1 INNOVATIVE MATERIALS

Innovations in materials are influencing contemporary architectural practice. Today, the focus is primarily on new materials that exhibit enhanced properties. Therefore, advanced and composite materials, smart and responsive materials, and biologically inspired materials are gaining popularity in architectural design. Advanced materials are those that have enhanced properties (such as thermal performance, structural properties, durability and so on), and exhibit sensitivity to the environment in terms of production and use. Smart and responsive materials are those that exhibit properties that can be changed or altered, so that they act as sensors or actuators, responding to changes in the environment. These new emerging materials offer radical changes to the built environment in terms of energy usage, thermal behaviour, structural performance and aesthetics. This chapter provides an overview of emerging materials and discusses their use, performance, benefits and drawbacks.

Advances in physical sciences have led to a new understanding of changeable materials, particularly those compromising the acoustic, luminous and thermal environments of buildings. A smart structure can be defined as a non-biological physical structure that has a definite purpose, means and imperative to achieve that purpose, and a biological pattern of functioning. Smart materials are considered to be a subset, or components of smart structures, and act in such a way as to mimic the functioning of a biological or living organism and adapt to changing conditions in the environment. Smart materials can be classified into two general categories – materials that can sense and inherently respond to the changes in the environment, and materials that need control in a systematic manner in order to actuate based on a certain change. Different types of smart materials include piezoelectric, electrochromic, electrostrictive, magnetostrictive, electrorheological, shape-memory alloys and fibre-optic sensors. Piezoelectric materials exhibit significant material deformation in response to an applied electric field and produce dielectric polarisation in response to mechanical strains. Electrostrictive materials exhibit mechanical deformation when an electric field is applied. Magnetostrictive materials generate strains in response to an applied magnetic field. Electrorheological materials exhibit the 'ER response' or 'Winslow effect', which refers to a significant and reversible change in the

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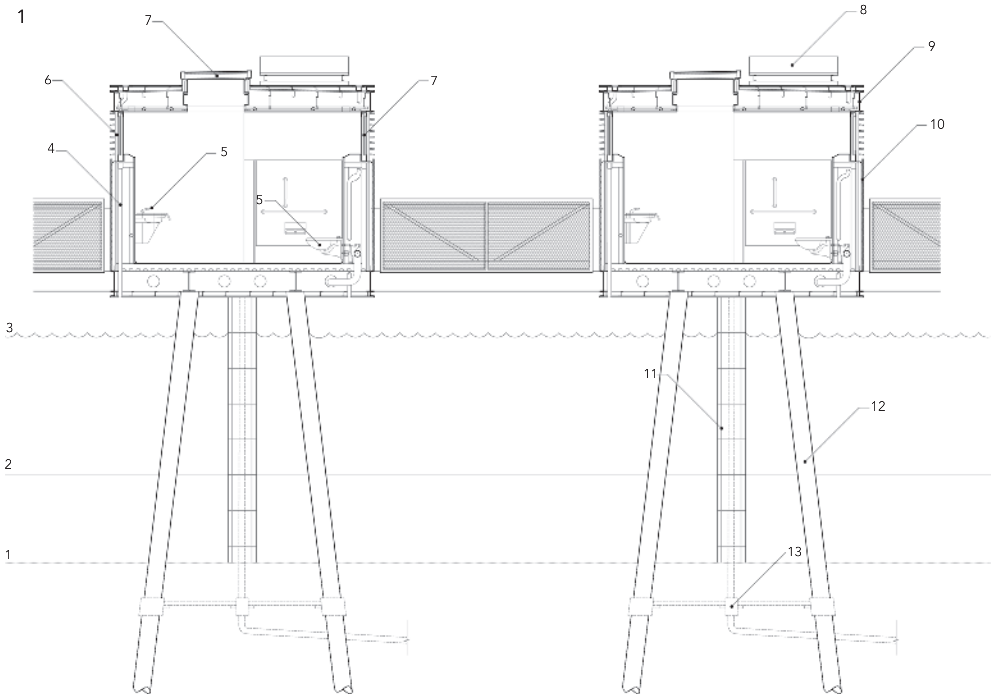

1 Garrison Architects, New York City Beach Restoration Modules, New York, USA, 2013. The section shows building elements and systems. The modules are raised on concrete legs to withstand significant sea level rise.

1 Sand
2 Boardwalk
3 Advisory base flood elevation
4 Building envelope
5 Low flow plumbing fixtures
6 Operable windows
7 Skylights
8 Photovoltaics
9 Galvanised steel frame
10 Fibre-reinforced concrete cladding
11 Pre-stressed concrete pilings
12 Utility chase
13 Piping connectors

2

rheological behaviour of fluids subjected to an external applied electric field – low viscosity fluid converts into a solid substance. Shape-memory alloys are metal compounds that can sustain and recover large strains without undergoing plastic deformation under externally applied stress or thermal changes.

ADVANCES IN CONCRETE

Transforming the design and construction industries are new advances in concrete- and cement-based products. Among many new materials being used are superplasticising admixtures, high-strength mortars, self-compacting concrete and high-volume fly ash and slag concretes. A number of advances in new concrete technologies have been made in the past decade, including materials, recycling, mixture proportioning, durability and environmental quality. There are also diverse new methods and techniques in today's construction world, such as high-performance concrete (HPC) and fibre-reinforced concrete (FRC). Advanced composite materials have become popular in the construction industry for innovative building design solutions, including the strengthening and retrofitting of existing structures. The interface between different materials is a key issue of such design solutions, as the structural integrity relies on the bond between different materials. Knowledge about the durability of concrete/epoxy interfaces is becoming essential, as the use of these systems in applications such as fibre-reinforced plastic (FRP) strengthening and retrofitting of concrete structures is becoming increasingly popular.

Recycled materials are usually added to HPC, thereby reducing the need to dispose of them.[1] Some of the materials include fly ash (waste by-product from coal burning), ground-granulated blast-furnace slag and silica fume. But perhaps the biggest benefit of some of these other materials is the reduction in the need to use cement, also commonly referred to as Portland cement. The reduction in the production and use of cement has many beneficial aspects, including a decrease in the creation of carbon-dioxide emissions and energy consumption. In addition, fly ash and furnace slag have properties that improve the quality of the final concrete and the use of them is usually more cost-effective than cement.

Today's concrete technologies have produced new types of concrete that have lifespans measured in the hundreds of years rather than decades. When compared with standard concrete, new concretes have better corrosion resistance, equal or higher compressive and tensile strengths, higher fire resistance, and rapid curing and strength gain. In addition, the production and life cycle of these new concretes will reduce greenhouse gas emissions by as much as 90%.

Glass-fibre reinforced concrete (GFRC) is a new type of concrete with a much higher tensile and flexural (bending) strength than standard concrete.[2] This glass-fibre reinforced concrete is combined with pre-mixed dry components. It has higher density than standard concrete, and structural systems and building components need less material than conventional concrete for

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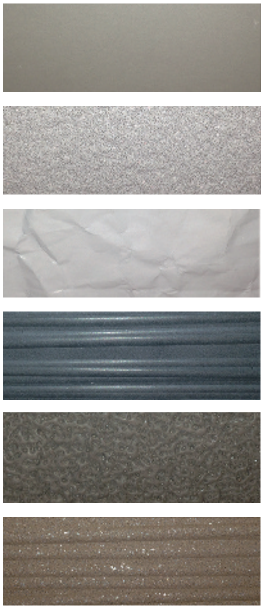
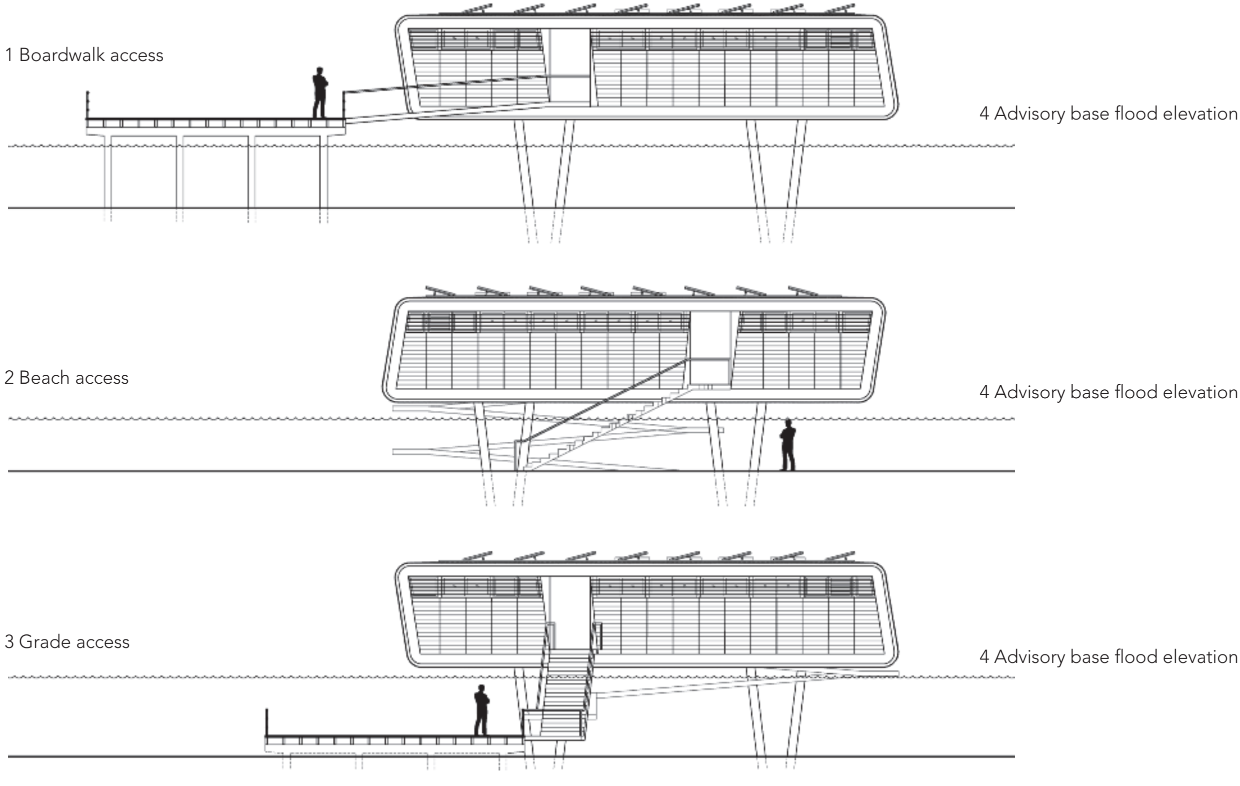


2 (opposite below and below) Garrison Architects, New York City Beach Restoration Modules, New York, USA, 2013.
The beach modules incorporate GFRC panels as facade cladding materials.

3 Surface, colour and finishing textures of GFRC concrete.
A variety of finishing techniques and colours are possible for GFRC concrete facade cladding, so facades can have interesting, dynamic patterns.



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4 Garrison Architects, New York City Beach Restoration Modules, New York, USA, 2013.
Elevations show facade treatment and indicate 500 year flood level.

5 Photocatalysis process for self-cleaning concrete.
The self-cleaning photocatalysis process for concrete consists of two steps: in the first step, UV light triggers an oxidation process on the titanium dioxide-coated surface, breaking down dirt and polluting substances; in the second (hydrophilic) stage, rain washes particles off the concrete surface.

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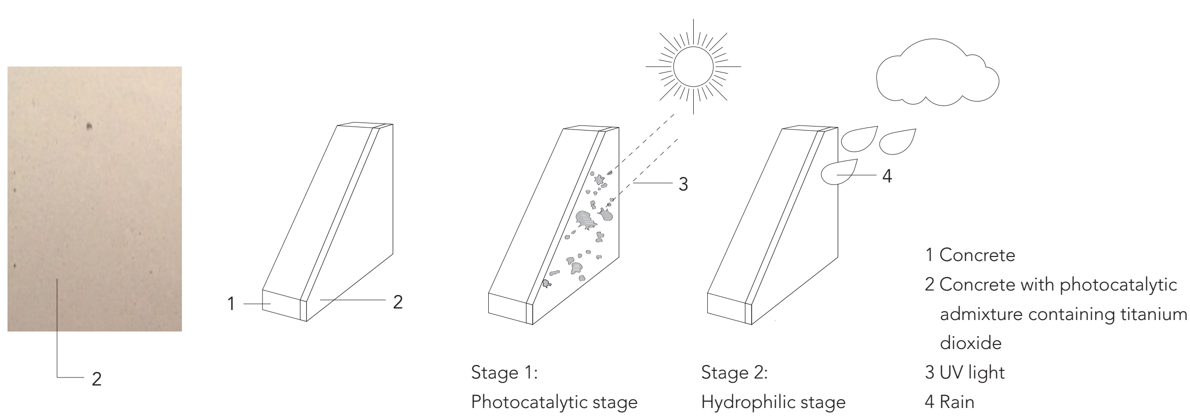

structural stability. This high density gives GFRC concrete other properties, such as extremely high resistance to corrosion from chemicals. The higher strength also eliminates the need for steel rebars in structural designs. GFRC, or a variation with metallic fibres and/or superplasticisers, can be used to build extremely thin structural elements. Overall, structures built with GFRC will have much greater lifespans and require less maintenance. Special surface effects can be created with aggregates and a variety of finishing techniques. New York City's Beach Restoration Modules, designed by Garrison Architects, incorporate GFRC panels. These factory-assembled modules were designed following the devastating Hurricane Sandy that destroyed the coastline of New York City. The modules are mounted on concrete legs, raising the modules above the 500 year flood level, as shown in the sections and elevations. The modules, designed to withstand the next major ocean storm, rely on photovoltaics and a solar water-heating system.

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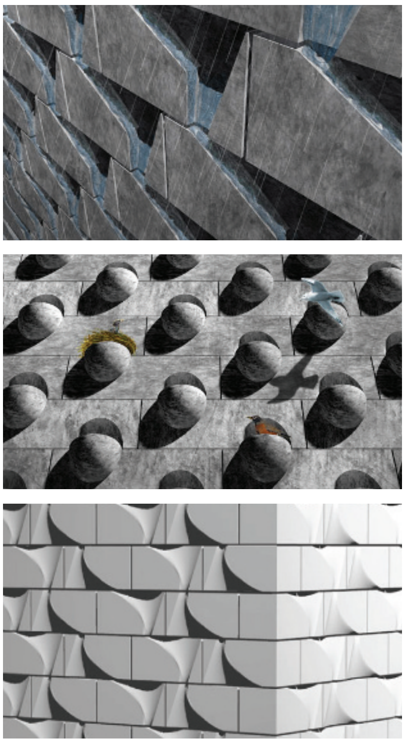

6 Variable surfaces of CMU blocks.
Innovative manufacturing processes result in CMU blocks with assorted patterns, which can be used to create dynamic facade patterns.

