UNVENTILATED ROOF TILE UNDERLAYMENTS IN DENMARK

By Erik Brandt
Morten Hjorslev Hansen
Tommy Bunch-Nielsen

INTRODUCTION

For some time, it has been common practice in Denmark to use underlayments in conjunction with sloping roofs, especially in constructions where the ceiling and the roof covering are parallel. The purpose of the underlayment is to act as an extra barrier against penetration of water and drifting snow from the exterior. Traditionally, roofs with underlayments have been ventilated with a gap between the insulation and the roof underlayment with openings to the surroundings (see *Figure 1*, left). The ventilation removes moisture which, by diffusion or convection, has penetrated from the interior of the building.

Some 10 or more years ago, a new type of material was introduced to the market. These products were used in a different way than previously, as they were placed as a roof tile underlayment directly on the insulation. The missing ventilation gap meant that moisture from the interior had to be removed in a way other than ventilation, namely diffusion. In order to achieve this, the new products must not only be watertight, but at the same time be very open to water vapor diffusion, similar to the way Gore-tex acts in clothing. The materials are mainly thin membranes that can be produced in a variety of ways and are often laminated and produced with a "carrier" material to reinforce and protect the membrane itself. Other types of materials act in the same way – e.g., gypsum board, bitumen-impregnated plywood (only in wood-based roof elements), and oil-impregnated or coated fiberboard. Oil-impregnated fiberboard has been used in Denmark as a roof tile underlayment for more than 30 years.

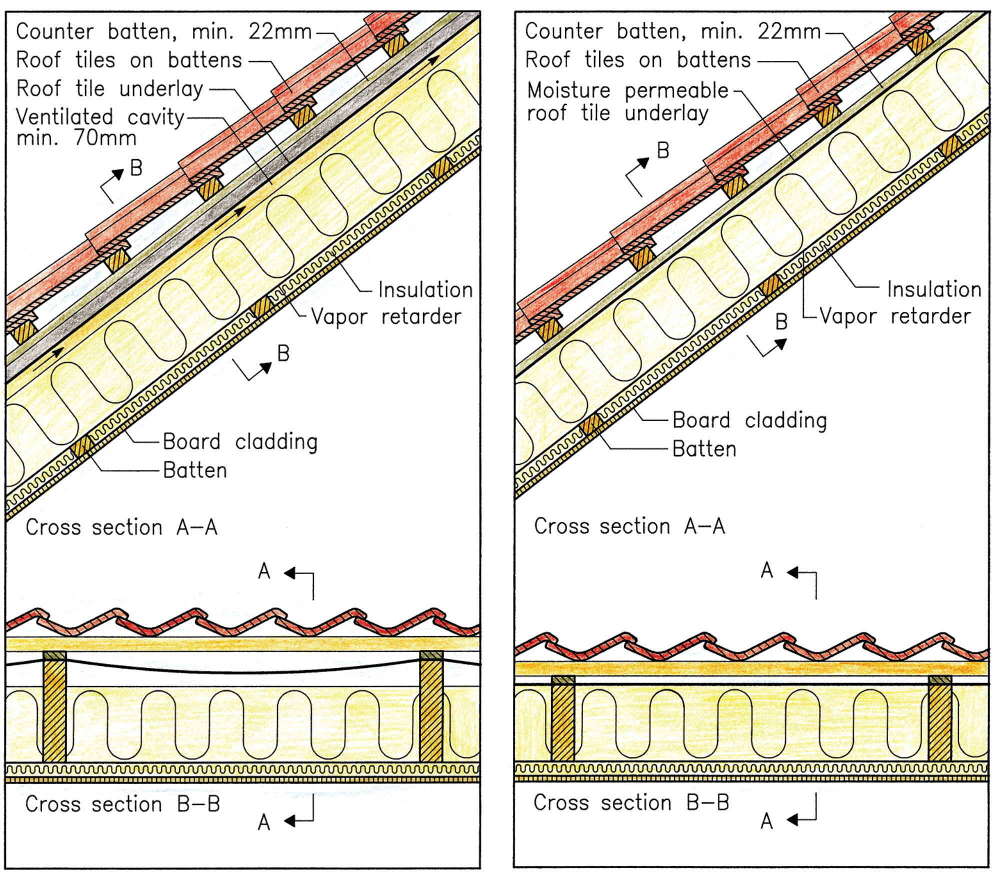


Figure 1 – Cross section of ventilated roof tile underlayment with a gap between insulation and underlayment (left) and unventilated roof tile underlayment with the underlayment directly on the substrate/insulation (right).

INVESTIGATIONS ON RELEVANT PROPERTIES AND THEIR SIGNIFICANCE

Shortly after introduction of the new materials, a project was launched to investigate the reasons for the problems, including identification and assessment of properties necessary to ensure a satisfactory performance. The project was primarily focused on properties related to moisture transport in the roofs, as this is normally considered to be crucial to performance and durability.

