

BUILDING CONSTRUCTIONS OF STONE CLADDED ROOFS IN CONTEMPORARY ARCHITECTURE

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Abstract. *Stone roof coverings have existed for hundreds of years now, but their application in contemporary representative architecture is quite different than it was in former times, and accordingly the underlying constructional details are much more complicated. The main role of the roof in today's architecture is to emphasize the abstract building volume and its homogeneity. The design (visual appearance) has priority over constructional considerations, while at the same time requirements for thermal insulation and the watertight buildup of the building envelope are rising. This is a big challenge for the design of the constructional details, since traditional methods do not apply anymore: almost all of the water gets under this exterior cladding where a completely waterproof underlayer is needed. Therefore a new type of constructions is borne. In this article I try to present innovative constructional alternatives for stone cladded roofs and try to define guidelines for their planning. These alternatives were created and refined based on analysis of historical and contemporary examples, the examination of the specific conditions and requirements that affect cladded roofs, their expected performance over their life-span, the difficulties that arise under construction and my work experience. I created seven groups, according to the method for fixing the individual stone elements, since this is the detail that most affects the buildup of the underlying structure. A new approach is needed with these unconventional constructions, with a much more detailed inventory of every little feature of the building in question. But since these features vary violently with the architectural conception the exact constructional solutions are usually unique as well.*

Key words: *stone cladding, roof, contemporary architecture, waterproofing.*

1. INTRODUCTION

Building with stone and stone claddings are a symbol for stability and power since the beginning of history. The purpose of stone claddings and roof coverings was to protect against rain, snow, wind and even summer heat. [Schunk, Oster, Barthel, Kiessl:2003] [Meyer-Bohe:1975] [Blaser:1980]

But the cladding of roofs with stone has a quite different meaning in contemporary architecture. A new trend of homogeneous buildings has emerged, where facade and roof are not clearly separated anymore, but the former continues seamlessly into the latter using the same materials. This is part of an architectural movement which does not consider the building in its traditional sense, but rather as an object, or even a statue, where the architect can design the form with total artistic freedom. [Vermeil:2007] [Andreas:2005] [Pawlitschko:2009] [Ekler:1999]

The purpose of the stone cladding of roofs today is not primarily the protection against rain, but a visual appearance identical with that of the façade. The roof becomes more of a visual element, where every little detail of the construction is an important design element (e.g. the size of the stones used, the joint layout, the connection between individual elements, etc.). On the other hand traditional (functional) details like gutters and snow guards do not fit into the architectural idea anymore, so architects try to avoid them.

"The roof should be the fifth façade of the building" – this idea is present in architecture ever since Le Corbusier. But the stone clad roof is not simply a stone façade with tilt, because a roof is subject to much more challenging conditions. Therefore to realize such a construction is a bold experiment, since stone is an inhomogeneous and not watertight natural building material. But architects are often have the view, that every problem can be solved by engineering when it comes to representative buildings where the client accepts the principle that design has priority over economic solutions. We can see a great many of such buildings in architectural magazines, but the factual constructive solutions are seldom published, and even then with very sketchy drawing, since these are often innovative solutions, and as such the intellectual property of the engineer in question.[Le Corbusier:1923]

In my opinion we can speak of an entirely new type of construction, where the conventional design methods for facades, roofs or even terrace roofs do not apply anymore. New construction layers, new details and new design guidelines are needed for the design of these roofs. My goal with this article was to try to lay down some of the necessary guidelines and possible constructional alternatives of stone clad roofs. This work was based on my experience from my work as university professor and my praxis as a designer in the field of building constructions. I am claiming that stone clad roofs are safely realizable, as long as we carefully analyze the specific attributes of the buildings in question and strictly observe some design criteria. But this also means, that there is no generally applicable solution for these kinds of structures, the optimal design is always unique, and only the guidelines remain the same. [Dobszay:2009] [Vasiliu:2009]

First of all let us have a look at traditional and contemporary examples for stone clad roofs, specially at those features which make traditional constructions unsuitable for use in today's buildings.

2. HISTORICAL EXAMPLES FOR STONE ROOF COVERINGS

Examples for stone roof coverings are present ever since the ancient times, in various regions and on both cultic and profane buildings. I have chosen four of these examples to show in this article.

2.1. The Gallarus Oratory in Ireland

The Gallarus Oratory in Ireland is believed to be an early Christian church from sometime around the 8th century. It is a corbel vault structure built without mortar. The stone as a building material was probably used because of frequent barbaric attacks, to protect the building against fire (Fig. 1.). The stone structure is façade and a roof at the same time, and it is protecting an interior without heating or any other comforts. The joints between the stones are almost horizontal, allowing some of the rainwater to enter into the building. The arched exterior of the building is causing the water to run down with a continuously increasing speed along the other surface. [Henry:1956]



Fig. 1. The Gallarus Oratory (photo by "Pdxgoat"
<http://en.wikipedia.org/wiki/File:Gallarusoratory.jpg>)

2.2. The Mausoleum of Theodoric in Ravenna

The Mausoleum of Theodoric in Ravenna is an example of 6th century Ostrogothic architecture. The roof of the building is a monolithic dome 11 meters in diameter made of limestone (Fig.2.). Unlike conventional roofs there are no joints of any kind, and although the stone itself is not completely watertight the moisture can safely evaporate from the inside surface because of the sufficiently large air volume of the room under the dome, so there is no danger of frost damage. The pitch of the dome decreases to zero at the top. Like in the frost example the inside of the building has no need for human comforts. There is no thermal insulation, no difference in temperature with the outside or vapour building. [Stuart:1975]



Fig. 2. The Mausoleum of Theodoric
(photo: Immanuel Giel,
<http://en.wikipedia.org/wiki/File:RavennaMausoleum.jpg>)

2.3. The cathedral of St James in Sibenik

The cathedral of St James in Sibenik, Croatia, built in the 15th century, shows the characteristics of Dalmatian and northern Italian architecture. The barrel vaulting of the three naves is made out of stone slabs resting on stone arches. This structure serves as roof as well, giving the church the same look from the outside as from the inside (Fig. 3.). The pitch of the roof at the ridge is zero, the stone is not watertight and the overlap between the individual stone elements is minimal. But there is no danger of frost damage, the stone can dry out towards the inside of the building as well, and there is no need for thermal insulation. The stone slabs of the roofs bear some degree of bending moment because of the structure of the roof. [Kadic:1962]



