

Structural System Engineering

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First Edition, 2012

ISBN 978-81-323-3106-3

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Published by:

Research World

4735/22 Prakashdeep Bldg,

Ansari Road, Darya Ganj,

Delhi - 110002

Email: info@wtbooks.com

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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

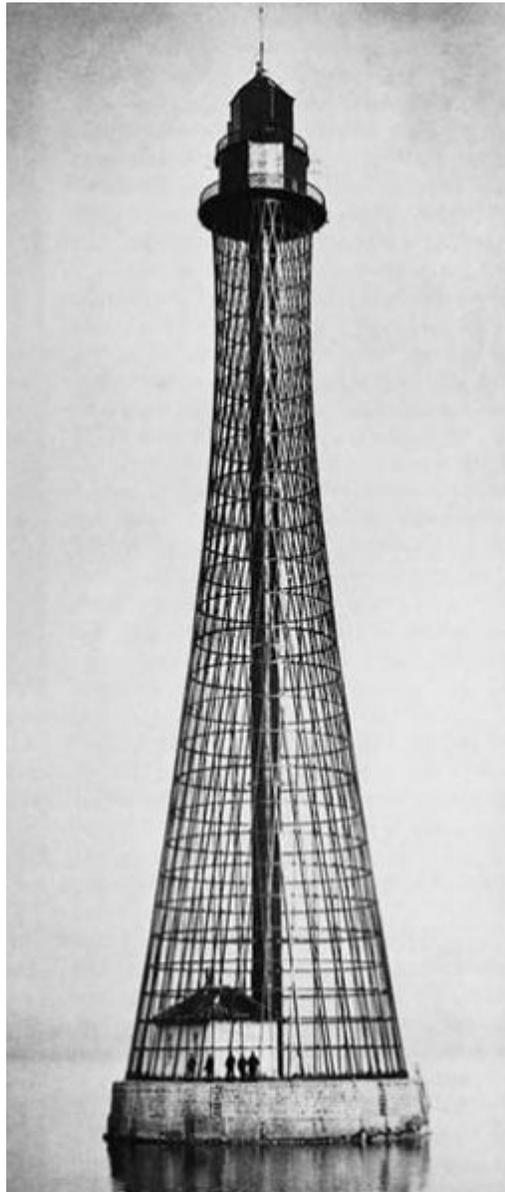
Properties of hyperboloid structures

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 laminated 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 material 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 bamboo 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.

Roofs 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 upper 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 roofs 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

high steeply-pitched roofs of Germany and Holland are typical in regions of snowfall. In parts of North America such as Buffalo, USA or Montreal, Canada, there is a required minimum slope of 6 inches in 12 inches, a pitch of 30 degrees.

There are regional building styles which contradict this trend, the stone roofs of the Alpine chalets being usually of gentler incline. These buildings tend to accumulate a large amount of snow on them, which is seen as a factor in their insulation. The pitch of the roof is in part determined by the roofing material available, a pitch of 3/12 or greater slope generally being covered with asphalt shingles, wood shake, corrugated steel, slate or tile.

The water repelled by the roof during a rainstorm is potentially damaging to the building that the roof protects. If it runs down the walls, it may seep into the mortar or through panels. If it lies around the foundations it may cause seepage to the interior, rising damp or dry rot. For this reason most buildings have a system in place to protect the walls of a building from most of the roof water. Overhanging eaves are commonly employed for this purpose. Most modern roofs and many old ones have systems of valleys, gutters, waterspouts, waterheads and drainpipes to remove the water from the vicinity of the building. In many parts of the world, roofwater is collected and stored for domestic use.

Areas prone to heavy snow benefit from a metal roof because their smooth surfaces shed the weight of snow more easily and resist the force of wind better than a wood shingle or a concrete tile roof.

Insulation, drainage and solar roofing



Snow on the roofs of houses in Poland.



The flat roofs of the Middle East, Israel.



Steeply pitched, gabled roofs in Northern Europe.



The overhanging eaves of China.



Green roof with solar panels, Findhorn, Scotland.

Solar roofs

Newer systems include solar shingles which generate electricity as well as cover the roof. There are also solar systems available that generate hot water or hot air and which can also act as a roof covering. More complex systems may carry out all of these functions: generate electricity, recover thermal energy, and also act as a roof covering.

Solar systems can be integrated with roofs by:

- integration in the covering of pitched roofs, e.g. solar shingles.
- mounting on an existing roof, e.g. solar panel on a tile roof.
- integration in a flat roof membrane using heat welding, e.g. PVC.
- mounting on a flat roof with a construction and additional weight to prevent uplift from wind.

Roof shapes



Flat roof, Western Australia.



Mansard roof on a county jail, Mount Gilead, Ohio.



Temple roof Chang Mai, Thailand with a decorated gable end and ceramic tile covering.

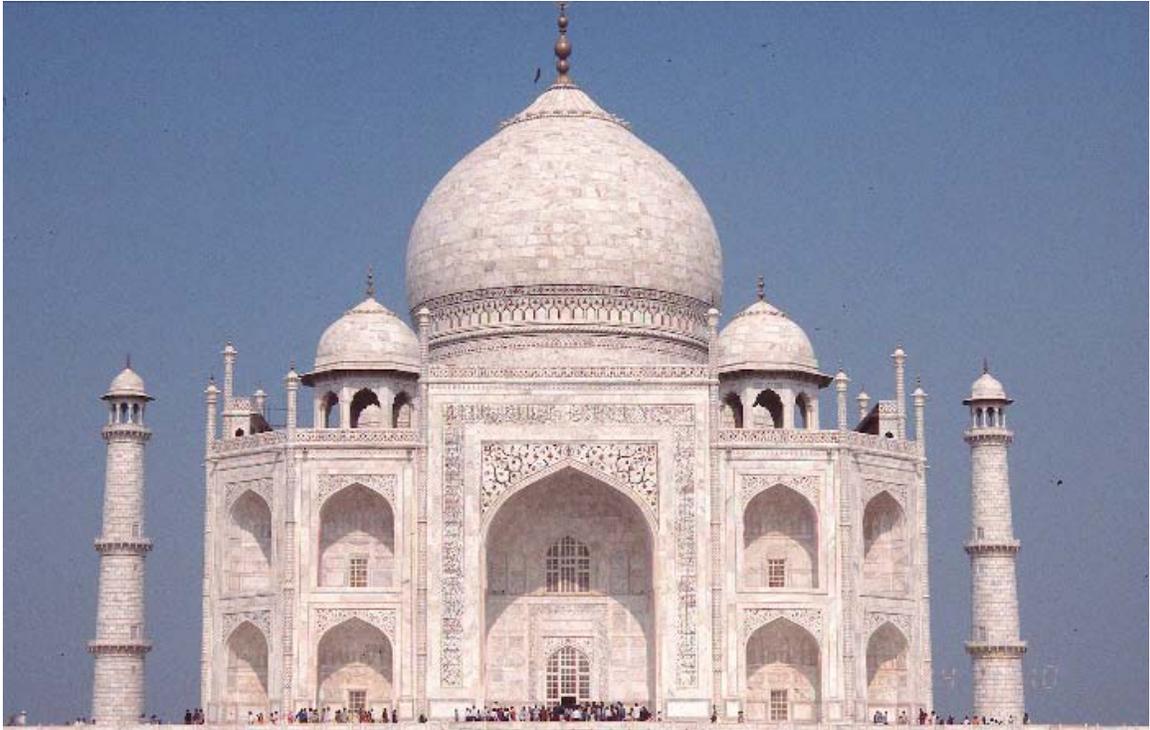


Conical Chinese roof at the Nanhai Academy in Taipei.

Gallery of significant roofs



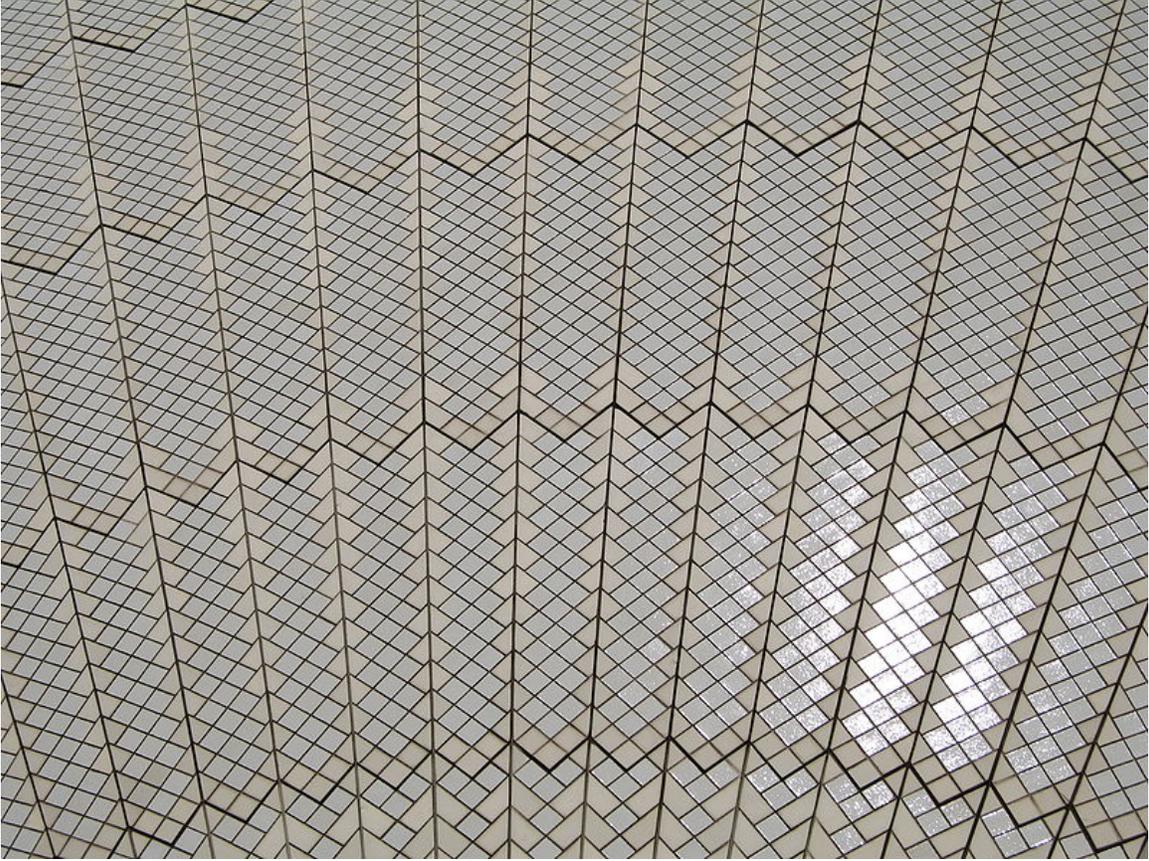
Imbrex and tegula tiles on the dome of Florence Cathedral.



The marble dome of the Taj Mahal.



The polychrome tiles of the Hospices de Beaune, France.



The glazed ceramic tiles of the Sydney Opera House.



The copper roof of Speyer Cathedral, Germany.



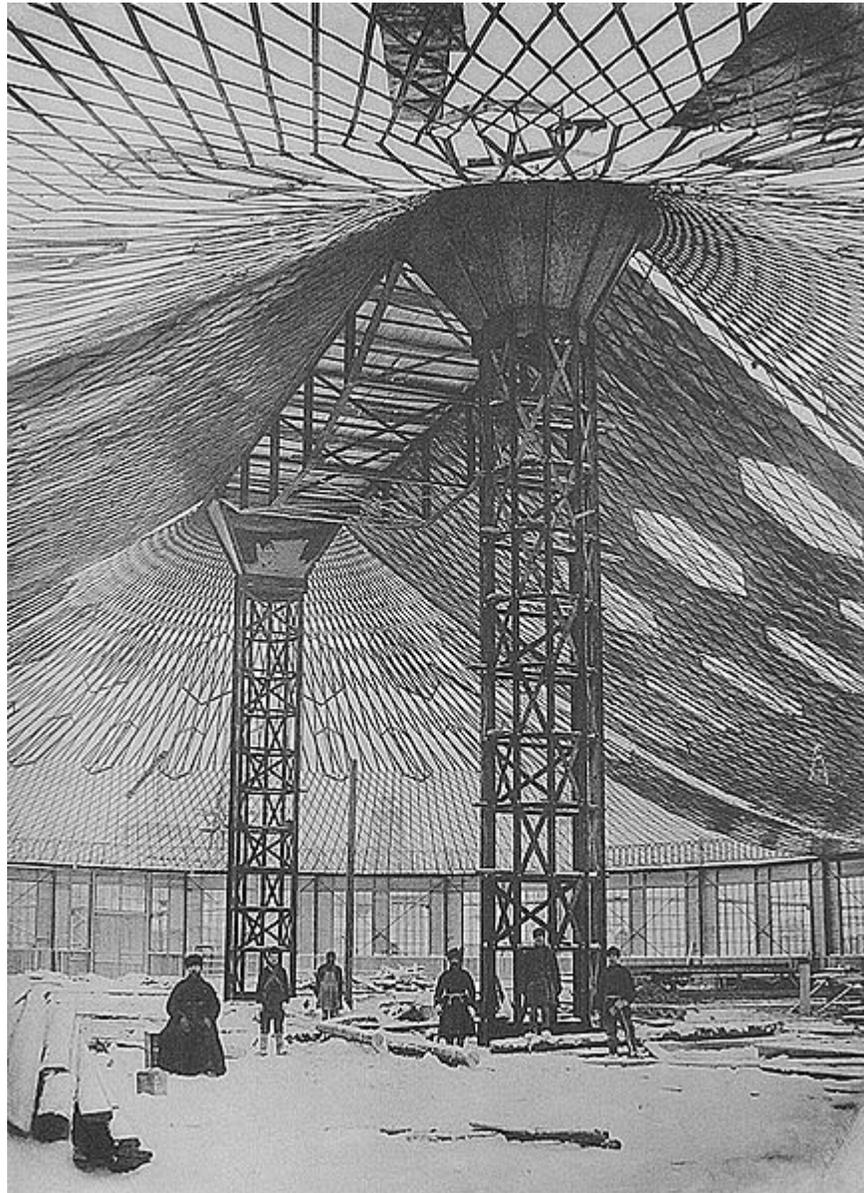
The lead roof of King's College Chapel, England.



The glass roof of the Grand Palais, Paris.

Chapter 3

Tensile Structure



The world's first tensile steel Shell by Vladimir Shukhov (during construction), Nizhny Novgorod, 1895



The Sidney Myer Music Bowl in Kings Domain, Melbourne

A **tensile structure** is a construction of elements carrying only tension and no compression or bending. The term tensile should not be confused with tensegrity, which is a structural form with both tension and compression elements.

Most tensile structures are supported by some form of compression or bending elements, such as masts (as in The O₂, formerly the Millennium Dome), compression rings or beams.

Tensile membrane structures are most often used as roofs as they can economically and attractively span large distances.

History



The Olympic Stadium in Munich makes extensive use of tensile roofing structures.

This form of construction has only become more rigorously analyzed and widespread in large structures in the latter part of the twentieth century. Tensile structures have long been used in tents, where the guy ropes provide pre-tension to the fabric and allow it to withstand loads.

Russian engineer Vladimir Shukhov was one of the first to develop practical calculations of stresses and deformations of tensile structures, shells and membranes. Shukhov designed eight tensile structures and thin-shell structures exhibition pavilions for the Nizhny Novgorod Fair of 1896, covering the area of 27,000 square meters. A more recent large-scale use of a membrane-covered tensile structure is the Sidney Myer Music Bowl, constructed in 1958.

Antonio Gaudi used the concept in reverse to create a compression-only structure for the Colonia Guell Church. He created a hanging tensile model of the church to calculate the compression forces and to experimentally determine the column and vault geometries.

The concept was later championed by German architect and engineer Frei Otto and René Gutierrez, whose first use of the idea was in the construction of the German pavilion at Expo 67 in Montreal. Otto next used the idea for the roof of the Olympic Stadium for the 1972 Summer Olympics in Munich.

Since the 1960s, tensile structures have been promoted by designers and engineers such as Ove Arup, Buro Happold, Walter Bird of Birdair, Inc., Frei Otto, Dante Velasco, Eero Saarinen, Horst Berger, Matthew Nowicki, Jorg Schlaich, the duo of Nicholas Goldsmith & Todd Dalland at FTL Design & Engineering Studio and David Geiger.

Steady technological progress has increased the popularity of fabric-roofed structures. The low weight of the materials makes construction easier and cheaper than standard designs, especially when vast open spaces have to be covered.

