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RESEARCH ARTICLE

Building construction problems for „covered roofs"

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Abstract

"Covered roof" is a new motif in contemporary building endeavors. The use of materials used thus far only to cover facades (stone, brick, concrete, wood, etc.) has brought about new problems on roofs, and necessitated development of new layer sequences. In accordance with a free design of buildings, optional pitches and shapes may be used on covered roofs. Conventional rules for roofing do not apply here. This paper will define concept of covered roofs, analyze possible layer sequences, and set out key designing principles. A multi-level drainage of rainwater, protection of slant layers against slide-off, handling of thermal expansion, and customized structural details are problems for which no sufficient literature and standards are available as yet.

Keywords

contemporary architecture · covered roofs · multi-level water drainage · slide-off · insulation.

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1 Covered roofs: a new architectural motif and sphere of building structure issues

In the architecture of nowadays, designers frequently intend to cover roofs with materials that have been long used with facades, but not as a roof covering so far. This is related to an aesthetic endeavor aiming at achieving a strong character in a building's mass formation. To ensure a solid, block-like appearance of a building, facade and roof are made in the same material. Roof pitch is selected and the gutter section between facade and roof shall be designed in such a way that a sharp borderline between the two is blurred, for a uniform appearance. Structures of this kind are referred to by a summary name "covered roofs".

"Roof is the fifth facade of a house", this is not a recent idea. However, this saying by Le Corbusier, the famous French architect is a bit out of place, as the tried and tested technical solutions of a facade cover cannot be transferred unaltered to a roof, since a roof has to withstand stresses more numerous and various than a facade. In times past, roof covering was not seen as impermeable to water, but underneath there was an open attic, ventilated, thus rainwater that got through, quickly evaporated. Today, under almost every roof there is a residential area, so the penetration of water is to be fully prevented, and further strict requirements shall be met.

Though many buildings of this type have been recently published in architecture journals, the related technical problems – as far as we know - have not been dealt with yet in publication. It is likely due to the fact that such new layer sequences and details had to be elaborated that have not been tested in sufficient number. So these buildings are to be considered as experimental, and the design task is more of an innovation than of a routine work. This paper is devoted to the analysis of principles of building structure solutions for covered roofs. Impacts on structures and special requirements for structures will be described. The major layer sequence versions will be studied, and proposals for aspect to be considered in designing will be made. Our paper may be useful for architectural and building structure designers, but it also contains important information for structural engineering designers. An understanding of functioning of covered roofs will also be instructive for practical problems of conventional structures. The important issue of detail designs for covered roofs is intended to be discussed in another paper.

2 A current issue: examples of buildings with covered roofs

It was not until a few years ago that covered roofs came out in significant number. DBZ and Detail German journals of the trade, in its 2006 volume, presents it only now and then, whereas most of the buildings presented in 2008 were of this type. The popularity of this motif is also evident by the fact that in the period 2006-2008, most of the designs marked excellent, awarded with a special prize at the Faculty of Architecture at the Technical University of Budapest were drawn up with such structures. The following examples, as seen worldwide, demonstrate a widespread use of covered roofs, and a diversity of materials and shapes (Fig. 1).

At first sight, the above photos show very different buildings:

The mass of the large-span space-coverage building is arched, covered with custom-bent aluminum sheet stripes. Roof and facade have the same structure. Even a flushed, concealed drainage of stormwater does not disrupt its uniform design. At the top, where pitch of covering is horizontal, water-proofing is not feasible unless with a complicated welding.

It is not common today to see high-pitched roofs covered with wooden covering. With a facade in the same material and the simplest possible mass, it no doubt makes a modern and forceful impression (by the way, the building accomodates an architect office).

Building shape is often created by truncating a simple geometric solid. The lines of extensions of covers made from metallic sheet or other materials are shaped in such a way that they are continuous across various planes, thus the borderline between a roof and a facade is eliminated.

Roof is also covered with facade ceramic sheets, while along the gutter, a hidden gutter is used.

Raw exposed concrete is a popular material in modern architecture. It may appear on a roof in a simple angular shape, with a rough surface, bearing traces of formwrok. Also, it is fit for designing arched surfaces where soft forms and smooth surfaces prevail. In both cases the facade and the roof are made of the same material.

Bricks and paving blocks have only been used on terraces so far, and in the case of a roof covering, it must also be ensured that layers do not slide off the slant surface.

Using large-board covers (fiber cement slabs, rusted steel-sheets, hardened glass panes) a wholly crystal-like mass effect can be attained. The prominent role of horizontal and vertical directions seems to come to an end.

Softer, organic forms may be made from concrete or plastic. In such cases, roof pitch is different at every point.

