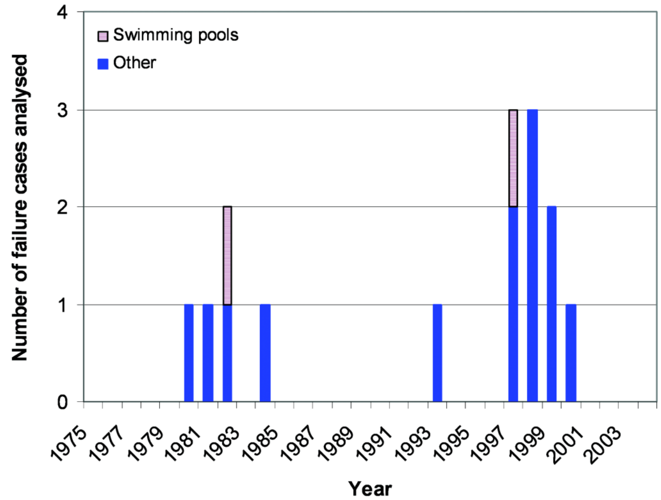

Figure 11 *Metal roof failure cases over the years.*

ACKNOWLEDGMENT

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