Other advances include translucent concrete, which is created by adding optical fibres to the concrete admixtures. This is changing the perception of concrete as a primarily opaque mass. Applications to date have been mainly for interior and decorative use, partitions, and so on. Self-consolidating concrete is a special concrete mix that eliminates the need for mechanical consolidation and yields a smooth surface finish.[3] Insulated concrete form (ICF) walls are gaining popularity in the residential building sector. They consist of rigid thermal insulation that acts as a formwork and stays in place as a permanent substrate after concrete is poured. Since these systems are modular the benefits include rapid construction, improved thermal performance and energy savings.

Another low-tech innovation in concrete is the new concrete masonry unit (CMU) with varying surface geometry, as seen in the pictures opposite, which can be used to create an interesting pattern, form and facade geometry. The manufacturing process uses forms to create projections and voids within the exterior surface of the CMU, which when arranged in a typical wall can create a varied and dynamic facade.

New types of admixtures are also advancing properties of concrete. For example, a polymeric admixture that integrally waterproofs concrete is available and eliminates the need for external membranes. It also protects against corrosion of steel rebar reinforcement, and makes recycling easier after demolition. Self-repairing cement has been developed, which expands the longevity of concrete by reducing porosity. Additives that contain titanium dioxide can create self-cleaning effects, and cement with titanium dioxide (photocatalyst) is available for self-cleaning concrete. Photocatalysts are compounds that use the ultraviolet bands of sunlight to facilitate a chemical reaction. When exposed to sunlight, the titanium oxide triggers a strong oxidation process that converts noxious organic and inorganic substances into harmless compounds. The self-cleaning process involves two stages, as seen in the diagram on page 24. In the photocatalytic

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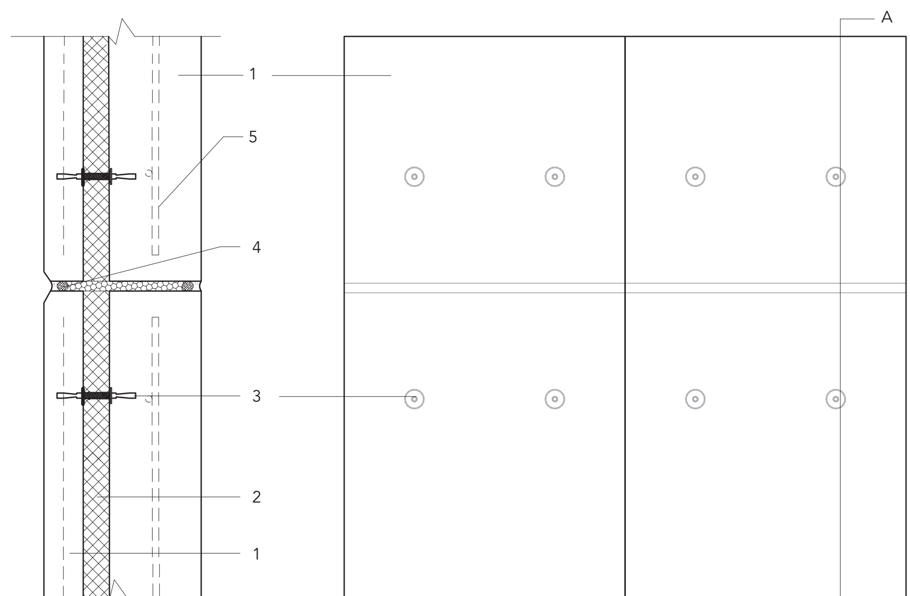

Section A-A

Partial elevation

1 Concrete
2 Insulation
3 Panel tie
4 Backer rod and caulk
5 Reinforcing

9

7 Perkins+Will, School of Business Building, University at Albany, SUNY, New York, USA, 2013.
The concrete cladding facade incorporates a titanium dioxide cement admixture, which creates a self-cleaning exterior surface.

8 Concrete sandwich wall system.
This system consists of high-strength fibre composite connectors, rigid insulation and concrete panels. Thermal performance is improved, since continuous insulation is integrated within the system.

9 Shepley Bulfinch, University of Michigan Cardiovascular Center, Ann Arbor, MI, USA, 2007.
The concrete facade consists of concrete panels, fibre-composite connectors and insulation.

stage, organic dirt breaks down when concrete is exposed to sunlight. Next, in the hydrophilic stage, rain washes the dirt from the concrete by picking up the loose particles. This is an effective way of keeping concrete surfaces clean without high maintenance costs. Research has shown that self-cleaning materials with titanium dioxide also help to reduce air pollutants in dense urban areas.[4] The photograph here shows an academic building (School of Business Building, University at Albany, SUNY), designed by Perkins+Will, which incorporated titanium dioxide cement as an admixture for concrete facade cladding.

Improving the thermal performance of concrete materials and systems has been one of the drivers of innovations for this material type. New pre-engineered, sandwich wall systems that consist of high-strength fibre composite connectors, rigid insulation and concrete panels are available, as shown opposite in the building section. These systems can be applied to tilt-up, precast or cast-in-situ concrete panels and improve the thermal performance of building skins. For example, the University of Michigan Cardiovascular Center in Ann Arbor, by design firm Shepley Bulfinch, uses this concrete exterior wall system. The centre was designed to create an inclusive learning and healing environment for patients, visitors and medical staff.

Composite, cement-based facade cladding materials are available, which are specifically suited for rainscreen facade systems. These materials are lightweight, recyclable and can be manufactured in many different colours and textures. The Giant Interactive Group Corporate Headquarters in Shanghai, designed by Morphosis, uses this type of exterior cladding material. This office building is in a natural setting and blurs the distinction between the landscape and architecture. It contains three zones, one of them cantilevers over a lake. The building's envelope includes a rainscreen facade with cement composite cladding. Another application is the Hyllie Train Station in Malmö, designed by Metro Arkitekter. This new station includes cement composite panels as the roof cladding material.

ADVANCES IN GLASS

Although glass is durable and allows a percentage of sunlight to enter a building, it has very little resistance to heat flow. For glazed facades, the thermal and optical properties of the glazing units must be considered during the design. These properties include the heat transfer coefficient (U-value), solar heat gain coefficient (SHGC), the visual transmittance (Tv), and the light-to-solar-gain (LSG) ratio. The solar heat gain coefficient (SHGC) quantifies the amount of solar radiation transmitted through the glass. It is expressed as a number between 0 and 1, with 0 meaning that no radiation is admitted and 1 meaning that no radiation is blocked. Low-emissivity (low-e) coatings significantly reduce admitted solar radiation and can reduce SHGC for all types of insulated glazing units. Visual transmittance (Tv) is the amount of visible light energy that enters through the glass, expressed as a percentage from 0% to 100%. The higher the Tv of a glazing unit, the more visible light

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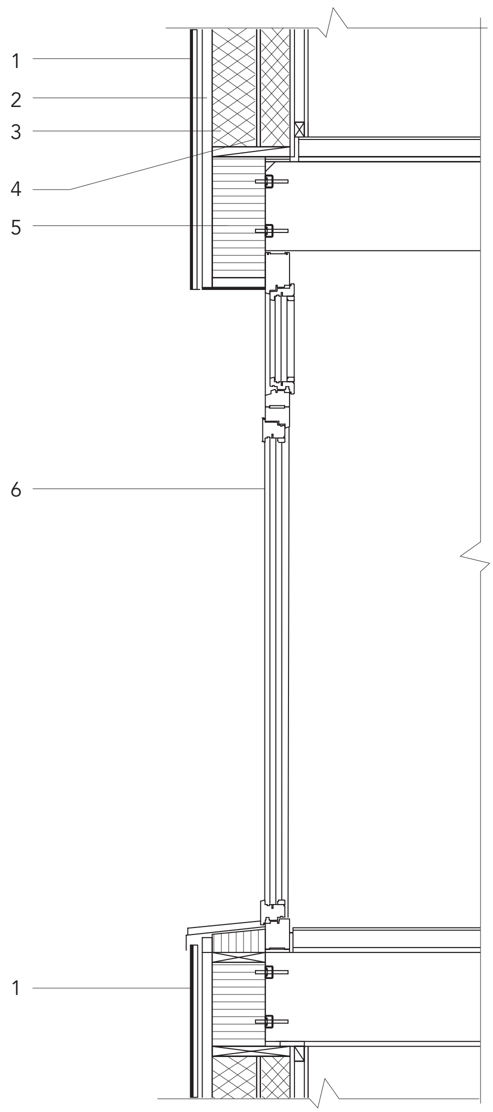

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1 Cement concrete cladding
2 Air cavity
3 Insulation
4 Framing
5 Firesafing
6 Glazing

is admitted into the interior spaces. A high visual transmittance usually means a higher solar heat gain coefficient, so it is necessary to find a balance between allowing light into the building and blocking solar radiation.

During the past two decades, glazing technology has greatly changed. Research and development into types of glazing have created a new generation of materials that offer improved glass efficiency and performance. While this new generation of glazing materials quickly gained acceptance in the marketplace, the research and development of even more efficient technologies continues. Building performance simulations have shown that advanced glazing materials with spectrally selective coatings can reduce cooling requirements.[5] Spectrally selective glazing balances solar heat gain and visual transmittance. The light-to-solar-gain (LSG) is the ratio between the amount of light transmitted by the glass and the amount of absorbed solar heat gain, and spectrally selective glazing has an LSG of 1.25 or more. The LSG ratio is calculated by dividing the Tv by the SHGC for a specific glass product. Facades in colder climates benefit from lower LSG ratios, since some solar heat gain is beneficial for passive heating. Higher LSG ratios are appropriate for facades in warmer climates, to keep solar heat gain as low as possible.

Recent developments in fenestration products using new advances in building technology allow transparent, yet energy-efficient facades. Glazing units can be insulated using two, three or more layers of glass. The spaces between the glass layers can be filled with inert gases or aerogel insulation to lower the U-value of the unit. Low-e, reflective or ceramic frit coatings can be applied to the glass to reduce transmission of solar heat gain. The glass itself can be tinted with a colour. Interlayer films within laminated glass can also provide shading. New glass types are continually being introduced into the market to satisfy a variety of functional, security and aesthetic requirements.

Coatings can be applied to glass to improve its thermal and light transmission performance. Low-e coatings applied to the glass surface can block and reflect some daylight (making the glass look darker and more reflective). Through improvements in the formulation of the coating materials and their application processes, manufacturers are continually introducing better-performing, yet clearer, low-e glass. Because low-e coatings are susceptible to damage and require protection, they can only be applied to the inner surfaces of an insulating glass unit. Also, new types of coatings are being applied to create dynamic glass with changeable properties.

Electrochromic glass incorporates a film that changes its tint when electrical voltage is applied. For example, clear electrochromic glass can change to a dark tint. To return the glass to its transparent state, voltage is applied again. Darkening (and lightening) occurs from the edges, moving inward, and can take several minutes. This type of glass provides dynamic shading control for the building.

10 Rainscreen facade system with cement-based composite cladding material and glazing.
The section shows the application of cement-based composite cladding panels in a rainscreen facade system and other material components.

11 Morphosis, Giant Interactive Group Corporate Headquarters, Shanghai, China, 2010.
Cement composite panels are used as the cladding material for the rainscreen facade.

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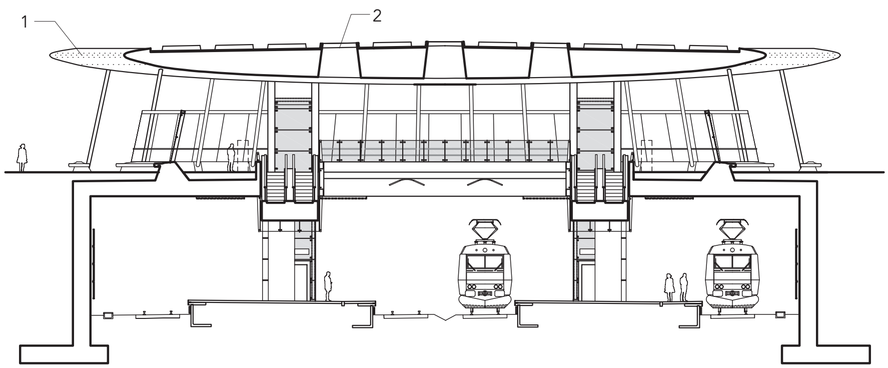
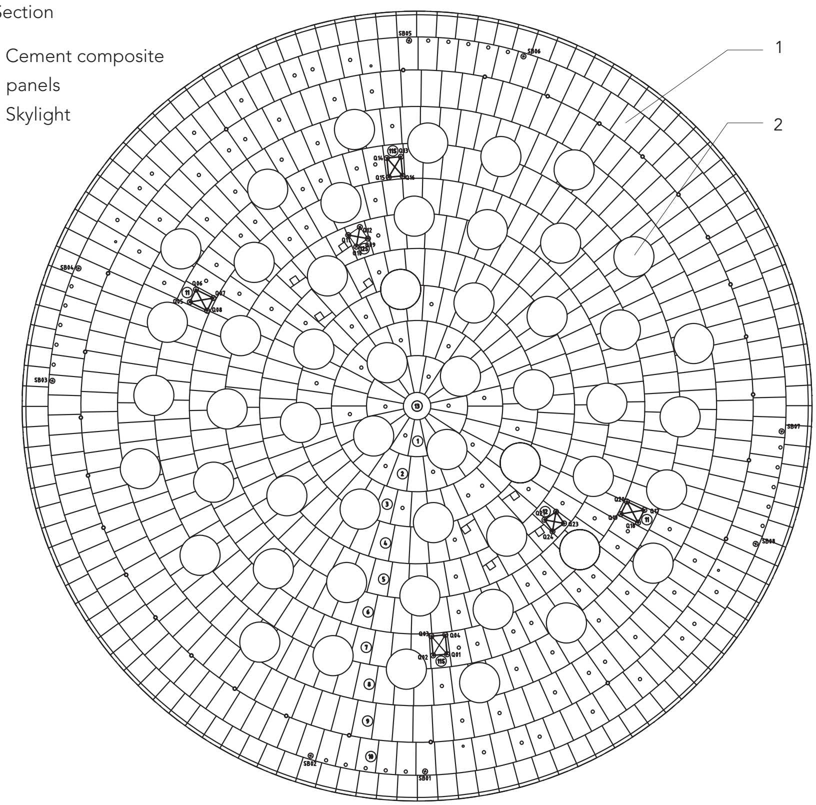


Section

1 Cement composite panels
2 Skylight



Reflected ceiling plan

12 Metro Arkitekter, Hyllie Train Station, Malmö, Sweden, 2010.
Cement composite panels are used as the roof cladding material for this train station.

