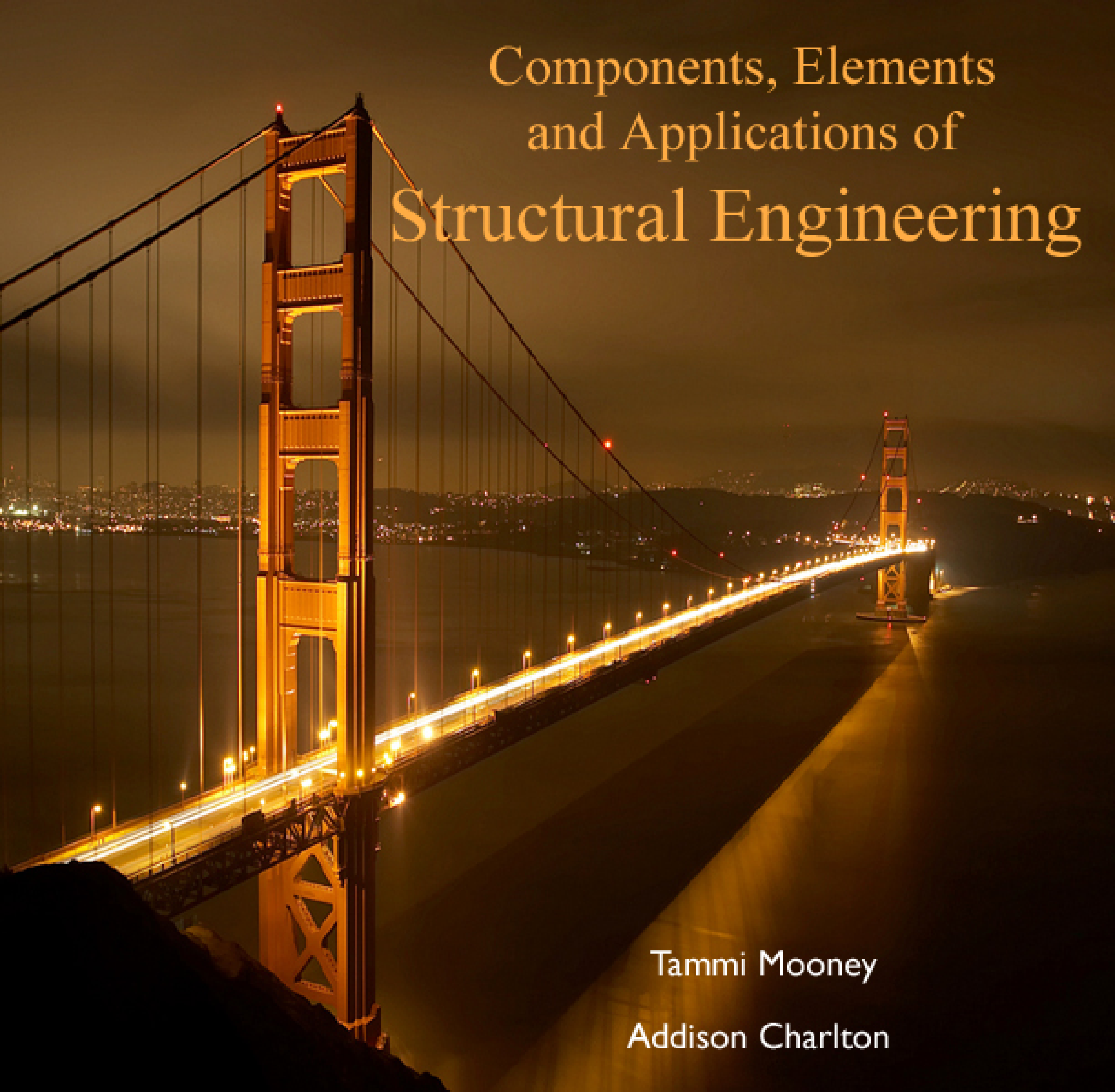

Components, Elements and Applications of Structural Engineering

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Chapter 1

Hyperboloid Structure

The world's first hyperboloid lattice 37-meter water tower by Vladimir Shukhov, All-Russian Exposition, Nizhny Novgorod, Russia, 1896

Hyperboloid structures are architectural structures designed with hyperboloid geometry. Often these are tall structures such as towers where the hyperboloid geometry's structural strength is used to support an object high off the ground, but hyperboloid geometry is also often used for decorative effect as well as structural economy. The first hyperboloid structures were built by Russian engineer Vladimir Shukhov (1853–1939). The world's first hyperboloid tower is located in Polibino, Lipetsk Oblast, Russia.