Types of structure with significant tension members

Linear structures

- Suspension bridges
- Draped cables
- Cable-stayed beams or trusses
- Cable trusses
- Straight tensioned cables

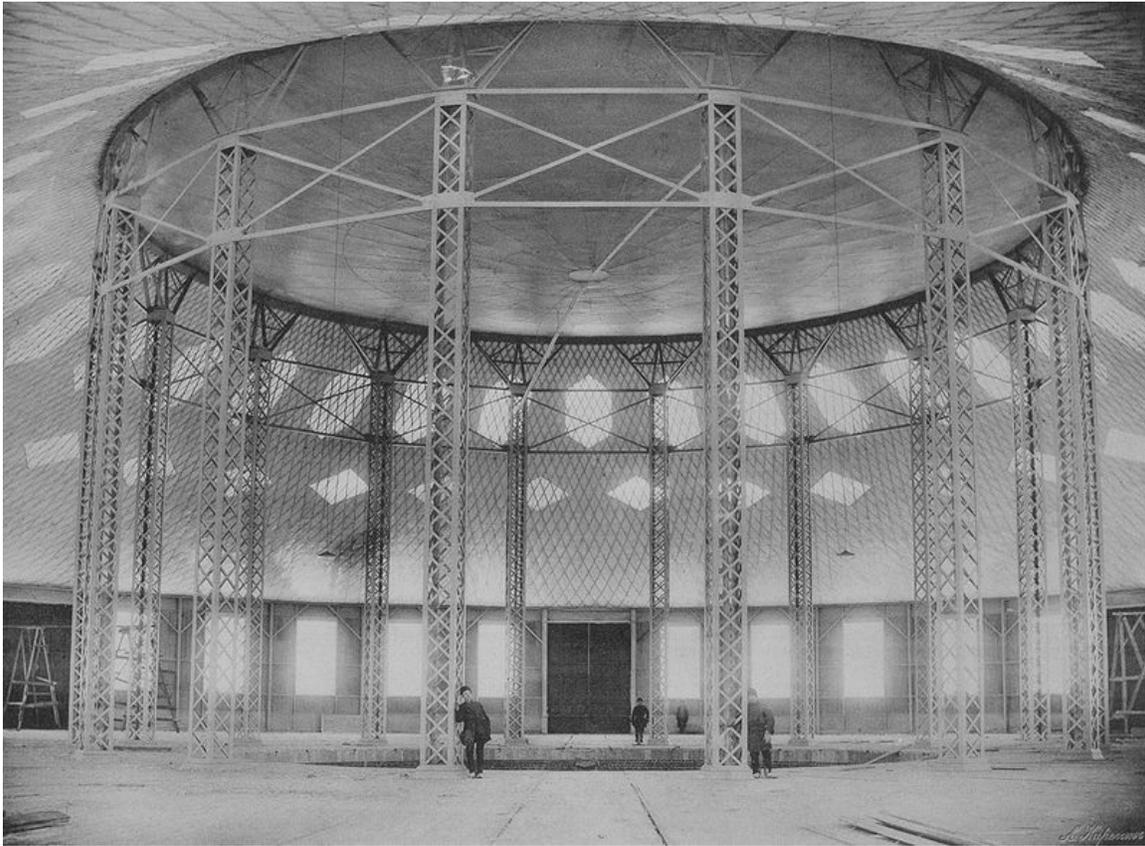
Three-dimensional structures

- Bicycle wheel (can be used as a roof in a horizontal orientation)
- 3D cable trusses
- Tensegrity structures
- Tensairity structures

Surface-stressed structures

- Prestressed membranes
- Pneumatically stressed membranes

Cable and membrane structures



The World First steel membrane roof and lattice steel Shell in the Shukhov Rotunda, Russia, 1895

Membrane materials

Common materials for doubly-curved fabric structures are PTFE-coated fibreglass and PVC-coated polyester. These are woven materials with different strengths in different directions. The warp fibres (those fibres which are originally straight—equivalent to the starting fibres on a loom) can carry greater load than the weft or fill fibres, which are woven between the warp fibres.

Other structures make use of ETFE film, either as single layer or in cushion form (which can be inflated, to provide good insulation properties or for aesthetic effect—as on the Allianz Arena in Munich). ETFE cushions can also be etched with patterns in order to let different levels of light through when inflated to different levels. They are most often supported by a structural frame as they cannot derive their strength from double curvature.

Cables



Simple suspended bridge working entirely in tension

Cables can be of mild steel, high strength steel (drawn carbon steel), stainless steel, polyester or aramid fibres. Structural cables are made of a series of small strands twisted or bound together to form a much larger cable. Steel cables are either spiral strand, where circular rods are twisted together and "glued" using a polymer, or locked coil strand, where individual interlocking steel strands form the cable (often with a spiral strand core).

Spiral strand is slightly weaker than locked coil strand. Steel spiral strand cables have a Young's modulus, E of 150 ± 10 kN/mm² (or 150 ± 10 GPa) and come in sizes from 3 to 90 mm diameter. Spiral strand suffers from construction stretch, where the strands compact when the cable is loaded. This is normally removed by pre-stretching the cable and cycling the load up and down to 45% of the ultimate tensile load.

Locked coil strand typically has a Young's Modulus of 160 ± 10 kN/mm² and comes in sizes from 20 mm to 160 mm diameter.

The properties of the individuals strands of different materials are shown in the table below, where UTS is ultimate tensile strength, or the breaking load:

	E (GPa)	UTS (MPa)	Strain at 50% of UTS
Solid steel bar	210	400–800	0.24%
Steel strand	170	1550–1770	1%

Wire rope	112	1550–1770	1.5%
Polyester fibre	7.5	910	6%
Aramid fibre	112	2800	2.5%

Structural forms

Air-supported structures are a form of tensile structures where the fabric envelope is supported by pressurised air only.

The majority of fabric structures derive their strength from their doubly-curved shape. By forcing the fabric to take on double-curvature the fabric gains sufficient stiffness to withstand the loads it is subjected to (for example wind and snow loads). In order to induce an adequately doubly curved form it is most often necessary to pretension or prestress the fabric or its supporting structure.

Form-finding

The behaviour of structures which depend upon prestress to attain their strength is non-linear, so anything other than a very simple cable has, until the 1990s, been very difficult to design. The most common way to design doubly curved fabric structures was to construct scale models of the final buildings in order to understand their behaviour and to conduct form-finding exercises. Such scale models often employed stocking material or tights, or soap film, as they behave in a very similar way to structural fabrics (they cannot carry shear).

Soap films have uniform stress in every direction and require a closed boundary to form. They naturally form a minimal surface—the form with minimal area and embodying minimal energy. They are however very difficult to measure. For large films the self-weight of the film can seriously and adversely affect the form.

For a membrane with curvature in two directions, the basic equation of equilibrium is:

$$w = \frac{t_1}{R_1} + \frac{t_2}{R_2}$$

where:

- R_1 and R_2 are the principal radii of curvature for soap films or the directions of the warp and weft for fabrics
- t_1 and t_2 are the tensions in the relevant directions
- w is the load per square metre

Lines of principal curvature have no twist and intersect other lines of principal curvature at right angles.

A geodesic or geodetic line is usually the shortest line between two points on the surface. These lines are typically used when defining the cutting pattern seam-lines. This is due to their relative straightness after the planar cloths have been generated, resulting in lower cloth wastage and closer alignment with the fabric weave.

$$\frac{t_1}{R_1} = -\frac{t_2}{R_2}$$

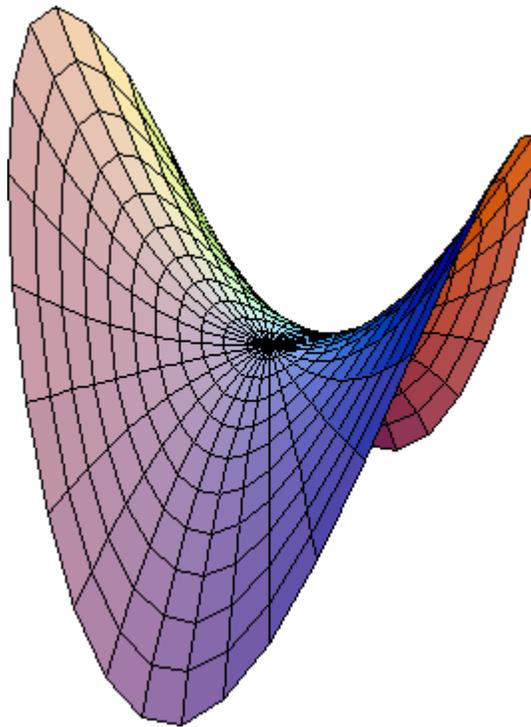
In a pre-stressed but unloaded surface $w = 0$, so

In a soap film surface tensions are uniform in both directions, so $R_1 = -R_2$.

It is now possible to use powerful non-linear numerical analysis programs (or finite element analysis) to formfind and design fabric and cable structures. The programs must allow for large deflections.

The final shape, or form, of a fabric structure depends upon:

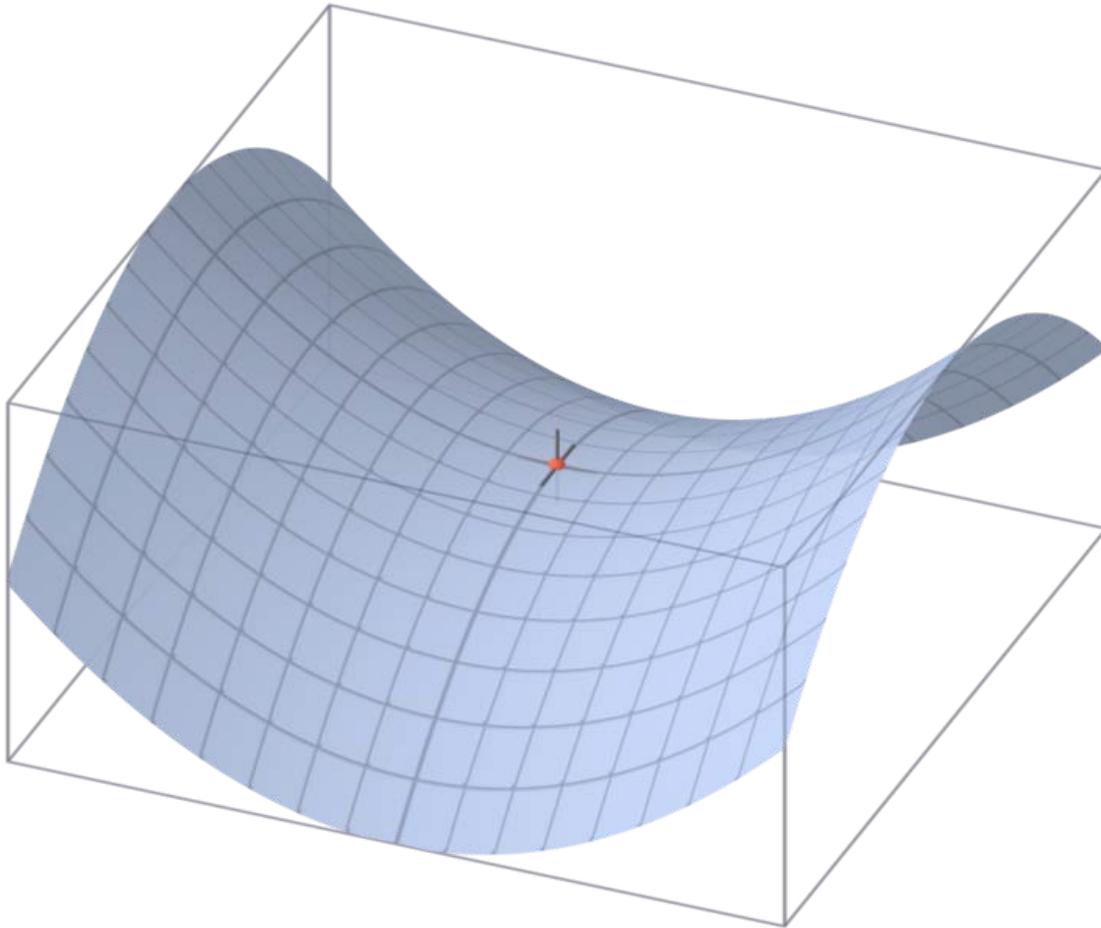
- shape, or pattern, of the fabric
- the geometry of the supporting structure (such as masts, cables, ringbeams etc.)
- the pretension applied to the fabric or its supporting structure



Hyperbolic paraboloid

It is important that the final form will not allow ponding of water, as this can deform the membrane and lead to local failure or progressive failure of the entire structure.

Snow loading can be a serious problem for membrane structure, as the snow often will not flow off the structure as water will. For example, this has in the past caused the (temporary) collapse of the Hubert H. Humphrey Metrodome, an air-inflated structure in Minneapolis, Minnesota. Some structures prone to ponding use heating to melt snow which settles on them.



Saddle Shape

There are many different doubly-curved forms, many of which have special mathematical properties. The most basic doubly curved form is the saddle shape, which can be a hyperbolic paraboloid (not all saddle shapes are hyperbolic paraboloids). This is a double ruled surface and is often used in both in lightweight shell structures. True ruled surfaces are rarely found in tensile structures. Other forms are anticlastic saddles, various radial, conical tent forms and any combination of them.

Pretension

Pretension is tension artificially induced in the structural elements in addition to any self-weight or imposed loads they may carry. It is used to ensure that the normally very flexible structural elements remain stiff under all possible loads.

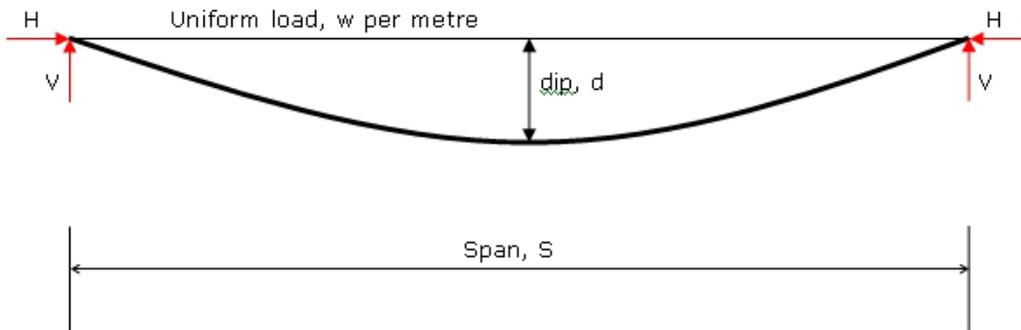
A day to day example of pretension is a shelving unit supported by wires running from floor to ceiling. The wires hold the shelves in place because they are tensioned - if the wires were slack the system would not work.

Pretension can be applied to a membrane by stretching it from its edges or by pretensioning cables which support it and hence changing its shape. The level of pretension applied determines the shape of a membrane structure.

Simple mathematics of cables

Transversely and uniformly loaded cable

For a cable spanning between two supports the simplifying assumption can be made that it forms a circular arc (of radius R).



By equilibrium:

The horizontal and vertical reactions :

$$H = \frac{wS^2}{8d}$$
$$V = \frac{wS}{2}$$

By geometry:

The length of the cable:

$$L = 2R \arcsin \frac{S}{2R}$$

The tension in the cable:

$$T = \sqrt{H^2 + V^2}$$

By substitution:

$$T = \sqrt{\left(\frac{wS^2}{8d}\right)^2 + \left(\frac{wS}{2}\right)^2}$$

The tension is also equal to:

$$T = wR$$

The extension of the cable upon being loaded is (from Hooke's Law, where the axial

stiffness, k , is equal to $k = \frac{EA}{L}$):

$$e = \frac{TL}{EA}$$

where E is the Young's modulus of the cable and A is its cross-sectional area.

If an initial pretension, T_0 is added to the cable, the extension becomes:

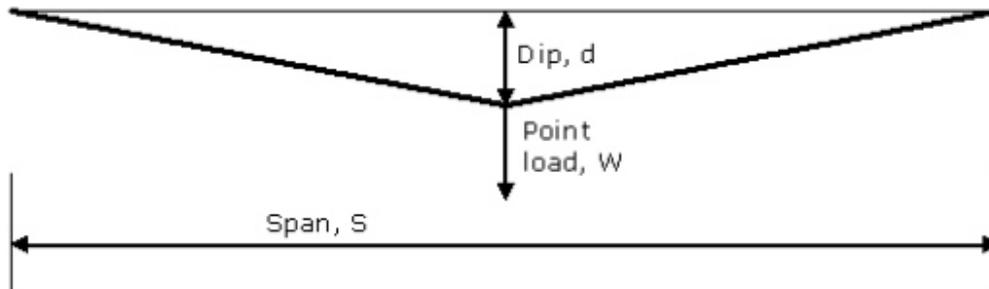
$$e = L - L_0 = \frac{L_0(T - T_0)}{EA}$$

Combining the above equations gives:

$$\frac{L_0(T - T_0)}{EA} + L_0 = \frac{2T \arcsin\left(\frac{wS}{2T}\right)}{w}$$

By plotting the left hand side of this equation against T , and plotting the right hand side on the same axes, also against T , the intersection will give the actual equilibrium tension in the cable for a given loading w and a given pretension T_0 .

Cable with central point load



A similar solution to that above can be derived where:

By equilibrium:

$$W = \frac{4Td}{L}$$
$$d = \frac{WL}{4T}$$

By geometry:

$$L = \sqrt{S^2 + 4d^2} = \sqrt{S^2 + 4 \left(\frac{WL}{4T} \right)^2}$$

This gives the following relationship:

$$L_0 + \frac{L_0(T - T_0)}{EA} = \sqrt{S^2 + 4 \left(\frac{W(L_0 + \frac{L_0(T - T_0)}{EA})}{4T} \right)^2}$$

As before, plotting the left hand side and right hand side of the equation against the tension, T , will give the equilibrium tension for a given pretension, T_0 and load, W .

Tensioned cable oscillations

The fundamental natural frequency, f_1 of tensioned cables is given by:

$$f_1 = \sqrt{\frac{\left(\frac{T}{m}\right)}{2L}}$$

where: T = tension in newtons, m = mass in kilograms and L = span length.

Notable structures

- Shukhov Rotunda, Russia, 1896
- Canada Place, Vancouver, British Columbia for Expo '86
- Yoyogi National Gymnasium by Kenzo Tange, Yoyogi Park, Tokyo, Japan
- Ingalls Rink, Yale University by Eero Saarinen
- Khan Shatry Entertainment Center, Astana, Kazakhstan
- Tropicana Field, St. Petersburg, Florida
- Olympiapark, Munich by Frei Otto
- Sidney Myer Music Bowl, Melbourne
- The O₂ (formerly the Millennium Dome), London by Buro Happold and Richard Rogers Partnership
- Denver International Airport, Denver
- Dorton Arena, Raleigh
- Georgia Dome, Atlanta, Georgia by Heery and Weidlinger Associates
- Grantley Adams International Airport, Christ Church, Barbados
- Pengrowth Saddledome, Calgary by Graham McCourt Architects and Jan Bobrowski and Partners
- Scandinavium, Gothenburg, Sweden
- Hong Kong Museum of Coastal Defence
- Ashford Retail Village, Kent, UK, by Buro Happold, Richard Rogers and Architekten Landrell
- Barclays Bank Headquarters, London
- Beckham Academy, London by Buro Happold
- Butlins Skyline Pavilion, Minehead, UK
- Carlos Moseley Music Pavilion, New York, NY
- Modernization of the Central Railway Station, Sofia, Bulgaria
- Columbus Center, Baltimore, Maryland
- Finnish Chancery, Washington, DC
- Imagination Headquarters, London
- National Symphony Orchestra, Washington, DC
- Pier6 Music Pavilion, Baltimore, Maryland
- Plashet Bridge, London by Birds Portchmouth Russum Architects
- Redbird Arena, Illinois State University, Normal, Illinois
- Desert Night resort, Wahiba Sands, Sultanate of Oman

Well known tensile structures



The roof tensile structures by Frei Otto of the Olympiapark, Munich



The Millennium Dome(now The O₂), London, by Buro Happold and Richard Rogers



Denver International Airport terminal



The THTR-300 cable-net dry cooling tower, hyperboloid structure by Schlaich Bergemann & Partner

Chapter 4

Timber Framing



Timber-frame barn in Shiner, TX.