The examples shown give a narrow cross-section of the scope of covered roofs, it being clear that architects, as opposed to conventional roof designs, strive for free shaping and material use. The number of variations is almost endless. The most likely reason for the spreading of covered roofs is an artistic striving in architecture, just like in any art, for an expression of a personal message and an ongoing renewal. That is why architecture constantly stretches the limits of technical feasibilities as well, giving ever newer tasks to constructors. Moreover, a fast improvement of building materials inspires designers to make use of new opportunities. A typical example of this strange interaction is represented by covered roofs.

3 Definition of covered roofs in terms of building structures

The essence of covered roofs can be grasped in comparison thereof to conventional structures. Diverse forms of roofing are known, tried and tested for centuries which are different depending on pitch, and classifiable in three categories in regard to their principle of design and capacity.

For high-pitched roofs (25° to 90°) small-element covering (e.g.: tiles), or large-board (e.g.: corrugated slate) is used where elements are overlapped in the direction of water flow. Its extent is determined by a "water threshold", typical of a given geographical location and climate, a vertical projection of the size of overlapping, required to prevent rainwater from getting under a cover even in response to wind. This method of covering is called "watertight", meaning that only a small amount of rainwater gets through the cover which can evaporate in a gap behind the cover, without causing any damage.

For low-pitched (5° to 25°) roofs, most often folded metal-sheet covering (zinc plate, aluminum, etc.) is applied. Here, covering is made from long stripes, and stripes located side by side are folded together along their edges. Covers thus made are considered as "featuring enhanced watertight".

For flat roofs (0° to 5°), "impermeable" insulation is needed, where not even the slightest moisture may get under the cover. This is attained by means of bituminous sheets or plastic foils whose extensions are made watertight by welding.

It can be seen that with conventional roofs, pitch is vital from the aspect of material to be used and thus the building's appearance. Contrary to this, for covered roofs, the material of covers may be diverse, in addition to heavy materials (concrete, stone, artificial stone, brick, ceramic), lighter and thinner materials (wooden and metallic sheets, various sorts of plastics, artificial construction sheets, glass) may occur, materials seen so far on facades and terrace roofs only. Selecting of materials does not depend on pitch, but architectural view is crucial. Moreover, a typical feature of covered roofs is the fact that the most diverse pitches vary while the surface remains the same. Furthermore, in order to ensure that the facade and the roof can have an identical apperance, such materials also appear on the roof, which are, due both to their materials and their extensions, unfit for roof covering. A connection of units conforming to the requirement of protection against stormwater (overlapping, folding or welding together of units) is not feasible either because the de-

Fig. 1. Examples of buildings with covered roofs: variations of materials and shapes

signer submits the roof's view to his architectural concept even in these details.

Stormwater protection for covered roofs is therefore always provided by a foil insulation of full value, irrespective of pitch. Above that, covering appears as an architectural link, in terms of which the categories of "watertight", "enhanced watertight", "impermeable" lose their meaning. A part of stormwater thus gets under a cover layer; and flows down on the waterproofing. The ratio of water flowing on the surface and underneath it depends on the covering material and the gap sealing between elements. This problem of covered roofs is called "multi-level water drainage". A proper handling of this issue is a most important condition for the functioning of covered roofs.

As a summary of the foregoing, the concept is defined as follows: a building falling under at least two of the following categories is called a building with a covered roof:

- It is not covered with conventional roofing materials but with ones used on facades or terraces, with the material of the facade and the roof being most often the same,
- There is no close connection between pitches and the material of a cover, with any roof pitch between 0°-90° even being variable in the same building in the form of either lines of break or arched transitions,
- For the covering, conventional design rules relevant to covers do not apply; instead of overlapping, extensions with blunt shock, sealed or open gap formations are typical,

- Stormwater typically flows not only on the outer plane, but also on lower levels of layer sequence in major quantities, therefore a waterproof underlay insulation and "multi-level water drainage" must be designed.

4 Layer sequence versions for covered roofs

Layer sequences which could be encountered in specific building designs and which we consider as good solutions for each material will be shown hereinafter. We emphasize that these examples do not include every possible variants and the series could be very long to continue. Such solutions allow us to formulate basic principles of design of covered roofs but are not suitable for being used for a specific building without being checked and altered because in reality there are so many aspects to take into consideration at the same time that an optimum solution can always be determined only in knowledge of the specific building and of its complexity. In the analysis of sequence of layers it is assumed that the reader is familiar with basic building structural terms and solutions. Here they cannot be discussed in detail due to insufficient place.

4.1 Low pitched roof with glued stone cover (Fig. 2)

Analysis of layer sequence:

This layer sequence is similar to that of terrace roofs but there are also significant differences. Stone cover cannot be glued unless it has a properly rigid base beneath it. To this end, the upper monolithic reinforced concrete slab is used which relies upon the underlying layers on the whole surface (tightening them), and stainless steel spacer/fixing pipe elements are used to couple it to the ceiling for protection against slide-off. They must be rated for shearing and bending stresses, and in this example they are preliminary concreted into the bottom slab. The pipe fitting is justified by the fact that it is the easiest way to collar waterproofing onto it in a watertight manner. Due to the heavy weight of cover, ceiling is reinforced by ribs at the bottom. Gluing of stone cover must also be rated for shearing depending on roof gradient, therefore, contrary to terraces, only synthetic based glues may be used instead of cement mortar.

