COPPER IN ARCHITECTURE
Facts on Characteristics and Usage of Copper for Architects
Copper was one of the first metals used by mankind and has a very long tradition in architecture – the Romans used golden bronze to cover the roof of the Pantheon and many of the great churches of medieval Europe were covered with copper. Its distinctive green patina still plays a major part in the skylines of most European cities, demonstrating timeless and enduring qualities.

Nowadays, copper can provide a complete external skin, wrapping around complex building forms with material continuity. Surfaces can be flat, curved or faceted and used at any inclination or pitch, and in any environment. But also, many designers have been keen to explore new manifestations of copper. In addition, there is growing interest in the use of copper for interior design.

There are many reasons to consider copper and copper alloys for architectural projects and not simply because their unique properties make them extremely malleable and versatile building materials to work with. The broad range of architectural possibilities offered by this natural material and its alloys allows for singular design, and conventional thinking to be challenged.

Visually, the aesthetic qualities of copper materials add character and quality to any project, whilst lightweight nature of their structure permits creative and cost-effective structures to be designed.

The natural development of a patina, with colours changing from red to chocolate brown, and eventually to the distinctive light green, is a unique characteristic of copper. Prefabricated systems offer a wide variety of solutions, while perforated and expanded copper sheets add new possibilities for transparency.

WHY COPPER?
1. natural material
2. environment-friendly
3. maintenance-free
4. durable, long lasting
5. 100% recyclable
6. corrosion-resistant
7. non combustible
8. waterproof
9. proven architectural material
10. malleable, not rigid
11. lightweight
12. homogeneous material
13. timeless, living surface
14. colorful and varied
15. creative and unique

In these days when ecological considerations in relation to the choice of construction materials have joined aesthetic and economic aspects, the impressive sustainability and environmental credentials of copper have been clearly demonstrated. Copper products include high levels of recycled materials, saving on energy and greenhouse gases, and contributing to the circular economy. In addition, copper scrap can be re-used ad infinitum without any loss of performance or qualities.

Maersk Building, Copenhagen, Denmark
Architect: C.F. Møller
Photo © Adam Mark

Front Cover: The Christie, Manchester, UK
AFL Architects

Back Cover: Novotel Paddington, London, UK
Dexter Moren Associates

Maersk Building, Copenhagen, Denmark
Architect: C.F. Møller
Photo © Adam Mark

The facade is built up in the form of a grid comprising stringy-high window fields that break up the building’s large scale.

Copper Concept 1997

Maersk Building, Copenhagen, Denmark
Architect: C.F. Møller
Photo © Adam Mark

The facade is built up in the form of a grid comprising stringy-high window fields that break up the building’s large scale.

Copper Concept 1997
Most copper is produced from open-pit mines and reserves are plentiful with deposits worked in all five continents. Usually, mines operate with copper concentrations of between 0.2 and 1%, although some of the richest ore bodies can contain 5-6% copper. Copper is extracted from ore, mainly copper sulphides, and transformed through various processes into high-purity copper (99.99%).

Another important source of copper is recycled scrap. Copper is one of the few raw materials which can be recycled ad infinitum without any loss of performance; there is no difference in the quality of recycled copper (secondary production) and mined copper (primary production).

European copper products for architectural applications are produced including high levels of recycled materials, typically 85% or more with scope up to 100%. As well as helping to satisfy the annual demand, recycling copper is a highly eco-efficient way of reintroducing a valuable material back into the economy, saving energy and reducing CO2 emissions.

While copper has always been naturally present in all environments, anthropogenic (man-made) emissions have been added in the last centuries – for example through the wear of brake pads or the use of salts in agriculture – and it is necessary to know whether these new additions of copper could be a matter of concern.

COPPER, THE RECYCLING CHAMPION

In 2015, 3.7 million tonnes of copper were used in the EU. Most of this is produced from ores not already mined or from secondary raw materials that need met by recycling.

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It is estimated that only 1% of the overall amount of copper that enters into the environment from anthropogenic sources can be attributed to copper from architectural surfaces. Research also shows that the bioavailable portion of copper in the runoff is quickly and considerably reduced as copper ions react with the environment – for example, in contact with solid surfaces such as pavement, limestone or rainwater pipes – forming non-available complexes and compounds in the immediate proximity of the roofs and facades. Reactions with organic matter, such as decaying leaves, could reduce the bioavailable portion even more.

This is indicated by the fact that runoff and discoloration appear always on a relatively short length, after rain water from gutter touches pavement, following the direction of the water. Where copper content of rainwater run low, these strips end, because water doesn’t transport copper anymore.

Much scientific research has demonstrated that extensive use of copper to clad buildings is environmentally safe. In addition, studies evaluating the dermatological and oral effects of a number of copper compounds have also demonstrated that copper roofs and facades do not pose any harm to human health. In conclusion: copper runoff from roofs should not be a matter of concern.
SUSTAINABILITY AND GREEN CREDENTIALS

European copper products for architectural applications are produced according to EN 1172 specifications in world class plants with strictly monitored environmental performance and well-established recycling routes. They include high levels of recycled materials, typically 85% or more with scope up to 100%, saving on energy and greenhouse gases, and contributing to the circular economy. Copper sheets (copper massive) interaction with the environment has been assessed under the European REACH chemical policy and has no classification/restriction. Copper occurs naturally as part of the cycle of metals which form in nature, being used by society and returning to nature or being recycled for further use by society. The economic value of copper drives recovery and recycling, not just of copper but also many other materials during dismantling and demolition. Copper is long lasting, can be used in challenging environments and installations are, for the most part, maintenance free resulting in savings in resources, cleaning chemicals and costs.