Red brick timberframe building in Poznań, Poland



Timberframe (16th century) in Vannes (Brittany)

Timber framing (German: *Fachwerk* literally "framework"), or **half-timbering**, is the method of creating structures utilizing heavy timbers jointed by pegged mortise and tenon joints.

In architectural terminology it can be defined as:

a lattice of panels filled with a non-loadbearing material or "nogging" of brick, clay or plaster, the frame is often exposed on the outside of the building

Naming

One of the first people to use the term *half-timbered* was Mary Martha Sherwood (1775–1851), who employed it in her book *The Lady of the Manor*, published in several volumes from 1823–1829. She uses the term picturesquely:

passing through a gate in a quickset hedge, we arrived at the porch of an old half-timbered cottage, where an aged man and woman received us.

Perversely, Sherwood does not use it equally for all timber-framed buildings, for elsewhere she writes:

an old cottage, half hid by the pool-dam, built with timber, painted black, and with white stucco, and altogether presenting a ruinous and forlorn appearance.

By 1842, the term "half-timbered" had found its way into *The Encyclopedia of Architecture* by Joseph Gwilt (1784–1863).

Structure



The completed frame of a modern timber-frame house



Projecting ("jettied") upper storeys of an English half-timbered village terraced house, the jetties plainly visible

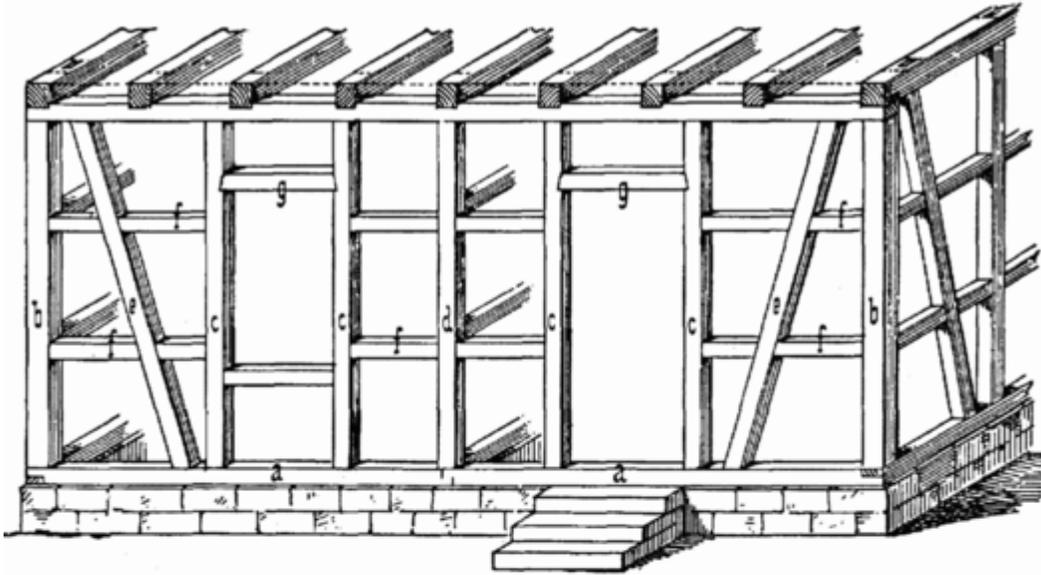


Fig. 1.

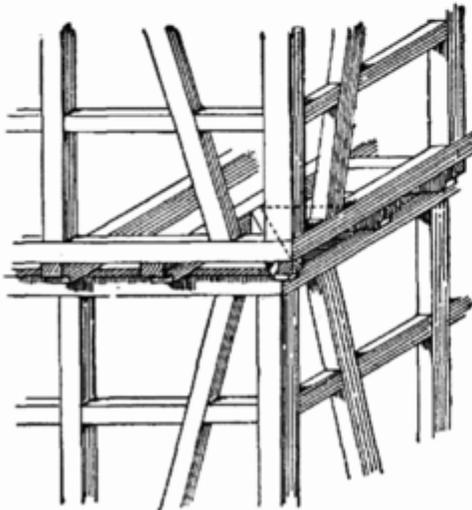


Fig. 2.

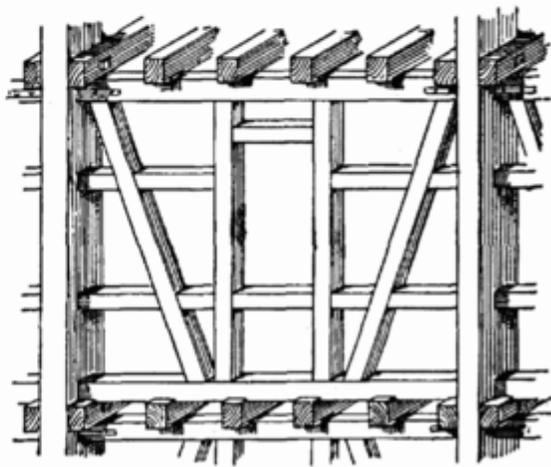


Fig. 3.

Illustration of timber framing from the Lexikon der gesamten Technik (1904)

Timber framing is the method of creating framed structures of heavy timber jointed together with various joints, but most commonly originally with lap jointing, and then later pegged mortise and tenon joints. Diagonal bracing is used to prevent "racking", or movement of structural vertical beams or posts.

Originally, German (and other) master carpenters would peg the joints with allowance of approximately an inch (25 mm), enough room for the wood to move as it *seasoned*, then cut the pegs and drive the beam home fully into its socket.

To cope with variable sizes and shapes of hewn (by adze or axe) and sawn timbers, two main carpentry methods were employed: scribe carpentry and square rule carpentry.

Scribing was used throughout Europe, especially from the 12th century to the 19th century and subsequently imported to North America where it was common into the early 19th century. In a scribe frame, timber sockets are fashioned or "tailor-made" to fit their corresponding timbers; thus each timber piece must be numbered (or "scribed").

Square-rule carpentry was developed in New England in the 18th century. It used housed joints in main timbers to allow for interchangeable braces and girts. Today, standardised timber sizing mean that timber framing can be incorporated into mass-production methods as per the joinery industry, especially where timber is cut by precision CNC machinery.

To finish the walls, the spaces between the timbers (in German called *Fächer*) were often infilled with wattle and daub, loam, brick, or rubble. Plastered faces on the exterior and interior were often "ceiled" with wainscoting for insulation and warmth.

This juxtaposition of exposed timbered beams and infilled spaces created the distinctive "half-timbered", or occasionally termed "Tudor", style.

Jetties

A *jetty* is an upper floor which requires a structural cantilevered horizontal beam called a *jetty bressummer* to bear the weight of the new wall, projecting outward from the preceding floor or storey.

In an era when houses were taxed with respect to ground-floor area (square footage) extensive jettying was employed to create higher storeys of greater area. In the city of York in the United Kingdom, the famous street known as The Shambles exemplifies this, where jettied houses seem to almost touch above the street.

Timbers

Historically, the timbers would have been hewn square using a felling axe and then surface-finished with a broadaxe. If required, smaller timbers were rip-sawn from the hewn baulks using pitsaws or frame saws. Today it is more common for timbers to be bandsawn, and the timbers may sometimes be machine-planed on all four sides.

The vertical timbers include

- posts (main supports at corners and other major uprights),
- Wall studs (subsidiary upright limbs in framed walls), for example, close studding.

The horizontal timbers include

- sill-beams (also called ground-sills or sole-pieces, at the bottom of a wall into which posts and studs are fitted using tenons),

- noggin-pieces (the horizontal timbers forming the tops and bottoms of the frames of infill panels),
- wall-plates (at the top of timber-framed walls that support the trusses and joists of the roof).

When *jettying*, horizontal elements can include:

- the jetty bressummer (or breastsummer): the main sill (horizontal piece) on which the projecting wall above rests and which stretches across the whole width of the jetty wall. The bressummer is itself *cantilevered* forward, beyond the wall below it.
- the *dragon-beam* which runs diagonally from one corner to another, and supports the corner posts above and supported by the corner posts below.
- the jetty beams or joists which conform floor dimensions above but are at right angles to the *jetty-plates* that conform to the shorter dimensions of "roof" of the floor below. Jetty beams are morticed at 45° into the sides of the dragon beams. They are the main constituents of the cantilever system and determine how far the jetty projects
- the jetty-plates, designed to carry the jetty beams. The jetty plates themselves are supported by the corner posts of the recessed floor below.

The sloping timbers include

- trusses (the slanting timbers forming the triangular framework at gables and roof),
- braces (slanting beams giving extra support between horizontal or vertical members of the timber frame),
- herringbone bracing (a decorative and supporting style of frame, usually at 45° to the upright and horizontal directions of the frame).

Modern features



Porch of a modern timber-framed house



Interior of a modern hand-hewn post and beam home.

In the United States and Canada, timber-frame construction has been revived since the 1970s and is now experiencing a thriving renaissance of the ancient skills. This is largely due to such practitioners as Steve Chappell, Jack Sobon, and Tedd Benson, who studied old plans and techniques and revived a long-neglected technique. Once a handcrafted skill passed down, timber-frame construction has now been modernized with the help of modern industrial tools such as the CNC machines. These machines and mass-production techniques have assisted growth and made for more affordable frames and shorter lead-times for projects.

Timber-framed structures differ from conventional wood-framed buildings in several ways. Timber framing uses fewer, larger wooden members, commonly timbers in the range of 15 to 30 cm (6" to 12"), while common wood framing uses many more timbers with dimensions usually in the 5 to 25 cm (2" to 10") range. The methods of fastening the frame members also differ. In conventional framing, the members are joined using nails or other mechanical fasteners, whereas timber framing uses the traditional mortice and tenon or more complex joints that are usually fastened using only wooden pegs. Modern complex structures and timber trusses often incorporate steel joinery such as gusset plates, for both structural and architectural purposes.

Recently, it has become common practice to entirely surround the timber structure in manufactured panels, such as SIPs (Structural Insulated Panels). This method has benefits: the timbers can only be seen from inside the building, but is less complex to build and provides more efficient insulation. Structural Insulated Panels are commonly two rigid composite materials usually wood-based like OSB or plywood with a foamed insulation material innard, between either gluing billets as in EPS (Expanded Polystyrene) or formed in place with foaming polyurethane. Another advantage is less of a dependency on extraneous bracing and auxiliary members, minor joists and rafters, as the panels can span considerable distances and add greater rigidity to the basic timber frame.



A Huf Haus near West Linton in Scotland

An alternate construction method is with concrete flooring with extensive use of glass. This allows a very solid construction combined with open architecture. Some firms have specialized in industrial prefabrication of such residential and light commercial structures such as Huf Haus as Low-energy houses or – dependent on location – Zero-energy buildings.

Straw-bale construction is another alternative where straw bales are stacked for non-loadbearing infill with various finishes applied to the interior and exterior such as stucco and plaster. This appeals to the traditionalist and the environmentalist as this is using "found" materials to build.

History and traditions



Anne Hvides Gaard, Svendborg, Denmark, from 1560

The techniques used in timber framing date back to Neolithic times, and have been used in many parts of the world during various periods such as ancient Japan, continental Europe as well as Neolithic Denmark, England, France, Germany parts of the Roman Empire and Scotland.

Half-timbered construction in the Northern European vernacular building style is characteristic of medieval and early modern Denmark, England, Germany and parts of France and Switzerland where timber was in good supply yet stone and associated skills

to dress the stonework were in short supply. In half-timbered construction timbers that were riven in half provided the complete skeletal framing of the building.

Some Roman carpentry preserved in anoxic layers of clay at Romano-British villa sites demonstrate that sophisticated Roman carpentry had all the necessary techniques for this construction. The earliest surviving (French) half-timbered buildings date from the 12th century.

English tradition



Timber-framed shops in Holborn, London

Some of the earliest known timber houses in Europe have been found in Scotland and England, dating to Neolithic times; Balbridie and Fengate are some of the rare examples of these constructions.

Molded plaster ornamentation, *pargetting* further enriched some English Tudor architecture houses. Half-timbering is characteristic of English vernacular architecture in East Anglia, Warwickshire, Worcestershire, Herefordshire, Shropshire, and Cheshire, where one of the most elaborate surviving English examples of half-timbered construction is Little Moreton Hall.

In South Yorkshire, the oldest timber house in Sheffield, the "Bishops' House" c.1500, shows traditional half-timbered construction.

In the Weald of Kent and Sussex, the half-timbered structure of the Wealden hall house, consisted of an open hall with bays on either side and often jettied upper floors.

Half-timbered construction traveled with British colonists to North America in the early 17th century but was soon abandoned in New England and the mid-Atlantic colonies for clapboard facings (another tradition of East Anglia).



Farmhouse in Wormshill, England



Historic timber-framed houses in Warwick, England

Many of the surviving streets lined with almost touching houses are known as The Shambles and are very popular tourist attractions.

French tradition



Coupesarte Manor (Normandy, France)

Elaborately half-timbered houses of the 13th, 14th, 15th, 16th, 17th and 18th centuries still remain in Strasbourg, Bourges, Troyes, Rouen, Thiers, Dinan, Rennes, Colmar and many other cities, except in Provence and Corsica. Timber framing in French is known colloquially as *pan de bois* or technically: *colombage*.

The *Normandy tradition* features two techniques: frameworks were built of four evenly spaced regularly hewn timbers set into the ground (*poteau en terre*) or into a continuous wooden sill (*poteau du sole*) and mortised at the top into the plate. The openings were filled with many materials including mud and straw, wattle and daub, or horsehair and gypsum.



Old houses in Troyes (Champagne, France)



Church of Drosnay (Champagne, France)



14th early corbelled house, Rouen (Normandy, France)



15th century manor, Saint-Sulpice-de-Grimbouville, (Normandy, France)

German tradition or *Fachwerkhäuser*

Probably the greatest number of half-timbered buildings are to be found in Germany. There are many small towns which escaped both war damage and modernisation and consist mainly, or even entirely, of half-timbered houses.

Some of the more prominent towns (among many) include: Hanau-Steinheim (the city of the Brothers Grimm); Bad Urach; Eppingen ("Romance city" with a half-timbered church dating from 1320); Mosbach; Vaihingen an der Enz with a UNESCO-listed Celtic abbey and monastery; Schorndorf (birthplace of Gottlieb Daimler; and perhaps most importantly, Calw which has over 200 17th-century half-timbered houses and Biberach an der Riß with both the largest medieval complex, the *Holy Spirit Hospital* and the oldest Southern German building, now the Museum of Weavers, dated to 1318.

The best are to be seen along the *Deutsche Fachwerkstraße* ("German Timber Framing Road").

German *fachwerk* building styles are extremely varied with a huge number of carpentry techniques which are highly regionalised. German planning laws for the preservation of

buildings and regional architecture preservation dictate that a half-timbered house must be authentic to regional or even city-specific designs before being accepted.

A brief overview of styles follows, as a full inclusion of all styles is impossible.

In general the northern states have *fachwerk* very similar to that of nearby Holland and England while the more southerly states (most notably Bavaria and Switzerland) have more decoration using timber because of greater forest reserves in those areas.

The German *fachwerkhaus* usually has a foundation of stone, or sometimes brick, perhaps up to several feet (a couple of metres) high, which the timber framework is mortised into or, more rarely, supports an irregular wooden sill.

The three main forms may be divided geographically:

- Lower Germany or Alemannic and Franconian:
 - In Franconian timber-work houses (particularly in the Central Rhine and Moselle): the windows most commonly lie between the rails of the sills and lintels.
- Central Germany (also very similar style to Poland):
 - In Saxony and around the Harz foothills, angle braces often form fully extended triangles.
 - Lower Saxon houses have a joist for every post.
 - Holstein *fachwerk* houses are famed for their massive 12-inch (30 cm) beams.
- Southern Germany including the Black and Bohemian Forests
 - In Swabia, Württemberg, Alsace, and Switzerland, the use of the lap-joint is thought to be the earliest method of connecting the wall plates and tie beams and is particularly identified with Swabia. A later innovation (also pioneered in Swabia) was the use of tenons — builders left timbers to season which were held in place by wooden pegs (*i.e.*, tenons). The timbers were initially placed with the tenons left an inch or two out of intended position and later driven home after becoming fully seasoned.

The most characteristic feature is the spacing between the posts and the high placement of windows. Panels are enclosed by sill, post and plate and are crossed by two rails between which the windows are placed—like "two eyes peering out".

In addition there is a myriad of regional scrollwork and fretwork designs of the non-loadbearing large timbers (braces) peculiar to particularly wealthy towns or cities.

The German Half-Timbered House Road (*Deutsche Fachwerkstraße*) is a tourist route that links places containing picturesque half-timbered buildings. It is more than 2 000 km

long and stretches across the states of Lower Saxony, Saxony-Anhalt, Hesse, Thuringia, Bavaria and Baden-Württemberg.



Buildings in Hornburg (Germany)



Buildings in Braubach (Germany)



House in Schwerin (Germany) built in 1698

Netherlands

The Netherlands is often overlooked for its timbered houses, yet many exist including windmills. It was in North Holland where the importation of cheaper timber combined with the Dutch innovation of widespread windmill-powered sawmills allowed economically viable widespread use of protective wood covering over framework. In the late 17th century the Dutch introduced vertical cladding also known in Eastern England as clasp board and in western England as weatherboard, then as more wood was available more cheaply, horizontal cladding in the 17th century. Perhaps owing to economic considerations, vertical cladding returned to fashion.

Americas

Most "haft-timbered" houses existing in Missouri, Pennsylvania (the Amish are actually ethnically German) and Texas were built by German settlers. Many are still present in Santa Catarina and Rio Grande do Sul, Brazil, where Germans settled in the Southern Brazilian states. Later, they chose more suitable building materials for local conditions (most likely because of the great problem of tropical termites.)

Canadian tradition

The style called *colombage pierroté* in Quebec as well other areas of Canada was half-timbered construction with infilled stone and rubble. The style had its origins in Normandy and was brought to Canada by very early Norman settlers. The Men's House at Lower Fort Garry is a good example of *colombage pierroté*. The walls of such buildings were often covered over with clapboards to protect the infill from erosion. Naturally, this required frequent maintenance and the style was abandoned as a building method in the 18th century in Québec. For the same reasons, half-timbering in New England, which was originally employed by the English settlers, fell out of favour soon after the colonies had become established.