13 Metro Arkitekter, Hyllie Train Station, Malmö, Sweden, 2010.
Section and reflected ceiling plan showing location and components of the roofing system and placement of the cement composite panels.

14 Components and functionality of electrochromic glass.
The electrochromic coating is applied to the glass surface, which is transparent without an electric current. When voltage is applied, the electrochromic coating changes to tinted colour, so lowering the solar heat gain coefficient and visual transmittance of the glass. This type of glass can be used for shading, as well as dynamic glare control.

15 Studiotrope, Morgan Library, Colorado State University, Fort Collins, CO, USA, 2012.
Electrochromic glass is incorporated into the western facade to provide dynamic shading.

Visual transmittance ranges from around 60% (for clear state) to 1% (tinted state), which is useful in controlling glare. The solar heat gain coefficient (SHGC) changes from 0.41 in the clear state to 0.09 in the tinted state. With this type of glass, the energy consumption of the building can be reduced despite the use of energy to change the tint of the glass. When used for shading applications, solar heat gain can be reduced. Morgan Library, Colorado State University in Fort Collins, designed by Studiotrope, uses this type of glass. The new addition to the library included an entry cube, which has western exposure. Electrochromic glass was used to mitigate harsh solar exposure along this orientation, while still providing views to the outside. The upper and lower floors are zoned separately, so that they can be controlled independently. Exterior light sensors are installed to allow automated control, but the glass can also be manually controlled. Another project that implemented electrochromic glass is the Cascade Meadow Wetlands and Environmental Science Center in Rochester, Minnesota, designed by LHB in conjunction with LKPB Engineers. This science centre includes a reception area, interactive exhibit spaces, classroom and meeting space, science laboratory, conference room and offices. The building site includes a restored wetland, a restored lake, outdoor learning spaces, native gardens and trails. Renewable energy systems are incorporated into the building and

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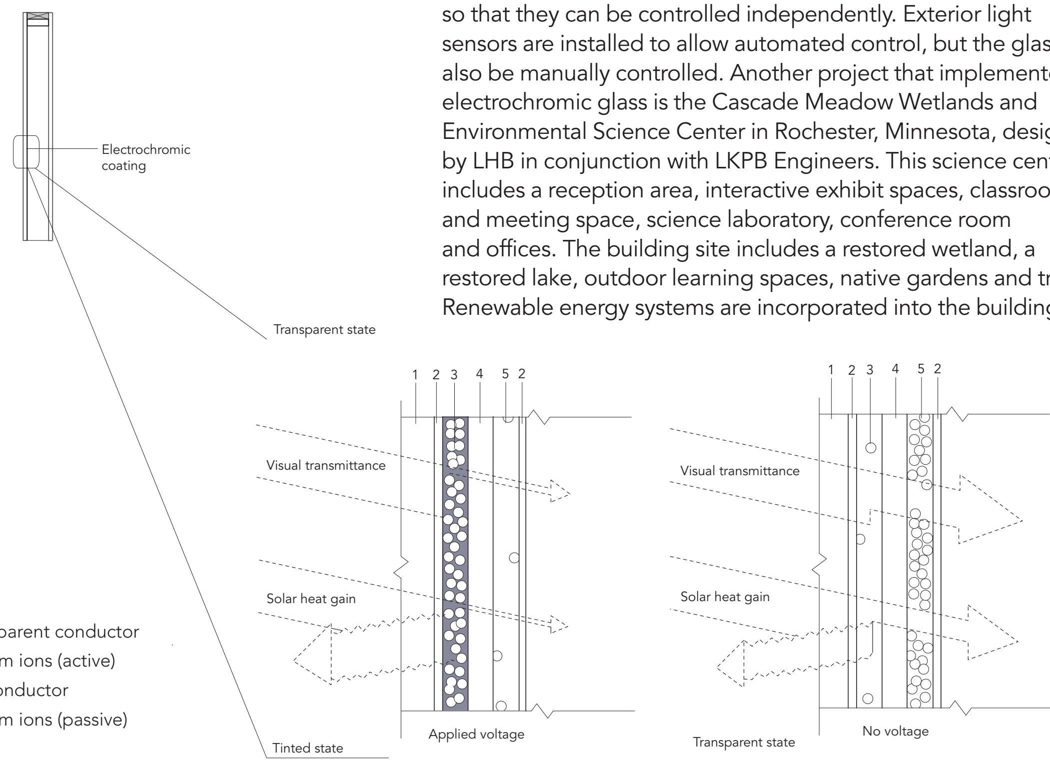

1 Glass
2 Transparent conductor
3 Lithium ions (active)
4 Ion conductor
5 Lithium ions (passive)

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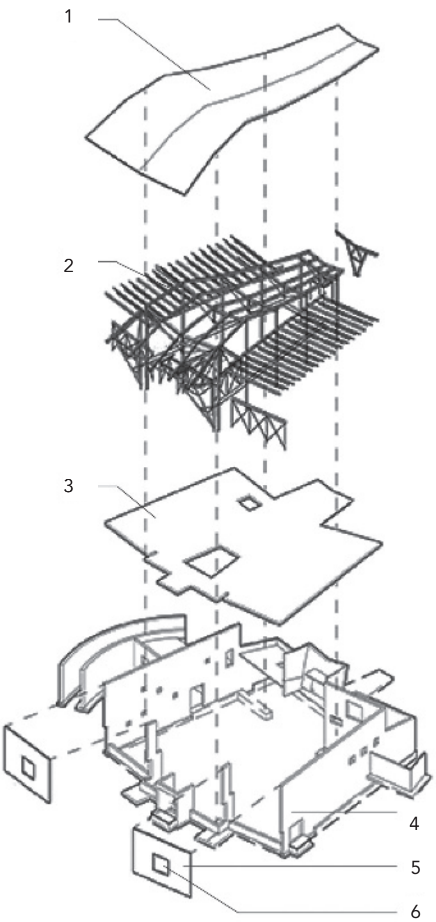
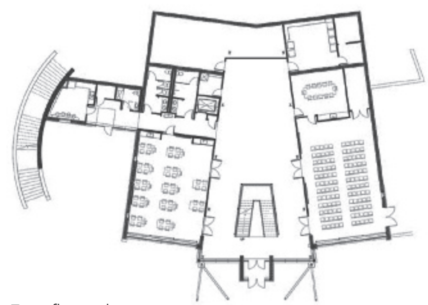
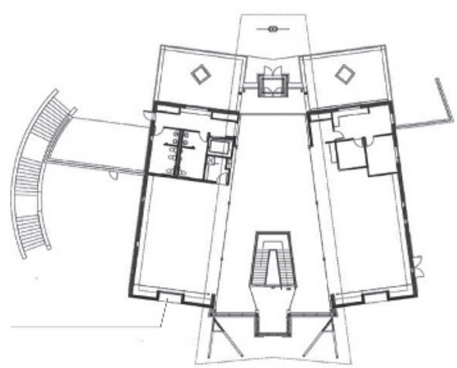


Axonometric



First-floor plan



Second-floor plan

1 Folded-plate roof with SIPs
2 Structural steel exoskeleton
3 Precast plank floor system
4 Insulated concrete perimeter walls
5 SIP walls
6 Electrochromic glazing

site, including solar hot-water system, photovoltaics, and both horizontal and vertical axis wind turbines. A geothermal system is also integrated, and the building's energy use and renewable energy production are monitored by a building management system. Innovative materials are used throughout the building, including structural insulated panels (SIPs), insulated concrete forms (ICFs) and electrochromic glass for windows.

Photochromic glass changes transparency in response to light intensity. Photochromic materials have been used in eyewear that change from clear, in dim indoor light, to dark in a bright outdoor environment. Photochromic glass may be useful in conjunction with daylighting, allowing enough natural light to penetrate interior space while cutting out excess sunlight that creates glare. However, small units have been produced in volume as commercial products for the construction industry, but cost-effective, large, durable glazing products are not yet commercially available.

Thermochromic glass adapts to changing sunlight intensity, where a thermochromic layer in the glass changes transmission over a range of temperatures. If properly designed, thermochromic layers are minimally sensitive to changing outdoor or ambient temperatures, but respond to changing amounts of direct sunlight. The glass tints and blocks solar heat gain.

Suspended particle device (SPD) glass consists of a thin film of liquid crystals suspended in a transparent conductive material and laminated between two layers of glass. By applying voltage, the amount of light passing through the glass can be controlled. In the SPD's normal, non-electrified state, these liquid crystals are randomly arranged and light is scattered between the crystals to give the glass a translucent appearance. When voltage is applied, the crystal particles align, allowing light to pass through the material and make it transparent. SPD glass is typically used for privacy control in interior spaces, since the switch between translucent and transparent states is almost instantaneous. However, the effects on energy savings are not significant, and this technology is not recommended for exterior building applications, such as facades.

16 LHB in conjunction with LKPB Engineers, Cascade Meadow Wetlands and Environmental Science Center, Rochester, MN, USA, 2011.
Electrochromic windows have been incorporated into the building's facade and dynamically shade the exhibition spaces.

17 LHB in conjunction with LKPB Engineers, Cascade Meadow Wetlands and Environmental Science Center, Rochester, MN, USA, 2011.
Axonometric view and floor plans demonstrating the different building systems and elements.

18 Functioning of suspended particle device (SPD) glass.
Without voltage SPD glass is translucent, but when voltage is applied it becomes transparent.

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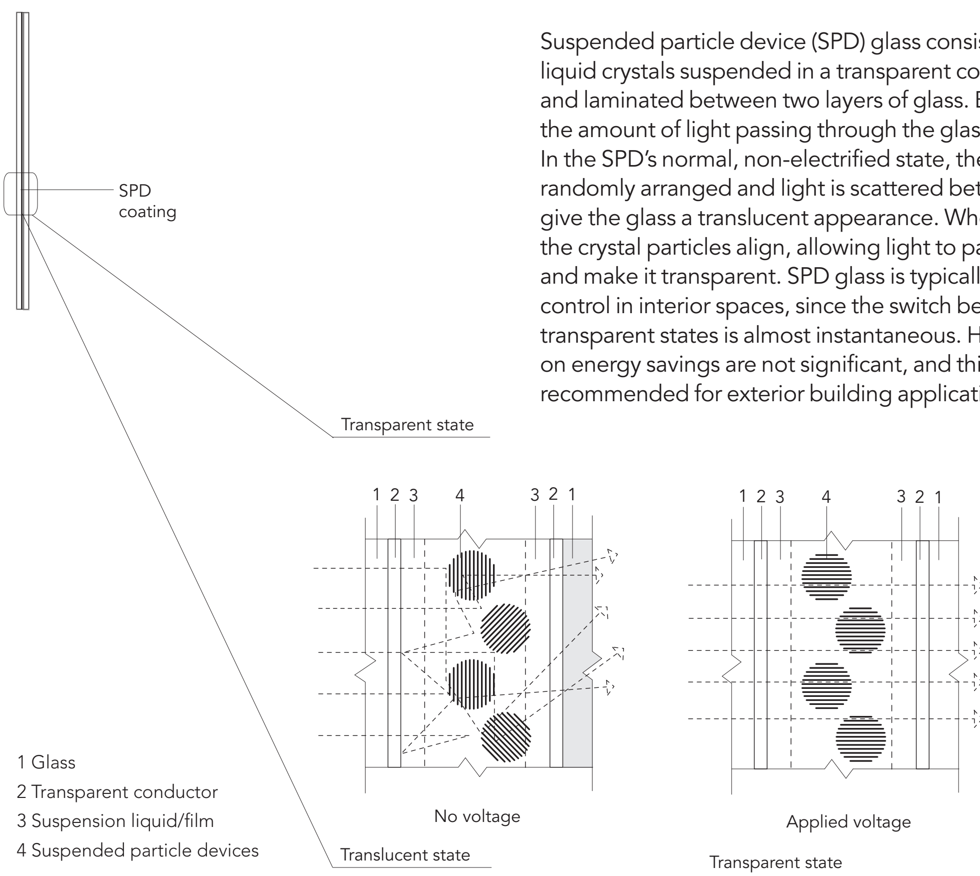
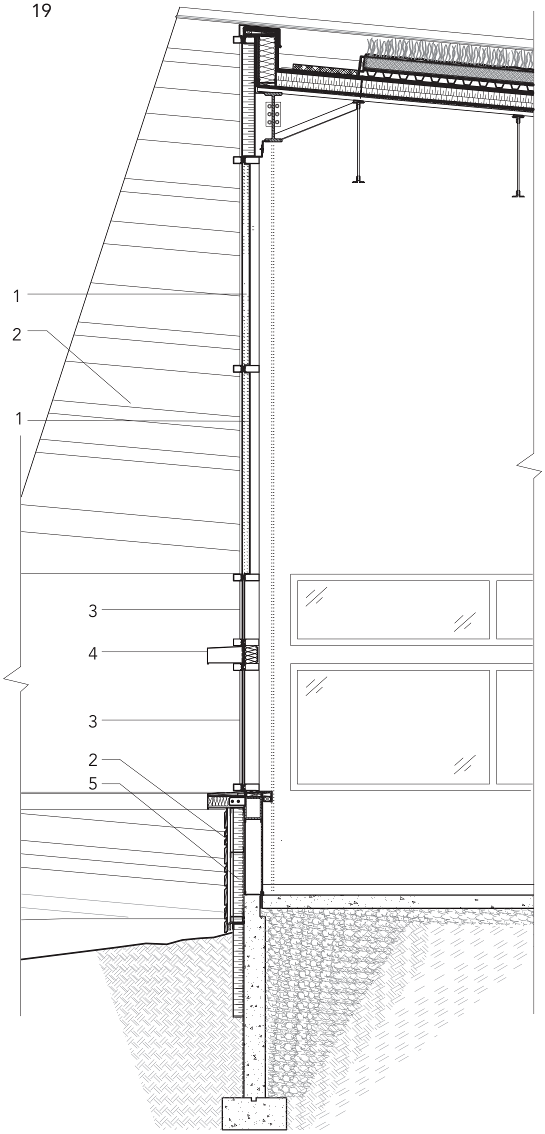


1 Glass
2 Transparent conductor
3 Suspension liquid/film
4 Suspended particle devices

19



1 Light diffusing glazing
2 Wood cladding
3 Transparent glazing
4 Shading device
5 Insulation

20

21

Vacuum-insulated glazing units provide improved thermal resistance compared with standard air- or gas-filled insulated glazing units. These units use a vacuum between two panes of glass to increase the assembly's thermal resistance. There is virtually no conduction or convection of heat between the two panes, since there is no gas to act as a medium for heat transfer. Vacuum-insulated glazing units can achieve U-values of less than 0.57 W/m^2-°K (0.10 Btu/hr-ft^2-°F). The vacuum between the two panes of glass places them under negative pressure, pulling them towards each other. To counteract this, a grid of spacers is placed between the panes. These spacers, or pillars, are made of material with low conductivity, and are positioned several inches from each other in both directions. Vacuum-insulated glazing units are typically thin, making them ideal where high-performance glazing needs to be installed in existing frames – a situation common for building retrofit projects.