Analysis of performance properties

An analysis was conducted in order to identify the properties necessary for a satisfactory performance of a roof underlayment. This was based on the functions the underlayment should fulfill and all the agents anticipated to act on it, as described in *CIB Publication 64.1* It should be noted that some of the functions and acting agents are only relevant for some materials and/or constructions; and, similarly, some properties are only relevant for certain materials and/or in certain periods of the service life, e.g., the construction period.

For this particular purpose, only properties related to moisture transportation and buildup have been investigated. The most important properties are found to be:

- **Tightness against precipitation –** This property is especially important during the construction period until the primary roof has been laid. (In Denmark, the underlayment often serves as a temporary roof during the construction period.)
- **Tightness against water –** This property covers standing water as well as water running on the surface. When well constructed, no ponding should occur on the underlayment, i.e., it should have a well-defined slope.
- **No tent effect –** It has been found that in several cases, water penetration occurs for underlayments laid directly on wood or insulation. In Denmark, this is called "tent effect," with reference to the well-known fact that touching the inside of a tent during rain may cause penetration of water. For roof underlayments, no tent effect should occur, as it would impair the watertightness.
- **Water-vapor permeability –** For unventilated constructions, it is evident that moisture from the interior of the building can only escape through the underlayment by diffusion. Consequently, the material must be very permeable to diffusion of water vapor.
- **Moisture-accumulating properties –** These can be supplementary assets if all other requirements of the roof are fulfilled. These allow the takeup and accumulation of moisture during periods of high exposure. The moisture is allowed to be removed during other periods.
- **Dimensional stability against changes in RH –** This is an important property, but it is not considered a problem with the current materials.

INVESTIGATIONS

Based on the findings of the analysis, it was decided to perform exposure tests in a full-scale, test-house, computer simulation of the moisture conditions in unventilated roofs with a number of laboratory tests. The investigations dealt with the new types of materials, as well as the changed require-

Figure 2 – Mounting of roof elements on the test house.

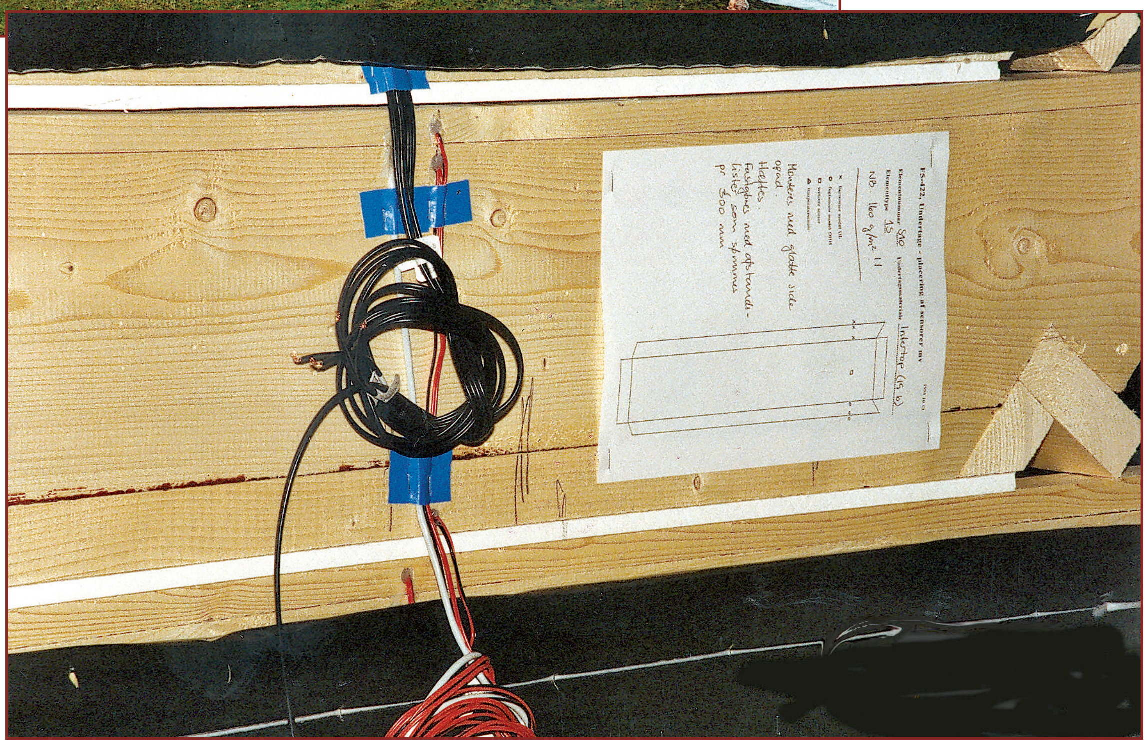


Figure 3 – Moisture sensors are embedded in the wood near the bottom and in the top sides of the element.

ments to the entire roof construction to which this might lead.