Consequently this gave rise to the **poteaux sur solle** style in which wood is used both for the frame and infill; for this reason it may be incorrect to call it "half-timbering". This technique proved better suited to the harsh climates of Québec and Acadia, which at the same time had abundant wood. It became very popular throughout New France, as far afield as southern Louisiana.

Nevertheless, despite the rising preference for *poteaux sur solle*, the *colombage pierroté* technique survived well into the 19th century in the Prairies, being employed by French-Canadian carpenters at outposts of the Hudson's Bay Company, as well as on the Red River Colony.

Revival styles in later centuries



The Saitta House, Dyker Heights, Brooklyn, New York built in 1899 has half-timber decoration.

When half-timbering regained popularity in Britain after 1860 in the various revival styles, such as the Queen Anne style houses by Richard Norman Shaw and others, it was often used to evoke a "Tudor" atmosphere, though in Tudor times half-timbering had begun to look rustic and was increasingly limited to village houses (*illustration, above left*).

In 1912, Allen W. Jackson published *The Half-Timber House: Its Origin, Design, Modern Plan, and Construction*, and rambling half-timbered beach houses appeared on

dune-front properties in Rhode Island or under palm-lined drives of Beverly Hills. During the 1920s increasingly minimal gestures towards some half-timbering in commercial speculative house-building saw the fashion diminish.

In the revival styles, such as Tudorbethan (Mock Tudor), the half-timbered appearance is superimposed on the brickwork or other material as an outside decorative façade rather than forming the main frame that supports the structure.

Advantages

The use of timber framing in buildings offers various aesthetic and structural benefits, as the timber frame lends itself to open plan designs and allows for complete enclosure in effective insulation for energy efficiency.

In modern construction timber-frame structure offers many benefits:

- it is rapidly erected
- it lends itself well to prefabrication, modular construction and mass-production.
- lends well to pre-fitting the frame usually in bent or wall-sections that are aligned with jig. This allows greater rapidity in erection on site and more precise alignments. Such pre-fitting in the shop is independent of a machine or hand-cut production line. Valley and hip timbers are not typically pre-fitted.
- an "average"-sized timber-frame home can be erected within 2 to 3 days.
- the frame can be encased with SIPs for the *drying in*: that is, ready for windows, mechanical systems, and roofing.
- it can be tailored to suit customer tastes and creativity such as carvings or incorporation of heirloom structures such as barns etc.
- it can use recycled or otherwise discarded timbers.
- it offers some structural benefits as the timber frame, if properly engineered, lends itself to better *seismic survivability*. Consequentially, there are lots of old half-timbered houses which still stand despite the foundation having partially caved in over the centuries.

In North America, heavy timber construction is classified Building Code Type IV: a special class reserved for timber framing which recognizes the inherent fire resistance of large timber and its ability to retain structural capacity in fire situations. In many cases this classification can eliminate the need and expense of fire sprinklers in public buildings.

Disadvantages

Traditional or historic structures

In terms of the traditional half-timber or *fachwerkhaus* there are maybe more disadvantages than advantages today. Such houses are notoriously expensive to maintain let alone renovate and restore, most commonly owing to local regulations that do not

allow divergence from the original, modification or incorporation of modern materials. Additionally, in such nations as Germany where energy efficiency is highly regulated, the renovated building may be required to meet modern energy efficiencies, if it is to be used as a residential or commercial structure (museums and significant historic buildings have no semi-permanent habitation are exempt). Many framework houses of significance are treated merely to preserve, rather than render inhabitable - most especially as the required heavy insecticidal fumigation is highly poisonous.

In some cases, it is more economical to build anew using authentic techniques and correct period materials than restore. One major problem with older structures is the phenomenon known as *mechano-sorptive creep* or slanting: where wood beams absorb moisture whilst under compression or tension strains and deform, shift position or both. This is a major structural issue as the house may deviate several degrees from perpendicular to its foundations (in the x-axis, y-axis and even z-axis) and thus be unsafe and unstable or so out of square it is extremely costly to remedy.

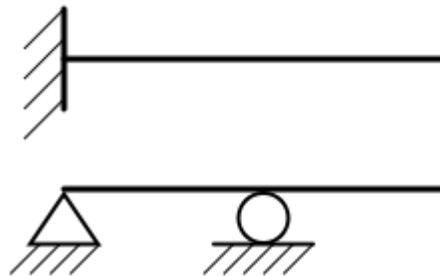
A summary of problems with *Fachwerkhäuser* or half-timbered houses includes the following, though many can be avoided by intelligent design and application of suitable paints and surface treatments and routine maintenance. Often, though when dealing with a structure of a century or more old, it is too late.

- "slanting"- *thermo-mechanical* (weather-seasonally induced) and mechano-sorptive (moisture induced) creep of wood in tension and compression.
- poor prevention of capillary movement of water within any exposed timber, leading to afore-described creep, or rot
- eaves that are too narrow or non-existent (thus allowing total exposure to rain and snow)
- too much exterior detailing that does not allow adequate rainwater run-off
- timber ends, joints and corners poorly protected through coatings, shape or position
- non-bevelled vertical beams (posts and clapboards) allow water absorption and retention through capillary action.
- surface paint or coatings allowed to deteriorate
- traditional gypsum, or wattle and daub containing organic materials (animal hair, straw, manure) which then decompose.
- in both *porteaux en terre* and *porteaux du sole* "insect, fungus or bacterial decomposition.
- rot including dry rot.
- infestation of xylophagous pest organisms such as (very common in Europe) the *Anobiidae* family particularly the common furniture beetle, termites, cockroaches powderpost beetles, mice and rats (quite famously so in many children's stories).
- Noise from footsteps in adjacent rooms above, below, and on the same floor in such buildings can be quite audible. This is often resolved with built-up floor systems involving clever sound-isolation and absorption techniques, and at the same time providing passage space for plumbing, wiring and even heating and cooling equipment.

- Other fungi that are non-destructive to the wood, but are harmful to humans such as black mold. These fungi may also thrive on many "modern" building materials.
- Wood burns more readily than some other materials, making timber-frame buildings somewhat more susceptible to fire damage, although this idea is not universally accepted: Since the cross-sectional dimensions of many structural members exceed 15 cm × 15 cm (6" × 6"), timber-frame structures benefit from the unique properties of large timbers, which char on the outside forming an insulated layer that protects the rest of the beam from burning.
- prior flood or soil subsidence damage

Chapter 5

Cantilever



A schematic image of two cantilevers. The top example has a full moment connection (like a horizontal flag pole bolted to the side of a building). The bottom example is created by an extension of a simple supported beam (such as the way a diving-board is anchored and extends over the edge of a swimming pool).

A **cantilever** is a beam supported on only one end. The beam carries the load to the support where it is resisted by moment and shear stress. Cantilever construction allows for overhanging structures without external bracing. Cantilevers can also be constructed with trusses or slabs.

This is in contrast to a simply supported beam such as those found in a post and lintel system. A simply supported beam is supported at both ends with loads applied between the supports.

In bridges, towers, and buildings

Cantilevers are widely found in construction, notably in cantilever bridges and balconies. In cantilever bridges the cantilevers are usually built as pairs, with each cantilever used to support one end of a central section. The Forth Bridge in Scotland is a famous example of a cantilever truss bridge.

Temporary cantilevers are often used in construction. The partially constructed structure creates a cantilever, but the completed structure does not act as a cantilever. This is very helpful when temporary supports, or falsework, cannot be used to support the structure while it is being built (e.g., over a busy roadway or river, or in a deep valley). So some truss arch bridges are built from each side as cantilevers until the spans reach each other and are then jacked apart to stress them in compression before final joining. Nearly all cable-stayed bridges are built using cantilevers as this is one of their chief advantages. Many box girder bridges are built segmentally, or in short pieces. This type of construction lends itself well to balanced cantilever construction where the bridge is built in both directions from a single support.

These structures are highly based on torque and rotational equilibrium.

In an architectural application, Frank Lloyd Wright's Fallingwater used cantilevers to project large balconies. The East Stand at Elland Road Stadium in Leeds was, when completed, the largest cantilever stand in the world holding 17,000 spectators. The roof built over the stands at Old Trafford Football Ground uses a cantilever so that no supports will block views of the field. The old, now demolished Miami Stadium had a similar roof over the spectator area. The largest cantilever in Europe is located at St James' Park in Newcastle-Upon-Tyne, the home stadium of Newcastle United F.C.



The Forth Bridge, a cantilever truss bridge.



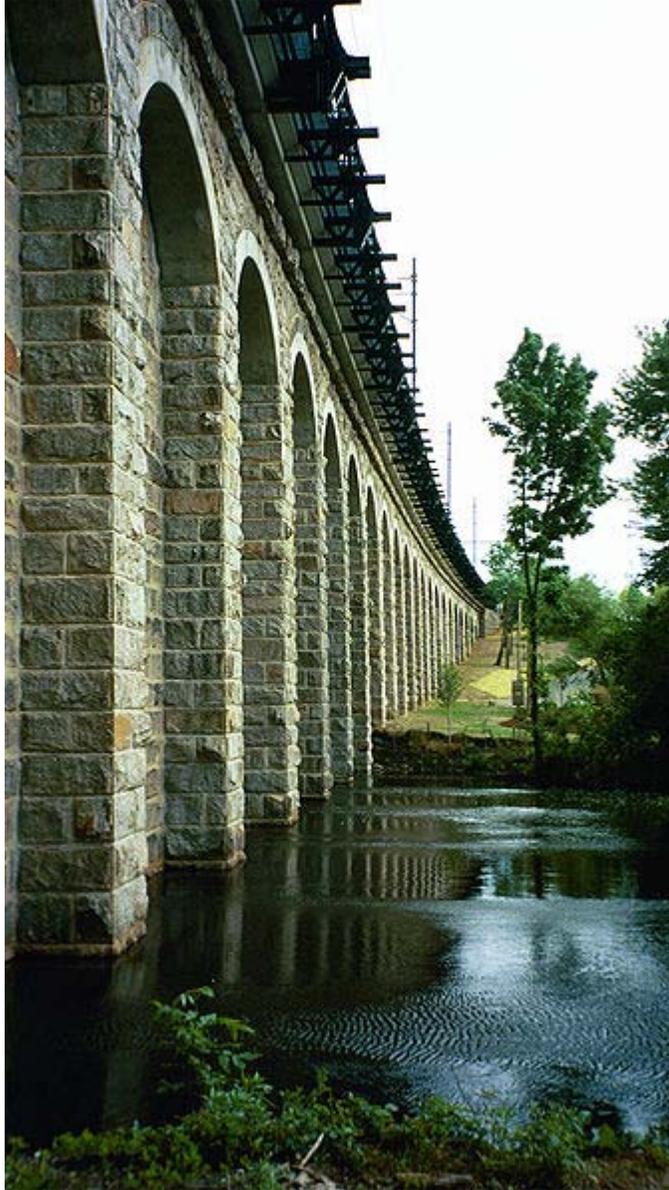
This concrete bridge temporarily functions as a set of two balanced cantilevers during construction - with further cantilevers jutting out to support formwork.



A notable cantilever balcony of the Fallingwater house, by Frank Lloyd Wright.



A balcony created by a cantilever slab.



A cantilevered railroad deck and fence on the Canton Viaduct



A cantilever barn from rural Appalachia

Less obvious examples of cantilevers are free-standing radio towers without guy-wires, and chimneys, which resist being blown over by the wind through cantilever action at their base.

In aircraft



The pioneering Junkers J 1 all-metal monoplane of 1915, the first aircraft ever to fly with cantilever wings

Another use of the cantilever is in fixed-wing aircraft design, pioneered by Hugo Junkers in 1915. Early aircraft wings typically bore their loads by using two (or more) wings in a biplane configuration braced with wires and struts. They were similar to truss bridges, having been developed by Octave Chanute, a railroad bridge engineer. The wings were braced with crossed wires so they would stay parallel, as well as front-to-back to resist twisting, running diagonally between adjacent strut anchorages. The cables and struts generated considerable drag, and there was constant experimentation on ways to eliminate them.

It was also desirable to build a monoplane aircraft, as the airflow around one wing negatively affects the other in a biplane's airframe design. Early monoplanes used either struts (as do some current light aircraft), or cables like the 1909 Bleriot XI (as do some modern home-built aircraft). The advantage in using struts or cables is a reduction in weight for a given strength, but with the penalty of additional drag. This reduces maximum speed, and increases fuel consumption.



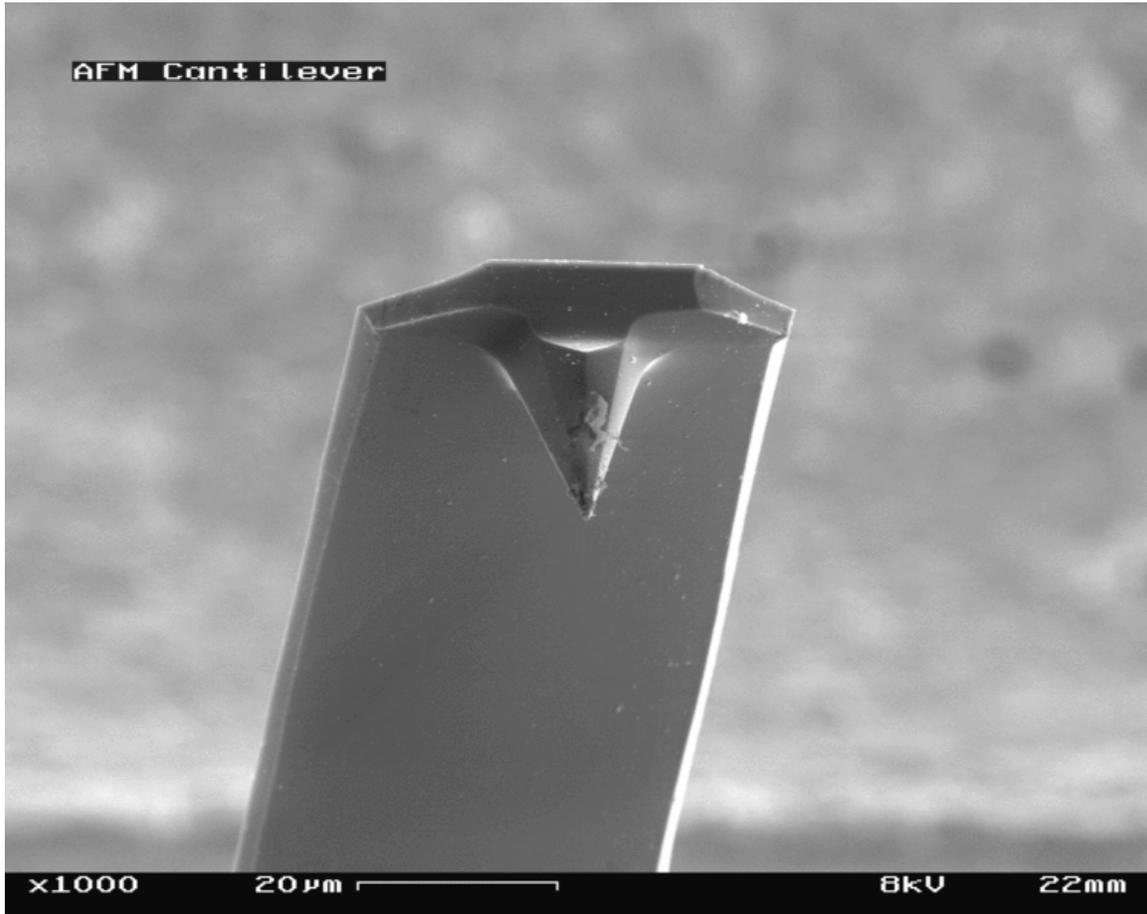
A British Hawker Hurricane from World War II with cantilever wings

Hugo Junkers endeavored to eliminate all external bracing, only a dozen years after the Wright Brothers' initial flights, to decrease airframe drag in flight, with the result being the Junkers J 1 pioneering all-metal monoplane of late 1915, designed from the start with all-metal cantilever wing panels.

The most common current wing design is the cantilever. A single large beam, called the *main spar*, runs through the wing, typically nearer the leading edge at about 25 percent of the total chord. In flight, the wings generate lift, and the wing spars are designed to carry this load through the fuselage to the other wing. To resist fore and aft movement, the wing will usually be fitted with a second smaller drag-spar nearer the trailing edge, tied to the main spar with structural elements or a stressed skin. The wing must also resist twisting forces, done either by a monocoque "D" tube structure forming the leading edge, or by the aforementioned linking two spars in some form of *box beam* or *lattice girder* structure.

Cantilever wings require a much heavier spar than would otherwise be needed in cable-stayed designs. However, as the size of an aircraft increases, the additional weight penalty decreases. Eventually a line was crossed in the 1920s, and designs increasingly turned to the cantilever design. By the 1940s almost all larger aircraft used the cantilever exclusively, even on smaller surfaces such as the horizontal stabilizer.

In microelectromechanical systems



SEM image of a used AFM cantilever

Cantilevered beams are the most ubiquitous structures in the field of microelectromechanical systems (MEMS). An early example of a MEMS cantilever is the Resonistor, an electromechanical monolithic resonator. MEMS cantilevers are commonly fabricated from silicon (Si), silicon nitride (SiN), or polymers. The fabrication process typically involves undercutting the cantilever structure to *release* it, often with an anisotropic wet or dry etching technique. Without cantilever transducers, atomic force microscopy would not be possible. A large number of research groups are attempting to develop cantilever arrays as biosensors for medical diagnostic applications. MEMS cantilevers are also finding application as radio frequency filters and resonators. The MEMS cantilevers are commonly made as unimorphs or bimorphs.

Two equations are key to understanding the behavior of MEMS cantilevers. The first is *Stoney's formula*, which relates cantilever end deflection δ to applied stress σ :

$$\delta = \frac{3\sigma(1-\nu)}{E} \left(\frac{L}{t}\right)^2$$

where ν is Poisson's ratio, E is Young's modulus, L is the beam length and t is the cantilever thickness. Very sensitive optical and capacitive methods have been developed to measure changes in the static deflection of cantilever beams used in dc-coupled sensors.