The recycling of copper is a well-established practice and its extent follows overall consumption patterns. This is due to the relative ease compared with other metals, of re-using both processing waste and salvaged scrap from eventual demolition, as well as the incentive of copper’s value. Copper can be recycled again and again without any loss of performance or qualities. For simplification, too many tools have used non-robust and unfair assumptions, resulting in extremely misleading comparisons. Easy mistakes to make include:

• comparing energy and cost per tonne rather than per m2 of material, thus misrepresenting thinner, lighter materials such as copper
• missing the cost and environmental benefits for complete construction of lightweight materials
• using inappropriate life span estimates, thus adding energy use for unnecessary replacement
• disregarding today’s efficient recycling practices.

As a recommendation, architects should focus their comparisons on: Primary Energy; Ozone depletion potential; Acidification potential; Eutrophication potential; and Photochemical Ozone Creation potential. These are impact categories that are well-known, global and mature – rather than other lesser known, non-robust and erroneous comparative indicators, especially in the field of toxicity, land use and resource use.

For more information, visit copperconcept.org/en/references and turn on “green building” filter or scan QR code.

GREEN BUILDINGS ON COPPER CONCEPT

The Eden Project: The Core, UK
Architect: Grimshaw Architects
Photo © Peter Cook
It is the education centre for the largest plant enclosure in the world, built in the lightest and most ecological way possible.
A key feature of the building is the 3,000m² copper cladding, which has 65% recycled content. Architectural copper can be produced out of 100% recycled content and can be recycled again in the future.
The European Standard EN 1172 – ‘Copper and copper alloys. Sheet and strip for building purposes’ specifies the composition and mechanical properties for copper and copper alloy sheets and strips used in building construction.

Copper is generally applied as a lightweight covering, requiring less supporting structure than many materials. With a low thermal expansion value, properly designed copper roofs and facades minimise movements due to thermal changes, avoiding deterioration and failure.

As evidenced by the following copper-clad projects, copper can be worked at any temperature and does not become brittle in cold weather:

• Capanna Regina Margherita - the highest mountain hut in Europe, placed at 4554 m, near the top of Monte Rosa Massif.
• Svalbard Science Centre - located in the north of Norway, where in winter months the average low temperatures fall below -10°C.

In addition, the high melting point of copper ensures that it will not ‘creep’ or stretch in hot weather, as some other metals do.

Copper is also classified as A1 (non-combustible material) in accordance with EN 13501-1; the highest ranking available. Copper and copper alloy sheets and strips are non-combustible and release neither fumes nor toxic gases. In case of fire, experience proves that copper acts as a barrier against the propagation of fire.

No other roofing material exists with similar elongation. Accordingly, copper is extremely formable, which makes it the most appropriate material for cladding complex forms.

Copper products (sheets and strips) can be supplied in a range of conditions or “tempers”. These conditions are designated in the Standard EN 1172 as soft (R220), half-hard (R240) or hard (R290). The letter R represents the tensile strength (in N/mm²); the higher the value, the stronger and harder the material.

MECHANICAL PROPERTIES OF COPPER

<table>
<thead>
<tr>
<th>Material</th>
<th>Designation</th>
<th>Condition</th>
<th>Symbol</th>
<th>Rm min.</th>
<th>max.</th>
<th>Rp0,2 min.</th>
<th>max.</th>
<th>A0 mm %</th>
<th>HV min.</th>
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<tr>
<td>Cu-Zn0,5</td>
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<td>CUZn0,5Sn1CW1170</td>
<td>R290</td>
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<td>-</td>
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The strength and hardness of copper can also be increased by alloying – that means that copper alloys have less workability (bending with low radius of curvature) but higher rigidity. They fit better for facades, where perfect planarity and resistance to impact and wear are required, and the material must be able to support its own weight.

The coefficient of thermal expansion of copper is one of the lowest among metal cladding materials: 1 m has a thermal expansion of 1.7 mm with a temperature difference of 100 °C.

 While the tensile strength of the so-called soft copper is lower, it is easily deformable and its minimum flexural radius value is smaller. Half-hard copper is stronger, but less flexible and less bendable.

For difficult-to-clad forms, where bending of sheets, drawing-out of seams, anchoring orbossing is required, it is better to use soft material, while in the case of continuously plane surfaces, manufacture of cassettes and profiled sheeting half-hard condition is advised.
The resistance of copper exposed to atmosphere has been measured under the supervision of the American Society for Testing and Materials (ASTM): tests have been carried out to evaluate the effectiveness of passivation, by measuring the thickness loss of sheets exposed for 20 years to different atmospheres. The results show an average yearly loss of 1 μm (one thousandth of millimetre), with the thickness loss decreasing with patination increasing.

The lifespan of copper roofing and cladding can therefore be regarded conservatively as 200 years, subject to substrate and structure – and this is endorsed by experience. Naturally, this has a significant effect upon comparative whole of life assessments in terms of energy consumption, CO2 generation and cost.

In addition, copper is 100% recyclable, without losing its original properties or performance. If demolition or renovation is needed, it can be recovered, saving natural resources and energy, while maintaining its value.