FULL-SCALE TEST HOUSE

To investigate the behavior of unventilated roofs, a new roof construction was made on the test house at the Danish Building Research Institute (SBi). The roof has a slope of 40º (1:1.2) and consists of 11 pairs of elements, each pair with an element oriented toward both the north and south.

Each element is 1 m wide and has a height of 240 mm. Ten pairs are unventilated, and the last one – acting as a reference – is ventilated. The elements are made with two timber members as sides and a gypsum board as interior surface. There is no vapor barrier, but the gypsum board is painted to achieve a desired water vapor permeability. The elements are totally filled with mineral wool as thermal insulation. On the outside, the underlayment is placed directly on top of the insulation material. The underlayment is fastened to the rafters, and a distance batten of 22 mm is attached to the rafters over the underlayment. The roof is finished with battens and roof tiles.

The climate in the test house is controlled in winter to 23˚C (73˚F) and 60 percent RH, a very high humidity level compared to the expected 30 percent RH or less under winter conditions. (See *Figures 2* and *3*.)

Measurements in the test house

The test house was equipped with sensors and datatakers to monitor temperature, humidity, etc., according to the following.

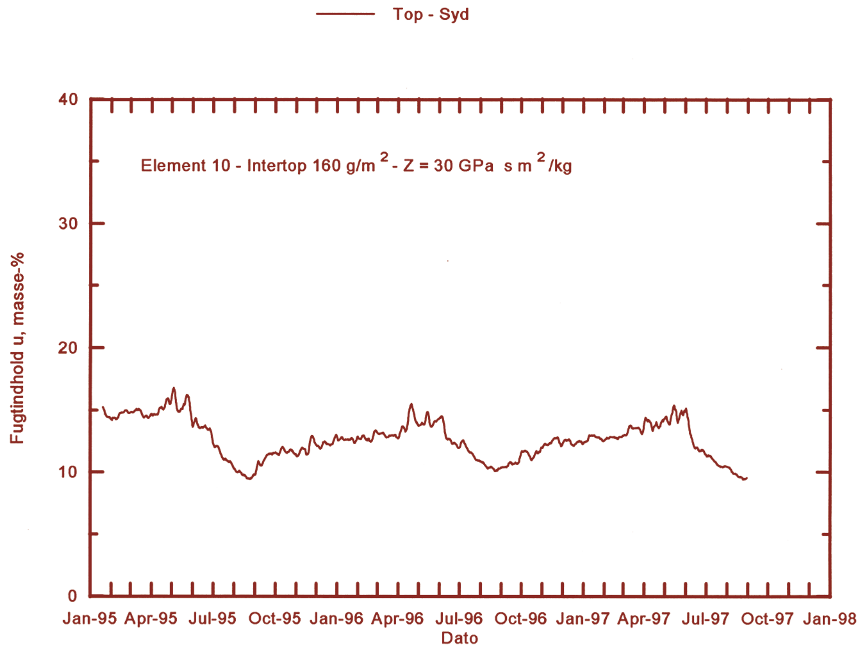
The roof elements are supplied with humidity sensors in the timber members so humidity can be recorded at 1) the bottom (inside), 2) just below the underlayment, and 3) in the counter (or distance) batten. Some of the humidity sensors are supplemented with temperature sensors. A number of the elements are supplied with humidity sensors glued to the underside of the underlayment. These sensors, made by Wetcor, were developed to measure time of wetness and are herein used to measure whether condensation occurs on the inside of the underlayment.

In two pairs of elements, sensors are mounted to monitor the amount of water running on the underlayment in use. Similarly, for two pairs of elements, the temperature on the inside of the tiles is measured with sensors mounted on the surface of the tiles.

Supplementary to the measurements of the roof elements, the temperature inside and outside the house, the relative humidity inside and outside, the number of hours of sunshine, the wind velocity, and the wind direction are monitored.

Results of the exposure in the test house

As expected, the humidity level in the roof construction showed a variation over the year with a rather high level in winter, drying to a lower level during the summer. Even though humidity level in winter is high, it is not assessed to be alarming, considering the use conditions, with 23°C and 60 percent RH in the test house.