Fig. 3. The cathedral of St James in Sibenik

(photo: www.yacht-chartercroatia.com/charter_base_sibenik/sibenik_north_dalmatia/sibenik-stjames.jpg)

2.4. Examples of stone covered roofs in the vernacular architecture

We can find examples of stone covered roofs in the vernacular architecture as well, for example in Northern Scotland (Rackwick), Switzerland (Tessin) and in South Italy (Alberobello). Regions and climates which are quite different at first sight (Fig. 4. and Fig. 5. and Fig. 6). The covering of roofs with stone is actually characteristic for regions with extreme weather conditions, or regions where other building materials such as wood and clay are in short supply, but at the same time there is an abundant source for foliated stone (like slate) which is easy to split into relatively slim and easily stackable sheets. Stone roof covers are resistant against snow, cold, stormy weather, and they offer some degree of protection against heat as well. Slate roof shingles are usually irregular, giving the roof a characteristic pattern. The overlapping is usually quite small and the pitch of the roof is often kept small as well, because the slates have a smaller chance of sliding down that way. At the overlaps, like with any other roof covering made out of small elements, there are two or three layers of slate present, reducing the effective pitch of the roof even further. Therefore these small overlaps cannot guarantee a sufficient seal for today's requirements. But the larger the elements are, the less joints are present, and the water has less chance to get under the slates. [Fasana, Nelva:2010]



Fig. 4. Trullo, Alberobello, South Italy
(photo: "spaggiari" www.clikon.it)



Fig. 5. Rackwick, Northern Scotland
(photo: James Morrison, www.flickr.com/photos/jamesm/1074278399/)



Fig. 6. Tessin, Switzerland
(photo Andreas Neumann,
http://www.carto.net/neumann/mountaineering/2006/valle_maggia_val_bavone_2006_06/35_rustici_in_bosco_gurin_ferder.html)

3. CONTEMPORARY EXAMPLES

Nowadays stone roof claddings are once again fashionable, but the elements have either insufficient overlaps, or non at all. The stone cladding serves primarily to stress the volume of the building, which I will demonstrate with six examples. [Schwarz:1999] [Schittich:1999]

3.1. Weekend house in Tihany, Hungary

The upper storey of the building is covered by a hemispherical dome with adjoining semicircular barrel vaults (Fig. 7.). A sphere is a double-curved shape that cannot be covered with large flat elements. Therefore the roof cladding was made with small stone elements and an irregular joint pattern. The walls and the roof are not separated from each other. The pitch at the top of the dome is close to zero, but it increases to almost vertical. The elements are fixed with conventional cement mortar with butt joints. The traditional components like gutter and snow guards are absent.



Fig. 7. Weekend house in Tihany, Hungary
architect: unknown, photo by G. Dobszay

3.2. Soulié-Bertho house, Sarzeau, France

The building volume is quite simple, the walls and the gable roof have an identical appearance. Completely regular rectangle shaped slate stone elements are used in a grid pattern (Fig. 8.). The stone elements do not overlap, they have completely open butt joints where the rainwater can easily get under the stone. The protection against the rain is achieved with a sheet metal layer under the stones. The cladding is supported by and fixed to steel rails, so the stones have to bear bending stresses. The building is thermally insulated. Traditional details (eaves, snow guards, lightning-rod) are not visible. The gutter is hidden and the ridge is not elevated from the plane of the roof. [Gouesnard:1999]



Fig. 8. Soulié-Bertho house, Sarzeau, France
architect: É. Gouesnard, photo by Philippe Ruault

3.3. Block of flats, Gül-baba street, Budapest, Hungary

The pitched roof serves the integration of the building to its urban environment, while its stone cladding is intended to reflect a contemporary look (Fig.9.). The stone elements are of different size, so a rail – fixing is not possible, therefore an individual fixing of the stones was designed. These individual fixing points require a continuous concrete substructure. The stone elements have to bear bending stresses. The water gets under the cladding, so a waterproofing layer has to be made under the stones. These individual fixing point points rupture the layer of the waterproofing at too many points, so instead of a membrane like layer a coating has to be applied. The building has an irregular ground-plan, the ridge is not horizontal, the eaves are sloping as well. The ridge has no ventilation outlet, the gutter is hidden, the windows are positioned at the outer plain of the cladding.



Fig. 9. Block of flats Gül-baba street, Budapest, Hungary

architect: J.Z.Halmagyi, G. Sajtos; building constructions: G.Dobszay, G.Kapovits

3.4. Conference and music hall, Pécs, Hungary

The architect choose a homogeneous statue like building volume for this huge complex. (Fig. 10.) The resulting roof shape has vast irregular surfaces with a varying pitch and extreme distances between the eaves and the ridges. The stone cladding has the same rectangular elements in a regular grid pattern with butt joints like the façade. The traditional constructional elements like flashings, snow-guards and ventilation in- and



Fig. 10. Conference and music hall, Pécs, Hungary

architect: F.Keller, R.Hönich, B.Sólyom, T.Fialovszky, building constructions: G.Becker, R.Reisch, G.Dobszay

outlets are absent. The gutter is hidden beneath the stone cladding. A part of the roof is passable, which means an elevated mechanical demand, and stresses the need for the exchangeability and a non-slipping surface of the stone cladding element.

3.5. Füleky winery, Bodrogkeresztúr, Hungary

The roof is characterized by small surfaces but greatly varying pitches (Fig.11). The load-bearing construction is an in situ reinforced concrete slab. The roof was planed with an inverted construction in consideration of the large vapour diffusion loads of the inside. The stone elements have a rebate joint giving the roof a staggered look, and to minimize the amount of water getting underneath the cladding. For the moisture that does get under the stone a fibre reinforced waterproofing is applied directly on the concrete slab. The stones are laid down without mortar onto a drainage layer. The rows are resting on each other, and every fourth row is secured against sliding down with a stainless steel L profile.