<table>
<thead>
<tr>
<th>Atmosphere Type</th>
<th>Thickness Loss (μm/year)</th>
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</thead>
<tbody>
<tr>
<td>Marine</td>
<td>0.5 - 1.27</td>
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<tr>
<td>Industrial</td>
<td>1.40</td>
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<tr>
<td>Industrial-marine</td>
<td>1.38</td>
</tr>
<tr>
<td>Rural</td>
<td>0.13 - 0.43</td>
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</table>

"Copper leaves plenty of opportunities for creativity and is known for its exclusivity and uniqueness of realised projects."
COMPATIBILITY OF COPPER WITH OTHER BUILDING MATERIALS

Corrosion in metallic materials on the outside of buildings can be caused for two reasons. The first is of a strictly galvanic type, i.e., when two different metals are in direct contact. The other is caused by runoff from one metal surface onto another metal surface.

Due to its placement on the positive side of the electrochemical series, copper is not negatively affected by other metals. However, if wrongly combined, other metals like zinc, aluminium and steel could be affected by copper. Therefore, building structures should be designed in such a way as to avoid contact – both direct and indirect – between these metals.

The combination of copper with stainless steel is harmless under most circumstances. Care should be taken in detailing any steel above copper as ‘rust’ marks can appear on the copper caused by iron rust drips from the steel.

A combination of copper and aluminium is only possible when the aluminium has an electrically non-conductive surface, after coating or anodising. In this way, copper-bearing runoff cannot form an electrochemical reaction with the aluminium. Direct contact between the metals should be prevented by inserting an intermediate layer of non-conductive material or by simply leaving a gap.

Arrangement of copper above zinc or galvanised steel should be avoided, because the copper ions washed away in the rainwater which then drains onto the zinc react with it, resulting in accelerated corrosion of the zinc. The opposite arrangement, of zinc above copper, is harmless. However, no direct contact points between the metals must exist.

It should also be noted that rainwater running off bitumen exposed to the sun can cause corrosion problems for various materials – including copper – and certain residues washed out of concrete or mortar can cause copper to take on a blue-green colour, so it is worth preventing. Also, the wash-off from red cedar shingles can cause metals to corrode.

WINDOWS PLACEMENT IN A COPPER FACADE

Window types such as wooden windows, copper-clad wooden windows, bronze framed and plastic windows do not normally generate corrosion. There are a number of window manufacturers that are specialists in delivering copper-clad wooden windows. Here, there are many possibilities for design effects with the aid of different profile solutions.

Anodized aluminium windows and windows of lacquered aluminium can also be used. It is, however, important to avoid direct contact with the copper surfaces and make sure that runoff from the copper surfaces will not run onto the aluminium surfaces. To eliminate the runoff-effect, the windows can be placed deep into the facade or alternatively protruding with an outside window flashing. It should be noted that cut aluminium profiles often have an untreated surface where the cut has been made. These surfaces will have to be treated to give a lasting corrosion protection.

Many effective runoff solutions can be reached with the aid of different types of joints and drop aprons. It is usually not the heavy runoffs that create corrosive problems; the ion level in those is often low as it is being diluted in large quantities of water. Dew and small quantities of rain, on the other hand, often mean aggressive water runoff.

Residential house, Amsterdam, The Netherlands
Architect: Hund Falk Architecten
Photo © Ivan Brodey
A flat wall completely covered with double-sided preoxidised copper tape and flat black aluminium frames provide an abstract view of the former buildings.
ARCHITECTURAL QUALITIES

COLOUR AND PATINA

When exposed to the atmosphere, the appearance of copper surface evolves through several phases from installation to the natural development of patina – this is a unique characteristic of copper. A full understanding of this process is important for building designers.

Immediately after installation, oxidation starts on copper surface exposed to natural weathering, the influence of which becomes visible very soon. Gradually, the surface turns matt and the material develops a protective oxide layer, changing its colour to russet brown. As weathering progresses over a number of years, the surface increasingly darkens to a chocolate brown.

Continued weathering can then result in development of the distinctive green patina – green-blue in marine environment. The patina layer provides impressive protection against corrosion and can repair itself if damaged, defining the exceptional longevity of copper cladding.

A certain amount of rainwater is necessary to form the green patina and its rate of development will depend on the water “dwell time” on a surface. As a result, the process takes much longer for vertical surfaces than exposed roofs, due to rapid runoff. In coastal areas vertical surfaces patinate quite readily.

Airborne pollution also increases the rate of patination, which therefore takes longer in cleaner environments than in cities or industrial areas. The complex combination of factors determines the nature and speed of development of patination, giving copper unique, living visual characteristics developing over time in response to local conditions.

Many architects and owners want to see the dark brown colour or the distinctive green patina right from the moment of installation, without waiting several years or decades for the gradual changes caused by natural weathering – even in situations such as vertical cladding and sheltered surfaces where rainwater driven patination might never occur.

Different surface treatments are now available which create very similar processes to those taking place over time in the environment and the leading manufacturers are able to provide oxidation and patination straightaway.

Pre-oxidised copper offers the aesthetic appearance of an attractive, naturally oxidised surface immediately. In addition, it minimises any surface markings which might occur on bright mill finish copper and can advance the natural patination process through the effects of sun, rain, snow and wind.

Pre-patinated copper is, of course, useful in the field of historic building preservation. But its potential is most exciting when considered as a completely modern building material, combining the distinctive green colour with the freedom of form available with copper. After installation, the surface continues to develop in a completely natural manner being characteristic of copper.