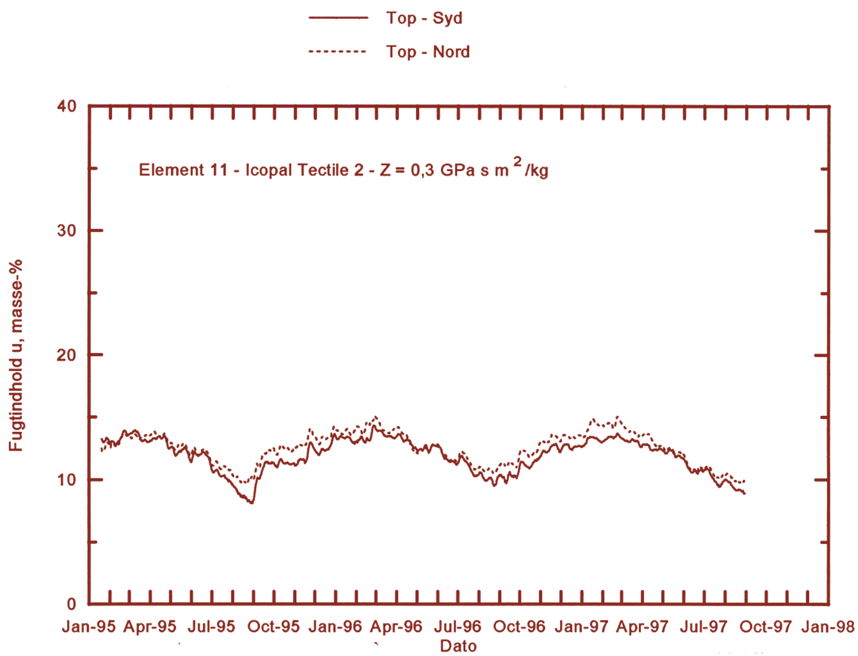


Figure 4 – Moisture in the top of two roof elements as measured with the sensors. Note that the properties for the underlayments are not the same.

Besides, it should be remembered that the construction has no vapor barrier, but only a surface treatment, providing a water vapor resistance of approximately 17 GPa s m^2/kg (1.0 perm) in contrast to at least 25-30 (0.58-0.7 perm) provided by a normal vapor retarder. Finally, it should be noted that the last winter of exposure was very cold.

Only the reference roof was found to be very wet, which is explained by unsatisfactory ventilation, as there is no connection from eave to eave; i.e., the ventilation gaps in the two elements on each side of the house have no connection, and consequently there is very restricted possibility for wind to pass through the construction and remove moist air. (See *Figure 4*.)

Computer simulation of moisture transfer

Planning of the full-scale tests was supported by computer simulation of the moisture transfer in a roof construction by means of the simulation program MATCH. MATCH is a dynamic, one-dimensional model for combined heat and moisture transfer in composite constructions. The model makes it possible to simulate the temperature and moisture conditions on an hourly basis in the individual layers of the construction based on knowledge of the materials, properties of the individual layers, and the boundary conditions to which the construction is subjected. The model takes vapor as well as liquid transfer (but not precipitation) into account. The climatic data used are from "The Danish Test Reference Year."

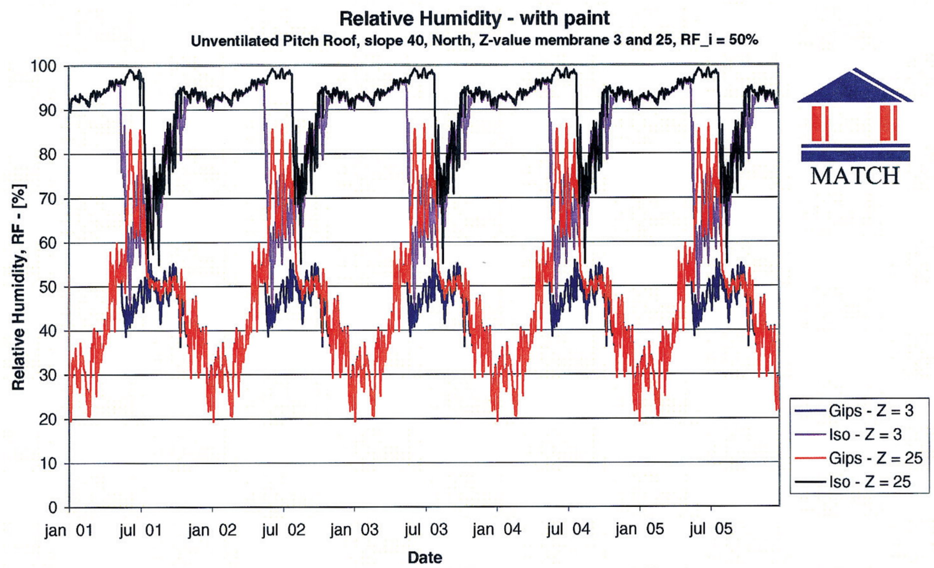
For practical purposes, a vapor retarder installed in a building might be expected to have a Z-value of 30 GPa s m^2/kg (0.58 perm) [Z denotes water resistance, not water vapor resistance as is used in North America. Resistance and permeability are reciprocal.] On the safe side, a value of eight was chosen for the calculations. With this assumption, the simulation showed that, dependent on the roof underlayment material used, condensation might occasionally occur. (See *Figure 5*.)