Fig. 11. Füleky winery, Bodrogkeresztúr, Hungary

architect: Zs.Félix, T.Fialovszky, building constructions: G.Dobszay, G.Kapovits

3.6. Thermal bath, Paks, Hungary

The building is cladded with an Indian sandstone which is also used on the pyramid shaped roof over the steam bath, which serves as a lantern and an air-shaft. (Fig.12.). Because of the high thermal insulation needs and the strong vapour pressure a cold roof



Fig. 12. Thermal bath, Paks, Hungary

architect: P.Fejérdy, I. Bartók, building constructions: L. Kakasy, G.Dobszay

construction was used. The stone is supported by a steel structure and a conventional flat roof construction could be made underneath. The cladding itself is made out of stone blocks staggered with very tight joint on top of each other.

4. COMPARISON OF THE HISTORICAL AND CONTEMPORARY EXAMPLES

It can be observed, that in the historical examples the stone is used primarily as a means of protection against rain, snow and wind. In other words it serves as a durable and weather resistant roof covering. In contemporary architecture the priorities have been rearranged. Visual appearance has dominance over traditional considerations, from the planning of the building volume to the last little detail. The most important differences are gathered in Table 1. The main difficulties in today's stone cladded roof constructions is the architect himself, who wants to control every bit of visual detail of the construction, often disregarding the underlying technical considerations.

As a next step I invented constructional alternatives assuming different materials, geometrical dispositions and architectural demands. Seven of them are presented in this article.

Table 1. Comparison of the historical and contemporary examples

	Historical examples	Contemporary examples
Function	The stone covering is not watertight, but this is not in conflict with the requirements of the period	There are human living-spaces underneath the roof, a completely watertight construction is indispensable
Joint, overlap	The stone elements have some degree of overlap	The stone elements usually do not overlap, the details of the joint is determined by the architectural idea
Pitch	There is a correlation between the disposition of the stones and the pitch of the roof: steep roof → corbel vault like structure, shallow roof pitch → large sheets of stone with overlap	The pitch can vary violently in one building, but it has no effect on the disposition of the stones, it is determined solely by the architectural idea
Fixing method	The stones are secured against sliding down by the right roof pitch and the right method for laying them	The protection against sliding down has to be achieved by some other method (e.g. mechanical fixing, sticking)
Material	Only naturally occurring easily splitting and durable stones are used	Sawn, porous, less durable stones are used as well, if the architect so desires

5. CONSTRUCTIONAL ALTERNATIVES

While creating these innovative design alternatives I analysed the kind of architectural dispositions they are the most suitable for, and what their critical points are regarding building physics, durability, the required building technology and costs.

5.1. Stone elements laid in thin set mortar

This kind of buildup comes from tilting a terrace roof. The use of and adhesive mortar requires a firm and load-bearing substructure, which can only be a reinforced concrete slab (because of the roof tilt). This slab has to be fixed to the main load bearing structure

of the roof (e.g. the reinforced concrete slab) against slipping down. This can be done with punctual consoles or with a linear connecting element along the eaves. The sub-structure must bear compressive, tensile and twisting forces, but no bending moments, so it can stay relatively slim (~8-10 cm, 3-4"). The buildup of the constructional layers is conventional, with the waterproofing above the thermal insulation.

Roofs of any size and shape can be achieved this way, with regular or irregular stones, even with lightly arched surfaces (as seen in 3.1.). The stone material is not watertight, neither is the grout, therefore a waterproofing layer needs to be installed. The setting mortar is subject to shear forces because it has to support the stone elements against sliding down, and because the expansion due to thermal loads. Therefore a conventional cement based mortar is not suitable, an epoxy setting mortar has to be used.

Both the stone the setting mortar and the concrete slab needs protection against frost damage (Fig. 13.). The water soaked up by the construction has to be allowed to dry out. The setting mortar has to be applied in a grid pattern on the bottom of the stones to leave most of their surface free for drying. The amount of water getting in can be limited by hydrophobisation, or we can use an opposite approach: the choice of a setting mortar with a good water permeability. Either way the water has to get to a drainage layer. [Zeki, Karaca:2009]

If the concrete slab is made with a normal concrete a drainage sheet has to be used. This sheet has to withstand the making of the reinforcements and the other concrete works. It has to be perforated or otherwise treated so it will not hold any of the water, otherwise the concrete might be damaged by the frost. The drainage layer has to be fixed against sliding down during the construction works. Even so it raises difficulties in the building phase, especially since it is covered with a filter fleece which protects it from clogging by the concrete, but makes it even harder to walk on. On the other hand the drainage sheet serves as a protecting layer for the waterproofing. Nonetheless the waterproofing layer has to be resistant enough on itself. HDPE membranes, fiber reinforced coatings, cementitious coatings, modified bitumen coatings, modified bitumen membranes or polyurethane foam waterproofings are applicable.

A mechanically strong enough waterproofing layer may be used in connection with a pervious concrete capable of leading down all the water that gets under the cladding, in which case the separate drainage layer may be omitted (Fig. 14.). Pervious concrete is made from a narrowly graded coarse aggregate held together with a thick cement paste. Little or no sand is used in the mixture, creating a system of interconnecting voids. A similar material has to be used as grout, only with a smaller aggregate. This way the concrete slab and the joints do not store any water and are not exposed to frost danger. But such a concrete cannot protect the reinforcement bars, so stainless-steel has to be used.

The thermal insulation has to be firm and well fixed for the concrete slab to be built above it. Foam glass, aerated autoclaved concrete, calcium silicate, extruded polystyrene or polyurethane can be used. The thermal insulation has to be glued on the whole surface or else mechanically fixed with properly dimensioned insulation anchors. Such stiff materials cannot be laid on an uneven surface, therefore the load bearing structure of the roof should be made with prefabricated elements, or an epoxy levelling compound needs to be used. The vapour barrier under the insulation must be made with a glued bitumen membrane or a coating system, otherwise the securing of the layers above it against sliding down would become impossible.

In case of a highly uneven structure a polyurethane foam insulation can be a solution, which can be used as a waterproofing layer as well. The surface of such a coating is un-

even as well, but this unevenness can be corrected with the concrete slab. The perforation points can be easily sealed watertightly with such a foam applied system.

Large surfaces must be divided with expansion joints. The concrete slab has to be sectioned at the same places as the cladding, and the joints have to be filled with a UV resistant elastic joint sealant.