Stormwater flows mainly on surfaces but in the case of a defect of gaps and if the material gets wet a part of water can get beneath the cover. So, it is necessary to apply the lower safety waterproofing and a drain layer overlying the thermal insulation. This setup of waterproofing and thermal insulation is referred to as an inverse layer sequence and only extruded polystyrol foam may be used for them for which the water absorption is practically zero. A problem of layer sequence is that water getting beneath the cover may cause the gluing to freeze out because - due to resistance of the upper reinforced concrete crust - it is hard for the water to get down to the drain sheet. Also, it is a delicate issue to allow for thermal motion, the movement gaps must be aligned as concerns the upper reinforced concrete slab and the stone cover, therefore, it needs a careful preliminary architectural designing. Care must be taken as well that water flowing on the surface can accelerate to a great extent, and the snow and ice accumulated on the roof may slide off. Also, ensure that stormwater getting onto the insulation should also be collected and drained. These problems will have to be observed when designing the details of eaves.

4.2 Roof with a monolithic exposed concrete cover (Fig. 3)

Analysis of layer sequence:

In this case a normal layer sequence is shown the condition for which is an appropriate lower vapourtight insulation. The vapourtight layer must be glued with the entire surface onto the inclined ceiling against slide-off, and it is sufficient to glue the thermal insulation overlying it in spots only. Thermal insulation must be so hard that waterproofing can be made onto it. This is called walk-resistance requirement. The soft foil waterproofing must be fixed to ceiling using disc type metal wall plugs in order to avoid slide-off and wrinklings, which can be solved free of wetting, covered by overlaps of the foil. Fix the drain slab temporarily only because the reinforced concrete to be applied onto it will keep it in place later. The filter veil lining is necessary in order to prevent cement liquid from getting into the drain layer during concrete placement.

There are two conditions of major importance for the application of an exposed concrete which are as follows: an in-situ concrete with a perfect surface and frost-resistant quality which only can be achieved with a carefully selected material composition and a perfect implementation and an expansion gap system dimensioned for expected thermal motions and properly designed. For concrete placement use concrete featuring less plastic consistency, and compact and post-cure it carefully.

It must be reckoned with the fact that an adherence to the foreseen geometry can only be provided - for higher gradients - by using two-sided formwork. After the concrete has set, a hydrophobization coating will be applied onto the surface, for the sake of safety. The upper reinforced concrete crust is fixed by corrosion resistant steel pipe brackets against slide-off, as with the previous example, but here they are not concreted but are fixed through a preliminary welded base plate to the inclined ceiling. Due to thermal expansion, it is recommended to ensure that the size of fields concreted monolithically should not exceed 10 to 15 m^2. After the formwork between fields has been removed, gaps will remain open so thermal motion of each field can take place smoothly. It is of importance that gaps should not be blocked by contamination washed in from the surface even on the long run, therefore, it is recommended to equip each gap with a covering profile piece to be snapped in from above.

In this example, stormwater flows not primarily on the external surface but it is led onto the surface of insulation through especially designed holes and grid where drain slab allows it to flow away quickly. It has the sense to ensure that water should stay as shortly as possible on the exposed concrete surface. This

Layer seqence in the example:

- 3 cm frost-resistant stone tile cover, glued
- 8 cm reinforced concrete slab, fixed with steel brackets for protection against slide-off, with expansion gaps at every 6 m^2
- 2 cm drain slab, with filter veil lining
- 16 cm extruded polystyrol foam as thermal insulation
- 1.5 mm soft P.V.C waterproofing (with protective layer)
- Industrial felt layer for base compensation
- 14 cm inclined reinforced concrete ceiling (with bottom ribs)

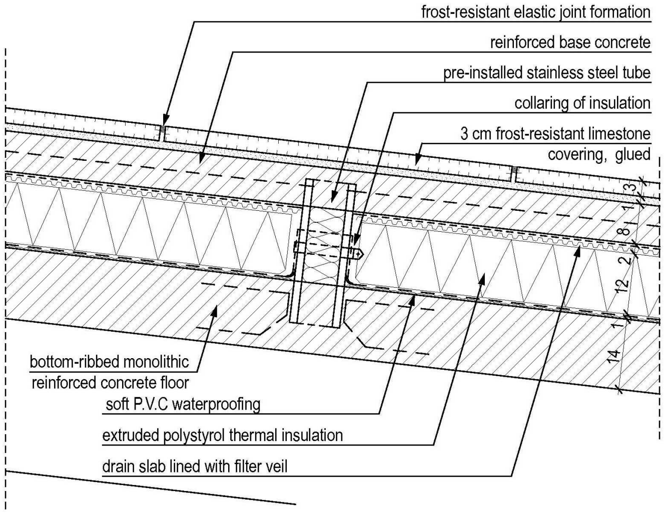

Fig. 2. Low pitched roof with glued stone cover

Layer seqence in the example:

- Colourless impregnation on surface
- 10 cm frost-resistant exposed reinforced concrete slab, fixed with steel brackets against slide-off, with covered gaps
- 2 cm drain slab with filter veil lining
- 1.5 mm soft P.V.C waterproofing with glass fabric insert, including mechanical fixation
- Industrial felt layer for base compensation
- Thermal insulation made from walk-resistant expanded polystyrol foam
- Bituminous sheet as vapourtight insulation
- 20 cm inclined reinforced concrete ceiling (in broken line)

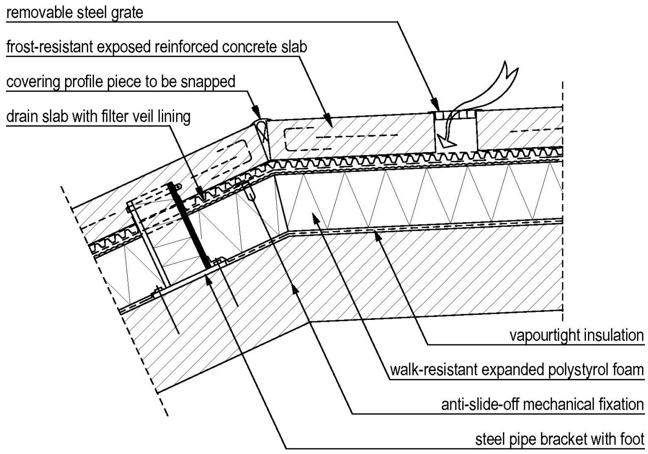

Fig. 3. Roof with a monolithic exposed concrete surface, with variable pitch

is also a kind of protection against frost. So, drainage can be implemented using hidden internal gullies at the level of insulation, at deep points of roof piece. The exposed concrete surface, structurally, acts as a protective layer only. In order to prevent drain slab from blocking, water inlets must be equipped with a removable filter and cleaning grids.

As shown in the figure, roofs featuring a broken line shape with variable pitch are also possible but this usually implies a significant increase in the required thickness of ceiling. It may be necessary when the building has a roof featuring a complicated organic shaped roof. For implementation related reasons it is recommended to divide, in such case, it into triangular plain plates determining the shape more precisely. Triangles must be fixed by means of the pipe brackets near their centre of weight, which form a fixed point in regard to thermal motion. The greatest deformation will take place along the edges of fields. Each field may have a different size and pitch but care must be taken to ensure that each plain should have a minimum (2 to 3 %) slope and that horizontal saddles cannot occur. Otherwise, the hazard of moss and frost will be increased. The maximum field size is jointly determined, in addition to architectural concepts, also by the possibilities of in-situ concrete placement, stresses caused by thermal motion, and the size of expansion gap between elements.

4.3 Roofs covered with precast exposed concrete crustal element (Fig. 4)

4.3.1 Analysis of layer sequence:

Precasting of an exposed concrete cover will allow us to ensure a higher quality and better resistance to frost than by applying in situ concreting. For precasting, prestressed steel reinforcement can also be made, thereby achieving production of elements with higher load bearing capacity with a reduced thickness. Prestressing allows to reduce deformation caused by thermal expansion as well as the gap size, which allows to produce larger components (even 15 to 20 m^2). Precast pieces can be coloured in their material or their surface can be made more interesting by using a kind of additive (for instance, granite grains, washed pearl pebbles). In the example, crustal boards rely upon brackets installed at the corners of the elements in order to be protected against slide-off, which are fixed to the attic wall. This

Layer seqence in the example:

- 10 cm precast reinforced concrete crustal element with washed gravel surface, fixed laterally with steel bracket in order to prevent slide-off
- 2 cm drain slab with filter veil lining
- 14 cm extruded polystyrol foam thermal insulation
- Bituminous sheet waterproofing
- Synthetic resin mortar smoothing for surface compensation
- Inclined reinforced concrete ceiling ribbed at the bottom