Laboratory tests

Laboratory tests were made for the most important of the performance properties related to moisture transfer, i.e.:

- Water vapor permeability
- Tightness against precipitation
- Tent effect

The water vapor permeability was tested according to ASTM E-96, wet-cup – i.e., with 100 percent RH in the cup and 50 percent outside. Some 25 materials were tested, including the new type of underlayment materials as well as the previous types. Those new types, available on a commercial



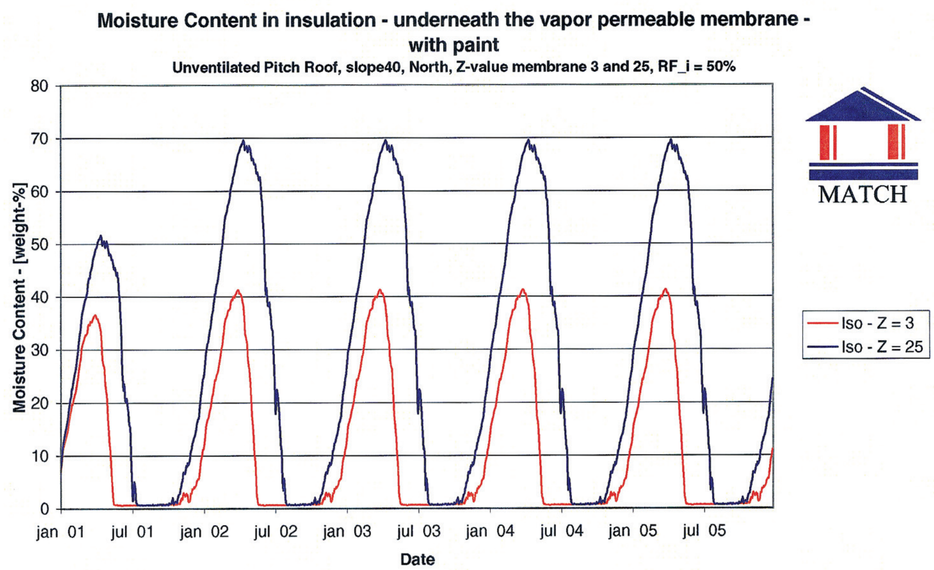


Figure 5 – Relative humidity and moisture content just beneath the vapor-permeable underlayment as calculated with MATCH for a five-year period. Two underlayments with Z values of 3 and 25 GPa s m²/kg, respectively, are compared. The upper figure shows the relative humidity in the insulation (Iso) just beneath the underlayment, as well as in the gypsum board (Gips) on the underside of the element. The lower figure shows that equilibrium is reached for both products, though on different moisture levels.

basis, all had Z values below 3 GPa s m²/kg (5.8 perm), whereas the old type had Z values ranging from 30 to 500 GPa s m²/kg (0.003 - 0.58 perm).

Tightness against precipitation was tested at Velux's (a major European skylight producer) wind tunnel. Two different investigations were carried out.

The first was primarily intended to assess the differences in the amounts of water penetrating through various roof coverings and underlayments. The tests were made on a test roof of 2.6 x 3.6 m. The tests on underlayments were made with slopes of 25° and 45° and wind directions of 0° and 22° (0° is wind perpendicular to the building/eave). For roof coverings, slopes of 25°, 35°, and 45° and wind directions 0°, 22°, and 45° were used.

For this first test round, a test simulating driving rain was used. The water is equivalent to 120 mm per hour and the wind is a dynamic wind profile with gusts up to 20 m/s and 30 m/s for underlayments and roof coverings, respectively.

The results were that considerably more water penetrated when the underlayment was mounted perpendicular instead of parallel to the rafters. For board materials, water penetrated the joints, irrespective of whether these were made with overlapping or with joint profiles. Some of the roof coverings had virtually no water penetrating, with a few drops at the most, whereas considerable amounts penetrated others (i.e., water was running in at some joints). The amount of water penetrating the roof covering depends on slope and wind direction, but the dependence varies from one roof covering to another.

In the second test round, the underlayment mounted perpendicular to the rafters was tested, together with the roof covering, where the highest amount of water penetrated in the first test. The result was that no water penetrated the inside of the underlayment when the roof covering was present. Water penetration of the underlayment is therefore considered to be a problem mainly during the building period.