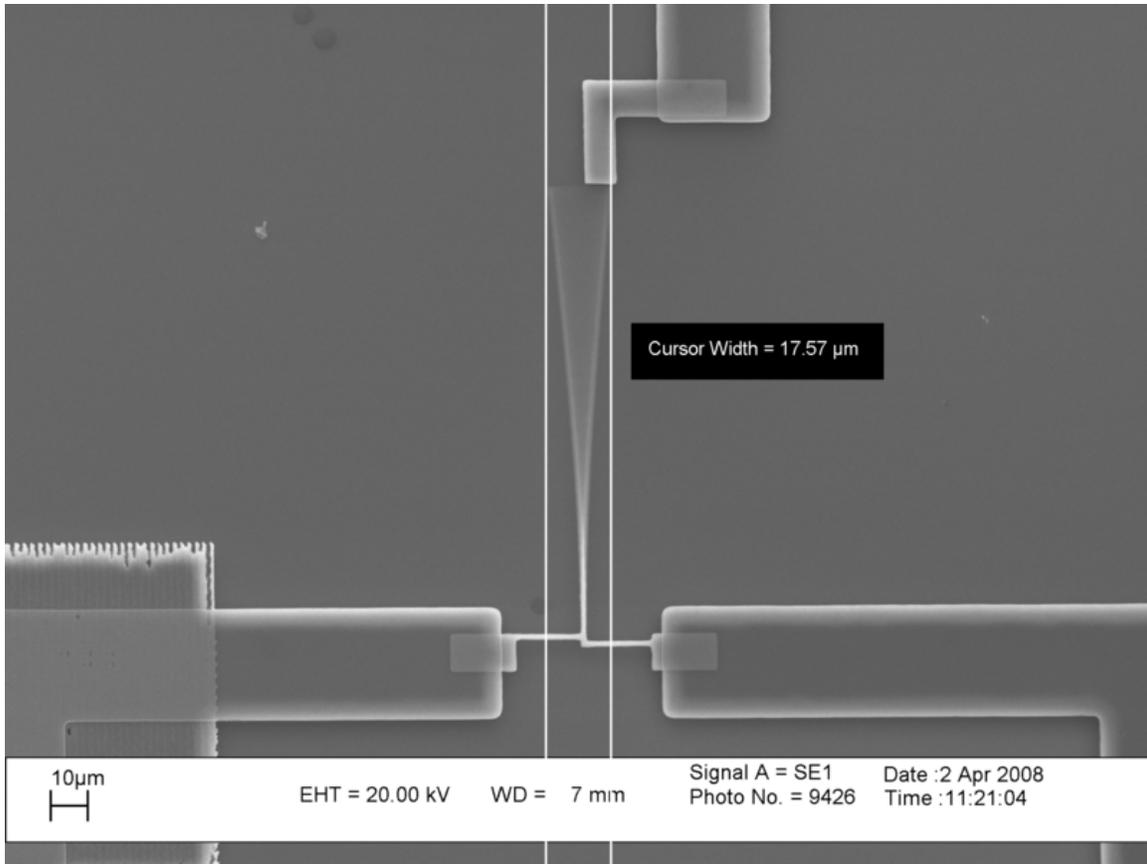
The second is the formula relating the cantilever spring constant k to the cantilever dimensions and material constants:

$$k = \frac{F}{\delta} = \frac{Ewt^3}{4L^3}$$

where F is force and w is the cantilever width. The spring constant is related to the cantilever resonance frequency ω_0 by the usual harmonic oscillator formula

$\omega_0 = \sqrt{k/m}$. A change in the force applied to a cantilever can shift the resonance frequency. The frequency shift can be measured with exquisite accuracy using heterodyne techniques and is the basis of ac-coupled cantilever sensors.

The principal advantage of MEMS cantilevers is their cheapness and ease of fabrication in large arrays. The challenge for their practical application lies in the square and cubic dependences of cantilever performance specifications on dimensions. These superlinear dependences mean that cantilevers are quite sensitive to variation in process parameters. Controlling residual stress can also be difficult.



MEMS cantilever in resonance

In storage applications

Warehouse storage

A cantilever rack is a type of warehouse storage system consisting of the vertical column, the base, the arms, and the horizontal and/or cross bracing. These components are fabricated from both roll formed and structural steel. The horizontal and/or cross bracing are used to connect two or more columns together. They are commonly found in lumber yards, woodworking shops, and plumbing supply warehouses.

Portable storage

A folding cantilever tray is a type of stacked shelf that can be unfolded to allow convenient access to items on multiple tiers simultaneously. The shelves can be collapsed when not in use for more compact storage. Because of these properties folding cantilever trays are often used in luggage and toolboxes.

Chapter 6

Floor



Floors may include mosaic or other artistic expression.

A **floor** is the walking surface of a room or vehicle. Floors vary from simple dirt in a cave to many-layered surfaces using modern technology. Floors may be stone, wood, bamboo, metal, or any other material that can hold a person's weight.

Floors typically consist of a subfloor for support and a floor covering used to give a good walking surface. In modern buildings the subfloor often has electrical wiring, plumbing, and other services built in. Because floors meet many needs, some essential to safety, floors are built to strict building codes in the first world.

Special floor structures

Where a special floor structure like a floating floor is laid upon another floor then both may be referred to as subfloors.

Special floor structures are used for a number of purposes:

- Balcony, a platform projecting from a wall
- Floating floor, normally for noise or vibration reduction
- Glass floor, as in glass bottomed elevators
- Nightingale floor makes a noise when an intruder walks on it
- Raised floor, utilities underneath can be accessed easily
- Sprung floor, improves the performance and safety of athletes and dancers

Floor covering



An example of a floor.

Floor covering is a term to generically describe any finish material applied over a floor structure to provide a walking surface. **Flooring** is the general term for a permanent covering of a floor, or for the work of installing such a floor covering. Both terms are used interchangeably but floor covering refers more to loose-laid materials.

Materials almost always classified as floor covering include carpet, area rugs, and resilient flooring such as linoleum or vinyl flooring. Materials commonly called flooring include wood flooring, laminated wood, ceramic tile, stone, terrazzo, and various seamless chemical floor coatings.

The choice of material for floor covering is affected by factors such as cost, endurance, noise insulation, comfort and cleaning effort. Some types of flooring must not be installed below grade (lower than ground level), and laminate or hardwood should be avoided where there may be moisture or condensation.

The subfloor may be finished in a way that makes it usable without any extra work, see:

- Earthen floor adobe or clay floors
- Solid ground floor cement screed or granolithic

There are a number of special features that may be used to ornament a floor or perform a useful service. Examples include Floor medallions which provide a decorative centerpiece of a floor design, or Gratings used to drain water or to rub dirt off shoes.

Subfloor construction

The subfloor provides the strength of a floor. Many floors have no separate floor covering on top. The subfloor may also provide services like underfloor heating or ducts for air conditioning.

A ground-level floor can be an earthen floor made of soil, or be solid ground floors made of concrete slab. Floors above may be built on beams or joists or use structures like hollow core slabs.

Ground floor construction

Ground-level slab floors are prepared for pouring by grading the base material so that it is flat, and then spreading a layer of sand and gravel. A grid of rebar is usually added to reinforce the concrete, especially if it will be used structurally, i.e., to support part of the building.

Upper floor construction

Floors in woodframe homes are usually constructed with joists centered no more than 16 inches or 40 centimeters apart, according to most building codes. Heavy floors, such as those made of stone, require more closely-spaced joists. If the span between load-

bearing walls is too long for joists to safely support, then a heavy crossbeam (thick or laminated wood, or a metal I-beam or H-beam) may be used. A "subfloor" of plywood or waferboard is then laid over the joists.

Utilities

In modern buildings, there are numerous services provided via ducts or wires underneath the floor or above the ceiling. The floor of one level typically also holds the ceiling of the level below (if any).

Services provided by subfloors include:

- Air conditioning
- Communication fibers
- Electrical wiring
- Fire protection
- Thermal insulation
- Plumbing
- Sewerage
- Soundproofing
- Underfloor heating

In floors supported by joists, utilities are run through the floor by drilling small holes through the joists to serve as conduits. Where the floor is over the basement or crawlspace, utilities may instead be run under the joists, making the installation less expensive. Also, ducts for air conditioning (central heating and cooling) are large and cannot cross through joists or beams; thus, ducts are typically at or near the plenum, or come directly from underneath (or from an attic).

Pipes for plumbing, sewerage, underfloor heating, and other utilities may be laid directly in slab floors, typically via cellular floor raceways. However, later maintenance of these systems can be expensive, requiring the opening of concrete or other fixed structures. Electrically heated floors are available, and both kinds of systems can also be used in wood floors as well.

Issues with floors

Wood floors, particularly older ones, will tend to 'squeak' in certain places. This is caused by the wood rubbing against other wood, usually at a joint of the subfloor. Firmly securing the pieces to each other with screws or nails may reduce this problem.

Floor vibration is a problem with floors. Wood floors tend to pass sound, particularly heavy footsteps and low bass frequencies. Floating floors can reduce this problem. Concrete floors are usually so massive they do not have this problem, but they are also much more expensive to construct and must meet more stringent building requirements due to their weight.

The flooring may need protection sometimes e.g. a gym floor alternately used for seating in a graduation ceremony. A gym floor cover can be used to reduce the need to satisfy incompatible requirements.

Floor cleaning

Floor cleaning is a major occupation throughout the world. Cleaning is essential to prevent injuries due to slips and to remove dirt. Floors are also treated to protect or beautify the surface. The correct method to clean one type of floor can often damage another, so it is important to use the correct treatment.

Chapter 7

Plate Girder Bridge

Plate Girder Bridge



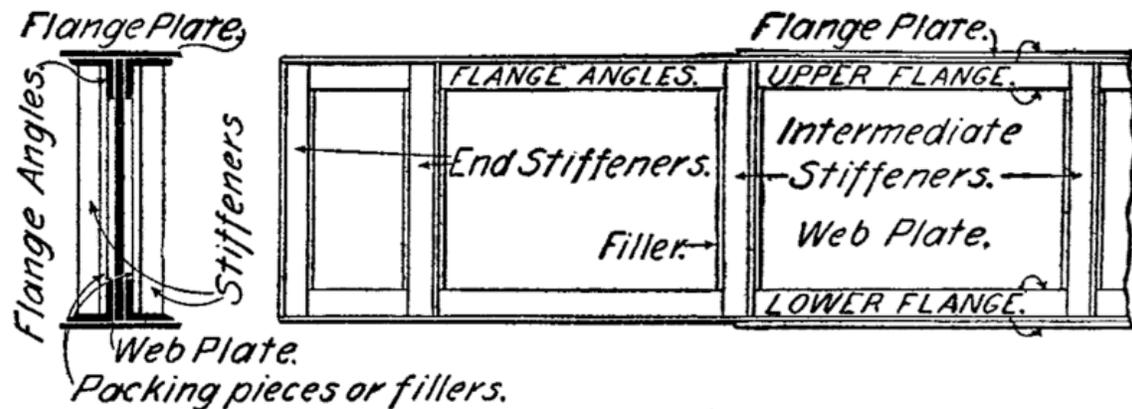
Wooden deck type

Ancestor	Beam bridge
Related	Trestle, truss bridge, moon bridge
Descendant	Leaf bascule, Tubular bridge
Carries	Pedestrians, automobiles, trucks, light rail, heavy rail
Span range	Short
Material	Iron, steel
Movable	No
Design effort	low
Falsework required	No

A **plate girder bridge** is a bridge supported by two or more **plate girders**. The plate girders are typically I-beams made up from separate structural steel plates (rather than rolled as a single cross-section), which are welded or, in older bridges, bolted or riveted together to form the vertical web and horizontal flanges of the beam. In some cases, the plate girders may be formed in a Z-shape rather than I-shape. The first tubular wrought

iron plate girder bridge was built in 1846-47 by James Millholland for the Baltimore and Ohio Railroad.

Plate girder bridges are suitable for short to medium spans and may support railroads, highways or other traffic. Plate girders are usually prefabricated, and the length limit is frequently set by the mode of transportation used to move the girder from the bridge shop to the bridge site.



Anatomy of a plate girder.

Generally, the depth of the girder is no less than $1/15$ the span, and for a given load bearing capacity, a depth of around $1/12$ the span minimizes the weight of the girder. Stresses on the flanges near the center of the span are greater than near the end of the span, so the top and bottom flange plates are frequently reinforced in the middle portion of the span. Vertical stiffeners prevent the web plate from buckling under shear stresses. These are typically uniformly spaced along the girder with additional stiffeners over the supports and wherever the bridge supports concentrated loads.

Deck-type plate girder bridge

In the deck-type bridge, a wood, steel or reinforced concrete bridge deck is supported on top of two or more plate girders, and may act compositely with them. In the case of railroad bridges, the railroad ties themselves may form the bridge deck, or the deck may support ballast on which the track is laid. Additional beams may span across between the main girders, for example in the form of bridge known as **ladder-deck** construction. Also, further elements may be attached to provide cross-bracing and prevent the girders from buckling.

Half-through plate girder bridge



Plate girder bridge: half-through type.

In the half-through bridge, the bridge deck is supported between two plate girders, often on top of the bottom flange. The overall bridge then has a 'U'-shape in cross-section. As cross-bracing cannot normally be added, vertical stiffeners on the girders are normally used to prevent buckling (technically described as 'U-frame behaviour'). This form of bridge is most often used on railroads as the construction depth (distance between the underside of the vehicle, and the underside of the bridge) is much less. This allows obstacles to be cleared with less change in height.

Multi-span plate girder bridge



Multispan Plate girder bridge: deck type on concrete piers.

Multispan plate-girder bridges may be an economical way to span gaps longer than can be spanned by a single girder. Piers serve as intermediate abutments between the end Abutments of bridge. Separate plate girder bridges span between each pair of abutments in order to allow for expansion joints between the spans. Concrete is commonly used for low piers, while steel trestle work may be used for high bridges.

Chapter 8

Retaining Wall



A gravity-type stone retaining wall

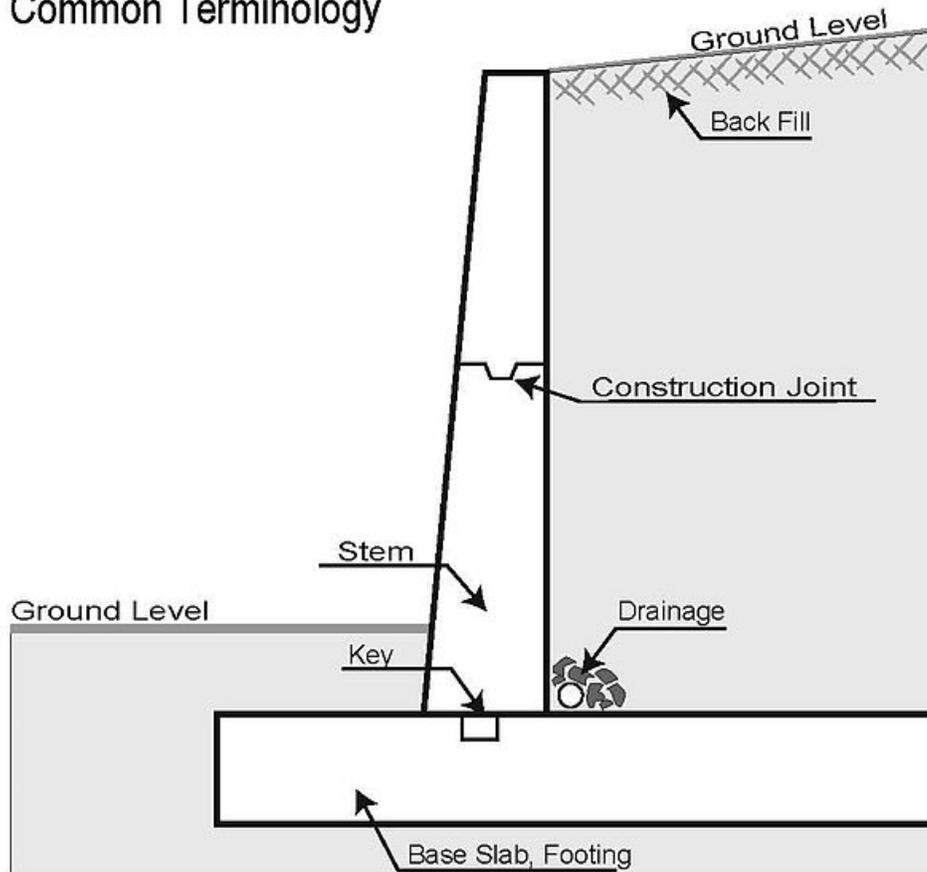
A **retaining wall** is a structure designed and constructed to resist the lateral pressure of soil when there is a desired change in ground elevation that exceeds the angle of repose of the soil. The active pressure increases on the retaining wall proportionally from zero at the upper grade level to a maximum value at the lowest depth of the wall. The total pressure or thrust may be assumed to be acting through the centroid of the triangular distribution pattern, one-third above the base of the wall.

Definition

Retaining walls serve to retain the lateral pressure of soil. The basement wall is thus one form of retaining wall.

However, the term is most often used to refer to a cantilever retaining wall, which is a freestanding structure without lateral support at its top.

Common Terminology



Typically retaining walls are cantilevered from a footing extending up beyond the grade on one side and retaining a higher level grade on the opposite side. The walls must resist the lateral pressures generated by loose soils or, in some cases, water pressures.

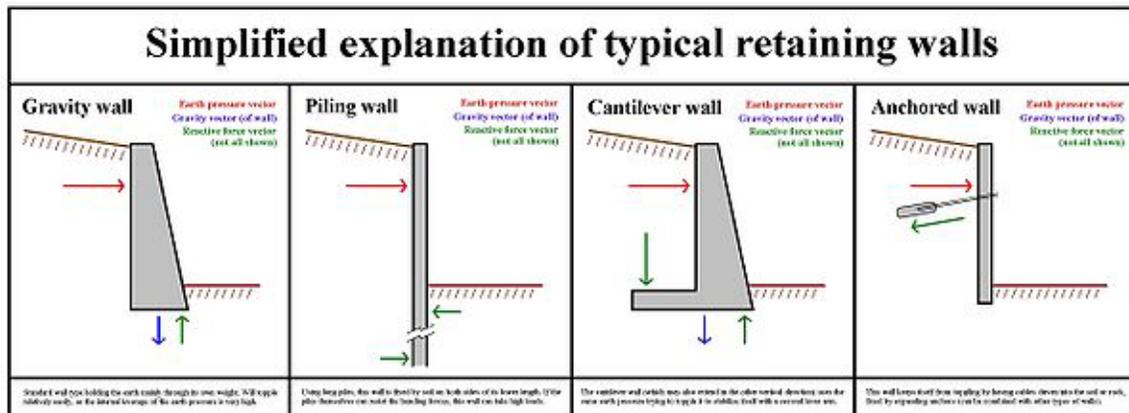
The most important consideration in proper design and installation of retaining walls is to recognize and counteract the fact that the retained material is attempting to move forward and downslope due to gravity. This creates lateral earth pressure behind the wall which depends on the angle of internal friction (ϕ) and the cohesive strength (c) of the retained material, as well as the direction and magnitude of movement the retaining structure undergoes.