Meripaviljonki (Sea Pavilion), Helsinki, Finland
Architect: Arkkitehtitoimisto Freese Oy
Photo © Esko Tuomisto

The choice of copper recognises the material’s sustainability credentials, long-life, minimal maintenance and beautiful patination. Photos taken 2014 and 2016 (weathered).
COPPER ALLOYS USED FOR ARCHITECTURE

There are more than 400 copper alloys, each with a unique combination of properties, to suit many different applications. Some of them – bronze, brass and golden alloy – are used in architecture, for roofing and cladding, thanks to several concomitant factors such as extreme durability, singular beauty and mechanical resistance. These copper alloys used in architecture also display individual characteristics as they weather naturally to exteriors. They are installed especially in facades, but they can be exploited for roofs as well. In addition, their colours can be slightly modified, for example by applying a wax, in order to provide appealing nuances to the surface.

**BRONZE**

An alloy of copper and tin and a synonym for metallic artworks. While artists have long made use of bronze, architects are now able to make optimum use of this material. It is also well-known in technology, especially where high resistance to wear is required (such as springs, gears and bearings).

In architecture, bronze is appreciated for its rigidity, resistance to wear, long lasting and resistance to corrosion. Its reddish-brown surface, when exposed to the atmosphere, gradually changes to dark brown anthracite in a manner characteristic for bronze through the effects of weathering. The patina coating forms much more slowly than with pure copper.

**GOLDEN ALLOY**

This is an alloy of copper with aluminium and zinc that shows an excellent corrosion resistance and very high mechanical properties (strength and wear resistance), due to the formation of a thin, hard, protective oxide layer containing all three alloy elements. For these reasons, it is also used in coins – the 10, 20 and 50 euro cents are made of CuAl5Zn5Sn1.

Aesthetically, it has an outstanding golden colour, with very little tarnishing over time, developing an elegant and long-lasting, matt gold coloured appearance.

**BRASS**

An alloy of copper and zinc with a distinctive golden yellow colour. The presence of zinc improves the mechanical strength and the hardness. Thanks to this improved strength, brass sheets used in architecture can support better their own weight as well as withstand unexpected impacts.

When exposed to the atmosphere, the original surface tarnishes and gradually turns into dark brown. Ultimately, it may develop a patina but much slower than copper. In addition, brass is really well-suited for interiors and its surface can be treated to provide a brownish finish.

**GARDEN MUSEUM, LONDON, UK**

Architect: Dow Jones Architects

Photo © David Grandorge

The pavilions are clad in bespoke bronze shingles set out to reflect the scale-like quality of the bark of the surrounding plane trees.

**COURTHOUSE, ST. PÖL TEN, AUSTRIA**

Architect: Christian Kronau

Photo © Thomas Ott

Through the inherent richness of the material, the building gets a pleasant and warm character that varies continuously, depending on changing light conditions over time.

**FERRY TERMINAL, STOCKHOLM, SWEDEN**

Architect: Marge Arkitekter

Photo © Johan Fowelin

Roofs and walls are clad with burnished brass, which harmonises well with the stone and stucco facades in the background and creates a unified, sculptural expression. In addition, variations in surface texture are achieved using different techniques.

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The structural formation of metal-plate claddings has been refined in the past centuries on the basis of characteristics of the material. Cladding metals are used in manufactured forms that are thin (0.5-1.5 mm), but have large surface. It is a consequence also of this fact, that the dimension of these plates change significantly on the influence of heat, and as roofing materials, they are frequently exposed to even 100°C difference of temperature.

The roofing must accommodate the dimensional changes caused by thermal expansion and at the same time it must fully satisfy requirements for roof membranes, i.e. they must be waterproof, frost-resisting, durable and strong.

Sheet metals used for roofing – and copper is outstanding among them – are easily formable and leakproof. The dimensions of trays must be selected and joints formed in ways that they must be able to tolerate thermal movement while preventing the infiltration of moisture along these joints.

It is a basic principle in case of any type of roofing that metal cladding sheets are never fixed in a non-removable way directly onto the substrate. Meeting sheets are adjoined by multiple splicing (seam) to each other and are fastened to the surface to be covered onto fixed retainers (cleats, lock strips) after folding.

Through this solution, expansion gaps are formed and trays are able to tolerate dimensional changes caused by the influence of heat without visible deformation, corrugation or other damages.

In practice, two types of roofing are common: standing seam roofing and batten seam (or batten roll) roofing.

Standing seam roofing is made up of trays arranged square to the cornice (i.e. parallel to the slope line) and are connected to each other with double standing seams. It is applicable for slopes above 3 degrees.

Generally, cleats are used for fastening copper to the substrate, with copper nails where two neighbouring trays meet. Cleats are folded together with trays to create the seams. Trays are fixed this way, but being an indirect fastening method, the joint allows some movement.

When laying trays, workers must leave gaps of a few millimetres to enable them to accept transversal thermal movement.

The usage of sliding cleats is a specialty of copper cladding. These consist of two parts capable of moving off from each other and allow an even greater thermal motion.

Montevergine Sanctuary, Mercogliano, Avellino, Italy
Architect: Studio Arch Luigi Picone
The machine-rolled copper sheets have been installed onto supporting wooden boards as double standing seam system.

For continuous fastening along a line, lock strips are used, which are fixed directly to the substrate on the whole length or spaced continually, and the sheets are folded on and hooked in them. Batten seam roofing, similar to standing seam roofing, is built up from strips, but these are not fastened directly to each other, but to battens, nailed or screwed on the substrate parallel to the slope line. U-shaped cleats are put under the battens. The whole batten is then covered with batten cladding sheet with drip bordering.

This solution is more impervious than standing seams, because joints are positioned higher. It can be used even in case of 3% slope of a roof.

Both can be made from trays assembled from sheet or strip cut to the length of the rafter or from prefabricated, profiled strip elements.
A major sports building mutates its straightforward rectangular plan into a complex faceted copper rooftop.