Advanced glazing products specifically suited for daylighting applications are also available. These include products with light-diffusing interlayers, which can increase the amount of natural light and reduce the potential for glare. The Joggins Fossil Centre – designed by Architecture49 – is on the stretch of cliffs and beach along Nova Scotia's Bay of Fundy, which is a UNESCO World Heritage site. The interpretative centre exhibits examples of geological and scientific significance to this region, and a number of high-performance and sustainable design strategies were used to reduce energy consumption of the building. The facade incorporates advanced glazing with a light-diffusing interlayer and insulation, increasing available daylight within the interior space. Other notable design strategies that were used to improve the performance of this building include locally sourced and recycled materials, solar hot-water panels, heat pumps, photovoltaic panels and a wind turbine. A significant portion of the centre's energy needs is produced from renewable energy sources.

Commercial glazing products using aerogel inserts are a relatively new type of glazing material and have enhanced thermal properties. In some of these products, the aerogel is integrated with polycarbonate sheets to form a translucent cladding material. In others, silica aerogel in granular form fills the spaces

19 Architecture49, Joggins Fossil Centre, Nova Scotia, Canada, 2008.
Section showing the facade with integrated light-diffusing glazing.

20 Architecture49, Joggins Fossil Centre, Nova Scotia, Canada, 2008.
On Nova Scotia's Bay of Fundy coast, the building form corresponds to the shape of the cliffs.

21 (opposite below and below) Architecture49, Joggins Fossil Centre, Nova Scotia, Canada, 2008.
Exterior views showing the building facade treatment and placement of advanced, light-diffusing glazing.

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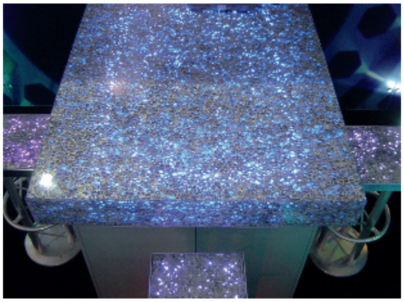


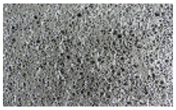
23

22 Goshow Architects, Nobel Halls, Stony Brook University, New York, USA, 2010.
Aerogel glazing is incorporated into the building's facade. This improves the thermal performance of the building envelope, while balancing daylight and allowing views to the outside through clear vision glazing.

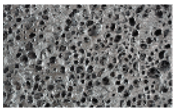
23 (below and opposite below) Interior applications of cellular aluminium foam.
Interior applications of cellular aluminium foam range from interior panels and furniture to windows.

24 Types of cellular aluminium foam.
Three cellular structures can be produced, depending on the size of cells (small, medium and large), sheets can also have various finishes.

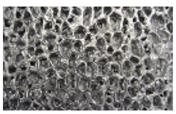
24
Aluminium foam cellular types



Small cell

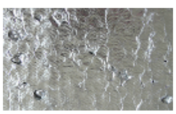


Medium cell

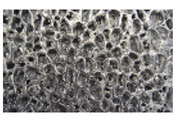


Large cell

Aluminium foam finish types



Normal



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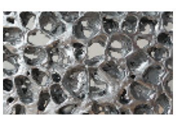

Open sided (two sided)

between the glass panes of insulating units or within the cavities of channel glass. Aerogels are synthetic solids that consist almost entirely of air. They have the lowest density among all known solids. Because of their low density, aerogels have extremely low thermal conductivity, so are ideal for applications where high thermal insulation is needed. Aerogel is a hydrophobic and non-combustible material with effective acoustic properties. The thermal resistance of aerogel-filled glazing – with U-values between 0.57 W/m^2-°K (0.10 Btu/hr-ft^2-°F) and 1.00 W/m^2-°K (0.18 Btu/hr-ft^2-°F) – is superior to standard insulating glazing units, which rarely achieve U-values less than 1.43 W/m^2-°K (0.25 Btu/hr-ft^2-°F). Silica aerogel is translucent, making it an excellent way to bring diffused daylight into interior spaces. On the other hand, its translucence makes it inappropriate for vision glass applications. Nobel Halls at Stony Brook University, New York, designed by Goshow Architects, is a hall of residence. The building envelope is highly insulated and includes aerogel glazing, which is combined with clear vision glazing. This design method allows views to the outside, while improving thermal performance and daylighting for the interior space.

ADVANCES IN METALS

Advances in the manufacturing processes of aluminium have resulted in the development of a new cellular aluminium foam material which can be produced as a continuously cast sheet. The manufacturing process consists of injecting air into molten aluminium, which contains a dispersion of ceramic particles. These particles stabilise the cells formed by the air. Three cellular structures can be produced, depending on the size of cells (small, medium and large). Aluminium foam sheets can also have varying textures, since continuous skin can be introduced to create a ‘closed’ cell arrangement, and removed to create an ‘open’ cell configuration. The aluminium foam sheets can be used in a variety of interior and exterior applications, including as facade cladding for rainscreen facades.

Weathering steel is a steel alloy that has a natural oxide coating which forms a protective layer for the steel surface and does not require painting. The finish of this material type has a natural patina, of reddish and brown hues. All low alloy steels have a tendency to rust in the presence of moisture and air, where the rust layer forms a protective layer for the steel surface. Specific alloying elements in weathering steel produce a stable rust layer that develops over time and protects this type of steel against corrosion. Although weathering steel has been available for several decades, the major disadvantages include a relatively slow oxidation process (since the weathering occurs in field after installation), and the possibility of staining adjoining elements if the detailing is not done properly. New advances in the manufacturing process have given rise to the development of pre-weathered steel materials produced by accelerating the natural weathering process in a controlled environment. This results in a pre-oxidised weathering steel that reduces the problems with staining. The Trinity River Audubon Center in Dallas, designed by architectural

25 Exterior applications of cellular aluminium foam.
Cellular aluminium foam used in facade applications.

26 Antoine Predock Architect PC, Trinity River Audubon Center, Dallas, TX, USA, 2008.
Pre-weathered steel cladding is used for the building's facade.

27 Aluminium composite panels.
These types of panels are available in a variety of colours and textures.

28 Patrick Arotcharen Agence d'Architecture, L'Office 64 de l'Habitat, Bayonne, Aquitaine, France, 2011.
Aluminium composite panels are used as one of the components for the building's facade. They are incorporated into a double-skin facade system along the south orientation, which consists of glass, wood-framing members and an internal layer of aluminium composite panels. On the north side, a single-skin facade system is used, where aluminium composite panels serve as cladding material.

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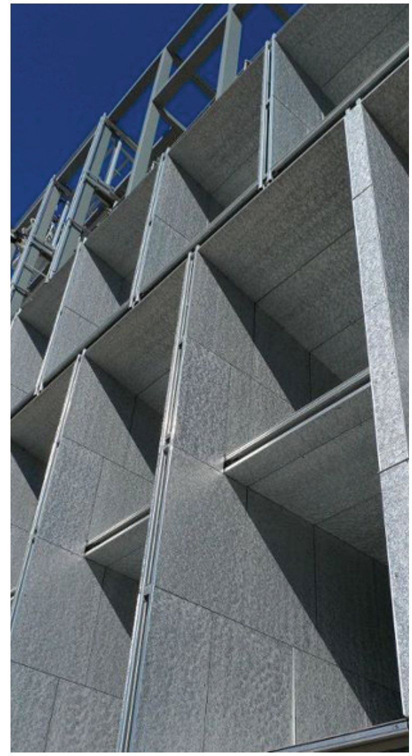

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firm Antoine Predock Architect PC, uses pre-weathered steel cladding for the building envelope. This building is within the largest urban forest in the United States and serves as an exhibition hall and education centre for environmental stewardship. The building includes a green roof, rainwater collection systems, energy-efficient systems and recycled materials.

27

Composite panels that integrate extremely thin aluminium sheets and a fire-resistant polyethylene core are suitable for facade applications. The aluminium sheets are thermo-bonded to the core, resulting in a highly durable material. This cladding material is lightweight, has the ability to form curves and comes in a variety of colours and textures. It is possible to use recycled aluminium. L'Office 64 de l'Habitat in Bayonne, France designed by Patrick Arotcharen Agence d'Architecture, integrates an intricate double-skin facade system along the south orientation, consisting of glass, wood-framing members and an internal layer of aluminium composite panels. The facade system also integrates operable windows, and aluminium composite panels are used as shading elements. The same type of material is used for the north facade too, where it is applied as a cladding material for the rainscreen facade system.

BIOMATERIALS

Biomaterials can be derived from nature or synthesised using different components and material sources, but their origin is based on a living structure. Biomaterials have been used mainly for medical applications and devices, but have recently been

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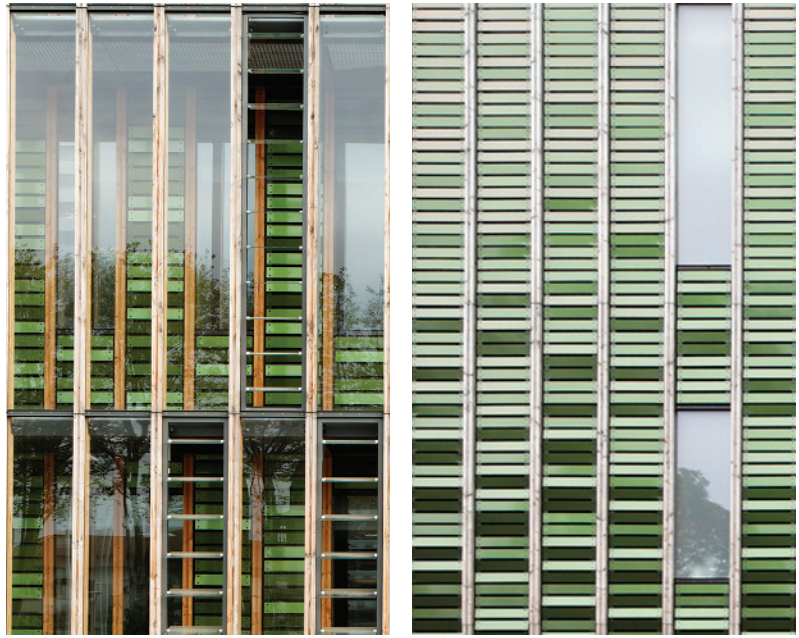

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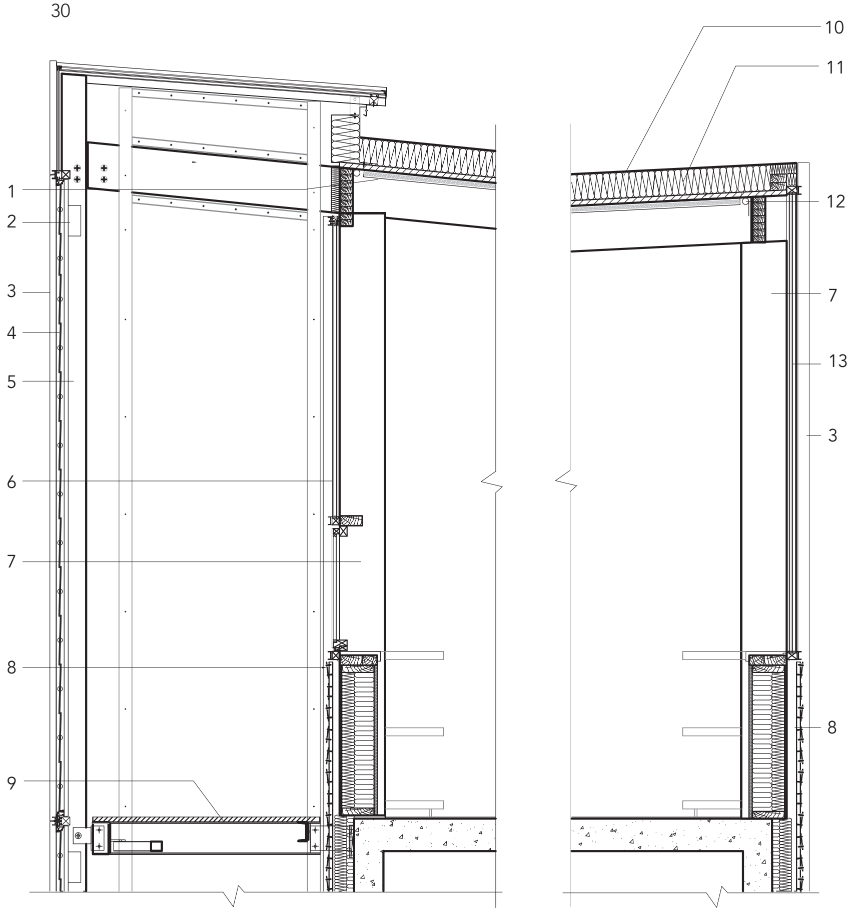

1 Acoustic boards
2 Motor for horizontal wood shades
3 Vertical wood components
4 Motorised horizontal wood shades
5 Secondary wood structure
6 Double glazing
7 Glulam column
8 Aluminium composite panels
9 Catwalk
10 Roof membrane
11 Insulation
12 Interior shade
13 Triple glazing

29 Patrick Arotcharen Agence d'Architecture, L'Office 64 de l'Habitat, Bayonne, Aquitaine, France, 2011.
South- and north-oriented facades showing the different applications of aluminium composite panels.

30 Patrick Arotcharen Agence d'Architecture, L'Office 64 de l'Habitat, Bayonne, Aquitaine, France, 2011.
Sections of the building's facades (double and single skin), indicating detailed components.

31 MAD Architects, Taichung Convention Center, Taiwan, proposal.
The design concept for this new convention centre integrates architecture and the landscape, creating mountain-like buildings to harmonise the relationship between nature and the built environment.