Lateral earth pressures are typically smallest at the top of the wall and increase toward the bottom. Earth pressures will push the wall forward or overturn it if not properly addressed. Also, any groundwater behind the wall that is not dissipated by a drainage system causes an additional horizontal hydrostatic pressure on the wall.

It is very important to have proper drainage behind the wall as it is critical to the performance of retaining walls. Drainage materials will reduce or eliminate the hydrostatic pressure and will therefore greatly improve the stability of the material behind the wall, assuming that this is not a retaining wall for water.

As an example, the International Building Code requires retaining walls to be designed to ensure stability against overturning, sliding, excessive foundation pressure and water uplift; and that they be designed for a safety factor of 1.5 against lateral sliding and overturning.

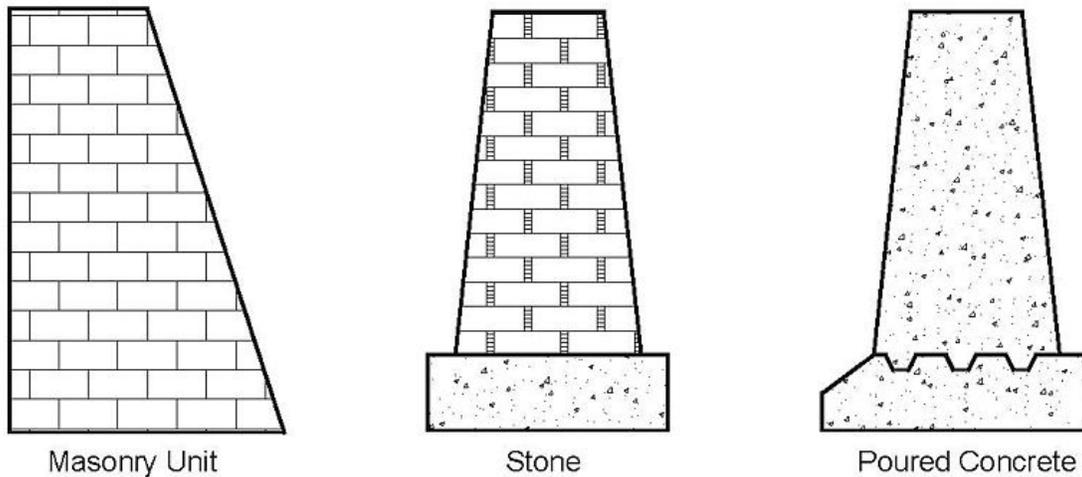
Types



Various types of retaining walls

Gravity

Gravity Retaining Walls



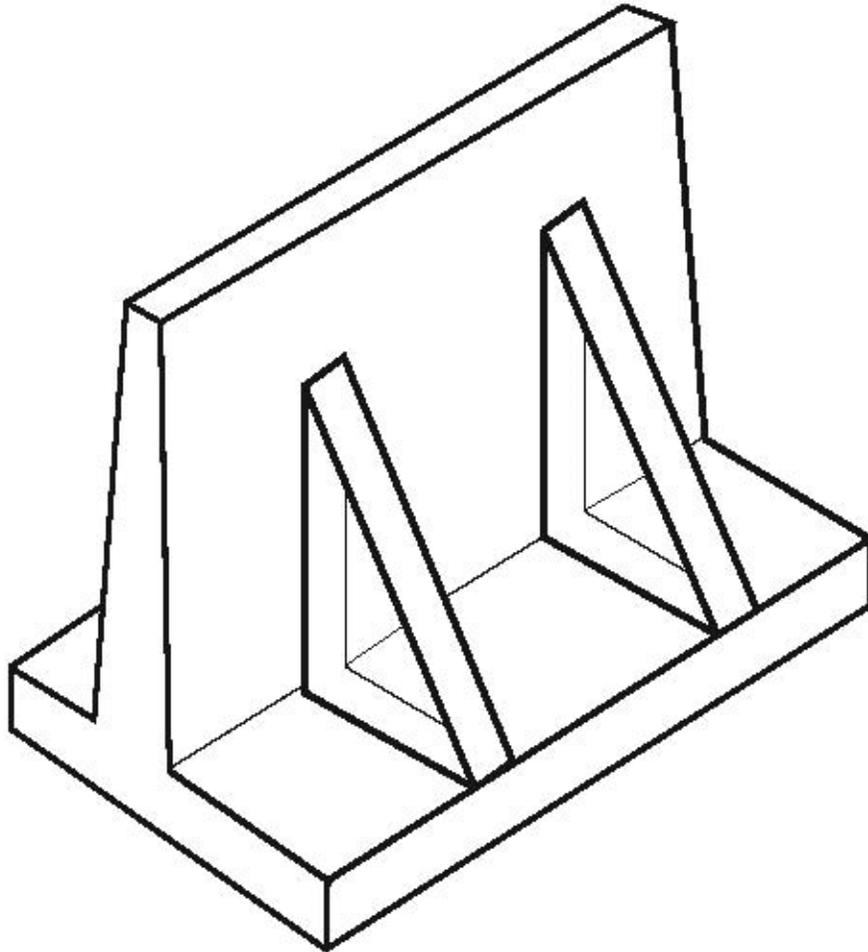
Construction types of gravity retaining walls

Gravity walls depend on the weight of their mass (stone, concrete or other heavy material) to resist pressures from behind and will often have a slight 'batter' setback, to improve stability by leaning back into the retained soil. For short landscaping walls, they are often made from mortarless stone or segmental concrete units (masonry units). Dry-stacked gravity walls are somewhat flexible and do not require a rigid footing in frost areas. Home owners who build larger gravity walls that do require a rigid concrete footing can make use of the services of a professional excavator, which will make digging a trench for the base of the gravity wall much easier.

Earlier in the 20th century, taller retaining walls were often gravity walls made from large masses of concrete or stone. Today, taller retaining walls are increasingly built as composite gravity walls such as: geosynthetic or with precast facing; gabions (stacked steel wire baskets filled with rocks); crib walls (cells built up log cabin style from precast concrete or timber and filled with soil); or soil-nailed walls (soil reinforced in place with steel and concrete rods).

Cantilevered

Counterfort or Buttress Retaining Wall



Counterfort/Buttress on Cantilevered Wall

Cantilevered retaining walls are made from an internal stem of steel-reinforced, cast-in-place concrete or mortared masonry (often in the shape of an inverted T). These walls cantilever loads (like a beam) to a large, structural footing, converting horizontal pressures from behind the wall to vertical pressures on the ground below. Sometimes cantilevered walls are buttressed on the front, or include a counterfort on the back, to improve their strength resisting high loads. Buttresses are short wing walls at right angles to the main trend of the wall. These walls require rigid concrete footings below seasonal frost depth. This type of wall uses much less material than a traditional gravity wall.

Sheet piling



Sheet pile wall

Sheet pile retaining walls are usually used in soft soils and tight spaces. Sheet pile walls are made out of steel, vinyl or wood planks which are driven into the ground. For a quick estimate the material is usually driven 1/3 above ground, 2/3 below ground, but this may be altered depending on the environment. Taller sheet pile walls will need a tie-back anchor, or "dead-man" placed in the soil a distance behind the face of the wall, that is tied to the wall, usually by a cable or a rod. Anchors are placed behind the potential failure plane in the soil.

Anchored

An anchored retaining wall can be constructed in any of the aforementioned styles but also includes additional strength using cables or other stays anchored in the rock or soil behind it. Usually driven into the material with boring, anchors are then expanded at the end of the cable, either by mechanical means or often by injecting pressurized concrete, which expands to form a bulb in the soil. Technically complex, this method is very useful where high loads are expected, or where the wall itself has to be slender and would otherwise be too weak.

Alternative Retaining Techniques

Soil nailing

Soil nailing is a technique in which soil slopes, excavations or retaining walls are reinforced by the insertion of relatively slender elements - normally steel reinforcing bars. The bars are usually installed into a pre-drilled hole and then grouted into place or drilled and grouted simultaneously. They are usually installed untensioned at a slight downward inclination. A rigid or flexible facing (often sprayed concrete) or isolated soil nail heads may be used at the surface.

Soil-strengthened

A number of systems exist that do not simply consist of the wall itself, but reduce the earth pressure acting on the wall itself. These are usually used in combination with one of the other wall types, though some may only use it as facing (i.e. for visual purposes).

Gabion meshes

This type of soil strengthening, often also used without an outside wall, consists of wire mesh 'boxes' into which roughly cut stone or other material is filled. The mesh cages reduce some internal movement/forces, and also reduce erosive forces.

Mechanical stabilization

Mechanically stabilized earth, also called MSE, is soil constructed with artificial reinforcing via layered horizontal mats (geosynthetics) fixed at their ends. These mats provide added internal shear resistance beyond that of simple gravity wall structures. Other options include steel straps, also layered. This type of soil strengthening usually needs outer facing walls (S.R.W.'s - Segmental Retaining Walls) to affix the layers to and vice versa.

The wall face is often of precast concrete units that can tolerate some differential movement. The reinforced soil's mass, along with the facing, then acts as an improved gravity wall. The reinforced mass must be built large enough to retain the pressures from the soil behind it. Gravity walls usually must be a minimum of 50 to 60 percent as deep or thick as the height of the wall, and may have to be larger if there is a slope or surcharge on the wall.

Chapter 9

Staggered Truss System and Space Frame

Staggered truss system

The **Staggered truss system** is a type of structural steel framing used in high-rise buildings. The system consists of a series of story-high trusses spanning the total width between two rows of exterior columns and arranged in a staggered pattern on adjacent column lines. William LeMessurier, the founder Cambridge, Massachusetts engineering firm LeMessurier Consultants has been credited in developing this award winning system as part of his research at the Massachusetts Institute of Technology.

History

The staggered truss system came about due to sponsored research at Massachusetts Institute of Technology's Departments of Architecture and Civil Engineering in the 1960s by U.S. Steel. The research attempted to achieve the same floor-to-floor height with steel as you could with flat plate concrete. The system was presented at the 1966 AISC Conference (the predecessor to the current North American Steel Construction Conference). Additional benefits discovered were high resistance to wind loads and versatility of floor layout with large column-free areas.

It has been used with on a number of LeMessurier Consultants work in hotels including Lafayette Place Hotel in Boston and the Aladdin Hotel in Las Vegas. Other locations that use this system include the Resorts International Hotel in Atlantic City, New Jersey, Embassy Suites hotel in New York City, Baruch College Academic Center in New York City, Trump Taj-Mahal in Atlantic City NJ, and the Renaissance Hotel in Nashville TN

Description

The staggered truss system for steel framing is an efficient structural system for high-rise apartments, hotels, motels, dormitories, and hospitals. The arrangement of story-high trusses in a staggered pattern at alternate column lines provide large column-free areas

for room layouts. These column free areas can be utilized for ballrooms, concourses, and other large areas.

The staggered truss structural system consists of story-high steel trusses placed on alternating column lines on each floor so that the long axis of one truss is always between the trusses on the floor below. The system staggers trusses on a 12' module, meaning that on any given floor the trusses were 24' apart.

The interaction of the floors, trusses, and columns makes the structure perform as a single unit, thereby taking maximum advantage of the strength and rigidity of all the components simultaneously. Each component performs its particular function, totally dependent upon the others for its performance.

The total frame behaves as a cantilever beam when subjected to lateral loads. All columns are placed on the exterior wall of the building and function as the flanges of the beam, while the trusses which span the total transverse width between columns function as the web of the cantilever beam.

While earlier staggered truss systems utilized channels for web diagonals and verticals, today most of the trusses are designed with hollow structural sections (HSS) for vertical and diagonal members because they are more structurally efficient and easier to fabricate. The trusses are fabricated with camber to compensate for dead load and are transported to the site, stored and then erected—generally in one piece.

Fabrication of this type of structure requires certified welders and overhead cranes capable of lifting 10 to 15-ton trusses and columns for projects up to 20 stories. Fabrication involves the following components: Columns, Spandrel Beams, Trusses, Secondary Columns & Beams and the Floor System.

Advantages

- Large clear span open areas for ballrooms, or other wide concourse are possible at the first floor level, because columns are located only on the exterior faces of the building. This allows for spaces as much as 60 feet in each direction with columns often only appearing on the perimeter of a structure. This also increases design flexibility especially for atrium placement and open space floor plans.
- Floor spans may be short bay lengths, while providing two column bay spacing for room arrangements. This results in low floor-to-floor heights. Typically, an 8'-8" floor-to-floor height is achieved.
- Columns have minimum bending moments due to gravity and wind loads, because of the cantilever action of the double-planar system of framing.
- Columns are oriented with their strong axis resisting lateral forces in the longitudinal direction of the building.
- Maximum live load reductions may be realized because tributary areas may be adjusted to suit code requirements.

- Foundations are on column lines only and may consist of two strip footings. Because the vertical loads are concentrated at a few column points, less foundation formwork is required.
- Drift is small, because the total frame is acting as a stiff truss with direct axial loads only acting in most structural members. Secondary bending occurs only in the chords of the trusses.
- High strength steels may be used to advantage, because all truss members and columns are subjected, for all practical purposes, to axial loads only.
- A lightweight steel structure is achieved by the use of high strength steels and an efficient framing system. Since this reduces the weight of the superstructure, there is a substantial cost savings in foundation work.
- Faster to erect than comparable concrete structures. Once two floors are erected, window installation can start and stay right behind the steel and floor erection. No time is lost in waiting for other trades, such as bricklayers, to start work. Except for foundations, topping slab, and grouting, all "wet" trades are eliminated.
- Fire resistance; steel is localized to the trusses, which only occur at every 58-to-70-feet on a floor, so the fireproofing operation can be completed efficiently. Furthermore, the trusses are typically placed within demising walls and it is possible that the necessary fire rating can be entirely by enclosing the trusses with gypsum wallboard. Finally, if spray-on protection is desired, the applied thickness can be kept to a minimum due to the compact nature of the truss elements.

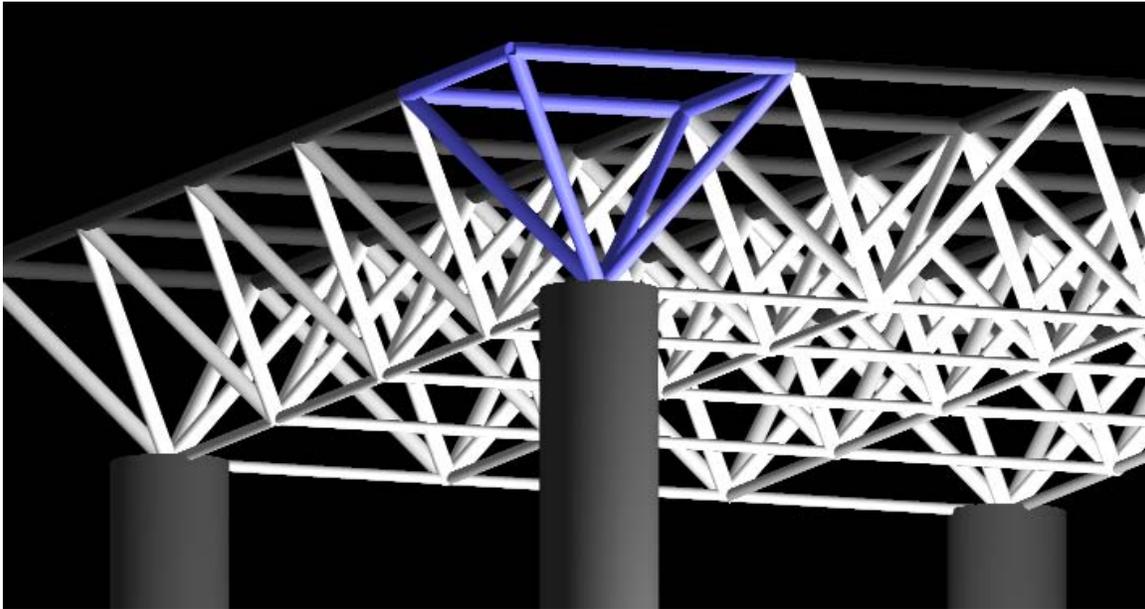
Space frame



The roof of this industrial building is supported by a space frame structure.

A **space frame** or **space structure** is a truss-like, lightweight rigid structure constructed from interlocking struts in a geometric pattern. Space frames can be used to span large areas with few interior supports. Like the truss, a space frame is strong because of the inherent rigidity of the triangle; flexing loads (bending moments) are transmitted as tension and compression loads along the length of each strut.

Overview



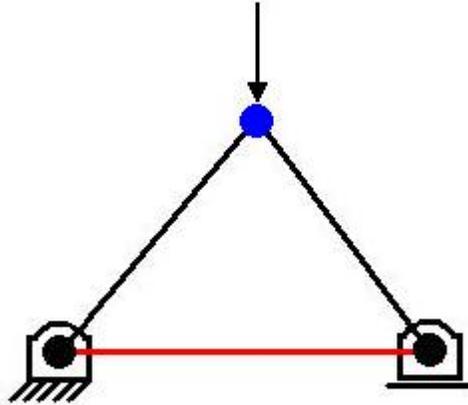
Simplified space frame roof with the half-octahedron highlighted in blue

The simplest form of space frame is a horizontal slab of interlocking square pyramids built from aluminium or tubular steel struts. In many ways this looks like the horizontal jib of a tower crane repeated many times to make it wider. A stronger purer form is composed of interlocking tetrahedral pyramids in which all the struts have unit length. More technically this is referred to as an isotropic vector matrix or in a single unit width an octet truss. More complex variations change the lengths of the struts to curve the overall structure or may incorporate other geometrical shapes.

History

Space frames were independently developed by Alexander Graham Bell around 1900 and Buckminster Fuller in the 1950s. Bell's interest was primarily in using them to make rigid frames for nautical and aeronautical engineering. Few of his designs were realised. Buckminster Fuller's focus was architectural structures; his work had greater influence.