In the choice of the waterproofing material the large number of flashings necessary should be taken into consideration. The consoles are used to secure the concrete under the cladding puncture the waterproofing layer at many places, so a site applied coating may be advantageous. But in case of a thick waterproofing membrane and a firm enough insulation a clamping rings may be used for watertight connections, if the number of puncture points can be limited [Ernst, Wolfgang:2006].

In case of a relatively small roof pitch the concrete slab can be made with a stiff concrete mixture, but on a steep roof a sprayed concrete must be used which is a further large mechanical strain for the thermal insulation and the waterproofing layer. An exterior formwork for a pured concrete is hardly possible because it cannot be fixed due to the already finished waterproofing.

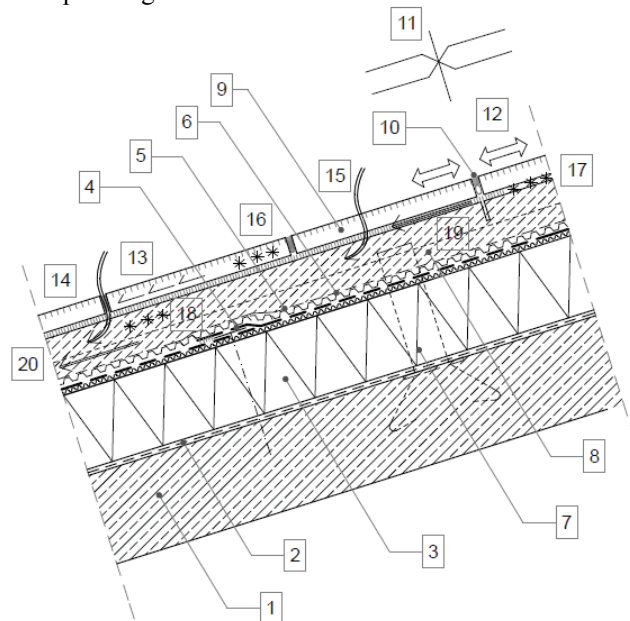


Fig. 13. Stone cladding laid in thin set mortar - frost sensitive unsuitable buildup

(1 - sloping reinforced concrete slab, 2 - vapour barrier, 3 - passable thermal insulation, 4 - mechanically fixed reinforced waterproofing membrane, 5 - perforated drainage layer, 6 - filter fleece, 7 - stainless steel supporting bracket, 8 - reinforced concrete substrate, 9 - stone cladding laid in thin set mortar, 10 - expansion joint in the cladding and in the reinforced concrete substrate – questionable durability of the elastic sealant, 11 - the distance between expansion joints, 12 - shear forces in the setting mortar due to thermal expansions in the cladding, 13 - shear forces in the setting mortar due to the weight of the cladding, 14 - water getting under the cladding through the joints, 15 - water getting under the cladding through the stones, 16 - frost damage of the stones, 17 - frost damage of the setting mortar, 18 - frost damage of the concrete, 19 - water filtering in the setting mortar, 20 - the concrete has a limited permeability, the drainage layer cannot function)

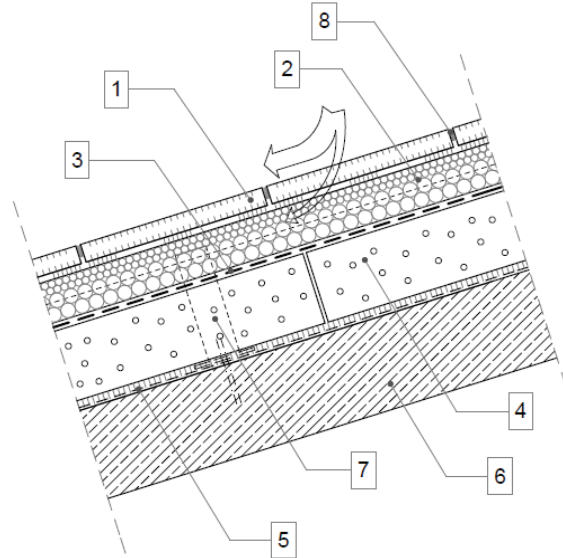


Fig. 14. Stone cladding laid in thin setting mortar – revised, innovative buildup

- (1 - stone cladding laid in a pervious setting mortar with a high elasticity,
 2 - pervious concrete substrate, 3 - mechanically resistant, passable waterproofing layer,
 4 - and passable thermal insulation, glued down, 5 - vapour barrier coating,
 6 - sloping reinforced concrete slab, 7 - stainless steel supporting bracket,
 8 - UV resistant elastic sealant)

5.2. Stone claddings with punctual fixings (Fig. 15.)

This method is suitable for claddings of equally thick, but irregular sized stone elements or irregular patterns (as seen in 3.3.). The need for fixing points at optional places necessitates a continuous reinforced concrete slab. Because of the roof pitch this slab has to be connected to the load bearing structure of the roof, in this case also a reinforced concrete slab. The concrete layer under the cladding must be made with sprayed concrete or with the use of an exterior formwork.

This outer concrete layer serves well as a base for a waterproofing coating. The thermal insulation is located between the two slabs (a sandwich structure). The stone elements are held in place with special stainless-steel fixing anchors known from conventional façade claddings. These are adjustable in three dimensions. Because of the depth of these anchors an air-gap is formed. The waterproofing can only be an elastic coating to guarantee the watertight sealing of the anchor points.

The air-gaps can lead down the water easily, which contributes to the rapid drying of the stones. However over the years it can easily be blocked by the accumulation of dirt. Therefore a sealing of the joints with a water permeable epoxy mortar with a ground stone aggregate is preferred. This lets water through in case of long soaking rains, but in case of sudden violent rain-showers most of the water runs down on the surface. The system is "self-regulating".

The stone elements must bear considerable bending moments from the vertical component of their own weight, and from live loads (e.g. repair loads!). The smaller the pitch is the bigger these loads are, so the stones have to be dimensioned accordingly.