The Orangery, Huizen, Netherlands
Architect: Braaksma & Roos Architectural Office
Photo © ECI
The entire roof is covered in prepatinated copper, same as the bays of the Mansion. Pre-patinated copper perforated screens are used in front of doors and on east elevation.

Sport and Leisure Centre, Budapest, Hungary
Architect: T2.a Architects
Photo © Zsolt Batár

A major sports building mutates its straightforward rectangular plan into a complex faceted copper rooftop.
Another type of roofing is where prefabricated profiled sheets are used, which is akin to fluted sheets made of any other metals. It is assembled from corrugated panels fitted with retainers. The system allows very quick work on large plane surfaces in the frame of a previously worked out system. The result resembles batten seam roofing.

The roofing system chosen – beyond any aesthetic regards – must be decided by the basic geometry, the slope of roof is a determining factor. Batten seam roofing or the application of profiled sheets gives a sharp-featured image by making large plane surfaces lively. But they are not applicable on arched surfaces or on more complex roof forms; what is more, the installation of batten seam roofing is rather labour-intensive.

Highly complicated roof forms can be relatively easily covered with standing seam roofing. The result will show a homogenous picture, where trays are less accentuated. The width of trays and the thickness of sheets are determined by aesthetic considerations and by the dimensions and relations of the roof, the location of roof superstructures and – last but not least – the wind force affecting the roof.

When selecting a roofing system, the designer must consider the reliability of the structure, its feasibility, etc., taking stock of all architectural and aesthetic requirements.

Le Safran festival hall, Brie Comte Robert, France
Photo © KME

Copper sheet has been used for roofing for centuries; this includes copper shingles (or rhombuses), small-sized metal sheets which have been used for the roofing of domes, facades and other roof areas.

A varied-texture surface can be installed with overlapping scales or shingles, which use the characteristics of the metal. It comprises uniform elements sold by the factory or made on-site. It is assembled from corrugated panels fitted with retainers. The system allows very quick work on large plane surfaces in the frame of a previously worked out system. The result resembles batten seam roofing.

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When selecting a roofing system, the designer must consider the reliability of the structure, its feasibility, etc., taking stock of all architectural and aesthetic requirements.
Copper can provide a complete external skin, wrapping around complex building forms with material continuity. Surfaces can be flat, curved or facaded and used at any inclination or pitch, and in any environment. Alternatively, it can give distinctive character to individual façade elements, particularly when used in conjunction with other high-quality materials such as stone, brick, glass and wood.

Apart from standard copper sheet, there are other copper products that create extra dimensions of modulation, texture and transparency for architectural surfaces. Installation techniques and systems also help to define architectural character – there is an extensive range of factory pre-fabricated systems for facades, as well as copper sheets and strips.

The cladding construction presented here follows the concept of a bracket mounted, ventilated cladding, creating an optimised system that securely envelops the closed, wind-tight inner construction. A ventilation area is generally required for several reasons: to reduce humidity, to allow penetrating rainwater to diffuse out of the construction, to create a capillary separation between the cladding and the breathable thermal insulation or support structure and to diffuse condensation on the underside of the cladding.
SHINGLES

Shingles offer a distinctive “fish scale” appearance with shapes including squares, diamonds, rhomboids and rectangles. These flat tiles are laid simply by hanging them and interlocking them with each other, offering a relevant economic advantage.

Shingles have a 180° folding on all borders – two sides are provided with a fold coming forward or with a downstand. All folds and notches are pre-processed in the factory. This ensures that the corners of buildings and connections to other constructive elements such as windows and doors are completely weatherproof.

PANELS

Panels are cladding elements pre-formed on two sides that can be assembled vertically, horizontally or diagonally to give a linear, striated appearance. Assembly at the building site is performed according to the tongue and groove principle or by overlapping. Individual lengths are as long as 4,000 mm with a width of up to approx. 500 mm.

As panels are not laid in contact with the underlying structure, it is necessary to put a solid material (wood, plastics) between the copper and the structure, especially at ground level up to approx. 2 m, in order to avoid signs and dents due to possible shocks.

CASSETTES

Cassettes are cladding elements with folded edges on all four sides available in a range of rectangular proportions. They are produced project-wise according to the specific design concept. Cassette cladding is suited for larger flat areas, offering great flexibility in terms of formats, the layout of joints and fixing principles.

Fixing is usually achieved by riveting, screwing, hidden/subsurface fittings or by means of bolt hooks to tie the cassettes directly to the substrate.

Special Education School in Dinkelscherben, Germany
Architect: Frech & Mair Architekten BDA, Augsburg
Photo: KME

Horizontal installed panels with visual gap give a specific architectural character of facades.

Clarion Hotel Post, Gothenburg, Sweden
Architect: Semrén & Månsson
Photo © Lennart Hyse

This was made up of copper in three strip heights – 200, 250 and 300 mm – and three different intensities of pre-patinated copper, by varying the amount of green over the dark brown background.

Field Street/Lekke Street, London, UK
Architect: Project Orange

The external façade is clad in oxidised copper scales that overlap and soften the dominant geometry of the building.
TRANSPARENT STRUCTURES

The copper industry is continuously developing new products in order to enhance the aesthetic merits of copper and copper alloys used in architecture, as well as to expand the freedom that architects can enjoy by working with copper.

One of the latest products are the perforated and expanded copper sheets and strips which add new possibilities for transparency and can be individually manufactured to the vision of the architect.