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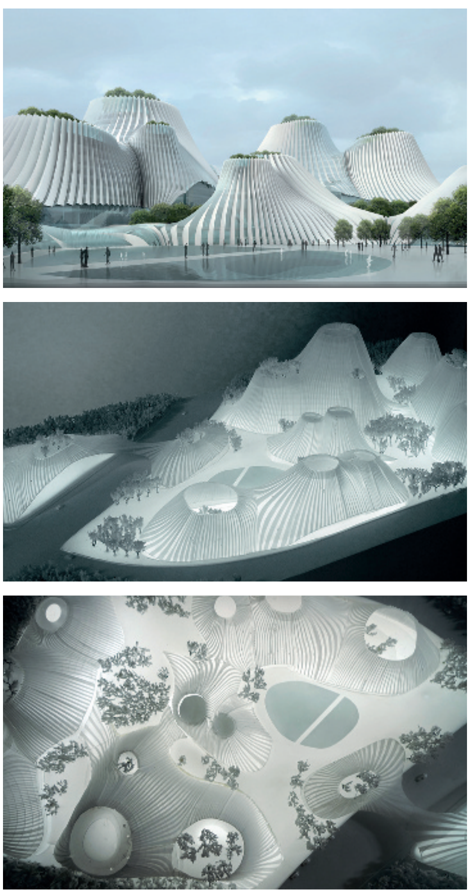

introduced to architectural and construction industries, primarily due to an interest in biomimicry and biomimetic design.[6, 7] An interest in renewable raw materials in buildings and sustainable design strategies (improving air quality, human health and well-being), have been the drivers for research and development, and the application of biomaterials in architecture.

The proposal for a new convention centre in Taichung, Taiwan, by MAD Architects is an example of biomimetic architecture. The complex consists of a convention centre, retail, hotel and office towers, and services. The aerodynamic form was developed to optimise ventilation around the buildings and the public plazas. The design – a series of mountain-like buildings –integrates buildings and landscape. One of the driving goals for the design was the harmony between nature and the built form. The surface of the buildings is a lightweight pleated skin system, allowing natural ventilation and creating a 'breathable' facade. The exterior skin also integrates photovoltaic panels.

New developments in wood composites are allowing the unprecedented use of this natural, renewable material. For example, glued laminated timber (glulam) is comprised of layers of dimensioned timber, bonded with moisture-resistant structural adhesives. Therefore, structural members can be fabricated and used for columns, beams, arches and curved shapes for long spans. Connections can be made with bolts and steel plates.

Phenolic wood composites consist of high-pressure wood laminates and thermosetting resins. Cladding panels for rainscreen facades are available and can be manufactured in a variety of colours. The HEMA building in Oosterbeek, the Netherlands, designed by Strategie Architecten, is a commercial building that uses innovative phenolic wood composite cladding for the facade system. Based on a Dutch painting from the 19th century, the facade was designed in a collaboration between the design team and the artist Jan van IJzendoorn. The design team developed an intricate pattern of different colours, and phenolic wood cladding was used to create this effect. The east facade has flush cladding panels, while the south facade incorporates different sizes of overlapping panels, some of which are twisted outwards to create interesting shading effects.

COMPOSITE MATERIALS

Composite materials are materials that consist of two or more components – such as reinforced concrete – and have been used in architecture and construction for decades. The primary advantage of composite materials is that the strengths and benefits of two or more components are combined to create a better performing material – in the case of reinforced concrete, steel rebars are used to improve concrete's tensile strength and ductility. But recent developments in material science and engineering are creating new composite materials, combining polymers, resins, matrices and fibres with different substrates, such as concrete and cement-based materials, metals, fabrics and ceramics.

32 MAD Architects, Taichung Convention Center, Taiwan, proposal.
Interior view of the convention centre, showing the lightweight pleated-skin system. It allows natural ventilation and creates a 'breathable' facade.

33 Glued laminated timber.
This composite material consists of wood and structural adhesives. Structural members, arches and curved shapes can be used for long spans.

34 Connections.
Connections for glued laminated timber.

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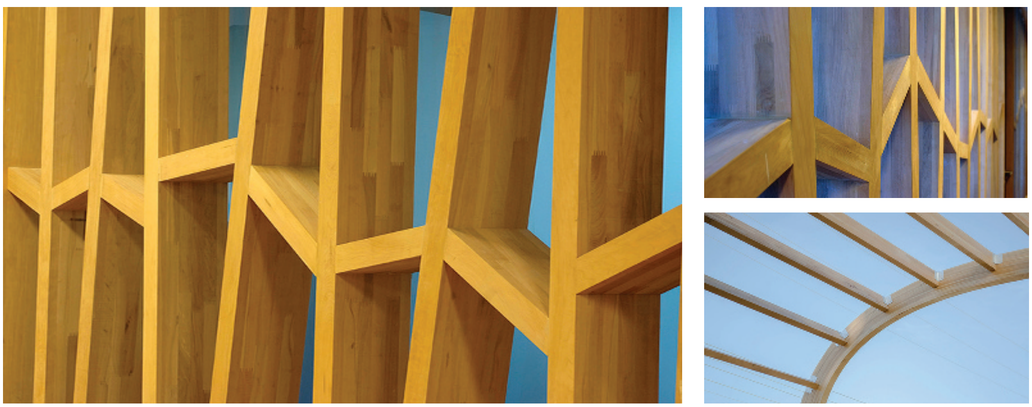

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35 Strategie Architecten, HEMA building, Oosterbeek, the Netherlands, 2009.
The elevations and facade technical detail show how phenolic wood cladding is used to create an intricate, colourful pattern on the building's facades.

36 Strategie Architecten, HEMA building, Oosterbeek, the Netherlands, 2009.
Flush phenolic wood cladding is used along the east facade and overlapping panels along the south facade.

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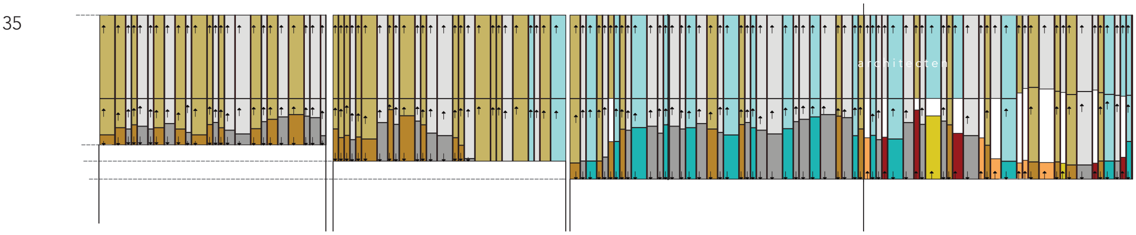
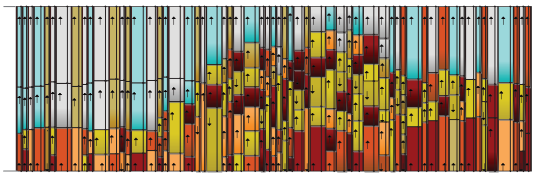
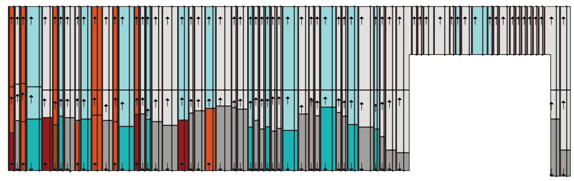


East elevation

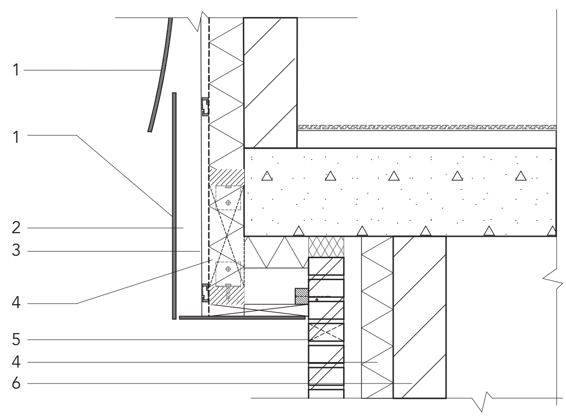


South elevation



West elevation

1 Phenolic wood cladding
2 Air cavity
3 Support system for cladding
4 Insulation
5 Brick
6 Support wall



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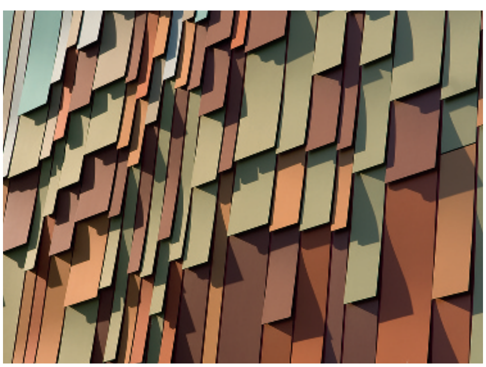

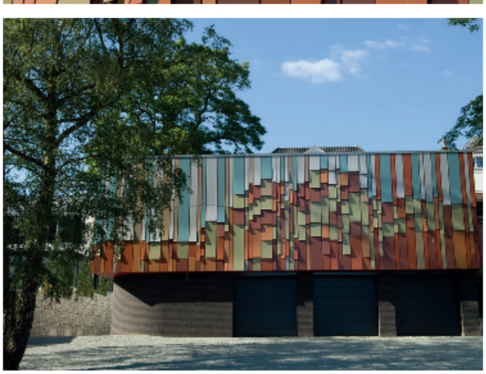

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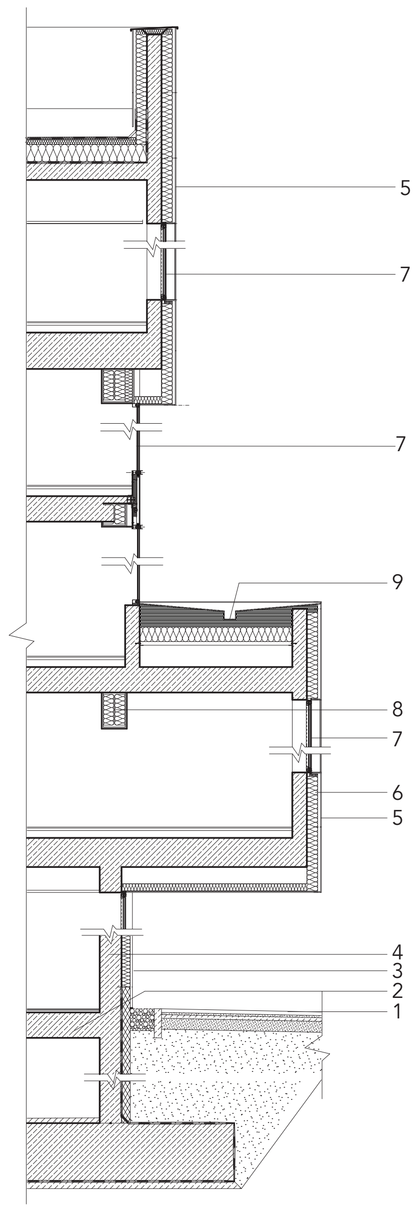


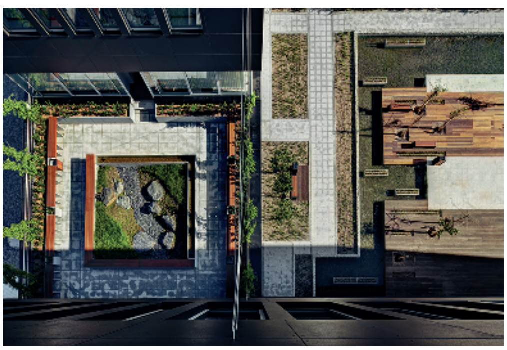
1 Pavers
2 Concrete slab
3 Slate facade panels
4 Concrete wall
5 Fibre-cement cladding
6 Insulation
7 Glazing
8 Steel truss
9 Rainwater drainage

37 FAAB Architektura, PGE GiEK Corporate Headquarters, Bełchatów, Poland, 2013.
Fibre-cement composite panels are used for the building's facade system.

38 FAAB Architektura, PGE GiEK Corporate Headquarters, Bełchatów, Poland, 2013.
The section demonstrates the material components of the facade.

39 FAAB Architektura, PGE GiEK Corporate Headquarters, Bełchatów, Poland, 2013.
The terraced garden provides a green open space for the building's occupants.

40 Molecular change in shape-memory alloys.
Molecular change in shape-memory alloys (SMAs) is achieved by thermally induced transformations.



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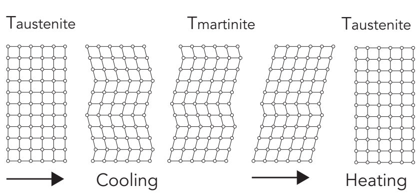
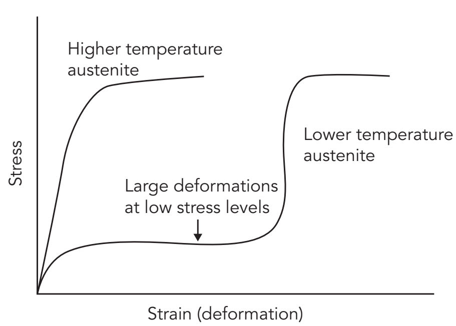


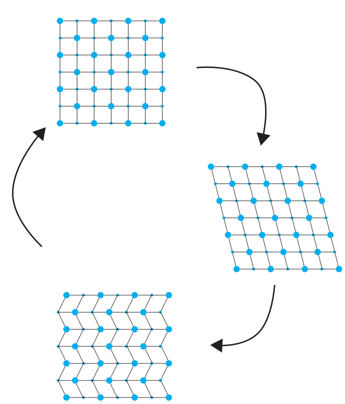
Fibre-cement composite panels – composed of cement, cellulose, mineral materials and reinforced with a fibre matrix – are available as a cladding material for facades. PGE GiEK Corporate Headquarters in Bełchatów, Poland, designed by FAAB Architektura, employs a fibre-cement composite cladding material. The office building is for one of the largest energy producers in Poland, and the building form and massing were inspired by energy production and distribution. Access to daylight was one of the driving forces for the building form, which features a narrow floor plan and an atrium. A terraced square and garden are included in the building, and a rainwater collection system is used for irrigation.