Applications



If a force is applied to the blue node, and the red bar is not present, the behaviour of the structure depends completely on the bending rigidity of the blue node. If the red bar is present, and the bending rigidity of the blue node is negligible compared to the contributing rigidity of the red bar, the system can be calculated using a rigidity matrix, neglecting angular factors.

Construction

Space frames are a common feature in modern construction; they are often found in large roof spans in modernist commercial and industrial buildings.

Notable examples of buildings based on space frames include:

- Stansted airport in London, by Foster and Partners
- Bank of China Tower and the Louvre Pyramid, by I. M. Pei
- Rogers Centre by Rod Robbie and Michael Allan
- McCormick Place East in Chicago
- Eden Project in Cornwall, England
- Globen, Sweden - Dome with diameter of 110 m, (1989)
- Biosphere 2 in Oracle, Arizona

Large portable stages and lighting gantries are also frequently built from space frames and octet trusses.

In February 1986, Paul C. Kranz walked into the U. S. Department of Transportation office in Fort Worth, Texas, with a model of an octet truss. He showed a staff person there how the octet truss was ideal for holding signs over roads. The idea and model was

forwarded to the US Department of Transportation in Washington, D. C. Today, the octet truss is the structure of choice for holding signs above roads in the United States.

Vehicles

Space frames are sometimes used in the chassis designs of automobiles and motorcycles. In a space-frame, or tube-frame, chassis, the suspension, engine, and body panels are attached to a skeletal space frame, and the body panels have little or no structural function. By contrast, in a monocoque design, the body serves as part of the structure. Tube-frame chassis are frequently used in certain types of racing cars.

British manufacturers TVR were particularly well known for their tube-frame chassis designs, produced since the 1950s. Other notable examples of tube-frame cars include the Audi A8, Lotus Seven, Ferrari 360, Lamborghini Gallardo, and Mercedes-Benz SLS AMG.

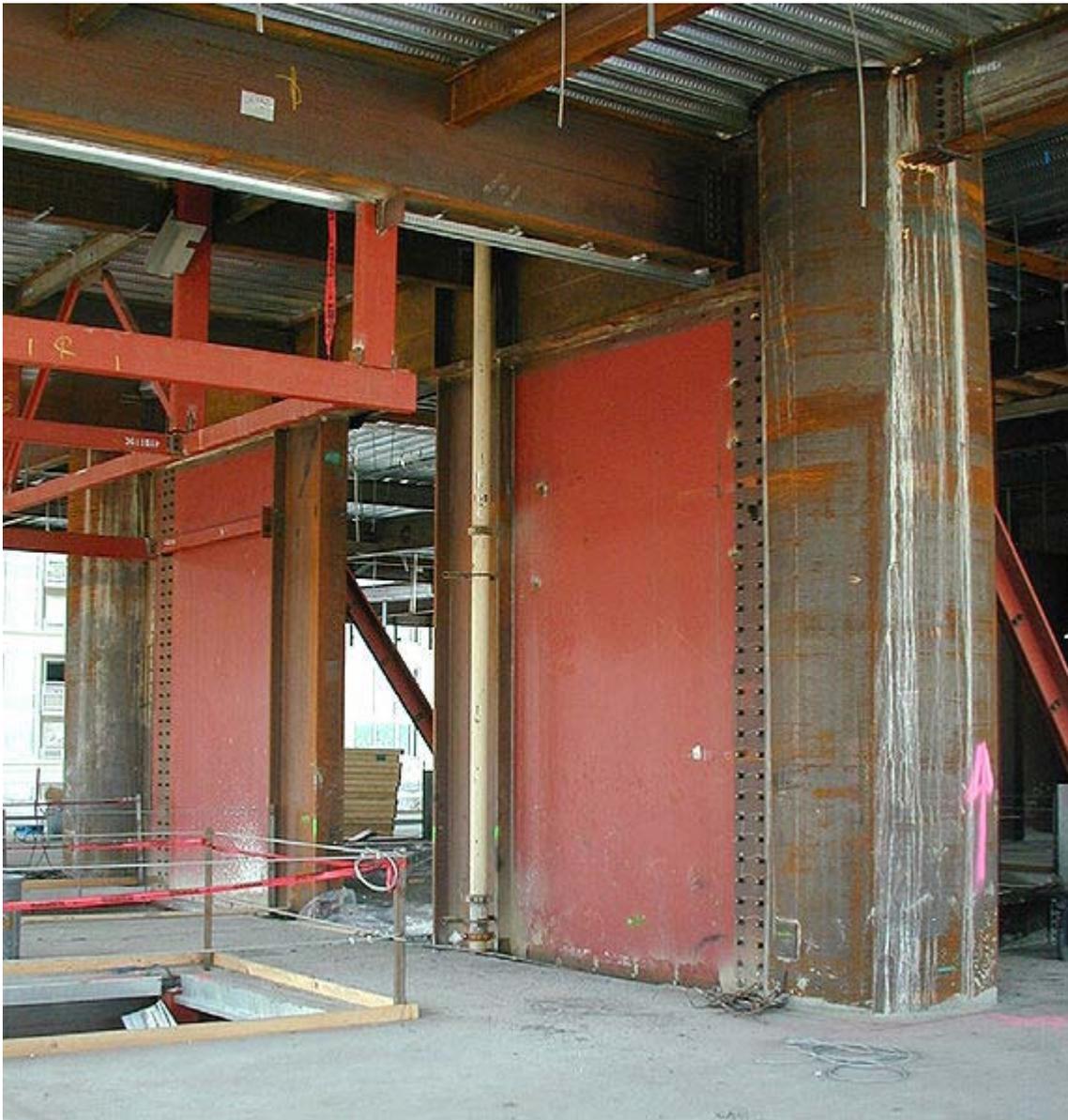
Space frames have also been used in bicycles, such as those designed by Alex Moulton.

Design methods

Space frames are typically designed using a rigidity matrix. The special characteristic of the stiffness matrix in an architectural space frame is the independence of the angular factors. If the joints are sufficiently rigid, the angular deflections can be neglected, simplifying the calculations.

Chapter 10

Steel Plate Shear Wall



Coupled steel plate shear wall - Seattle - WA, Copyright Mehdi Kharrazi

A **steel plate shear wall (SPSW)** consists of steel infill plates bounded by a column-beam system.

Overview

They constitute an SPSW. Its behavior is analogous to a vertical plate girder cantilevered from its base. Similar to plate girders, the SPW system optimizes component performance by taking advantage of the post-buckling behavior of the steel infill panels. An SPW frame can be idealized as a vertical cantilever plate girder, in which the steel plates act as the web, the columns act as the flanges and the cross beams represent the transverse stiffeners. The theory that governs the design of plate should not be used in design of SPW structures since the relatively high bending strength and stiffness of the beams and columns have a significant effect in the post-buckling behavior.

Capacity design of structures is: to control failure in a building by pre-selecting localized ductile fuses (or weak links) to act as the primary location for energy dissipation when a building is subjected to extreme loading. The structure is designed such that all inelastic action (or damage) occurs at these critical locations (the fuses), which are designed to behave in a ductile and stable manner. Conversely, all other structural elements are protected against failure or collapse by limiting the load transfer to these elements to the yield capacity of the fuses. In SPSWs, the infill plates are meant to serve as the fuse elements. When damaged during an extreme loading event, they can be replaced at a reasonable cost and restore full integrity of the building. In general, SPWs are categorized based on their performance, selection of structural and load-bearing systems, and the presence of perforations or stiffeners (Table 1).

A significant amount of valuable research has been performed on the static and dynamic behavior of SPSWs. Much research has been conducted to not only help determine the behavior, response and performance of SPWs under cyclic and dynamic loading, but also as a means to help advance analysis and design methodologies for the engineering community.

The pioneering work of Kulak and co-investigators at the University of Alberta in Canada led to a simplified method for analyzing a thin unstiffened SPSW - the strip model. This model is incorporated in Chapter 20 of the most recent Canadian Steel Design Standard (CAN/CSA S16-01) and the National Earthquake Hazard Reduction Program (NEHRP) provisions in the US.

Table 1. Categorization of steel plate walls based on performance characteristics and expectations

Performance Characteristic	Performance Expectations or SPW Characteristics
Type of Loading carried by SPW	Lateral Load Only / Lateral Load + Wall's Dead Load (or so called 50% Gravity Load)/ Gravity + Lateral Loads
Structural System	Single wall with and without infill Columns / Coupled wall with and without infill Columns
Stiffener Spacing and Size	Post-Buckling effect can be seen in the sub panels / Panel buckles with the stiffeners globally / Stiffeners produces sub-panels which can be categorized as thick panel
Web Plate Behavior	Web plate yields before critical elastic buckling occurs (thick plate) / Web plate buckles elastically, develops post-buckling tension field, then yields (thin plate)
Web Plate Perforations	With perforations / Without perforations

History

In the past two decades the steel plate shear wall (SPSW), also known as the steel plate wall (SPW), has been used in a number of buildings in Japan and North America as part of the lateral force resisting system. In earlier days, SPSWs were treated like vertically-oriented plate girders and design procedures tended to be very conservative. Web buckling was prevented through extensive stiffening or by selecting an appropriately thick web plate, until more information became available on the post-buckling characteristics of web plates. Although the plate girder theory seems appropriate for the design of an SPW structure, a very important difference is the relatively high bending strength and stiffness of the beams and columns that form the boundary elements of the wall. These members are expected to have a significant effect on the overall behaviour of a building incorporating this type of system and several researchers have focused on this aspect of SPWs. The energy dissipating qualities of the web plate under extreme cyclic loading has raised the prospect of using SPSWs as a promising alternative to conventional systems in high-risk seismic regions. A further benefit is that the diagonal tension field of the web plate acts like a diagonal brace in a braced frame and thus completes the truss action, which is known to be an efficient means to control wind drift.

Advantages

From a designer's point of view, steel plate walls have become a very attractive alternative to other steel systems, or to replace reinforced concrete elevator cores and shear walls. In comparative studies it has been shown that the overall costs of a building can be reduced significantly when considering the following advantages :

- An SPW system, when designed and detailed properly, has relatively large energy dissipation capability with stable hysteretic behaviour, thus being very attractive for high risk earthquake zones.

- Because the web tension field acts much like a diagonal brace, an SPW system has relatively high initial stiffness, and is thus very effective in limiting wind drift.
- Compared to reinforced concrete shear walls, SPWs are much lighter, which ultimately reduces the demand on columns and foundations, and reduces the seismic load, which is proportional to the mass of the structure.
- Compared to reinforced concrete construction, the erection process of an all-steel building is significantly faster, thus reducing the construction duration, which is an important factor affecting the overall cost of a project.
- By using shop-welded, field-bolted SPWs, field inspection is improved and a high level of quality control can be achieved.
- For architects, the increased versatility and space savings because of the smaller cross-section of SPWs, compared to reinforced concrete shear walls, is a distinct benefit, especially in high-rise buildings, where reinforced concrete shear walls in lower floors become very thick and occupy a large proportion of the floor plan.
- All-steel construction with SPWs is a practical and efficient solution for cold regions where concrete construction may not be feasible, as very low temperatures complicate construction and freeze-thaw cycles can result in durability problems.
- In seismic retrofit applications, SPWs are typically much easier and faster to install than reinforced concrete shear walls, which is a critical issue when building occupancy needs to be maintained throughout the construction time.

In comparison with conventional bracing systems, steel panels have the advantage of being a redundant, continuous system exhibiting relatively stable and ductile behaviour under severe cyclic loading (Tromposch and Kulak, 1987). This benefit along with the high stiffness of the plates acting like tension braces to maintain stability, strongly qualifies the SPW as an ideal energy dissipation system in high risk seismic regions, while providing an efficient system to reduce lateral drift. Thus, some of the advantages of using SPWs compared with conventional bracing systems are as follows:

- Reduces seismic force demand due to higher SPW ductility characteristics and inherent redundancy and continuity
- Accelerates structural steel erection by using shop-welded and field-bolted steel panels, and thus, less inspection and reduced quality control costs
- Permits efficient design of lateral-resisting systems by distributing large forces evenly.

A steel plate shear element consists of steel infill plates bounded by a column-beam system. When these infill plates occupy each level within a framed bay of a structure, they constitute an SPW. Its behaviour is analogous to a vertical plate girder cantilevered from its base. Similar to plate girders, the SPW system optimizes component performance by taking advantage of the post-buckling behaviour of the steel infill panels. An SPW frame can be idealized as a vertical cantilever plate girder, in which the steel plates act as the web, the columns act as the flanges and the cross beams represent the transverse stiffeners. The theory that governs the design of plate girders for buildings

proposed by Basler in 1960, should not be used in design of SPW structures since the relatively high bending strength and stiffness of the beams and columns is expected to have a significant effect in the post-buckling behaviour. However, Basler's theory could be used as a basis to derive an analytical model for SPW systems.

Designers pioneering the use of SPWs did not have much experience nor existing data to rely upon. Typically, web plate design failed to consider post-buckling behaviour under shear, thus ignoring the advantage of the tension field and its added benefits for drift control and shear resistance. Furthermore, the inelastic deformation capacity of this highly redundant system had not been utilized, also ignoring the significant energy dissipation capability that is of great importance for buildings in high-risk seismic zones. One of the first researchers to investigate the behaviour of SPWs more closely was Kulak at the University of Alberta. Since the early 1980s, his team conducted both analytical and experimental research focused on developing design procedures suitable for drafting design standards (Driver et al., 1997, Thorburn et al., 1983, Timler and Kulak, 1983, and Tromposch and Kulak, 1987). Recent research in the United States by Astanteh (2001) supports the assertion by Canadian academia that unstiffened plate, post-buckling behaviour acts as a capable shear resisting system.

Analytical Models

There are two different modelling techniques:

- Strip Model
- Modified Plate-Frame Interaction (M-PFI) model

The strip model represents shear panels as a series of inclined strip elements, capable of transmitting tension forces only, and oriented in the same direction as the average principal tensile stresses in the panel. By replacing a plate panel with struts, the resulting steel structure can be analyzed using currently available commercial computer analysis software. Research conducted at the University of British Columbia by Rezai et al. (1999) showed that the strip model is significantly incompatible and inaccurate for a wide range of SPW arrangements.

The strip model is limited mostly to SPSWs with thin plates (low critical buckling capacity) and certain ratios. In the development of this model, no solution has been provided for a perforated SPSW, shear walls with thick steel plates and shear walls with stiffeners. The strip model concept, although appropriate for practical analysis of thin plates, is not directly applicable to other types of plates. Moreover, its implementations have yet to be incorporated in commonly used commercial computer analysis software.

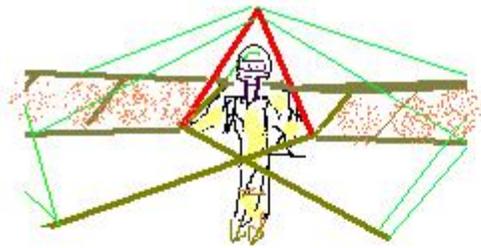
In order to overcome this limitation, a general method was developed for the analysis and design of SPWs within different configurations, including walls with or without openings, with thin or thick plates, and with or without stiffeners. This method considers the behavior of the steel plate and frame separately, and accounts for the interaction of these two elements, which leads to a more rational engineering design of an SPSW

system. However, this model has serious short comings when the flexural behavior of an SPSW needs to be properly accounted for, such as the case of a slender tall building.

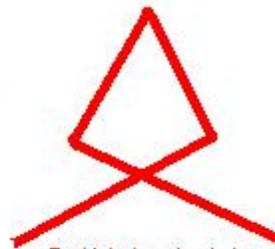
Modified Plate-Frame Interaction (M-PFI) model is based upon an existing shear model originally presented by Roberts and Sabouri-Ghomi (1992). Sabouri-Ghomi, Ventura and Kharrazi (2005) further refined the model and named it the Plate-Frame Interaction (PFI) model. In this paper, the PFI analytical model is then further enhanced by ‘modifying’ the load-displacement diagram to include the effect of overturning moments on the SPW response, hence the given name of the M-PFI model. , The method also addresses bending and shear interactions of the plastic ultimate capacity of steel panels, as well as bending and shear interactions of the ultimate yield strength for each individual component, that is the steel plate and surrounding frame.

Chapter 11

Triangle Control Frame



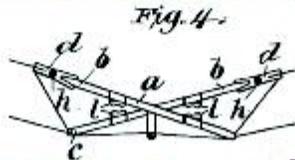
The drawing captures the scheme of upper and lower kingposting of Otto Lilienthal's sketch for his second hang glider of 1891 or 1892. The drawing here is made in 2008. The TCF basebar here is complex as it served as leads to lower kingposting. He and other glider builders also used two upper kingposts.



Red ink drawing is to emphasize the TCF which grab basebar was complex so lower kingpost could occur. Apex was double-functioned as an upper kingpost.

Later in 1895 he patented a Flying Machine that indicated the nature of the basebar still retained. However, in the patent, he did not have upper kingposting.

O. LILIENTHAL.
FLYING MACHINE.



United States Patent No. 544,816

Filed: 28 February 1894. Approved: 20 August 1895

Otto Lilienthal sketched for his second hang glider a key A-frame (TCF) with complex basebar in order to have lower kingposting. Two years later his patent would not show the upper kingpost, but he still directed pilot to hold "the bar" for carrying the hang glider on the ground and controlling flight.



Octave Chanute was an expert in bridge building, and truss engineering.

Multiple Wing Gliding Machine

Inventor:
Octave Chanute, C.E.
1896

Octave Chanute "First Form" 1896 hang glider

"The " Multiple-wing " machine was provided with a seat, but, goodness ! there was no time to sit down, as each glide of two to three hundred feet took but eight to twelve seconds, and then it was time to alight." Octave Chanute in article: Experiments in Flying

Octave Chanute patented his Multiple-Wing Flying Machine in 1896. The hang glider included a seat and TCF. ; Experiments in Flying



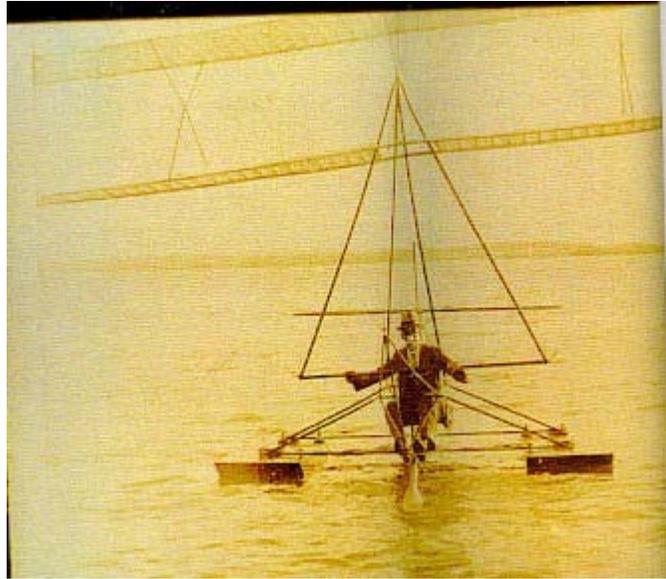
1904
France



Lavezzari tests his hang glider at Berck Beach, France, 1904.