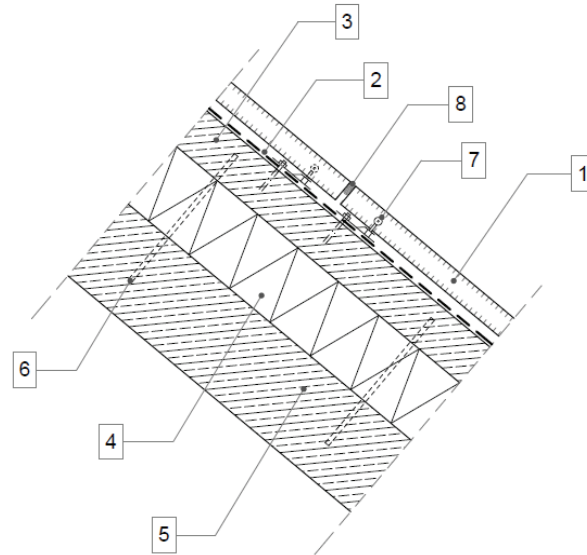


Fig. 15. Stone cladding with punctual fixings on a concrete structure with interior core insulation (1 - stone cladding, 2 - waterproofing coating, 3 - exterior reinforced concrete layer, 4 - extruded polystyrene thermal insulation core, 5 - load-bearing reinforced concrete slab, 6 - composite plastic brackets, 7 - adjustable stone anchor, 8 - pervious grouting)

5.3. Blocks of stone laid on supporting steel rails (Fig. 16.)

The stone cladding which is of utmost importance for the architectural appearance is in reality only a show. It is a double construction, where the outer cladding shell is supported by a completely independent and expensive steel structure (as seen in 3.4. and 3.6.). The architect enjoys a significant freedom in his design, since the interior and the exterior volumes of the building become independent. The stone blocks are supporting each other to some degree, and they are secured against sliding down with pins welded to the steel frame.

Regarding the constructional principles the stone cladding serves as a primary, but not sole protection against weather. The joints are not sealed, so smaller amounts of water do get under the cladding. This moisture drops down to the waterproofing layer underneath or it runs down sticking to the steel frame. The area between the exterior and the interior shells can have varying dimensions and it helps the evaporation of the moisture under the cladding and the drying out of the stone itself, thus reducing the danger of steel corrosion in the support frame. [Gnoth:2008]

The thermal insulation and the watertight buildup are ensured by the interior shell, which is shielded by the exterior, thus reducing the UV irradiance and the mechanical requirements because of wind suction and heavy downpour.

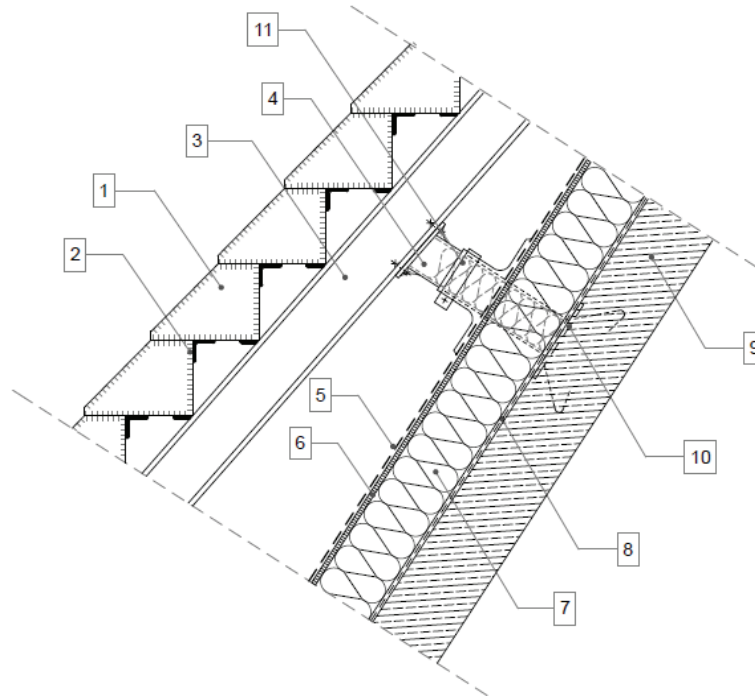


Fig. 16. Blocks of stone laid on supporting steel rails

(1 - stone blocks, 2 - supporting steel sections, 3 - uniquely formed steel frame, 4 - stainless steel supports with a cylindrical cross section, 5 - reinforced waterproofing membrane, 6 - epoxy mortar coating, 7 - high density mineral wool insulation, 8 - vapour barrier, 9 - sloping reinforced concrete slab, 10 - cast-in steel footplate, 11 - watertight sealing of the waterproofing membrane to the steel column)

5.4. Small stone elements laid in a bedding layer (Fig. 17.)

Claddings with small elements cannot be laid in a setting mortar like we saw in 5.1., since total length of the joints is so high that it cannot be sealed economically, and thus too much water would get between and under the stones. The solution is a substructure that can lead down the water and enable the drying out of the stones, thereby reducing the danger of frost damage. The cladding is secured against wind suction by its own weight. The joints are filled with epoxy bounded grit-sand or stone-dust.

With this method even stones with irregular shapes and varying thickness can be used because the bedding layer can compensate for these irregularities. For durability the bedding has to be compacted and made with a material without settlement (like gritty basalt stone-dust). Compacting is relatively simple on roofs with a low pitch, but in case of steep constructions a water pervious epoxy bonding is needed. The bedding layer acts as a drainage, but this ability is dependent on the distance between the ridge and the eaves and has to be calculated. A separate drainage sheet (e.g. a plastic drainage sheet) cannot be used because it hinders the compaction. No bedding material can be used that contains lime that can be washed out by the water, because it would clog the drainage.

The cladding and the bedding have to be secured against sliding down, so the roof surface is divided into smaller fields with stainless steel sections and perforated sheets that act as support. Between these supports the stones are holding each other so a load bearing filling of the joints is needed (epoxy bounded stone-dust). Also expansion of these fields because of thermal loads can happen independently. The steel supports are held in place by fixing brackets made of stainless steel tube sections. The number of these brackets can be reduced by strengthening them, thus reducing number of points where the waterproofing is punctured.