The shapes are doubly ruled surfaces (hence can be built with a lattice of straight beams), which can be classed as:

- Hyperboloid of one sheet, such as cooling towers
- Hyperbolic paraboloids, such as saddle roofs

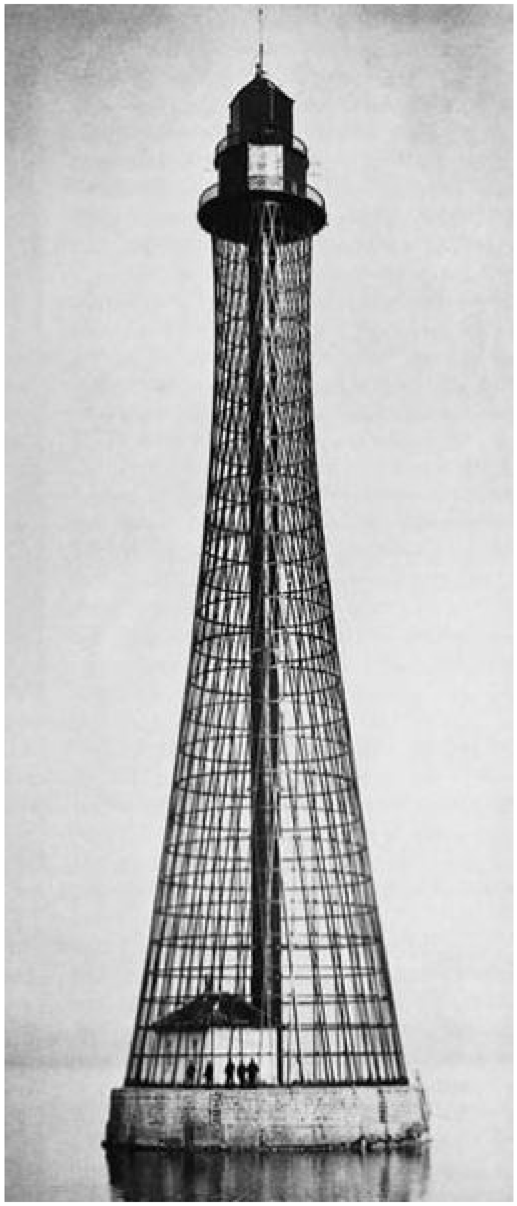
Properties of hyperboloid structures

Hyperbolic structures have a negative Gaussian curvature, meaning they curve inward rather than outward or being straight. As doubly ruled surfaces, they can be made with a lattice of straight beams, hence are easier to build and, all else equal, stronger than curved surfaces that do not have a ruling and must instead be built with curved beams.

Hyperboloid structures are superior in stability towards outside forces than "straight" buildings, but have shapes often creating large amounts of unusable volume (low space efficiency) and therefore are more commonly used in purpose-driven structures, such as water towers (to support a large mass), cooling towers, and aesthetic features, but their cross section is much more commonly seen in hyperbolic bridges.

With cooling towers, a hyperbolic structure is preferred. At the bottom, the widening of the tower provides higher surface area for water to boil in. As the water first boils and steam rises, the narrowing effect helps accelerate the laminar flow, and then as it widens out, contact between the heated air and atmospheric air supports turbulent mixing.

Work of Shukhov



Hyperboloid lattice Adziogol Lighthouse by V.G.Shukhov near Kherson, Ukraine, 1911

In the 1880s, Shukhov began to work on the problem of the design of roof systems to use a minimum of materials, time and labor. His calculations were most likely derived from mathematician Pafnuty Chebyshev's work on the theory of best approximations of functions. Shukhov's mathematical explorations of efficient roof structures led to his invention of a new system that was innovative both structurally and spatially. By applying his analytical skills to the doubly-curved surfaces Nikolai Lobachevsky named "hyperbolic", Shukhov derived a family of equations that led to new structural and constructional systems, known as hyperboloids of revolution and hyperbolic paraboloids.