Perforations on copper sheets and strips offer many possibilities for singular design, including subtle patterns, images and even text. Many different levels of transparency can be created – from almost complete transparency to a subdued translucence.

The effect of back-lit facades can be designed very individually by using a large number of different perforation patterns. There are also virtually no limits to the use of perforated copper and copper alloys as decorative indoor elements.

Expanded mesh structures are made by perforating and then stretching the material to create a metal curtain with functional aesthetic qualities. The many different structures of the copper rib mesh provide openness and create a solid barrier, offering both transparency and mechanical protection.

On the building, the use of copper mesh designs brings a pleasant lightness to the facade. When installed in front of glass areas, they offer security in an aesthetic form as well as fascinating impressions from inside and outside.

Centre Culturel Alb’Oru, Bastia, France
Architect: DDA Devaux & Devaux Architectes
Photo © Jean-Braico

The transparent copper alloy mesh facades encase open circulation routes around three sides of the building, generating external spaces for reading and enjoying the views. At night, the building becomes a glowing beacon with internal lighting shining out.
DYNAMIC FACADES

The building facade has to protect the building and to act as its face to the outside world. It must have a durable, weatherproof sealing layer – a surface which protects it against the wind and weather and is simple to maintain. In addition, the outermost layer of the facade must be combined with an effective, functional insulating material.

But in the last few years, another function has been added to the well-known aesthetic, weatherproof and insulating facades’ functions – the optimization of energy consumption. Either through passive shading and ventilation or through complex systems, the building skin transforms dynamically to regulate the internal environment in order to reduce its energy demands.

Of course, copper has a prominent role to play in dynamic facades. Durable, malleable and scalable, it is a material of choice for architects who innovate in designing functional cladding. In the form of copper sails or strips, they are able to better manage light and heat, and improve the energy performance of buildings. In the form of a raw surface that evolves over time, the façade gives life to a building and becomes the key to its environmental integration.

DYNAMIC FACADES ON COPPER CONCEPT

To discover more project examples and information on dynamic facades go to copperconcept.org/en/references and turn on “dynamic facade” filter or scan QR code.

Merchant’s house, Copenhagen, Denmark
Architect: HUS arkitekter AS
Photo © Jens Markus Lindhe

Areas of the copper curtain can simply fold up to generate a pattern of fenestration matching that of the adjacent buildings. When closed, the curtain becomes homogenous and impenetrable – but then dissolves to reveal the interior with lighting at night.

Conservatoire Claude Debussy, Paris, France
Architect: BasaltArchitecture architectes
Photo © Sergio Grazia

A skin perforated by the beat of the melody that emerges and takes shape in the outer walls.

Responding to changes in urban life—both organisational, technological and societal—architects and town planners must innovate. Dynamic copper façades enable modern buildings to interact with their environment, and can limit the use of artificial lighting and heating, regulate aeration, light or transparency, and create unprecedented visual effects.
Copper and its alloys allow great architectural creativity, and are the go-to materials for functional façades thanks to their malleability and ease of installation. Copper sheets are lightweight, easy to work and assemble, aesthetically pleasing and extremely durable without maintenance. A wide range of finishes are also available: smooth and glossy, perforated, embossed, pure or alloyed, raw or pre-patinated.

Copperconcept.org 3534 Copper in Architecture 2019

La Monnaie de Paris (Paris Mint), France
Architect: AAPP / Philippe Prost
Photo © Benjamin Chelly and Aitor Ortiz
Creating an architecture where the chosen materials evoke the expertise of the practitioners working inside the house.

Experimentarium - The Helix Staircase, Copenhagen, Denmark
Architect: CEBRA
Photo © Adam Mørk
An entirely new architectural setting that brings science and technology into focus – from the illustration of fluid dynamics on the facades, to the spectacular Helix staircase that meets the guests as a shining icon immediately upon passing the main entrance.

DESIGN CONTINUITY
As a roofing material, copper has traditionally been used to form associated elements such as flashings, vents, gutters and downpipes. Modern design took this further with the growing use of copper for vertical cladding, rain screens and curtain walling, focusing on copper as a comprehensive skin to express building form and maintain performance and material continuity. Nowadays, architects continue to exploit this flexibility and freedom of form, with complex shapes made possible by computer-aided design techniques.

Pegasus Academy, London, UK
Architect: Hayhurst and Co.
Photo © Kilian O’Sullivan
A golden copper alloy frontage announces the entrance to this south London school – recipient of several awards, including Winner of the 2015 Architectural Review Schools Award – unifying disparate existing buildings.
A complete roof drainage system is required – with correctly sized gutters and pipes – for the roof to provide effective protection against rain, snow, sleet, etc. It is no less important for the roof drainage system to be designed to withstand the weight of snow and the formation of ice.

The roof drainage system may be based on surface mounted gutters and downpipes or on recessed, built-in systems, or on a combination of these. Gutters and downpipes made of copper must meet the demands of the European standards EN 612 and EN 1462. In particular, the standard EN 612 specifies requirements for gutters and downpipes under the usual service conditions, i.e. catching and draining away rainwater, melted snow or ice water from a building to a drainage system or a sewer outside the building.

The performance of a gutter and drainage system made with standardized products depends not only on the properties of the products, but also on the design, construction and behaviour of the relevant parts of the building.

Maintenance, durability and longevity are important factors to consider when designing gutters and downpipes. Copper is an excellent choice because of its low maintenance, high resistance to corrosion and long life. Even in severe climates such as marine atmospheres, a well-designed copper rainwater system can provide many years of low maintenance service.