Because of the mechanical loads associated with the compaction of the bedding the waterproofing can only be from a mechanically resistant material (HDPE or modified bitumen membranes). The same applies for the thermal insulation. Hard polystyrene, polyurethane, foam glass and aerated concrete sheets can be used. With the use of such rigid thermal insulation materials the unevenness of the surface of the load bearing reinforced concrete slab is not allowed. Both the waterproofing and the insulation has to be secured against sliding down, but only for the time of the construction works, afterwards they are held in place by the weight of the cladding. The best solution is a mixture of glue and insulation anchors. The vapour barrier can be a bitumen membrane, in case of a glued fixing of the upper layers or a coating system, in case of a mechanical fixing.

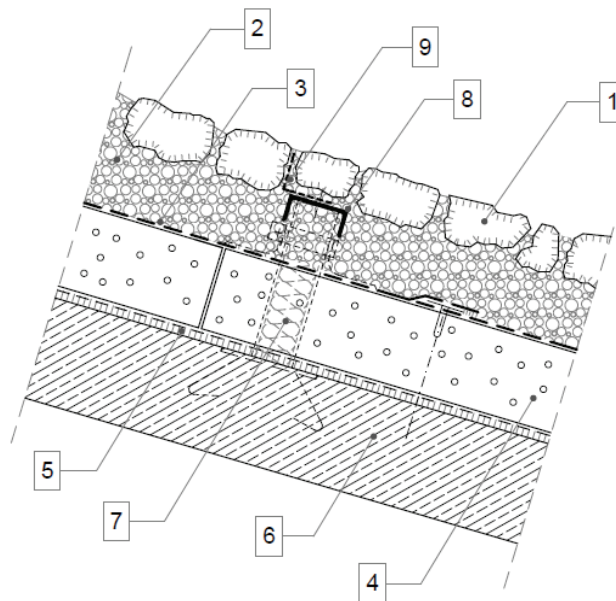


Fig. 17. Claddings with stones laid in a bedding layer

(1 - small, irregularly shaped stones, 2 - pervious bedding layer, 3 - mechanically resistant reinforced waterproofing membrane, 4 - mechanically resistant and passable thermal insulation (e.g. foam glass), 5 - vapour barrier coating, 6 - sloping reinforced concrete slab, 7 - stainless steel tube bracket, 8 - stainless steel support, 9 - stainless steel perforated shutter)

5.5. Stone elements laid dry on a drainage sheet (Fig.18.)

Flat stone elements cannot be laid directly on a plain surface (e.g. the waterproofing layer), because a water layer is formed by the capillary forces between the two surfaces. This water layer increases the danger of frost damage and its vapour resistance is practically infinite, which makes the drying out of the layers underneath impossible. The solution is an underlay that serves as frost damage prevention, drainage, vapour outlet and separating layer alike. This underlay has to be load bearing, passable and quick to lead down water (e.g. hard form-pressed plastic drainage sheets and expanded stainless steel sheets). Because the stones are laid down with a dry technique the individual elements are easy to replace, which increases the life-span of the whole construction (as seen in 3.5.).

In the example presented in the picture the stones have a rebate joint giving the roof a staggered look. Only a small amount of water can get through the overlap, except in case of heavy showers and high wind loads. The quantity of dirt getting under the stones is also reduced. The drainage sheet also ensures some level of ventilation thus aiding the drying out of the stones and reducing frost damage. [Künzel:1975]

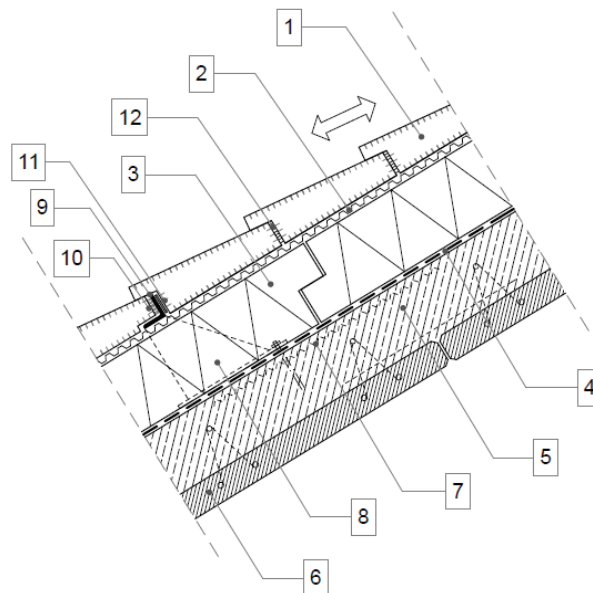


Fig. 18. Stone elements laid dry on a drainage sheet

(1 - cladding stones with uniquely shaped joints, 2 - drainage layer with a filter fleece bonded to its upper side, 3 - extruded polystyrene thermal insulation, 4 - bituminous waterproofing coating, 5 - in-situ reinforced concrete topping, 6 - precast lattice girder floor, 7 - expanded stainless steel sheet permanent formwork, 8 - stainless steel bracket, 9 - stainless steel supporting section, 10 - expansion joint, 11 - rubber bearing strip, 12 - load bearing joint)

The whole surface of the stones is supported by the underlay, so they do not have to bear bending moments, therefore weaker stones can be used as well. The securing against sliding down is done with a stainless steel rail in every eighth or tenth row. An elastic band is used between the steel and the stones. Between the supporting rails the cladding

elements are supporting each other, and the expansions due to thermal loads can happen freely because the underlay is also a separating layer.

The thermal insulation has to bear the weight of the cladding, which is according to the inverted buildup of the roof is an extruded polystyrene foam. This dry method for the laying of the stones cannot compensate for any surface unevenness so an epoxy levelling compound has to be used.

5.6. Stone elements laid on corrugated steel sheets (Fig. 19.)

The use of thin stones with limited bending resistance can be compensated with a dense support system. Corrugated steel sheets ensure such a support over a large surface. It is also advantageous that corrugated sheets need only far-between fixing points, thus reducing the number of steel supports that puncture the waterproofing and the cause thermal bridges. Only stainless steel or aluminium can be used. According to vapour diffusion calculations an anti-condensation coating may be necessary.

The corrugated sheet has other functions as well. The water that gets through the joints can be drained in the valleys of the steel sheets. Likewise the vapour coming from the inside can be led out through the waves on the downside of the sheets if they are properly ventilated. This also means, that if the sheet overlaps are properly sealed and tapping screws are used for the fixing points no further waterproofing layer is needed (as seen in 3.4.).