For the testing of tent effect, no suitable existing methods were found. Instead, a proposal for a test method was made by the SBi. The test method is comprised of accelerated aging followed by a test of watertightness of the product when placed in contact with the substrate. The aging is assessed to simulate roughly six months' exposure to sunlight in Denmark. A flat aluminum "tray" is used to collect any water

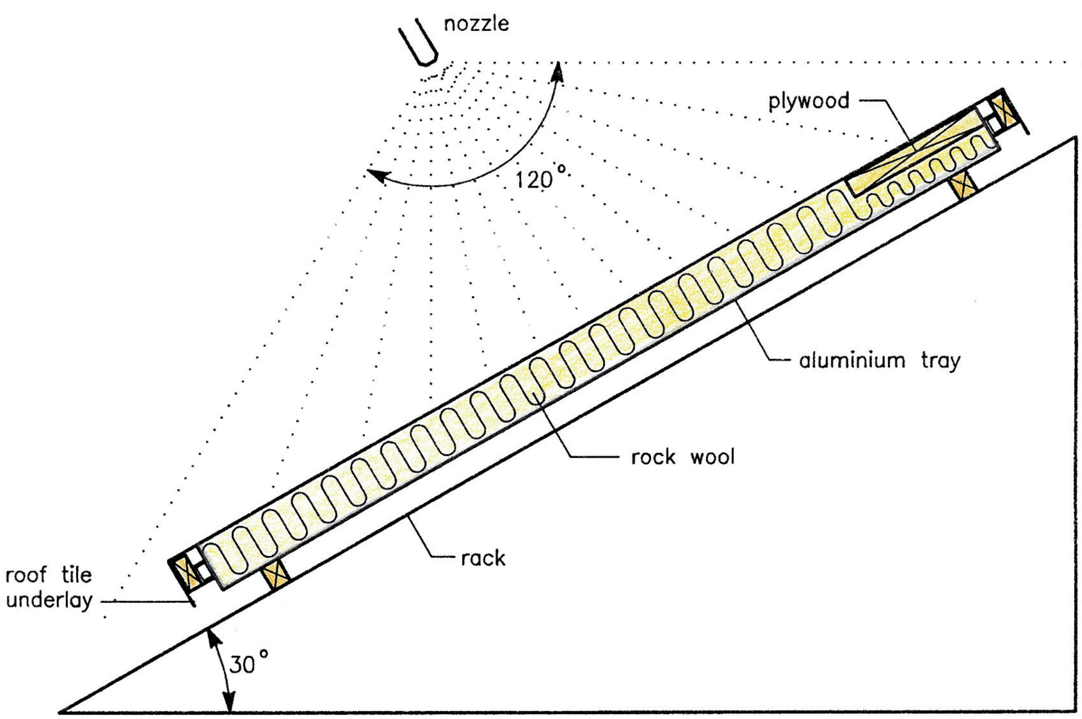


Figure 6 – Testing of tent effect. The underlayment is placed over a substrate, composed partly of plywood and partly of insulation. Any water passing through the underlayment during exposure to water spray from the nozzle is accumulated in the aluminum tray and weighed.

penetrating the underlayment during the water exposure. A batt of mineral wool is placed in the lower end of the tray. In the upper end, a piece of plywood is placed. Both materials are slightly higher than the aluminum tray. The underlayment is mounted on a wooden frame that fits around the aluminum tray. When mounted, the frame is placed around the tray, causing the underlayment to rest around the mineral wool and the plywood, respectively. The underlayment is held in place by the weight of the frame and the underlayment, which is intended to simulate the conditions of a real roof. Water is sprayed from a nozzle over the entire surface of the specimen for six hours. The water pressure in front of the nozzle is very low, simulating a fine to medium rain. The test method has evolved into a Nordtest test method, NT BUILD 488, "Roof Tile Underlays: Watertightness – Tent Effect." (This may be downloaded at **www.nordicinnovation.org.**)

Some of the materials tested using this method showed a considerable penetration of water during the test, which is unsatisfactory, as water will flow on the underlayment in most roofs. (See *Figure 6*.)

In-situ investigations/ experience from practice

A small number of *in-situ* investigations were made in the winter of 1995-96. It was found that some materials suffered from water leakage – probably due to tent effect – resulting in a number of products being withdrawn from the market. The testing of tent effect has subsequently become common for new products. A number of products that failed the test either have not been marketed or have only been marketed after improvements.

Some of the underlayments have been attacked by mold growth, and in a few cases, ice has formed on the inside of a roof underlayment during long-lasting cold periods. This shows that the underlayments sometimes have moisture

Figure 7 – Example of detail around ventilation duct – very poor workmanship!

accumulation on the inside. Visual inspections in a number of identical houses suggest that the problem is especially pronounced where the vapor retarder is not perfect; e.g., where it has been perforated or where there are leaks around openings. Visual inspections in the test house showed that ice had formed on one of the two underlayments. This stresses the importance of an airtight construction. It is especially important to avoid convection, which might transport considerably more water vapor into the roof construction than can be removed by diffusion through the underlayment.

Even though the underlayments are very open to diffusion, it is now considered necessary to have at least some ventilation of open roof spaces to prevent moist air from accumulating in the top of the roof.

Quite a few problems are associated with the detailing and workmanship of roof underlayments. Some suppliers only sold the products but did not give any advice as to their installation. Others described just a few of the most-used/easy details. Consequently, the detailing was often designed by the contractor on the building site, resulting in mediocre quality. Over the years, a number of leaflets have been published showing the principles of the most-used details. Lately, a rather large number of details have been issued by the Danish Timber Information Council (TOP). These may be downloaded from **www.top.dk**. TOP is currently finishing a booklet about underlayments with wooden materials, e.g., boards, plywood, and fiberboards (with or without a supplementary, watertight membrane) that will also have a number of details.