The shape and dimensions of a gutter are defined by the quantity of water to be drained away from the roof to the downpipes and by architectural design requirements. The tendency of the guttering to become blocked due to the accumulation of rubbish for example, also has to be taken into account.

There are many different types of prefabricated system on the market, such as semi-circular and rectangular gutters, and lengths of between three and six metres are the most common. A number of bespoke systems are available as well.

In addition, flashings are required to prevent moisture from entering the building by diverting it. Copper is an excellent material for flashing because of its malleability, strength and high resistance to the caustic effects of mortars and hostile environments. Since flashing is expensive to replace if it fails, copper’s long life is a major asset in this application.

Copper cladding offers a good basis for exterior lightning protection because the seams make a conductive covering over the entire surface. Instead of conductor tapes the metal cladding on roofs, facades and gutters may be used as conducting part of the lightning protection system. For further guidance see IEC EN 62305 and national regulations.
It is a basic requirement that the substrate for copper sheets and strips must always be smooth, even and strong, letting nails or screws be securely fixed. The most common substrates for copper are steel trapezoidal sheet, insulated panels and wood, but other materials that meet these criteria can be used as substrates as well. It is also necessary to be sure that the substrate is compatible with copper – for example, the wood may contain fire retardant, preservatives or insect-killers. Concrete and brick structures (e.g. coping) should be covered with a proper layer in order to level their surface, as uneven areas can easily be seen in the finished covering or underlying walls, facade decorations and windows, the mortar screed is enough of a foundation. Hard mineral wool can be used under certain conditions.

With warm roof constructions, rigid insulation panels can provide a suitable substrate. However, fixing becomes more complicated. There are two basic approaches: either to provide two layers of insulation, each laid between battens, with the second layer counter-battened to the first; or to use specially extended fixing clips which pass through the depth of the insulation to an additional nailable substrate beneath. For fastening copper or copper alloy sheets to the substrate copper nails or stainless steel screws, clamps or rivets are recommended to avoid corrosion problems.

Profiled copper (as well as most types of cassettes) is more rigid than flat sheet on account of their design. This means that an absolutely flat surface is not required in respect of bearing strength. However, it is important for the substrate to be sufficiently even and flat to ensure that the surface of the sheet metal does not become uneven or dented.

Substrate and copper must be separated with a tangential separation underlay, which can allow movement in the copper sheeting, provide a temporary weathering for the building during construction, deal with irregularities on the substrate surface and absorb sounds caused by wind or rain at a great extent. There are several types of separation underlay. What is important: it must be durable and must ensure easy diffusion. In most circumstances, industrial felt is the preferable solution, because this material has very good tangential, noise barrier and vapour diffusing properties.

SUBSTRATES FOR FACADES

The seamed copper-clad wall with facade sheeting in the form of strips or sheets requires a firm substrate, as does traditional copper roof, and this substrate must be able to withstand dressing of the sheet and permit clips to be used for fixing purposes. In the case of profiled sheets, panels and cassettes, the technical requirements for the substrate are more or less the same. Irrespective of whether the building is new or being renovated, the underlaying surface must be level. Nowadays, adjustable metal spacers are available which permit even old, uneven surfaces to be fitted simply so that they are level.

The Lizard Lifeboat Station, UK
Architect: PBWC Architects
Photo © Geoff Squibb (Cornish Pixels)

Lofts Antwerp, Belgium
Architect: Hub
Photo © Hub / Platteau Bvba

All Saints’ Academy, Cheltenham, UK
Architect: Nicholas Hare Architects LLP
Photo © Nicholas Hare Architects LLP

The building is predominantly timber frame with glulam-curved members providing the iconic shape. The double skin roof is finished in copper trays with standing seam joints.

The cladling of the chapel was undertaken with real craftsmanship, the copper shingles gradually reducing in size to accommodate the conical shape reaching through the atrium roof.
RAINFALL AND SNOW

Roofs and exterior walls must not be permeable to rain and snow. Where high driving rain is expected, special attention should be given to roof slopes, joints and seam details, eaves, ridges, flashings and connections to higher walls.

Taking into account that a copper cladding is “discontinuous”, proper design and technical solution must be followed in order to avoid any infiltration through the sheets. Continuous sheets must be overlapped and bent together, according to well-known techniques, like the standing seam or the batten roll. The choice of the proper joint depends also on the roof slope.

The height of the standing seam should be 25 mm at least, and the direction of the bending must take into account also the direction of the main wind.

If the slope of the roof is less than 7°, sealing strips should be applied between the sheets, in order to prevent all kinds of ice formation.

In order to avoid the rise of water by capillarity, strips should be applied between the sheets, in particular, at the corners and upper section of the facade. The geometrical design of the building and the topography of the surrounding area.

TEMPERATURE

Roofs and facades are subject to great temperature variations, which in turn give rise to stresses and movements in the material. Primarily the roof, but also the facade, has to be designed with a view to the fact that temperature variations may occur between the external surface and the underlying structures.

Infiltration through the sheets. Contiguous sheets must be overlapped and bent together, according to the proper design and technical solution must be followed in order to avoid any infiltration through the sheets. Continuous sheets must be overlapped and bent together, according to well-known techniques, like the standing seam or the batten roll. The choice of the proper joint depends also on the roof slope.

When it is necessary to use nails, installers must enlarge the hole on the sheet, in order to allow the nail to move freely if it is attached using sliding clips and including a degree of movement at either or both ends. A copper sheet is normally used across the width of the sheet, irrespective of the slope. Lateral movements are absorbed by the basic spacing (about 3-5 mm) irrespective of the slope. Lateral movements are absorbed by the basic spacing (about 3-5 mm) irrespective of the slope. Lateral movements are absorbed by the basic spacing (about 3-5 mm) irrespective of the slope.