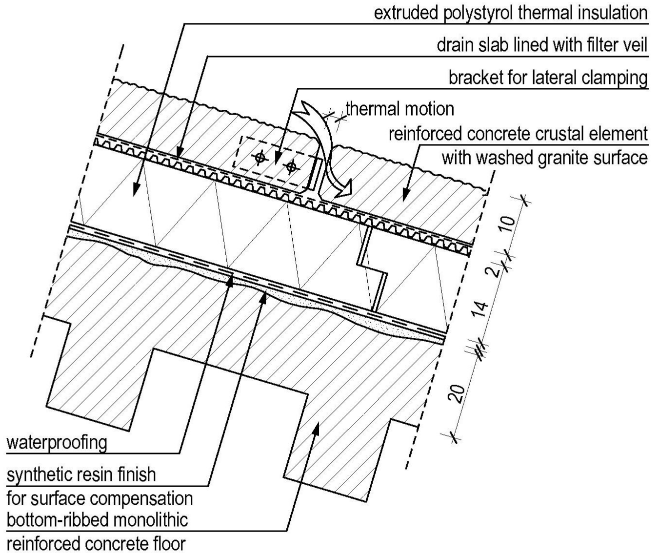

Fig. 4. Layer sequence for roofs covered by exposed concrete crustal element with granite grains

method is recommended for use in the case of not too wide and simple shaped buildings only. Large boards, however, require an even seating and a completely flat base which can hardly be achieved with an inclined reinforced concrete ceiling. So it is necessary to apply a synthetic resin bonded compensation mortar smoothing on the upper plain of the raw ceiling.

Roof has an inverse layer sequence here also. Each board seats onto an embossed sheet slab drain layer equipped with a filter veil which must be checked for load bearing capacity. The boards will load the roof layers, otherwise an inverse layer sequence cannot be designed.

The gaps between covering elements must be designed to have such a width that an expansion corresponding to larger elements can take place. This has a strong influence on the appearance of roof, therefore, the outline of the gap must be designed carefully. Gaps between boards must be furnished with durably flexible and UV resistant sealing. The elongation capacity of up-to-date seals can attain even 100 to 200%. However, the lifetime of seals is limited, therefore, they need to be renewed at every 5 to 10 years. Should any expensive sealing be selected, you cannot expect that it should ensure impermeability of the roof. If water gets in through the gaps, it will flow in a concealed way in the drain, then it can be drained through hidden drains at the bottom part of the roof. Therefore, this kind of a layer sequence cannot be designed with a gradient of 0 degree (roof with no pitch).

4.4 Mount type artificial stone cover, for a high pitched roof with core thermal insulation layer of sequences (Fig. 5)

Analysis of layer sequence:

For a high gradient ($>45^o$), the size of horizontal projections of roof, and the specific amount of stormwater are smaller, it flows down more quickly, thereby it exerts a smaller pressure on the waterproofing. This allows that waterproofing against stormwater can be a speared coat insulation which has lower capability but is less expensive. This solution is also preferred because the fittings of mount fixation of covers (which have been developed for use with the frontage) could not be installed on foil insulation because they would pierce it at too many points. However, for the spread insulation the shanks of stainless steel stud bolts fixing the fittings can be sealed in an easy way. An advantage of mount cover is that it is easier to correct minor geometric defects of the base by means of the fittings. The inclined covering pieces will also be subjected to a bedding stress resulting from the dead weight and maintenance loads perpendicular to their own plains between the supporting points, for which their thickness must be rated. This requirement supports prefab artificial stone elements - for which the load bearing capacity can be rather designed, instead of stone covers (for which the material properties are less reliable). The coating insulation requires a high quality concrete base.

The core thermal insulation sequence of layers consists of an internal load bearing reinforced concrete slab, extruded polystyrol hard foam thermal insulation and external reinforced concrete layer between which there is no gap. Between the inner and outer reinforced concrete layers, the static engineering connection is provided by a special spacer made from the mix of glass fibre and synthetic resin. This structure can be implemented by using patented Thermomass®system in Hungary. The upper crust is exposed to temperature changes, therefore, for a surface exceeding 10 m^2 expansion gaps must be designed. The upper slab is suitable for receiving the spread insulation but at the expansion gaps flexible insert zones must be embedded into the insulation which are made from mesh reinforced rubber. The spread insulation must be protected against damages which is ensured by artificial stone cover.

The air gap beneath the cover is needed for the adjustment of fixing appliances, and allows, at the same time, leakage water to

Layer seqence in the example:

- 4 to 5 cm frost-resistant artificial stone cover fixed with stainless steel brackets
- 3 cm air gap
- Cement based elastic coating insulation
- 10 cm upper reinforced concrete slab
- 16 cm extruded polystyrol foam as thermal insulation
- 20 cm inclined reinforced concrete ceiling