The steel gridshells of the exhibition pavilions of the 1896 All-Russian Industrial and Handicrafts Exposition in Nizhny Novgorod were the first publicly prominent examples of Shukhov's new system. Two pavilions of this type were built for the Nizhni Novgorod exposition, one oval in plan and one circular. The roofs of these pavilions were doubly-curved gridshells formed entirely of a lattice of straight angle-iron and flat iron bars. Shukhov himself called them *azhurnaia bashnia* ("lace tower", i.e., lattice tower). The patent of this system, for which Shukhov applied in 1895, was awarded in 1899.

Shukhov also turned his attention to the development of an efficient and easily constructed structural system (gridshell) for a tower carrying a large gravity load at the top – the problem of the water tower. His solution was inspired by observing the action of a woven basket holding up a heavy weight. Again, it took the form of a doubly-curved surface constructed of a light network of straight iron bars and angle-iron. Over the next twenty years, he designed and built close to two hundred of these towers, no two exactly alike, most with heights in the range of 12m to 68m.

The gridshell of Shukhov Tower in Moscow. Currently under threat of demolition.

At least as early as 1911, Shukhov began experimenting with the concept of forming a tower out of stacked sections of hyperboloids. Stacking the sections permitted the form of the tower to taper more at the top, with a less pronounced "waist" between the shape-defining rings at bottom and top. Increasing the number of sections would increase the tapering of the overall form, to the point that it began to resemble a cone.

By 1918 Shukhov had developed this concept into the design of a nine-section stacked hyperboloid radio transmission tower for Moscow. Shukhov designed a 350m tower, which would have surpassed the Eiffel Tower in height by 50m, while using less than a quarter of the amount of material. His design, as well as the full set of supporting calculations analyzing the hyperbolic geometry and sizing the network of members, was completed by February 1919; however, the 2200 tons of steel required to build the tower to 350m were not available. In July 1919, Lenin decreed that the tower should be built to a height of 150m, and the necessary steel was to be made available from the army's supplies. Construction of the smaller tower with six stacked hyperboloids began within a few months, and Shukhov Tower was completed by March 1922.

Other architects

Hyperboloid lattice Canton Tower

Antoni Gaudi and Shukhov carried out experiments with hyperboloid structures practically simultaneously, but independently, in 1880-1895. Antoni Gaudi used structures in the form of hyperbolic paraboloid (hypar) and hyperboloid of revolution in the Sagrada Família in 1910. In the Sagrada Família, there are a few places on the nativity facade - a design not equated with Gaudi's ruled-surface design, where the hyperboloid crops up. All around the scene with the pelican, there are numerous examples (including the basket held by one of the figures). There is a hyperboloid adding structural stability to the cypress tree (by connecting it to the bridge). The "bishop's mitre" spires are capped with hyperboloids.

In the Palau Güell, there is one set of interior columns along the main facade with hyperbolic capitals. The crown of the famous parabolic vault is a hyperboloid. The vault of one of the stables at the Church of Colònia Güell is a hyperboloid. There is a unique column in the Park Güell that is a hyperboloid. The famous Spanish engineer and architect Eduardo Torroja designed a thin-shell water tower in Fedala and the roof of hippodrome "Zarzuela" in the form of hyperboloid of revolution. Le Corbusier and Félix Candela used hyperboloid structures (hypar).

A hyperboloid cooling tower was patented by Frederik van Iterson and Gerard Kuypers in 1918.

The Georgia Dome was the first Hypar-Tensegrity dome to be built.

Chapter 2

Roof

The roofs of Olomouc, Czech Republic

The roofs of San Cristobal de las Casas, Mexico

Roofs of Antananarivo, Madagascar

A **roof** is the covering on the uppermost part of a building. A roof protects the building and its contents from the effects of weather. Structures that require roofs range from a letter box to a cathedral or stadium, dwellings being the most numerous.

In most countries a roof protects primarily against rain. Depending upon the nature of the building, the roof may also protect against heat, sunlight, cold, snow and wind. Other types of structure, for example, a garden conservatory, might use roofing that protects against cold, wind and rain but admits light. A verandah may be roofed with material that protects against sunlight but admits the other elements.

The characteristics of a roof are dependent upon the purpose of the building that it covers, the available roofing materials and the local traditions of construction and wider concepts of architectural design and practice and may also be governed by local or national legislation.