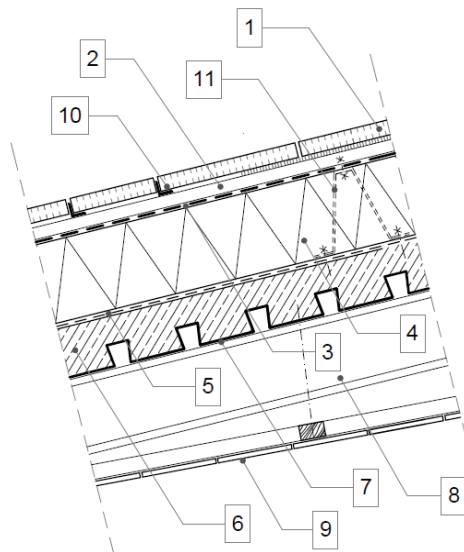


Fig. 19. Stone elements laid on corrugated steel sheets

(1 - thin stone elements fixed with strips of glue, 2 - stainless steel or aluminium corrugated sheet, 3 - roof underlay, 4 - passable thermal insulation, 5 - vapour barrier membrane, 6 - reinforced concrete topping, 7 - permanent steel formwork, 8 - load-bearing steel beam, 9 - interior cladding, 10 - stainless steel fixing rails (alternative to glue), 11 - steel fixing bracket)

The fixing of the stones to the steel is done with self drilling pins or glue. Since there is no load bearing connection between the stones the expansion due to thermal loads can happen in the joints, so these can remain relatively narrow. The filling of the joints only serves to keep put the dirt from the inside of the construction, the material used must be UV resistant and permanently elastic.

This system has the clear advantage, that less frost resistant and weaker stones can be used as well, and even passable roofs can be constructed. Also the construction works needed are relatively simple, quick, and independent from weather conditions. In case of damage the individual elements are easily replaced. The roof offers some degree of protection against heat loads, it is relatively cheap and can be recommended even for large spans.

5.7. Stone cladding fixed to a steel mesh (Fig. 20.)

With well dimensioned stainless steel props of varying length and angle and stainless steel meshes of the right thickness and mesh density all kind of shapes can be constructed independent of the reinforced concrete slab. The architectural freedom is almost without limits, double-curved forms with inflexions, biomorf or geometrical surfaces can be created. The mesh can lend support to even completely irregular, roughly-worked stones with relatively low quality and bending resistance. The fixing of the elements to the steel is done with braces glued to their backside or clips that can be snapped into the mesh. [Langer:2008]

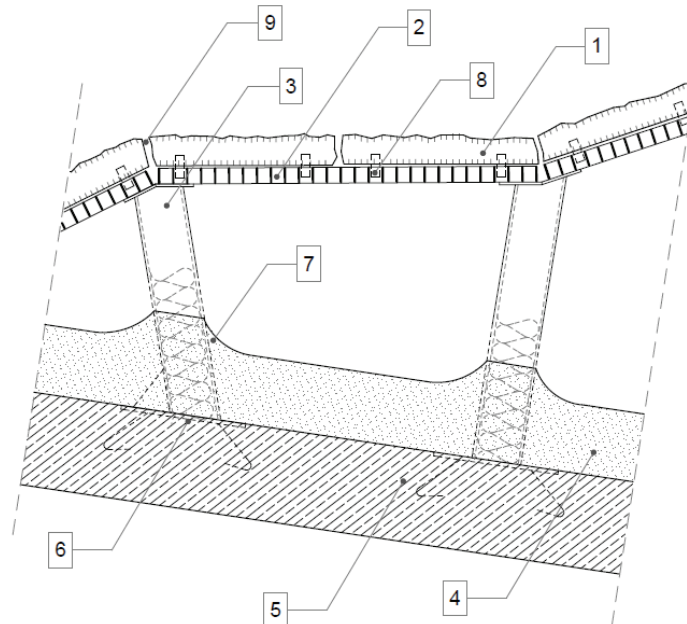


Fig. 20. Stone cladding fixed to a steel mesh

(1 - small, irregularly shaped stones, 2 - well dimensioned stainless steel mesh, 3 - stainless steel props, 4 - spray applied polyurethane foam waterproofing and thermal insulation, 5 - sloping reinforced concrete slab, 6 - cast-in steel footplate, 7 - waterproofing foam applied to the steel props, 8 - fixing clips snapped into the mesh, 9 - open joints)

The joints are not sealed, so all the water gets under the cladding. The space under the exterior shell is well ventilated and helps the drying out of the stone. The individual stone elements can be replaced individually.

The waterproofing layer is shaded by the cladding, the expansions due to heat loads and the UV radiance are significantly reduced. Therefore almost all kind of waterproofing and thermal insulation can be used, but no inverted roof construction because the ballasting of the insulation is not possible. Waterproofing coatings and soft membranes are preferred because of the need for the watertight sealing of the stainless steel props. A foam applied polyurethane coating can be used as well, since this can serve as both thermal insulation and a seamless waterproofing. [Kramer, Gerhardt:1983] [Amano, Fujii, Tazaki:1988] [Holdø, Houghton, Bhinder:1983]

The completely open joints hold the danger of dirt buildup beneath the cladding, therefore openings must be plane in the steel mesh structure for cleaning purposes.

6. ANALYSIS OF THE ALTERNATIVES

It can be observed, that the constructional buildup of stone cladded roofs is closer to pitched roofs and terrace roofs than facades or flat roofs. Some of the illustrated constructional alternatives are even simpler than traditional pitched roof designs. Properly designed stone cladded roofs can perform as well as traditional constructions regarding the protection against summertime heat loads, vapour diffusion, and ecology. With the right design method stone materials of inferior mechanical quality and frost resistance can be used as well. If the cladding elements can be replaced individually, the life-span of the roof can be adjusted to the life-span of the whole building. [Sedlbauer, Gottschling:1999] [Künzel, Sedlbauer:2007]

The stones can be fixed individually or together in larger groups. From all the fixing methods, the laying of the stones dry, without any kind of glue or mortar is the most preferred, because it is key, that the bottom surface of the stones be allowed to dry. The whole buildup of the roof can be categorised according to the method used for fixing the stones, because this is the detail that most affects all the others. Even the kind of architectural design that the specific construction is suitable for. Rail fixings and punctual fixing elements are used less frequently, because the cladding elements have to bear considerable bending moments that only thick, good quality, and therefore more expensive stones are capable of.