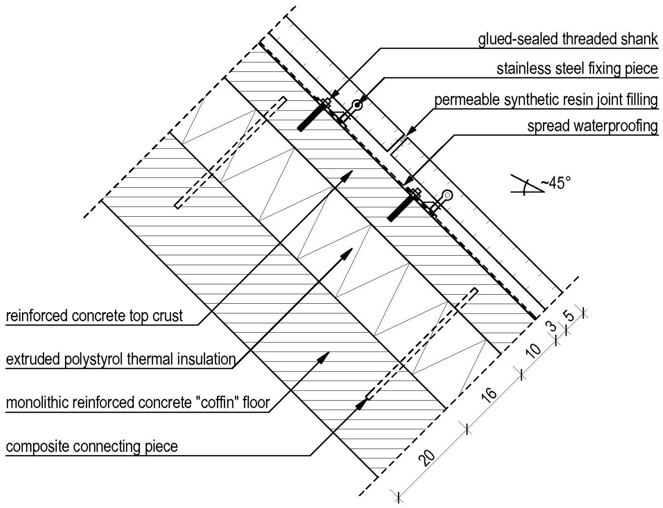

Fig. 5. Mount artificial stone cover, core thermal insulation layer of sequence type coating insulation

be drained. Gaps of the cover must be filled because the ingress of contamination must be prevented but thermal expansion must not be impeded. There are kinds of synthetic resin which - when mixed sandsilt - provide an elastic but water and vapour permeable gap filler agent. By using it, a part of stormwater will get onto the insulation but the great amount of stormwater will flow down quickly on surface which is advantageous from the aspect of self-cleaning of the cover. On the other hand, the system will remain "breathing" which means that vapour will not be confined in the air gap but the structure can be dried up.

For the core thermal insulation structure, the outer crust is generally not a load bearing one because, for smaller buildings, it is simpler to implement. The composite working of inner and outer crusts is also possible which allows to produce a structure having an higher load bearing capacity which may be necessary for high span buildings, and large building cantilevers. The composite working of inner and outer crusts may also be advantageous when you want to reduce thermal motion of outer crust by it (for instance, you want to increase spacing between expansion gaps). However, the connecting reinforcing steel ensuring the composite working of inner and outer crusts has to be custom-designed and its implementation is more complicated and the steel elements cause a much greater thermal bridge than the glass fibre / synthetic connecting pieces.

4.5 Small element (brick, concrete outdoor stone paving) paved roof (Fig. 6)

Analysis of layer sequence:

For small element covers, gluing is not a proper solution because - due to the small size of elements - a great number of gaps must be reckoned with for which a watertight sealing is very expensive. On the other hand, if the gap lets water get in, then there is a risk that the glue will freeze out. Instead, it is worth designing a dry base which acts, in addition to a bed for the cover, also as a drain layer. The best material for this purpose is crushed basalt because due to its sharp grains it ensures a collapse-free bedding. This layer sequence is a standard solution for terrace roofs with the difference that in our case that cover must be supported for protection against slide-off. Through steel profile pieces and perforated sheet relying on spot-like brackets, the surface has to be divided into something like cassettes. This solution can be properly implemented up to about 30^o but for higher values the crushed stone will remain in its place during construction work. Over about 60^o it can be used again, here - as with frontages with rear fill - the granular material must be filled behind it at the same time with walling the cover.

It is recommended to use such layer sequence including cassette type supporting for the inclined green roofs which are more and more widespread. It is an important condition that waterproofing should withstand piercing stresses caused by the bedding/drain layer having sharp grains, and for a green roof it should be qualified for root withstand and resistance to microorganisms.

4.6 Large board fibre cement cover on ribbed frame with ventilated air gap (Fig. 7)

Analysis of layer sequence:

The layer sequence presented is a qualified, commercially available system but you can act in the same way for wooden or thick (>5 mm) steel sheet boarded and preserved by heat treatment and possibly hardened glass covers as well. The large board size (2 to 3 m^2) allows for a large scale gap drawing liked by architects but the rib spacing has to be more dense otherwise due to a bending stress perpendicular to the plain of cover an irrealistically large cover thickness would have to be applied. For light covers, the design stress will be the suction impact imposed by wind for which the fixation of elements (break-off of bolts) must also be rated. On the other hand, fixations must not impede thermal motion which is solved for instance by rubber-containing underlays.

For the large board size, wide gaps (about 10 mm) are required because in such a way the slight inaccuracy of elements

A layer seqence in the example:

- Frost-resistant small element cover with sandsilt gap filling, supported using stainless steel profile pieces against slide-off
- 8 cm crushed basalt bedding
- Soft P.V.C. waterproofing with mechanical fixation using disc type metal wall plug
- 16 cm walk-resistant polystyrol foam as thermal insulation
- Vapourtight insulation
- Inclined reinforced concrete ceiling