Poor workmanship often results in problems, mainly because the work is not done as prescribed or repairs are done incorrectly or not at all. A common and easy-to-detect example occurs when the underlayment has not been mounted sufficiently tight. It might flap, thereby creating considerable noise, and eventually, puncture of the underlayment where it touches the tile clips. Otherwise, the main problem is that details are not made watertight because the correct procedure is time consuming. Some of these problems might not only be difficult to see in the finished roof (especially if covered by a ceiling afterwards), but also very expensive to repair. This calls for more responsibility by the craftsman and/or more rigorous supervision. (See *Figure 7*.)

ROOF UNDERLAYMENT CLASSIFICATION SYSTEM - DUKO

For some years, a private organization collected information on available documentation from all the suppliers of roof underlayments. A couple of years ago, this task was handed over to a new organization called DUKO (Danish Roof Underlayment Classification Scheme). The organization is owned by a number of interested parties, including contractor representatives and building owners.

The organization's main purpose is to make a voluntary classification of products with documentation for the most important properties, including strength, watertightness, potential for water vapor diffusion, tent effect, and durability. Based on physical properties, the underlayments are classified into a number of exposure classes. The suppliers have to provide the documentation in the form of test reports, including proof of constructability; i.e., they must show how to make details such as eaves, chimneys, skylights, etc.

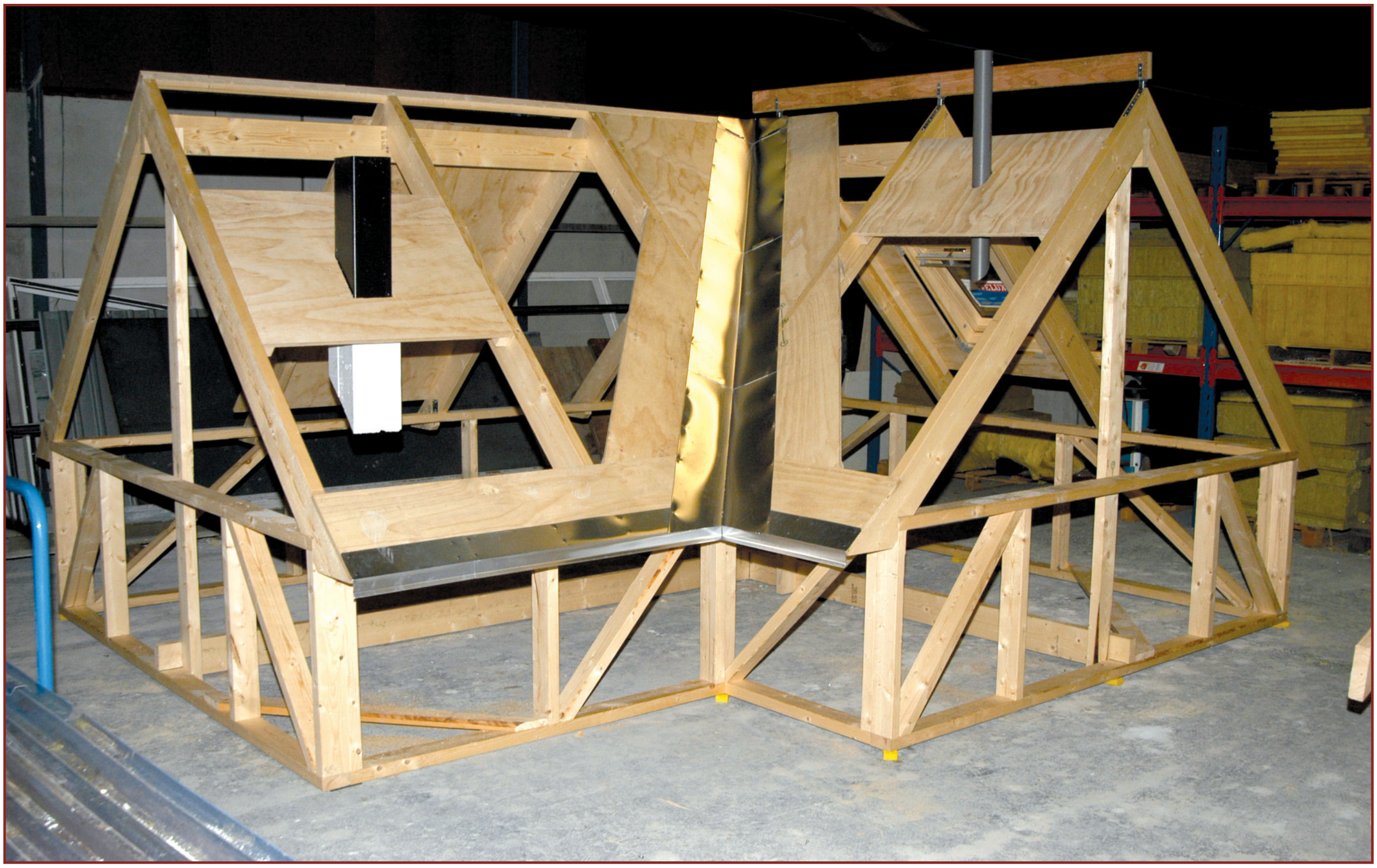


Figure 8 – Mock-up to be used for the suppliers' proof of constructability.