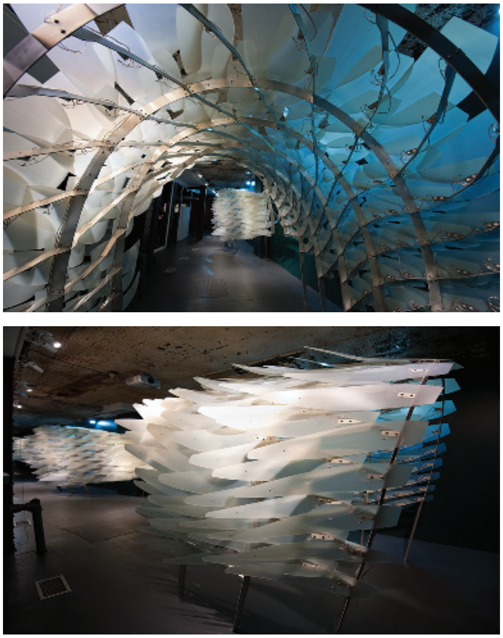
ELECTROCHROMICS
Electrochromic materials are characterised by an ability to change their optical properties reversibly, and persistently, when a voltage is applied across them. Electrochromic glass has been discussed in a previous section, advances in glass. Electrochromic glass controls sunlight to optimise daylight, outdoor views and comfort while preventing glare, fading and overheating. By letting sunlight in on cool days and blocking it on hot days, electrochromic windows can reduce energy demand.

SHAPE-MEMORY ALLOYS
Shape-memory alloys (SMAs) belong to a class of shape-memory materials that have the ability to 'memorise' or retain their previous form when subjected to certain stimulus, such as thermomechanical or magnetic variations. SMAs have attracted significant attention and interest in recent years in a broad range of applications, due to their unique and superior properties. This commercial development has been supported by fundamental and applied research studies.

Perhaps surprisingly, bendable eyeglass frames, medical stents for opening arteries that are implanted in a compressed form and then expand to the right size and shape when warmed by the body, tiny actuators that eject disks from laptop computers, small micro-valves and a variety of other devices, all share this common material technology. The transformable behaviour of these devices relies on a phenomenon called the 'shape-







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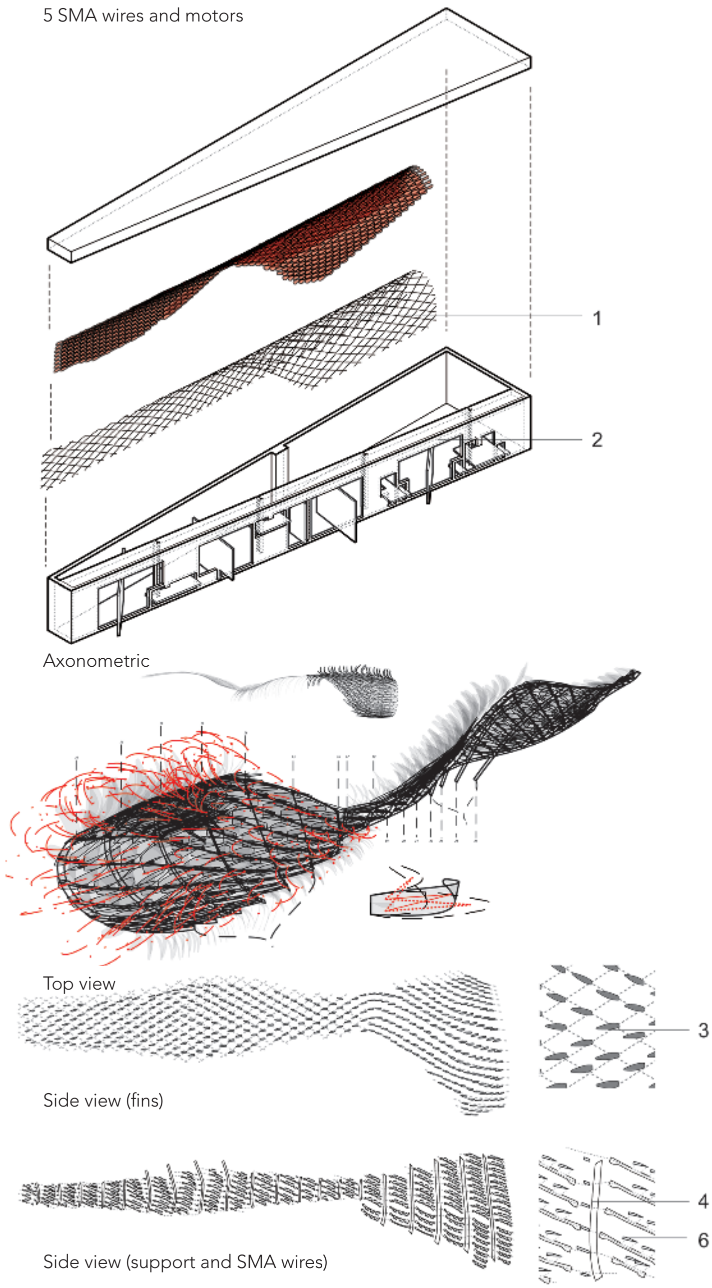
1 Reef installation
2 Gallery enclosure
3 Fins
4 Wood support system
5 SMA wires and motors

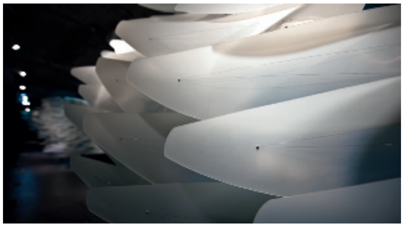


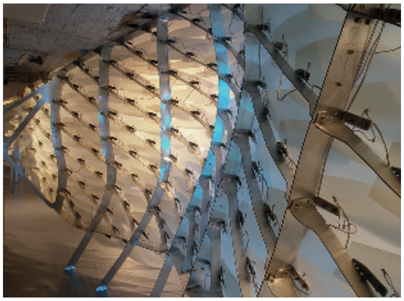
41 Rob Ley (Urbana) and Joshua Stein (Radical Craft), Reef, New York, USA, 2009.
This installation is a kinetic, responsive surface consisting of an aluminium frame, SMA wires (nitinol), fibre-reinforced composite fins and a control system. The fins rotate and change form as the SMA wires are heated with an electric current.

42 Rob Ley (Urbana) and Joshua Stein (Radical Craft), Reef, New York, USA, 2009.
Diagrams and illustrations showing different components of the installation.

43 Rob Ley (Urbana) and Joshua Stein (Radical Craft), Reef, New York, USA, 2009.
Components of the installation, showing the fibre-reinforced composite fins and SMA wires that are used as a primary mechanism for the kinetic changes.

44 Principle for self-healing materials.
Self-healing materials contain microcapsules filled with polymeric substances. If the material cracks, the microcapsules open and release polymeric substances that harden and repair the crack.





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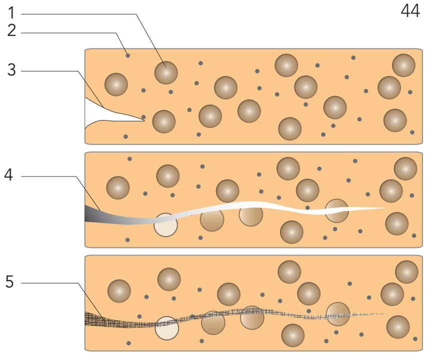

1 Microcapsule
2 Catalyst
3 Crack
4 Healing agent
5 Polymerised healing agent

memory effect', which refers to the ability of a particular kind of alloy material to revert to, or remember, a previously memorised or pre-set shape. The characteristic derives from the phase-transformation characteristics of the material. A solid-state phase change (molecular rearrangement) occurs in the shape-memory alloy that is temperature-dependent and reversible. For example, the material can be shaped into one configuration at a high temperature, deformed dramatically while at a low temperature, and then reverted back to its original shape on the application of heat in any form, including electrical current. Diagram 40 indicates the process for thermally induced change in SMA materials.

Nickel-titanium (NiTi) alloys are commonly used in shape-memory applications, although many other kinds of alloys also exhibit shape-memory effects.[8] These alloys can exist in final product form in two different temperature-dependent crystalline states or phases. The primary and higher temperature phase is called the austenite state. The lower temperature phase is called the martensite state. The physical properties of the material in the austenite and martensite phases are different. The material in the austenite state is strong and hard, while it is soft and ductile in the martensite phase. The austenite crystal structure is a simple body-centred cubic structure, while martensite has a more complex rhombic structure. With respect to the stress–strain curve, the higher temperature austenite behaves similarly to most metals. The stress–strain curve of the lower-temperature martensitic structure, however, resembles an elastomer, since it has 'plateau' stress-deformation characteristics where large deformations can easily occur with little force.

Although SMA materials have been widely used in medical and aerospace applications, their application in architecture is still limited to installations and small-scale projects, mainly due to cost-prohibitive applications for larger, structural uses. Reef, a collaboration between Rob Ley (Urbana) and Joshua Stein (Radical Craft), incorporated SMAs within the responsive, kinetic installation. The installation consists of an aluminium frame, nitinol wires, fibre-reinforced composite fins and a control system. The length of nitinol wires changes when heated with an electric current, having an impact on the shape and form of 600 fins. The result is a kinetic, responsive surface that changes its shape.

SELF-HEALING MATERIALS

Self-healing materials are a subset of smart materials that have the ability to repair damage caused by mechanical or structural use over time. They are typically composite materials that contain microcapsules filled with polymeric substances. When the material cracks, the microcapsules open and seal up the crack. Recent research and development has focused on different types of self-healing materials, including concrete, paint and polymer-based composites.[9, 10,11] Self-healing paint is especially interesting, because with this system tiny scratches can be automatically sealed. To achieve this, a highly elastic resin is used, which spreads itself out evenly over the surface and seals small cracks.

The first production-line use of such a paint has recently been implemented, and in the near future its use is likely to be extended to scratch-prone items.

Research and development of self-healing concrete with calcite-precipitating bacteria is currently under way at TU Delft.[12] The principle behind this research is that certain types of bacteria produce calcium carbonate-based minerals which can be used to repair cracks in concrete. By embedding calcite-precipitating bacteria in concrete as an admixture, the researchers are working on determining the right conditions for the bacteria to produce as much calcite as possible, as well as the self-healing ability of bacterial concrete and how this is affected by different environmental conditions. This material was used for the First Aid Emergency Post in Galder, the Netherlands, designed by Frank Marcus. The concrete structure includes a protective layer of self-repairing concrete with bacteria, and the photograph below shows a self-healed crack.

SENSORS AND CONTROLS

Sensors and control systems are gaining popularity in architecture and construction. Sensing equipment, building management systems and controls that regulate the performance of building systems are increasingly being used, ranging from sensors for specific building elements (such as sensors and controls used for lighting fixtures), to specific systems (such as HVAC) or whole-building controls (building energy management software and controls).

There are many different types of sensors used in buildings. Lighting sensors include photodiode sensors or phototransistors, which allow lighting levels to be monitored and controlled. Thermal sensors include classic thermometers, thermocouples and thermistors, and are used to monitor thermal conditions in the environment. Humidity sensors are used to monitor humidity levels. Motion and occupancy sensors are used to detect the presence of building occupants, and are mainly integrated with lighting systems. There are also a variety of sensors that have been developed to detect the presence of different types of chemicals. These are used for environmental sensing, mainly for the detection of air pollutants.

Environmental sensors are used to test or measure changes in environmental conditions and include many types of sensors described above. A variety of sensor-based devices have been developed to initially assess and continuously monitor environmental conditions at different scales (element, building and urban scale).

A recently developed prototype for an exterior shading system (consisting of folding geometry and a movable track system) uses sensors, a control system and a mobile application to transform its form. This shading system has been developed by Sean McKeever (NBBJ), and uses occupancy sensors to detect building occupants.

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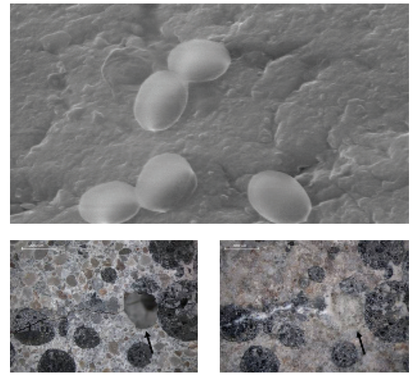

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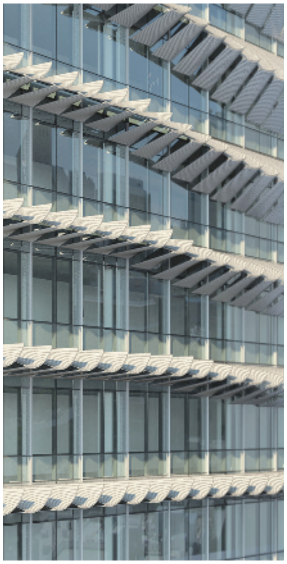
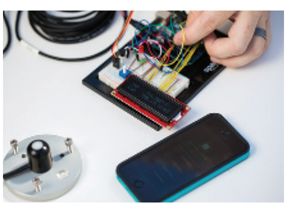
45 Microscopic view of self-repairing concrete.
Self-repairing concrete incorporates calcite-precipitating bacteria. The bacteria create minerals that repair cracks in concrete.

46 Frank Marcus, First Aid Emergency Post, Galder, the Netherlands, 2011.
The concrete structure includes a protective layer of self-healing concrete with calcite-precipitating bacteria.

47 Sean McKeever (NBBJ), exterior shading system prototype.
This prototype consists of folding geometry and a movable track system. Folding geometry, sensors, a control system and a mobile application are used to control the form of the shading system.

The shades open automatically if occupants are present, but can also be overridden by building occupants. Sensors for environmental conditions are integrated, specifically for measuring solar radiation and weather conditions, allowing the control of shading devices based on the exterior environment.





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Control systems are an integral part of high-performing buildings. Building automation systems (BAS) are centralised, interlinked networks of sensors, hardware and software, which monitor and control building systems and performance. Mechanical, electrical and plumbing systems, lighting, power, security and vertical circulation (elevators and escalators) can be monitored and controlled via BAS. Although BAS have been around for decades, significant innovations have occurred with the introduction of digitised systems, wireless sensors and open communication protocols between different systems. Also, the improvement of energy efficiency and buildings' energy performance has demanded wider adoption of BAS and energy management systems. Monitoring, tracking and visualising energy usage in buildings allows improved operations and facility management. Smart and intelligent buildings rely on BAS, where the variety of sensors, controls and monitoring systems are integrated to detect environment conditions or respond and influence building operation.

PHASE-CHANGE MATERIALS

In principle, all materials that are able to reversibly change their state in response to external influences are classified as phase-change materials (PCM). Most of the known materials exhibit temperature-dependent phase changes. There are also other influences, such as chemical stimuli, which can trigger phase changes and these are often associated with changes in elasticity. In addition to the states of solid, liquid and gas, there are other, largely stable intermediate states, such as the colloidal state derived from gels.

In the architecture and construction industries, the term PCM has become generally applicable to materials and products that can be used as temperature regulating media, for example latent heat or latent cold storage media for the regulation of temperature. They have the ability to change their state from liquid to solid by crystallisation below an inherent material-dependent phase-change temperature, and to release a quantity of heat energy previously taken in and stored at a high temperature. The temperature of the material remains constant during the course of the phase change, from solid to liquid, and during the heat energy input.