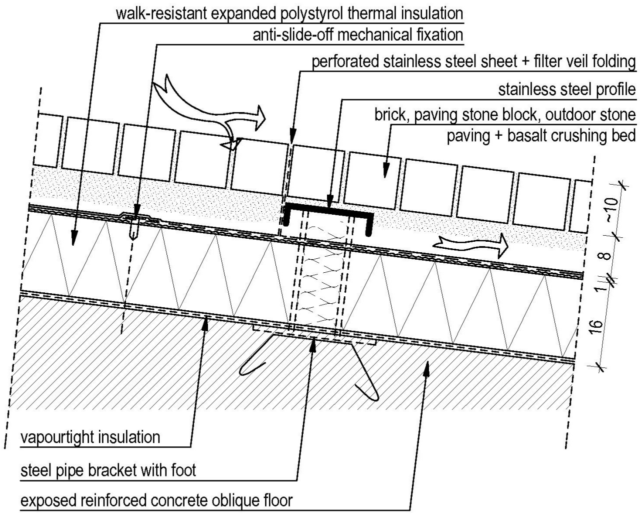

Fig. 6. Brick cover on dry bed

A layer seqence for the example:

- Large board cover with open gaps, fixation to the ribs using self-tapping screws
- Bidirectional metal rib frame, with ventilated air gap inbetween
- Slope oriented wooden rib frame rafter with passing the insulation through
- Thermal insulation and waterproofing for ceiling

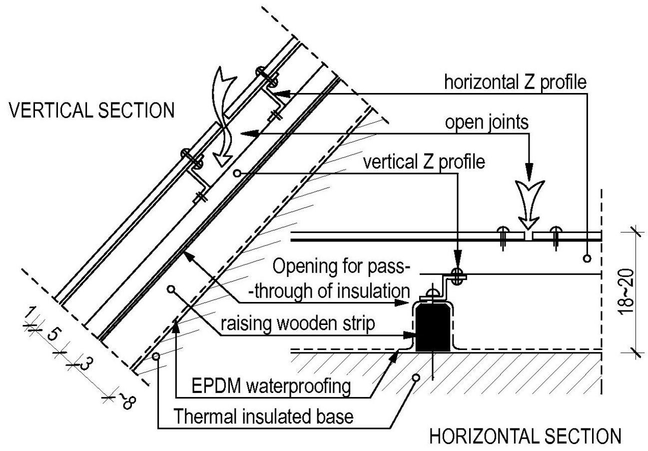

Fig. 7. Large board cover on ribbed frame with air gap above impermeable

would be less visible. Gaps must be left open due to thermal expansion and in order to allow the system to dry up as well, therefore the total amount of stormwater will get beneath the cover. In accordance with the current guideline in Hungary, in such case the rib frame must be elevated from the plain of insulation, then the insulation must be led over it. Although this guideline has been worked out for conventional high pitched roofs, it is suitable for use here as well. At the same time, here we note that such smooth inlet of water is the most typical difference between conventional covers and covered roofs. Through open gaps, small sized contamination can get in as well but the larger gap produced due to the multi-level rib frame is less sensitive to clogging. However, it is recommended to provide openable inspection/cleaning holes at least along the eaves but even at several points. Large air gap is favourable for ventilation and heat damping in summer but the total thickness of structure would be unfavourably high which is not always feasible. It is not recommended to use a cover thinner than mentioned in the example (contrary to facades). The rigidity of covers having a smaller thickness is generally enhanced by edge bending and cassette like design but it will not ensure sufficient protection against forces perpendicular to the cover, and the material will bulge, and be damaged.

Ribbed system may also be used in conjunction with steel tube feet as shown in former examples. This would allow us to restrict piercing of insulation to a few points only. Through a free selection of length of feet and of the shape of a secondary cover-holding bar system, the shape of outer crust can become independent of the roof ceiling geometry, so very abstract arched convex, concave surfaces are also feasible. This would provide an architect with the possible greatest freedom in designing in regard to the appearance of the building.

5 Results: Specific building structural requirements for covered roofs

Impacts on covered roofs are stronger and stresses on them are more special than either for conventional roofs, terrace roofs or facades:

5.1 Stormwater:

- The specific amount of stormwater is much greater than for a frontage.
- Water drainage and collection must be performed at more than one level.

- In every case, a watertight underlay insulation is required.
- Water drainage paths are longer than for conventional roof shapes.
- Waterproofing is broken several times by other structural elements, mainly by the fixations supporting the upper layers and by ruptures (chimneys, skylights, lightning arresters, etc).

5.2 Waterproofing:

- It is recommended to select easy to form, soft sheets due to ruptures, bracket edges.
- Waterproofing must be equipped with a mechanical fixation against slide-off.
- Check the material for proper elongation, and tensile strength.
- For certain sequences of layers, mechanical properties of waterproofing (punctures), root withstand and resistance to microorganisms must also be checked.