Proof of constructability is achieved by companies mounting their roof underlayment mock-ups, including all imaginable details. The basic idea of the classification system is that the underlayment is chosen dependent on the watertightness of the roof covering when subjected to driving rain, slope of the roof, complexity of the roof design, serviceability of the underlayment after installation, and exposure to wind. For example, some roof coverings are exposed to UV light as well as to rain and consequently require a very durable underlayment.

Products appearing on the classification list from DUKO can be considered to have sufficient documentation for their properties, including constructability. Further information may be downloaded from **www.duko.dk**. (See *Figure 8*.)

DISCUSSION AND CONCLUSION

Roof tile underlayments have been used for 50-plus years in Denmark. As a whole, they have functioned properly. Roof-tile underlayments are a prerequisite for the use of attics over occupied spaces – i.e., with at least part of the ceiling and the roof parallel (because earlier tightening of the tiles with mortar, bitumen, etc., is not durable and cannot be maintained).

The ventilated underlayments have functioned properly for a long period of time (after some early problems with durability of the products), provided common knowledge about the construction/ventilation is used.

In regard to unventilated underlayments, costly errors have shown the need to fulfill certain requirements if a well-performing roof is to be achieved. These include most of the following:

- The underlayment shall remain tight when subjected to precipitation, including driving rain. The underlayment shall pass a Nordtest Build 118 test (or similar) without experiencing water penetration.
- The underlayment must have no tent effect. Only a very small amount of water is allowed to pass the artificially aged underlayment (in Denmark, the requirement is less than 15 g) when tested according to Nordtest Build 488.
- The water-vapor permeability of the underlayment shall be low. In Denmark, the requirement is that the Z-value shall be less than 3 GPa s m^2/kg.
- The inside of the roof construction shall be sufficiently tight to avoid diffusion and convection. The tightness shall be seen in relation to the permeability of the underlayment. The Z-value of the inside of the construction should be greater than 30 GPa s m^2/kg. Normally, this is achieved by using a vapor retarder that, when well mounted with overlapping, taped joints and no perforations, will fulfill the requirements for both permeability and air tightness.
- Documentation that all imaginable details that can be made securely shall exist.

Further, the instructions from the supplier should be taken into account, especially related to how long the underlayments can be used as a temporary roof directly exposed to UV light and precipitation. In this connection, it should be noted that some roofing tiles on the Danish market will allow a penetration of as much as five percent of the surrounding UV light. Finally, the workmanship is crucial to the overall performance of the roof construction. Only when properly mounted may an underlayment be expected to fulfill its duty for many years.

Provided that the above are fulfilled, it is assessed that unventilated roof underlayments are able to function in a temperate climate such as Denmark's.

Editor's Note: This article is reprinted from the Proceedings of the RCI 22nd International Convention and Trade Show, March 1-6, 2007, Orlando, Florida.

FOOTNOTES

1. *Working With the Performance Approach in Building*, CIB Report, Publication 64 (International Council for Research and Innovation in Building and Construction, Rotterdam, 1982).

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Erik Brandt

Erik Brandt is a senior researcher at the Danish Building Research Institute. He has worked for many years with building-technology problems in general and problems dealing with moisture, service life, building surveys, roofs, and floors. Erik is a member of a number of national, as well as international working groups, standardization committees, etc. He is the author of a large number of scientific papers and publications about building technological problems.

Tommy Bunch-Nielsen

Tommy Bunch-Nielsen earned a master's degree in structural engineering in 1974 and has worked as a consulting engineer for more than 30 years. He has specialized in building physics and is director of the consulting company BMT A/S and the contracting company Micro Clean A/S. The firm works with chemical-free mold removal from buildings. He is also the chairman of the Danish Roofing Advisory Board.

IRS Grants RCI Group Exemption for Chapters

RCI has received a letter of notification from the IRS confirming RCI's group exemption for U.S.-affiliated chapters. Each affected chapter was provided a copy of the letter and a list of those affiliated chapters included in the group exemption as submitted by RCI.

Chapters not shown on the submitted list that want to be included in the group exemption should contact Catherine Moon by phone at 800-828-1902 or e-mail at cmoon@rci-online.org to discuss the matter.