These types of materials are solid at room temperature, but liquefy at higher temperatures, absorbing and storing heat in the process. PCMs are either organic (such as waxes) or inorganic (such as salts). When PCMs are incorporated into the building elements, they can absorb high exterior temperatures during the day and dissipate the heat at night.

Different types of PCM materials used in architecture include paraffin and paraffin mixtures, salt hydrate and salt hydrate mixtures, and water. The melting point of paraffin mixtures depends on the particular paraffin used and any added constituents. The advantages of these mixtures are that they are widely available, can be made in large quantities and can be used over a relatively large temperature range, approximately -12°C (10°F) to 180°C (356°F) for many applications. The disadvantages are that they are highly combustible, change volume during phase change and are relatively expensive compared with other types of PCM materials. Salt hydrate mixtures are non-combustible and can be used over a relatively large temperature range, approximately -70°C (-94°F) to 120°C (248°F). They are relatively inexpensive compared with paraffin-based PCMs. Disadvantages include a tendency to supercool when used for cold storage, a tendency to segregate and promote corrosion, and also to change volume during phase change. Water mixtures can be used over a relatively large temperature range, approximately 40°C (104°F) to 100°C (212°F). They do not segregate, and are comparatively inexpensive compared with other types of PCMs. Disadvantages are relatively poor thermal conductivity compared with paraffin and salt hydrate PCMs and volume change during phase change.

Products such as triple-insulated glazing units (IGUs) with integrated PCM are commercially available. These IGUs consist of four layers of glass and three insulating gaps. A prismatic pane is placed within the outermost gap. Inert gas fills the two outer gaps, and a PCM encapsulated within transparent polycarbonate containers fills the inside gap. This type of IGU acts as a passive heat source. During the winter months, the prismatic pane allows low-angle sunlight to pass through the glass layers and heat up the PCM. This causes the PCM to liquefy and release heat to the interior. During the summer months, the prismatic pane acts as a barrier, reflecting high-angle solar rays back to the outside, allowing the PCM to stay in its solid form. Insulating properties of this type of glazing unit are very high, with U-values for commercial products of 0.48 W/m²-°K (0.08 Btu/hr-ft²-°F). Visual transmittance for a solid-state PCM is between 0% and 28%, with an SHGC as low as 0.17 and as high as 0.48. Liquid-state PCM has visual transmittance from 4% to 45%, with an SHGC as high as 0.48 and as low as 0.17. In either its solid or liquid state, a PCM makes the glazing unit translucent, so this material is not appropriate for applications where views to the outside are desired.

For thermal storage in buildings PCMs are applicable and can be integrated in Trombe walls, exterior walls, underfloor heating systems and ceiling boards. The benefits of using PCMs in Trombe wall applications are that PCMs require less space than mass walls and are lighter in weight. Applications for underfloor heating systems and ceiling applications have been investigated.

One of the first large-scale commercial applications of PCMs is the iCon Innovation Centre in Daventry, UK, designed by Consarc Architects. This is a new type of publicly funded building, aimed

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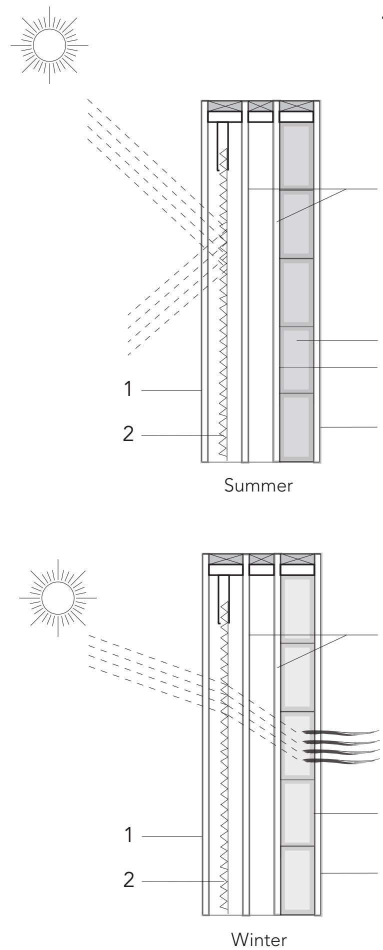

1 Tempered glass
2 Prismatic pane
3 Low-e glass
4 Solid PCM
5 PCM containers
6 Liquid PCM

actively to promote economic sustainability through the promotion of innovation networks. This high-performance building includes incubation units for start-up businesses, public exhibition space, conference facilities and a café. The building's structural system is composed of a timber-frame construction (glulam). Sustainable design strategies included a natural ventilation system, efficient heat recovery and PCMs to limit overheating. PCM panels have been introduced into interior spaces at soffit level to reduce interior temperature peaks, so improving thermal comfort levels and energy savings. The PCMs reduce the interior temperature by as much as 7°C (45°F), which decreases air-conditioning costs by 35% and heating costs by 15%. The PCM panels are sealed behind the plasterboard in walls and above ceiling panels, where they absorb ambient heat as the interior temperature rises at around 22°C (72°F), storing it until the temperature drops to around 18°C (64°F), and then releasing it back into the interior space. The building facade is constructed of wood and includes vertical shading fins to reduce solar heat gain. The central atrium of the building is covered by an Ethylene Tetrafluoroethylene (ETFE) skylight.

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PHOTOVOLTAICS

Photovoltaics (PVs) are among the most commonly used active energy-generation systems for buildings. They convert sunlight into electricity and can be integrated into roof or facade applications. There are different types of PVs, but the most common differentiation is between thin films and solid cells. Thin films consist of interconnected solar cells which convert visible light into electricity, and can be applied to different building materials (glass, metals, ETFE and so on). Thin-film cells can be integrated into almost any surface, such as shading devices, spandrels, vision glass and roofing elements. Solid solar cell modules are integrated into panels and are commercially available in standard and custom shapes and sizes. These types of PV panels can be installed on roofs and building facades, and integrated with spandrel areas or shading devices. The performance and aesthetic appearance of PVs depend on their type, their size and their position relative to the sun's path.

There are also many different types of PVs, depending on the material structure and components. Monocrystalline silicon cells are uniform in colour and structure and are the most conventional type of cells used in PV modules. Their efficiency, measured as a percentage of solar energy converted into electric energy, is typically not larger than 25% under the best conditions. Polycrystalline silicon cells have a non-uniform surface structure and colour, with visible variations in the silicon structure. Polycrystalline cells generally have lower costs and lower efficiencies than monocrystalline cells. Amorphous silicon cells use hydrogenated amorphous silicon, with only a few microns of material needed to absorb the incident light. Since they can be deposited on both rigid and flexible substrates, thin films typically use this type of cell. Manufacturing costs for amorphous cells are relatively low, but their efficiencies are also low, typically no more than 7%. The advantage of amorphous thin films is that they work

48 Insulated glazing unit with phase-change material (PCM) inserted.
During the winter months, the prismatic pane allows low-angle sunlight to pass through the glass layers and heat up the PCM. This causes the PCM to become liquid and release heat to the interior. During summer months, the prismatic pane acts as a barrier, reflecting high-angle solar rays back to the outside, allowing the PCM to stay in its solid form.

49 Consarc Architects, iCon Innovation Centre, Daventry, Northamptonshire, UK, 2011.
This new type of publicly funded building actively boosts economic sustainability through the promotion of innovation networks and sustainability.

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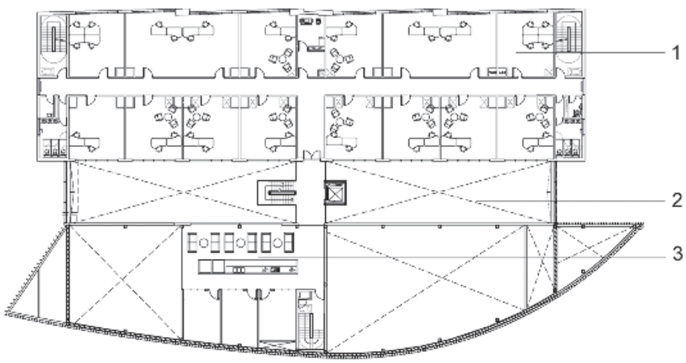
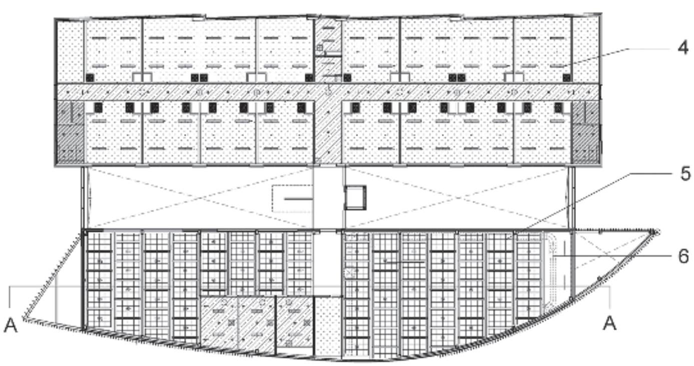
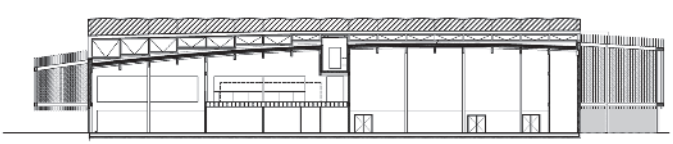


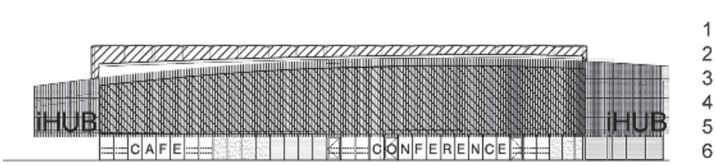
First-floor plan



First-floor reflected ceiling plan



Section A-A



South elevation

1 Offices
2 Atrium
3 Lounge
4 Lighting
5 PCM incorporated into ceiling
6 HVAC distribution

50 Consarc Architects, iCon Innovation Centre, Daventry, Northamptonshire, UK, 2011.
Timber-frame construction was implemented, reducing embodied energy associated with the structural system.

51 Consarc Architects, iCon Innovation Centre, Daventry, Northamptonshire, UK, 2011.
Floor plan, reflected ceiling plan, section and elevation showing spatial arrangement, facade treatment and materials.

52 Consarc Architects, iCon Innovation Centre, Daventry, Northamptonshire, UK, 2011.
PCM panels are used within interior spaces, they are sealed behind the plasterboard in walls and above ceiling panels, where they absorb ambient heat as the interior temperature rises. This is released when the temperature drops. These panels help to improve thermal comfort levels and energy savings.

53 Types of PV glass.
Semitransparent PV glass uses amorphous silicon. It allows some daylight to penetrate into the interior space and provides views to the outside. Opaque PV glass uses solid PVs and is appropriate for spandrels and other non-vision areas of the facade.

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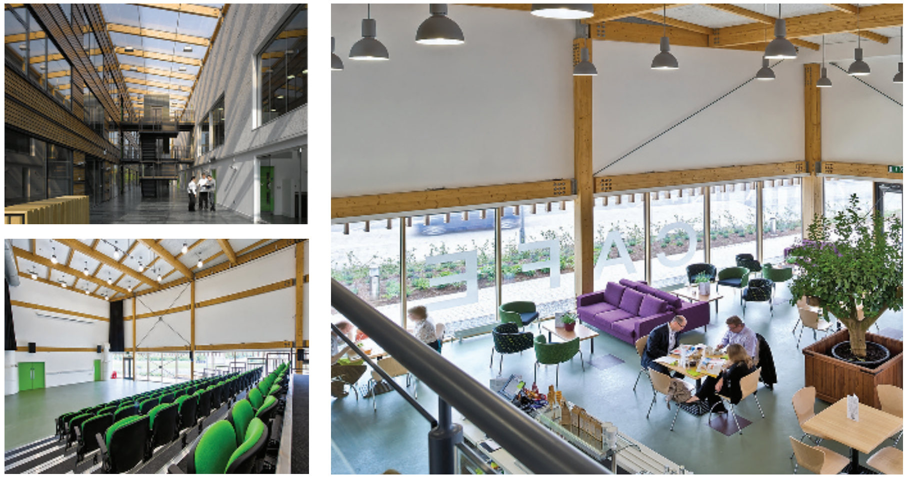

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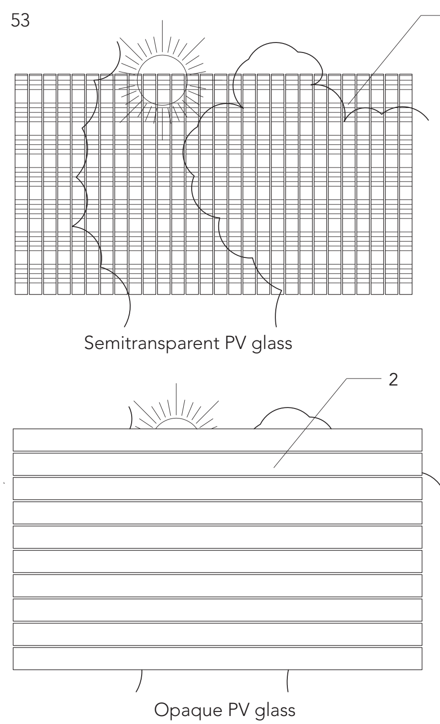

1 Amorphous thin-film PV cells
2 Crystalline PV cells

equally well in shaded areas as in direct sunlight. Monocrystalline and polycrystalline cells require direct sunlight to achieve their highest efficiencies. Their energy production is reduced if they are shaded, not oriented in the optimal way to receive the maximum amount of sunlight, or covered by snow, sand or dust.

Photovoltaic glass integrates crystalline solar cells or amorphous thin films, where the PV cells are integrated into laminated or double-glazed units and are applicable for building facade integration. There are two general types of PV glass: semitransparent and opaque. Semitransparent PV glass is similar to patterned ceramic frit, allowing some daylight to penetrate through the glass while giving occupants views to the outside. Opaque PV glass uses solid PVs, and is appropriate for spandrels and other non-vision areas of the facade.