The elements in the design of a roof are:

- the material
- the construction
- the durability

The **material** of a roof may range from banana leaves, wheaten straw or seagrass to lamininated glass, aluminium sheeting and precast concrete. In many parts of the world ceramic tiles have been the predominant roofing material for centuries.

The **construction** of a roof is determined by its method of support and how the underneath space is bridged and whether or not the roof is *pitched*. The *pitch* is the angle at which the roof rises from its lowest to highest point. Most domestic architecture, except in very dry regions, has roofs that are sloped, or *pitched*. The pitch is partly dependent upon stylistic factors, but has more to do with practicalities. Some types of roofing, for example thatch, require a steep pitch in order to be waterproof and durable. Other types of roofing, for example pantiles, are unstable on a steeply pitched roof but provide excellent weather protection at a relatively low angle. In regions where there is little rain, an almost flat roof with a slight run-off provides adequate protection against an occasional downpour.

The **durability** of a roof is a matter of concern because the roof is often the least accessible part of a building for purposes of repair and renewal, while its damage or destruction can have serious effects.

Form of a roof

The **shape of roofs** differs greatly from region to region. The main factors which influence the shape of **roofs** are the climate and the materials available for roof structure and the outer covering. The basic shapes of roofs are flat, skillion, gabled, hipped, arched and domed. There are many variations on these types. Some roofs follow organic shapes, either by architectural design or because a flexible mmaterial is used in the construction.

Parts of a roof

There are two parts to a roof, its supporting structure and its outer skin, or uppermost weatherproof layer. In a minority of buildings, the outer layer is also a self-supporting structure.

The roof structure is generally supported upon walls, although some building styles, for example, geodesic and A-frame, blur the distinction between wall and roof.

Support

The roof of a library, Sweden.

The supporting structure of a roof usually comprises beams that are long and of strong, fairly rigid material such as timber, and since the mid 19th century, cast iron or steel. In countries that use bamboo extensively, the flexibility of the material causes a distinctive curving line to the roof, characteristic of Oriental architecture.

Timber lends itself to a great variety of roof shapes. The timber structure can fulfil an aesthetic as well as practical function, when left exposed to view.

Stone lintels have been used to support roofs since prehistoric times, but cannot bridge large distances. The stone arch came into extensive use in the ancient Roman period and in variant forms could be used to span spaces up to 140 feet (43 m) across. The stone arch or vault, with or without ribs, dominated the roof structures of major architectural works for about 2,000 years, only giving way to iron beams with the Industrial Revolution and the designing of such buildings as Paxton's Crystal Palace, completed 1851.

With continual improvements in steel girders, these became the major structural support for large roofs, and eventually for ordinary houses as well. Another form of girder is the reinforced concrete beam, in which metal rods are encased in concrete, giving it greater strength under tension.

Outer layer

This part of the roof shows great variation dependent upon availability of material. In simple vernacular architecture, roofing material is often vegetation, such as thatches, the most durable being sea grass with a life of perhaps 40 years. In many Asian countries bamboo is used both for the supporting structure and the outer layer where split bammboo stems are laid turned alternately and overlapped. In areas with an abundance of timber, wooden shingles are used, while in some countries the bark of certain trees can be peeled off in thick, heavy sheets and used for roofing.

The 20th century saw the manufacture of composition shingles which can last from a thin 20-year shingle to the thickest which are limited lifetime shingles, the cost depending on the thickness and durability of the shingle. When a layer of shingles wears out, they are usually stripped, along with the underlay and roofing nails, allowing a new layer to be installed. An alternative method is to install another layer directly over the worn layer. While this method is faster, it does not allow the roof sheathing to be inspected and water damage, often associated with worn shingles, to be repaired. Having multiple layers of old shingles under a new layer causes roofing nails to be located further from the sheathing, weakening their hold. The greatest concern with this method is that the weight of the extra material could exceed the dead load capacity of the roof structure and cause collapse.

Slate is an ideal, and durable material, while in the Swiss Alps roofs are made from huge slabs of stone, several inches thick. The slate roof is often considered the best type of roofing. A slate roof may last 75 to 150 years, and even longer. However, slate roofs are often expensive to install – in the USA, for example, a slate roof may have the same cost as the rest of the house. Often, the first part of a slate roof to fail is the fixing nails; they corrode, allowing the slates to slip. In the UK, this condition is known as "nail sickness". Because of this problem, fixing nails made of stainless steel or copper are recommended, and even these must be protected from the weather.