A zone of fixed clips is necessary on a roof covered by long strips to secure the copper to the roof. Sliding clips allow the copper sheet to move, expand and contract.

The movements of the strips are assumed to originate from the fixed zone or centre of movement (shaded area in the figure below; sliding clips are placed to secure the sheet above this zone). The recommended strip lengths are exceeded, in order to avoid the rise of water by capillarity.

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INTERRELATIONS WITH BUILDING PHYSICS

GENERAL CONSIDERATIONS

When considering building physics related to metal sheet covered structures, the most important factors are heat transfer and vapour diffusion through the building components that form the roof or the wall. Proper insulation and vapour control are important for low energy, healthy and comfortable buildings.

The roof can be heat insulated in different forms, e.g. with the traditionally used insulating layers placed between and/or under the rafters or with heat insulating panels designed specifically for sheet metal roofing, which at the same time serve as the substrate of cladding.

The partial pressure of water vapour is dependent on room temperature and relative humidity. If there is a temperature difference between in- and outdoors, a difference in pressure arises and different potentials tend to seek equilibrium in the direction of the pressure drop – the moisture diffusion starts from inside out.

VENTILATED STRUCTURES

In case of this solution the outside shell of metal cladding is separated from the insulating and load bearing construction by a ventilating air gap connected to outside air by inlets and outlets. This ventilated air gap works with natural ventilating effect; thus, its effectiveness is dependent on following key factors:

- If the partial pressure of water vapour remains below the maximum possible partial pressure (dependent on temperature) throughout the whole building structure condensation does not occur. As a simple rule building is free of condensation, if:
  - The thermal insulation of construction layers increases from inside to outside: thermal transmittance (U value) becomes progressively smaller from inside to out.
  - The water vapour diffusion resistance of the construction layers decreases from inside to out.

When considering a metal clad building, the first impulse is that this principle is reversed: the metal layer on the outside has the best thermal conductivity and the highest water vapour diffusion resistance. There are two basic ways to solve this problem: ventilated structures and non-ventilated structures.

VENTILATION PATH AND HEIGHT (SLOPE)

Ideally, the best thermal current occurs with the stack effect where the relationship of height and distance is most favourable. As the slope becomes flatter, this relationship becomes more and more unfavourable. The stack effect no longer occurs in roofs pitched below 10°, so in case of such roofs ventilation must go crosswise, utilising wind pressure.

LOCATION AND FORM OF VENTILATION OUTLET OPENINGS

Inlets must be located at the lowest and outlets at the highest point and must be adequately sized.

LENGTH OF THE VENTILATION AREA

Generally, in ventilation spaces greater than 15m long the air current will come to a standstill. If ventilation path length is longer it must be divided into shorter sections.

VENTILATION LAYER GUIDES

A narrowing of the layer, obstructions, interruptions and direction changes in the ventilation layer could cause the air current to stall, which would lead to moisture build-up.
NON-VENTILATED STRUCTURES

Copper has been installed on non-ventilated roofs for many years for design purposes or under conditions that do not allow ventilation (e.g., large, low-pitched roofs). When properly constructed, the non-ventilated structures offer many advantages for sophisticated roof geometry, well insulated buildings in modern architecture.

The efficiency of non-ventilated metal cladding is essentially dependent on the following key factors:

- Installation of an effective vapour barrier ($\delta \geq 100\,\text{mm}$) that eliminates the diffusion of vapour into the roof structure.
- Choice of metal for the cladding which can withstand small amounts of moisture in the roof structure without corroding. Copper is especially well suited because it does not suffer from underside corrosion.
- If an underlay beneath the copper sheeting is used, it must be a breathable membrane otherwise condensation could form underneath the underlay.
- Carefully avoid possible damage of the vapour barrier layer during or after installation. It may cause the penetration of moisture into the structures.

In conclusion, it is clear that in individual cases a decision must be made depending on the building requirements as to which kind of structure should be used – either ventilated or non-ventilated.

In summary, let us suggest the usage of ventilated roofing systems in cases of simple roofs unbroken by superstructures and in cases of great slope angle, while the usage of non-ventilated roofing systems is better in cases of more complex forms.
INTERIOR DESIGN

Besides its popularity in architecture as a thoroughly modern material for roofing, facades and other external architectural elements, copper forms part of the designer’s palette for interior items such as door furniture, handrails and contact surfaces (where its hygienic characteristics are also important), cornice mouldings and detailing (to provide continuity throughout an entire building), and feature elements (like fireplaces and light fittings).

Copper and its alloys are ideal for interior design instead of, or in combination with conventional materials. The surface of copper can be varnished or waxed to preserve its distinctive colour and shine indoors.

Nowadays, there is also a growing trend for wider, innovative uses in interior design inspired by copper as wall, ceiling and floor coverings or copper-clad sculptural staircases. Additionally, copper mesh and perforated copper sheets can be used internally as partitions, screens and other interior elements. Three-dimensional shapes also provide endless opportunities in interior design and decoration.

INTERIOR SUPPLEMENT IN COPPER ARCHITECTURE FORUM MAGAZINE

The Copper Architecture Forum design supplements issued under the title Copper Inside are celebrating the diversity of applications of copper and its alloys inside buildings. Order your free printed copy or read them online attached to issue 39 and 43: copperconcept.com/copper-forum or scan QR code.

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