The SwissTech Convention Center at the École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland, designed by architects Richter Dahl Rocha & Associés, incorporates newly developed dye-synthesised PV panels within the western facade of the building. The building has become a new landmark for this institution, creating a clearly identifiable volume within the landscape. It is also connected to the newly designed student housing centre and a hotel, to the east of the convention centre. The metallic roof shell cantilevers over the interior and glazed facades, allowing maximum daylight for interior spaces. The building consists of a large auditorium for 3,000 people, a foyer and supporting spaces. The auditorium has been designed to allow subdivision into smaller spaces, which defined the building's form. Hydraulic platforms and rotating seat mounts allow the auditorium to be transformed into a multi-purpose room. Anodised aluminium diamond-shaped tiles are used for the building envelope. The west facade of the building integrates dye-sensitised solar cells, which is the first, large-scale commercial application of this type of PVs. These translucent panels are integrated as vertical shading devices, and create an interesting pattern through a variety of different colours. For these

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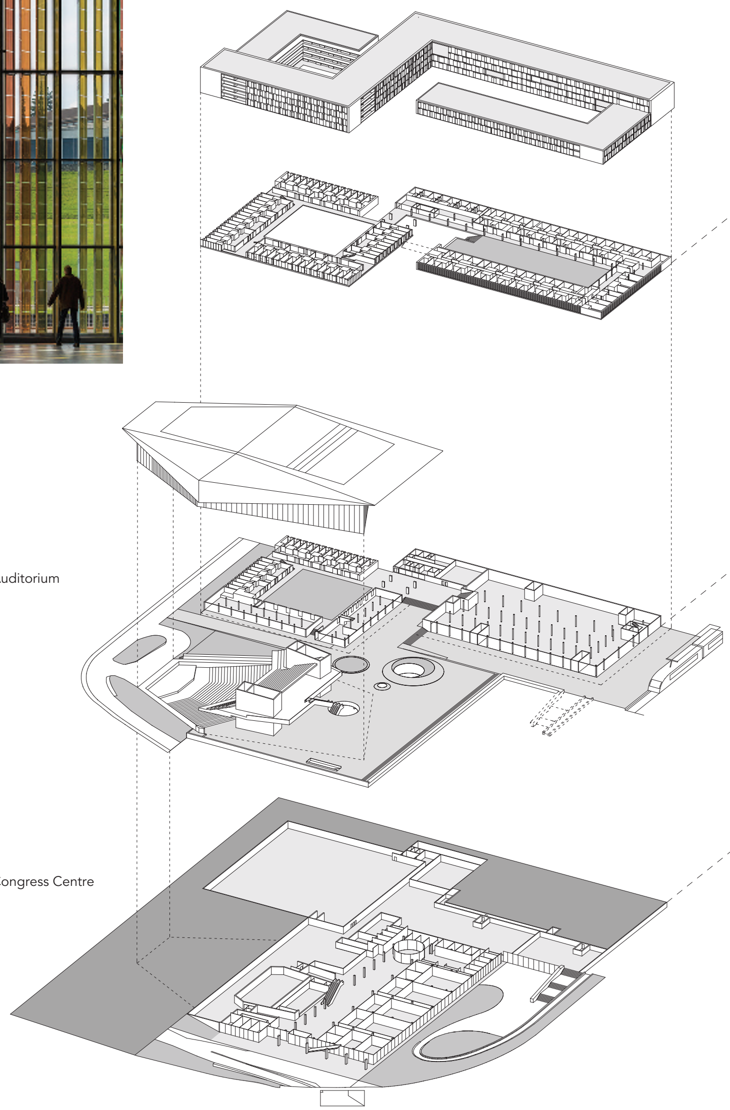

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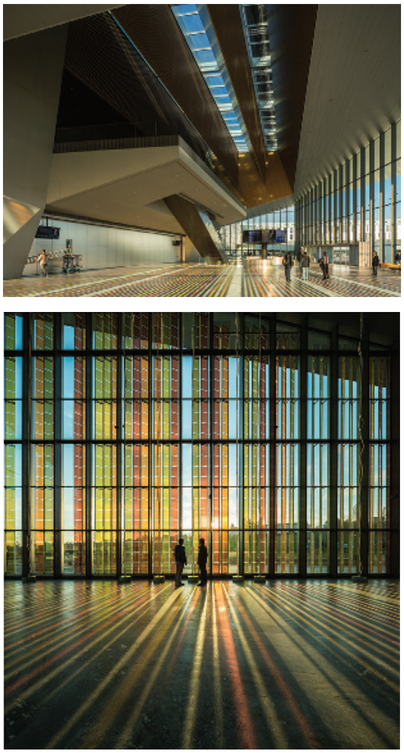
54 Richter Dahl Rocha & Associés, SwissTech Convention Center, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, 2014.
The building form and volume clearly identify this building as a landmark within the EPFL campus.

55 Richter Dahl Rocha & Associés, SwissTech Convention Center, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, 2014.
The axonometric shows different parts of the complex, and spatial organisation.



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56 Richter Dahl Rocha & Associés, SwissTech Convention Center, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, 2014.
Dye-synthesised PV cells are used along the western facade creating an interesting pattern of colours.

57 Richter Dahl Rocha & Associés, SwissTech Convention Center, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, 2014.
The building form and volume were primarily influenced by the design of a large auditorium that can transform into multiple spaces with the use of movable partitions, hydraulic platforms and rotating seats.

types of solar cells, vertical orientation does not reduce energy output, and they produce 2,000 kWh of electricity per year.

The new headquarters building for Brussels Environment, the government authority overseeing environmental and habitat issues, demonstrates an innovative application of PVs. Designed by Dutch architects, cepezed, the building is in Brussels' largest urban renewal district. It has a compact volume with stepped receding floors, protected by a rounded and mainly transparent roof. The building includes a visitors' centre, an auditorium, multimedia library, conference centre, offices, laboratory and a central atrium. The facade incorporates triple-insulated glazing units with thermally broken framing, as well as automatic shading devices that respond to solar radiation. Natural ventilation is used throughout the building, along with a minimal amount of mechanical ventilation. A geoexchange system is incorporated, as well as a heat recovery system. The sloping roof and facade integrate 366 PVs, consisting of black monocrystalline solar cells, black foils, glass and black aluminium frame. All panels have identical dimensions, and 36 of them are curved. The total capacity of all the PV panels is 104,130 W, which outputs 87,000 kWh annually. The roof is covered by aluminium, therefore the seamless integration of the roofing, facade and PVs was achieved by precise detailing. Recessed gutters and black grates are incorporated for rainwater drainage. Brussels Environment is BREEAM-Excellent and PHPP (Passivhaus) certified.

THERMOELECTRICS

Thermoelectric materials exhibit thermoelectric effects, referring to phenomena where either a temperature difference creates an electric current, or electric potential creates a temperature difference. Thermoelectric modules are commercially available that consist of flat wafers, an array of miniature alloy junctions, connected electrically in series but operating thermally in parallel. When operating, the modules work as a heat pump, with a specific

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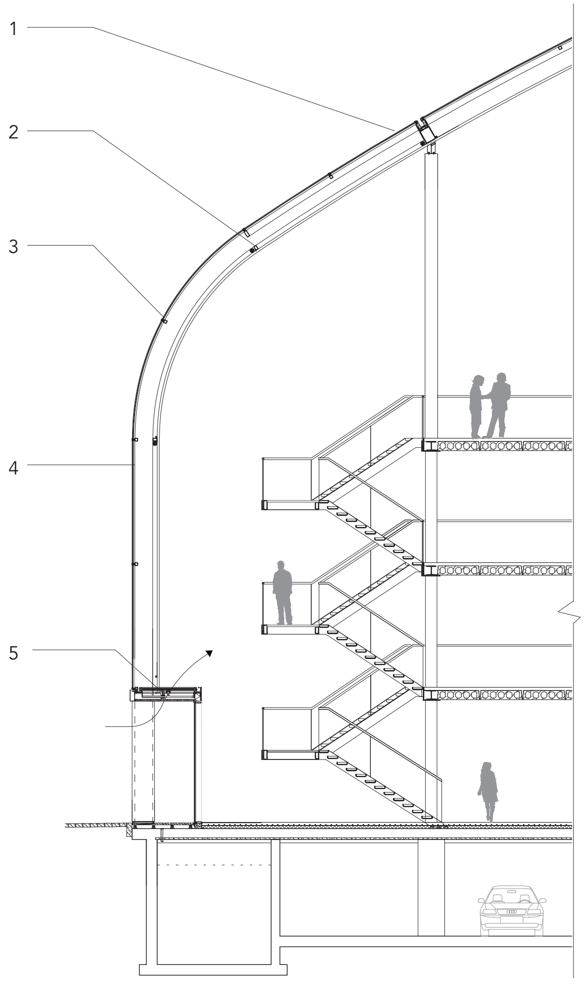
1 Skylight glazing
2 Interior shades
3 Framing
4 Glazing
5 Ventilation opening



Enlarged section

58 cepezed, Brussels Environment, Brussels, Belgium, 2014.
The building's compact form is protected by a rounded roof. The facade and roof are continuous and integrate black monocrystalline PV panels.

59 cepezed, Brussels Environment, Brussels, Belgium, 2014.
The enlarged section demonstrates the material components of the building envelope.

60 cepezed, Brussels Environment, Brussels, Belgium, 2014.
Plans, section and elevation showing spatial organisation, layout and building envelope treatment.

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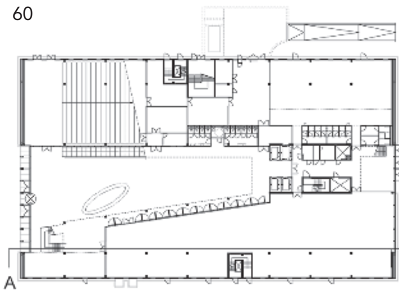
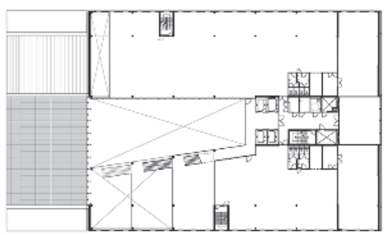
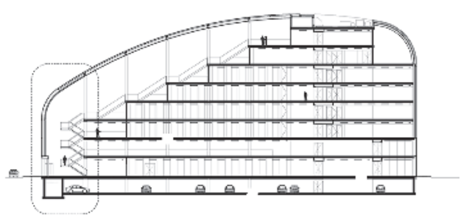


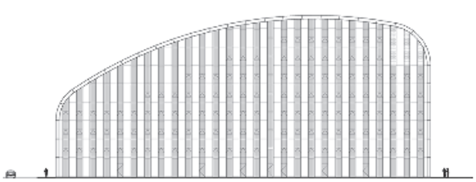
First-floor plan



Sixth-floor plan



Section A-A



East elevation

amount of heat being transferred from one side of every junction to the other side of the module, thus yielding hot and cold sides. Alternatively, the temperature difference between the different sides of the module generates electricity.

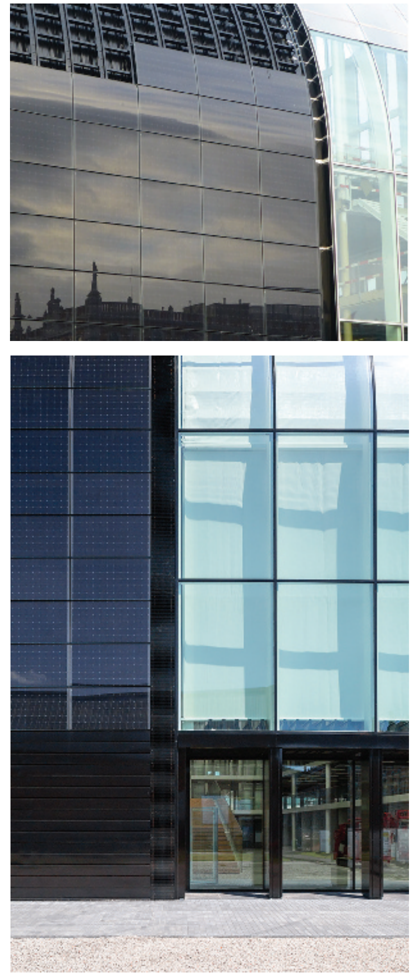
Traditionally the efficiency of thermoelectric generation had been as low as 2%, restricting its applications within architectural and construction industries. Moreover, with the high cost of thermoelectric materials, commercialisation of this technology for large-scale architectural applications had been considered financially unfeasible. With the advent of nano-materials and structure synthesis techniques, recent years have seen an increased surge of interest in thermoelectric research and applications. Specifically, researchers are investigating new types of materials that would increase efficiency and energy production, including graphene and carbon nanotubes.[13, 14]

A novel application of thermoelectric modules has been explored, focusing on the integration of micro and nanoscale thermoelectric materials with window glass to generate electricity based on the temperature difference that exists between the exterior and interior environments.[15] The major challenge is that thermoelectric materials need to be integrated through the entire depth of glass to take advantage of the temperature differential between the exterior and interior environment. Conventional deposition techniques cannot achieve this thickness, so alternative fabrication techniques need to be developed. Current research focuses on milling micrometre-sized thermoelectric powders and then hot pressing into a mould to form thermoelectric modules that can be inserted into window glass. This fabrication technique needs further research and development to be widely adopted in the architecture and construction industries.

CONCLUSION: THE IMPACT OF ADVANCED AND SMART MATERIALS ON ARCHITECTURAL DESIGN

As we have seen in this chapter, numerous developments in materials are influencing how architects, engineers and other design professionals are envisioning better performing buildings and spaces, and how they are utilising advanced and smart materials to turn these ideas into built work. Advances in glass, concrete, metals and biomaterials are creating new classes of materials that have enhanced properties, such as improved structural performance, thermal properties, acoustic, optical and visual characteristics and environmental impact. Various types of composite materials are being developed and becoming increasingly used in the architectural and construction industries, since they combine two or more materials to enhance their properties and performance, such as polymers, resins, matrices and fibres with different substrates, with concrete and cement-based materials, metals, fabrics, ceramics, and so on. Smart materials adapt to changing conditions in the environment, and mimic the functioning of a biological or living organism. They can be classified into two general categories – materials that can sense and inherently respond to the changes in the

environment, and materials that need control, in a systematic manner, in order to be active based on a certain change. We have discussed different types of smart materials and their applications in architecture and design. These types of materials are initiating new typologies in architecture – smart and intelligent buildings that can react to changes in the environment and operation, and adjust their functionalities accordingly. The main barriers for the implementation of advanced and smart materials in architectural design are lack of long-term performance data and their higher costs. New, cost-effective manufacturing processes and economies of scale are influencing economic impacts. For example, the cost of electrochromic glass has drastically reduced over the last five years due to the development of new manufacturing techniques and higher demand. The increased number of applications, as well as performance monitoring and continued research, will address the lack of performance data for these innovative materials.
The future of architectural design is highly dependent on the advancements in materials, improved and new products and the development of new classes of materials.



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61 cepezed, Brussels Environment, Brussels, Belgium, 2014.
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IMAGES

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