Asbestos, usually in bonded corrugated panels, has been used widely in the 20th century as an inexpensive, non-flammable roofing material with excellent insulating properties. Health and legal issues involved in the mining and handling of asbestos products means that it is no longer used as a new roofing material. However, many asbestos roofs continue to exist, particularly in South America and Asia.

Roofs made of cut turf (modern ones known as Green roofs, traditional ones as sod roofs) have good insulating properties and are increasingly encouraged as a way of "greening" the Earth. Adobe roofs are roofs of clay, mixed with binding material such as straw or animal hair, and plastered on lathes to form a flat or gently sloped roof, usually in areas of low rainfall.

In areas where clay is plentiful, roofs of baked tiles have been the major form of roof. The casting and firing of roof tiles is an industry that is often associated with brickworks. While the shape and colour of tiles was once regionally distinctive, now tiles of many shapes and colours are produced commercially, to suit the taste and pocketbook of the purchaser.

Sheet metal in the form of copper and lead has also been used for many hundreds of years. Both are expensive but durable, the vast copper roof of Chartres Cathedral, oxidised to a pale green colour, having been in place for hundreds of years. Lead, which is sometimes used for church roofs, was most commonly used as flashing in valleys and around chimneys on domestic roofs, particularly those of slate. Copper was used for the same purpose.

In the 19th century, iron, electroplated with zinc to improve its resistance to rust, became a light-weight, easily-transported, waterproofing material. Its low cost and easy application made it the most accessible commercial roofing, world wide. Since then, many types of metal roofing have been developed. Steel shingle or standing-seam roofs last about 50 years or more depending on both the method of installation and the moisture barrier (underlayment) used and are between the cost of shingle roofs and slate roofs. In the 20th century a large number of roofing materials were developed, including roofs based on bitumen (already used in previous centuries), on rubber and on a range of synthetics such as thermoplastic and on fibreglass.

Outer layer

Cameroon, a wattle and daub house, roofed with banana leaves

Japan, rice straw thatch

England, slate.

Hungary, terracotta tiles

Namibia, metal roof

Functions of a roof

Insulation

Because the purpose of a roof is to protect people and their possessions from climatic elements, the insulating properties of a roof are a consideration in its structure and the choice of roofing material.

Some roofing materials, particularly those of natural fibrous material, such as thatch, have excellent insulating properties. For those that do not, extra insulation is often installed under the outer layer. In developed countries, the majority of dwellings have a ceiling installed under the structural members of the roof. The purpose of a ceiling is to insulate against heat and cold, noise, dirt and often from the droppings and lice of birds who frequently choose roofs as nesting places.

Forms of insulation are felt or plastic sheeting, sometimes with a reflective surface, installed directly below the tiles or other material; synthetic foam batting laid above the ceiling and recycled paper products and other such materials that can be inserted or sprayed into roof cavities. So called Cool roofs are becoming increasingly popular, and in some cases are mandated by local codes. Cool roofs are defined as roofs with both high reflectivity and high emissivity.

Roof that are not well insulated can suffer from problems such as the formation of ice dams around the overhanging eaves in cold weather, causing water from melted snow on uper parts of the roof to penetrate the roofing material.

Drainage

The primary job of most roofs is to keep out water. The large area of a roof repels a lot of water, which must be directed in some suitable way, so that it does not cause damage or inconvenience.

Flat roof of adobe dwellings generally have a very slight slope. In a Middle Eastern country, where the roof may be used for recreation, it is often walled, and drainage holes must be provided to stop water from pooling and seeping through the porous roofing material.

Similar problems, although on a very much larger scale, confront the builders of modern commercial properties which often have flat roofs. Because of the very large nature of such roofs, it is essential that the outer skin is of a highly impermeable material. Most industrial and commercial structures have conventional roofs of low pitch.

In general, the pitch of the roof is proportional to the amount of precipitation. Houses in areas of low rainfall frequently have roofs of low pitch while those in areas of high rainfall and snow, have steep roofs. The longhouses of Papua New Guinea, for example, being roof-dominated architecture, the high roofs sweeping almost to the ground. The