5.3 Thermal insulation:

- It is recommended to design thermal insulation without air gap because condense water dripping back will deteriorate thermal insulation, and the ventilation of air gap generally cannot be provided.
- An inverse sequence of layers may be designed with loading only.
- For a cover with closed gap, it is difficult to ensure drying-up of an inverse sequence of layers.
- Mount type covers may be designed with ventilated air gap and normal sequence of layers.
- Normal sequence of layers may be designed with a strong vapour-damping insulation and vapour-engineering checkup only.
- Only a hard walk-resistant thermal insulation may be used.
- Rarely, thermal insulation on the internal side is also applied. This special case is possible with a strict vapour-engineering checkup only, and in such case only a single reinforced concrete structure will be made.
- Steel coupling pieces used to fix the external crust represent a very considerable thermal bridge which may not be disregarded during thermal engineering checkup.
- Impacts imposed by thermal bridges must be compensated by increasing the thickness of thermal insulation (20 - 25 cm) and by applying thermal insulation of the interior of pipe brackets.

5.4 Forming of gaps:

- As concerns outline and width of gaps between the elements, the expansion requirements and architectural aesthetic expectations must be met at the same time.
- For covers with closed gaps, expansion joints must be sealed using an impermeable UV-resistant sealing agent.
- Dirt accumulated in gaps can impede the thermal motion of elements and the drying-up of the sequence of layers.
- By selecting different gap-forming ways (sealed, partially sealed, covered, open) properly the amount of water getting beneath the cover can be controlled.

5.5 Snow and ice:

- Only frost resistant and UV resistant cover materials shall be used.
- Covers with a rough surface will reduce risk of snow and ice slide-off but will impede self-cleaning, and the contamination of surface will contribute to settlement of microorganisms.
- Snow accumulated on a low-pitch roof forms a water barrier behind which a water pressure will build up.
- For a roof with smooth surface, the risk of snow and ice slide-off is higher, and protection in order to prevent it from tilting over onto the frontage is required otherwise it may lead to an accident.
- If no snow trap or ice breaker can be made for an architectural reason, the covered roof must be equipped with electric surface heating.

5.6 Static engineering issues:

- They are comparatively heavy structures so they are made onto an inclined reinforced concrete ceiling.
- Fixations intended to prevent upper layers from slide-off must be rated for shearing and bending stresses.
- Friction between layers as a transfer of load may not be taken into account due to seismic risk.
- Mounted covers are also subject to a bending stress perpendicular to the own plain.
- The spacing and width of motion gaps, the crack size of upper crust must also be calculated for rating.
- Elements supporting the upper layers, and fixation of the cover must also be rated for a stress caused by its expansion.
- For large composite working surfaces, the slide of boards must be allowed otherwise friction will impede expansion.
- In the case where thermal motion is impeded, the upper crust must also be rated for stresses resulting therefrom.

5.7 Other requirements including but not limited to (not detailed here):

- It is necessary to work out customized detailed solutions (eaves, ridge edge, building-in of skylights, roof superstructures, etc) because standard solutions will not work here.
- Fixing capability: supporting of additional elements (such as aerials, snow traps, maintenance walkways), as well as fixation thereof against wind pressure (tilting up, wind suction) for which a special customized solution must be found out for each sequence of layers.
- Protection against fire propagation on surface and between covered roof layers.
- Interaction of materials used for covered roof, chemical compatibility
- Accuracy of substructure, stricter dimensional tolerance, and allowing for a subsequent correction
- Feasibility of inclined and arched surfaces: preparing two-sided formwork, temporary fixations, temporary scaffolds
- Quality protection for completed structures against other layers applied on them.

6 Conclusion

It has been stated that covered roofs represent a new architectural motive the building structural solutions of which necessarily differ from that of conventional roofs, frontages and terrace roofs as well. Rules for design for covered roofs are being developed only, and there is neither enough number of examples completed nor experimental experience for handling the related problems. The existing standards and guidelines do not offer sufficient information and guidance. The structure is strongly defined from architectural aspect, and there is no issue in which you can make a decision solely on a technical basis.

Designing requires an innovative attitude and a close cooperation between different sectoral designers. For freely formed masses, documenting the geometry is also more difficult. Another problem is that the construction materials applied here are qualified, certified for applications other that this kind.

It is shown that covered roofs are complicated and expensive structures and are encountered not on standard buildings but on exclusive public buildings. Many project owners and designers still consider that complex problems related to covered roofs including special requirements thereof are not significant, therefore, they provide neither sufficient time nor appropriate designing fee for a careful designing thereof.

During further research, the options of multi-level collection and drainage of stormwater must be considered including solutions to ensure fixations in order to prevent upper covering crust from slide-off and other new type details are needed to be worked out. It is necessary to determine experimentally the ratio of amounts of water flowing on the cover and beneath it, as a function of sequence of layers, pitch and gap-forming. Further examinations are required by conditions for feasibility of uninsulated exposed concrete roofs: crack size, water absorption, thermal motion, roofs without eaves gutter and snow trap, and the issue of tilting of water and snow onto frontage shall also be taken into consideration.

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