The sealing of the joints is determined by the size of the cladding elements, the size of the cladding surface between expansion joints, the need for load bearing connection between elements and the need for protection against dirt getting under the cladding layer.

Another basic question is the secondary roof covering layer under the cladding, which ensures the watertight buildup of the whole construction. The percentage of water getting under the stone varies violently in the demonstrated examples. The amount of water the system is capable of leading down under the cladding has to be calculated. The mechanical resistance is a key aspect in the choice of the waterproofing material. But coating are generally favorable to sheets or membranes because it is easier to guarantee a watertight seal at intersecting structures (e.g. steel supports and consoles). [Horvath, Pataky:2006] [Ernst, Wolfgang:2006]

Traditional and inverted construction can be used alike, but inverted constructions are less frequent, because the necessary ballasting is not always possible. Because of the difficulties that arise during construction works in these pitched roofs a robust, load bearing thermal insulation is needed. For the insulation and the vapour barrier homogeneous or glued products are favourable to mechanically fixed solutions.

The load bearing structure of the roof must have a sufficiently high strength, limited deformations and in some cases an even surface. Therefore reinforced concrete slabs are used primarily, if necessary with a surface levelling compound.

7. CONCLUSIONS

In my article I was trying to determine whether it's possible to design stone cladded roofs that suit contemporary architectural notions but meet the ever increasing technical requirements as well. I found several constructional alternatives that can function well and with the desired life-span and architectural appearance. But the rules for choosing the appropriate materials, the exact requirements and design rules are quite different from traditional roofs. Therefore we can speak of an entirely new kind of constructions.

To make the optimal choice in the constructional buildup a thorough inventory of every little architectural and geometrical feature of the building is needed. I tried to demonstrate that even the most extreme architectural dream is possible if the designer of the constructional details can empathize with the idea. We must not stick rigidly to the traditional constructional principles, we must explore the unique constructional possibilities in every building. Intuition, creativity and good ideas are needed instead of the mechanical application of the rules. With a good assessment of the designed life-span of the building and its unique usage we can more accurately design some built-in redundancies and maybe reduce some of the requirements. If the solutions are more exactly adapted to the specific buildings even the use of weaker materials can become possible, resulting in considerable savings. But these solutions cannot simply be copied from building to building.

All this might appear unrealistic in today's environments of rules, decrees and standards. But this has to change. With the use of orthodox rules we cannot meet the new challenges of our age. It is necessary, that while observing the legal framework we design and test unique constructions which are based upon our experience and the true conditions and requirements.

Meanwhile the education of building constructions must transform as well. Instead of teaching specific solutions to specific problems the emphasis should be on the fundamental principles, trends and methods for optimization and integration, with the use of real life examples. A key element in this approach is the comparison of different constructional alternatives which is what I tried in this article.

8. THE NEED FURTHER RESEARCH

This subject presents a lot of new opportunities for further research. New phenomenon have to be investigated and requirements determined, like the water's runoff on multiple layers (e.g. cladding and drainage sheet), or the dirtying of drainage layers. Index-numbers and constructional categories have to be developed to make it possible to objectively deal with them.

It would be beneficial to examine the building physics of the more unusual cases. The vapour diffusional operation of some of the design alternatives presented in this article is somewhere between the traditional and the inverted constructions. This examination can only be done with computer modeling and the monitoring of real life examples.

Another area of interest is the behavior of these constructions in case of a fire, because these unusually shaped buildings and roofs do not fit into any of the categories in the previous fire safety regulations.

Beside a multitude of other examinations recommendations should be made for the changing of the building regulations and standards, to try to loosen today's overregularization in the industry. In my article I presented some notions that are contradictory to traditional principles, in other cases I extended the traditional rules. I believe I made some findings that go beyond the question of cladded roofs, and can be useful for researchers, engineers and legislators, and can help a little to advance a new more analytic approach into the education of architecture.

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BUILDING CONSTRUCTIONS OF STONE CLAD ROOFS IN CONTEMPORARY ARCHITECTURE

Gergely Dobszay

Krovni pokrivači od kamena postoje već stotinama godina, ali njihova primena u modernoj arhitekturi se potpuno razlikuje od one u prošlosti, i shodno tome konstruktivni detalji su mnogo komplikovaniji. Glavna uloga krova u današnjoj arhitekturi je da naglasi apstraktni gabarit objekta i njegovu homogenost. Vizuelno ima prioritet nad konstruktivnim, ali se u isto vreme povećavaju zahtevi za toplotnom izolacijom i vodonepropusnošću omotača zgrade. To je veliki izazov za projektovanje konstruktivnih detalja, jer se tradicionalne metode više ne mogu koristiti: sva voda prodire kroz ovaj spoljni omotač, tako da je ispod njega potrebno konstruisati apsolutno vodonepropustan sloj. Stoga je rođen nov tip konstrukcije. U ovom radu, nastojim da iznesem inovativne konstruktivne alternative krovovima sa pokrivačima od kamena i da definišem smernice za njihovo planiranje. Ova alternativna rešenja su bila stvorena i doterana na osnovu analize istorijskih i savremenih uzora, na osnovu ispitivanja specifičnih uslova i zahteva koji utiču na ove krovove, njihovog učinka tokom radnog veka, teškoća koje se javljaju kod izgradnje i mog radnog iskustva. Podelio sam ih u sedam grupa, prema načinu pričvršćivanja pojedinačnih elemenata od kamena, jer ovaj detalj najviše utiče na konstrukciju strukture ispod nje. Potreban je novi pristup kod ovih nekonvencionalnih konstrukcija, sa mnogo detaljnijim inventarom svih karakteristika predmetne zgrade. Ali budući da ove karakteristike veoma variraju u zavisnosti od arhitektonskog koncepta, konkretna konstruktivna rešenja su obično jedinstvena.

Key words: kameni pokrivači, krov, savremena arhitektura, hidroizolacija.