The base bar--inked in red--of the TCF is integrated with the spanwise spar and split keel beams. In this flight he did not use a swing seat.

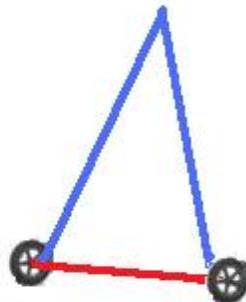
The red ink is placed to indicate the triangle's base bar used for control.



Dr. George A. Spratt towed his hang glider on floats using a motorboat demonstrating cable-stayed triangle control frame (TCF) or A-frame for use in pilot-pendulumed weight-shift control of hang gliders, trikes, ultralights. USA, 1929.

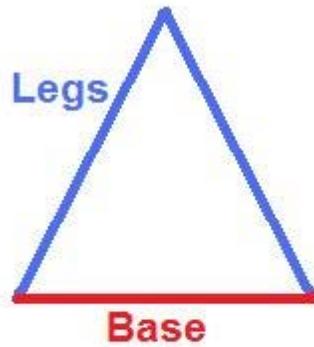


Early 1970s.



TCF with wheels on basebar extension is only one way to mount wheels.

Other positions for mounting wheels: interior of the TCF legs on basebar or added brackets attached to the TCF.



Triangle Control Frame

Control Frame

Elementary scheme for the aircraft TCF

The **triangle control frame (TCF)**, similar to the A-frame, exhibited in *Flight* magazine in 1910 cable-stayed is widely used in hang gliders, powered hang gliders, and ultralight aircraft. TCF is just one of many sorts of control solutions, especially as take-off and landing undercarriage. TCF resolves a means of using weight-shifting attitude control in parasol aircraft. Also, a large use of the TCF in aircraft has been the holding of landing/take-off wheels and bracings for the wings.

Flying like a bird has become possible and practical partly because of the isosceles triangle. Beginning with and Leonardo da Vinci, the triangle played a role in the control of flying machine experiments.

The vast majority of modern hang gliders, and foot-launch powered hang gliders (FLPHG) use a triangle control frame (TCF) to help control the flight experience during gliding and soaring. Aircraft that are towed, onboard powered, or used in gliding-or-soaring-unpowered mode have structures and airframes that allow successful flight, controlled flying, and takeoff and landing mechanisms. A nearly ubiquitous elementary truss or triangle has found its way into airframes in a very strong way, when it comes to control, safety, flight performance, economical construction, handiness, and even aerobatic flying. TCF disadvantages and advantages both lead to a culture of TCF improvement. Beginning as the most simple truss, the TCF evolved its place in aviation through experiments, use, and commercial competition. The design and use of particular TCF affects points won in sport competitions. Pricing varies from pennies for three bamboo sticks to several hundred dollars for yacht-level design and quality.

The most elementary simple truss - the single triangle - stayed in aircraft airframes by cables or rigid struts has shown itself over at least three centuries in aircraft. When the triangle is collapsed to a single post (two down tubes joined as one), then a head-butting control part occurs. When the triangle loses the lower tube, then control is achieved only by using the two downtubes. When the triangle is stayed by struts, some advantages

occur for some aircraft. When the triangle is cable stayed, then some benefits and disadvantages occur. The A-frame control sub-assembly has a colorful history spanning over at least three centuries; crafts from the following aircraft makers are included: Leonardo da Vinci, Percy Pilcher, Augustus Herring, John J. Montgomery, Gottlob Espenlaub, George A. Spratt, Charles Richards, Barry Hill Palmer, Mike Burns of Aerostructures, and others in the manned ski-kite sport, and then many in the modern hang glider, trike, and ultralight world. Various, the A-frame allowed both rigid and non-rigid pilot holds while the A-frame permitted various ways of controlling the aircraft from foot-rest all the way to the simple single-point pendulum swing-seat hold of the pilot exhibited by George A. Spratt in 1929 for hang gliders—after which any designer was free to use the same efficient arrangement. This chapter will study the history, physics, specifications, modifications, advantages, disadvantages, safety interfaces, and other aspects of the triangle control airframe part that is nearly ubiquitous in modern manned towed ski kites, hang gliders, trikes, and ultralights.

Physics of the A-frame or TCF



High performance flexible wing hang glider. 2006 The TCF continues to be used mostly cable-stayed; few hang gliders bother to streamline the TCF-staying cables to get lower drag.

Statics, stresses, buckling, defects, damages, resonance, etc. of the TCF are foci of engineers, manufacturers, and using pilots. When TCF is cable-stayed and being operated

in normal flight-loaded position, the two side edges or legs of the TCF are in compression and the lower base edge is in tension. The integrity of the two side compression edges of the TCF is important to avoid buckling, as they are mostly used in compression. The base edge - when a tube - sometimes has an internal backup cable inside of the base tube; since normally that base edge is in tension during flight, if the main base edge's tube broke, then the cable would still hold much of the aircraft's flight integrity. A fully cable-stayed TCF often has three cables to each foot of each of the two legs (one to the spanwise spar, one to the front of the wing, and one to the rear of the wing or central keel). A fully strut-stayed TCF is trussed in various ways while having no position-staying cables to the TCF; struts in flight stresses may at times be tensional, neutral or compressional—depending on negative or positive or zero wing loadings. Struts are frequently carefully faired; but TCF staying cables and/or struts and legs are sometimes faired (but when faired, there is a reduction in profile drag) as the subject aircraft tolerates the drag arriving from the unfaired cables. Specific windtunnel testing provides engineers with data to describe and improve TCFs. TCF is set at a certain angle relative to the wing's root chord; TCF at its apex is located along the wing's central root chord at specific places; these setting affect the stresses and flight handling characteristics of a particular TCF-using aircraft. Octave Chanute was an expert in both bridge and glider trussing familiar with queenposts and kingposts; the TCF can be traced back into work done by him. Octave Chanute Glider; Trusses Truss Types; Science and Technology; Octave Alexandre Chanute & Augustus Moore Herring

Positioning and Staying the Position of the A-frame or TCF



Gottlob Espenlaub's first hang gliding competition at Wasserkuppe, Germany, 1921. Notice that he chose to rigid strut the TCF.

In 1895 Augustus Herring's TCF was positioned so that the top parts of the two side edges of the triangle were able to doubly serve as a two-part kingposting that he used to hold considerable dihedral in the wings of his hang glider. In 1908 a gliding club used for a hang glider a cable-stayed TCF Schlesischer Flugsport Klub of Breslau 1908. from

Stephan Nitsch Collection. Sometimes the TCF was stayed with rigid struts instead of cables Biography, Gottlob Espenlaub with 1929 photograph of strut-stayed TCF.

Barry Hill Palmer, aeronautical engineer in 1960-62 chose deliberately not to cable-stay his versions of the TCF as he wanted to avoid cable kinking; his first strut-staying of the TCF also allowed him to use two long frontal struts for exploring correct control positions of the pilot; his seventh or eighth version of a Rogallo-wing (Fleep inspired) hang glider was with strut-stayed TCF in front of him and finally with a swing seat; he went on to invent a motorized Rogallo-wing hang glider or trike. In 2008 there is yet a Rogallo-winged ultralight using the TCF in a lateral-strutted manner (the four fore and aft cables still help stay the TCF); the advantages involved are several: no cable-set replacements, no kingposts, less drag, easy ground handling, firm handling, and hangarable. A long-leg TCF with image echo of the George A. Spratt longer-legged $1,929 \times 10^{12}$ cu ft (54,600 km³) showed up mid-leg cable stayed in a first commercial hang glider in Britain in 1971 by McBroom and Partners; the airframe of the wing was the four-boom structure seen around the world from NASA's Paresev 1B variants: The First, British Hang Gliding Museum.

Cable-staying the TCF along the lines specially exhibited in 1929 by George A. Spratt for hang gliders included such designers as John Dickenson of Australia, Bill Moyes, Bill Bennett, Dave Kilbourne, Michael Riggs of Seagull Aircraft, Dick Eipper, and many others. Strut-staying or cable-staying the TCF involves advantages and disadvantages no matter the choice; streamlining for low drag is a challenge; portability choices affect the design decision on how to stay the TCF. In 1921 Gottlob Espenlaub decided to strut stay the TCF.

Some ultralights are having the TCF base or lower tube partially enclosed in a enclosed cockpit without abandoning the George A. Spratt contribution of cable-staying the TCF;

Alternative Terms for the A-frame or TCF

Since the TCF or *A-frame* was used naturally as a simple truss in early aviation in the 19th century, specific names are difficult to find. It is the near ubiquitous use of the part in modern times that permitted a high focus on the part along with names. Contemporary manufacturers making TCF will abbreviate to "control frame" for the TCF. The two upgoing edges of the TCF receive various names including *uprights* (UK), *downtubes* (US) or *uptubes* (Self-Soar Association, USA; alternate spelling: "up tubes" or "up-tubes"; "up" was favored over "down") or *legs*. The horizontal lower edge of the TCF is sometimes called *base tube*, or *control bar* (CB) or variously spelled *basetube* or *controlbar* (CB) or *basebar*. Some high performance TCFs receive special names for the edges of the TCF; e.g., *speed bar* or *speedbar* or "speed-bar" or *fast bar*, or "fastbar", or "fast-bar" for a well streamlined low-drag basetube. Sometimes "control bar" refers to the entire TCF and sometimes to the basetube only. In the early 1970s manufacturer Bill Bennett's published plan for Model 210 Glider Kite named the basebar "handlebar." The two legs of the TCF are sometimes called *control bar legs* while the basetube would be called *control bar base*. Also, "bottom bar" refers to the TCF's basebar. Occasionally the

TCF is called the fuselage of the aircraft when the TCF is the predominant part below the wing; the fuselage would also include the parts that hang and hold the pilot and the TCF staying cables or staying struts. Other terms are in the literature: tandem control bar and carbon basebar. Also, aerofoil uprights, round base bar fast base bar, and carbon fiber speed bar.

In the 1970s tall-sitting hang glider pilots in standard hang gliders sometimes used a basebar with a forward double-jogged portion in its center that allowed pulling one's belly forward for pitching the hang glider for speed. Some mixed use of the term of bellybar to early speedbars occurred as many more pilots flew prone. The bellybar's double jog in the basebar allowed for an ergonomic gripping for prone and upright pilots that aided pilots in flying and speeding. Slightly different was the streamlining of not just the TCF's uprights (legs, downtubes, uptubes) but the basebar also for low drag for better performance, speed, and penetration of the glider. A speedbar that had the belly jogs (evolving to be more an ergonomically correct holding-angled portion of the basebar) became a leading format for high performance basebars.

Distinctions of TCF from other flying controlbars

The following control bars are very different from the TCF of hang gliders, trikes, and ultralights:

- Control bar specifically designed for kite boarding, landboarding and snowkiting.
- In paragliding there is a **very different part** called "speedbar" or "speedbar." This paraglider part should not be confused with the basebar of the TCF in framed hang gliders.

Streamlining the A-frame or TCF to Effect Low Drag

Various studiers have faced the challenge of streamlining the TCF for low drag. Some people have studied publicly the question of net drag over the alternative of staying the TCF with cables versus staying with rigid streamlined struts. Streamlining of the TCF up-going edges has been achieved by special low drag tear-drop cross-section aluminum extrusions and also by hand layup of carbon fiber composites.

The Paresev and Bensen gyrocopter control wing TCF essentially joined the two legs of TCF to have a down control stick; however, a contemporary experiment on a gyrocopting hang glider (unpowered and flight not achieved more than a hop) by Stephan Nitsch used an open-legged George A. Spratt-like TCF AUTOGIRO AS HANG GLIDER?.

Usage of the A-Frame

TCF as "Cockpit" and holder of accessories

Since the pilot is near and even in touch with the TCF, the TCF often holds accessories: variometers, GPS instruments, transponders, altimeters, flight planners, transceivers,

airspeed indicators, Issues of crowding the TCF space with accessories where the pilot operates includes hazards and distractions.

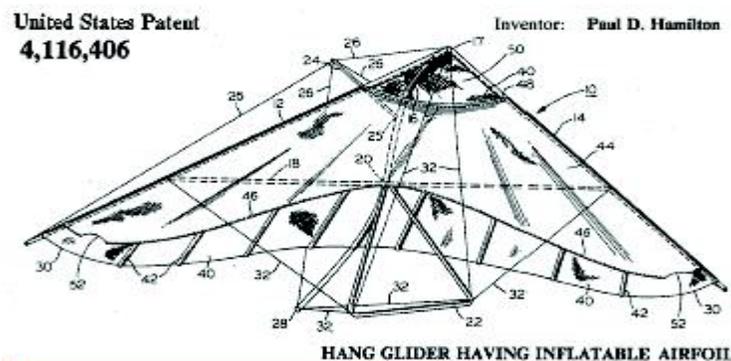
TCF as a hazard in some formats

When a TCF inappropriately gouges into the ground or water during a landing, the momentum of the pilot's moving mass will put the pilot moving forward either to hit or miss the TCF; in hitting the TCF, both the TCF and the pilot's body may be injured; the TCF staying cables or staying struts may be broken or weakened—for safety sake, such a situation should be logged in a pilot's log book and be cause for initiating an inspection of parts. Pilots making good landing will avoid such TCF ground gouging of the TCF's basebar.

Wheels, skids, skis, floats, etc. and the A-frame or TCF

The TCF as a place to mount aircraft wheels has a strong presence. Many various wheel mounting methods have punctuated the history of aviations TCF. The lower feet of the two upper sides of the triangle's "A" in "A-frame" remain vertical or are sometimes structured horizontally as extensions of the lower "base" beam or bar or cross-beam of the "A" in the TCF; such lower feet or extension form one of the places that wheels have historically been places. Wheels have been used for several purposes (ground handling, takeoff rolls, landing rolls, water holding, assistive-fuel holding, etc. Instead of wheels, skids and skis and floats and even surfboards have been mounted on the TCF to meet specific utility.

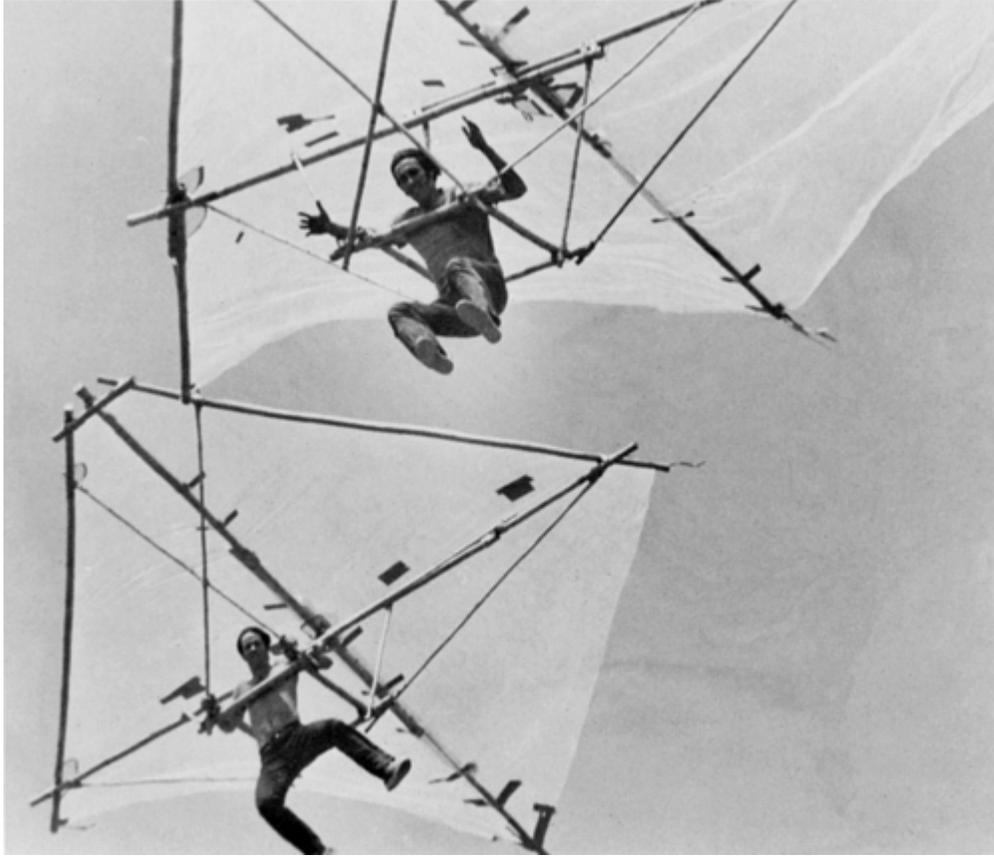
Specific Uses



The triangle control frame (TCF) is joined with innovative claims by Paul D. Hamilton involving a double-surface (DS) Rogallo-winged hang glider having air frontal air inflation and constrained exiting of air in rear portions of the hang glider. He notes that struts may replace the TCF cable-staying method in order to reduce drag of kingpost and cable stays.

Filed: 17 June 1977 Approved: 26 September 1978

Full patent. | TCF used in inflated double-surface (DS) hang glider. |



Recreation and play! 1970s: Wills brothers; notice small TCF.



MilesFagerlie_early_hg_photo.jpg was used to form this clip to show the 1975 example of a TCF being cable stayed at a significant point above the basebar corners. This photo also show corners that are without segments or connectors.

The shown TCF does not have the "belly" indent in the basebar.

1975 straight basebar, cable-staying significantly above basebar, no base corner connectors, tall-sitting pilot; the belly indent is not in this TCF example.



HANG GLIDER FLIGHT SIMULATOR

**United States Patent
4,355,982**

**Inventor: Christopher James,
Sydney, Australia**

Patent number: 4355982

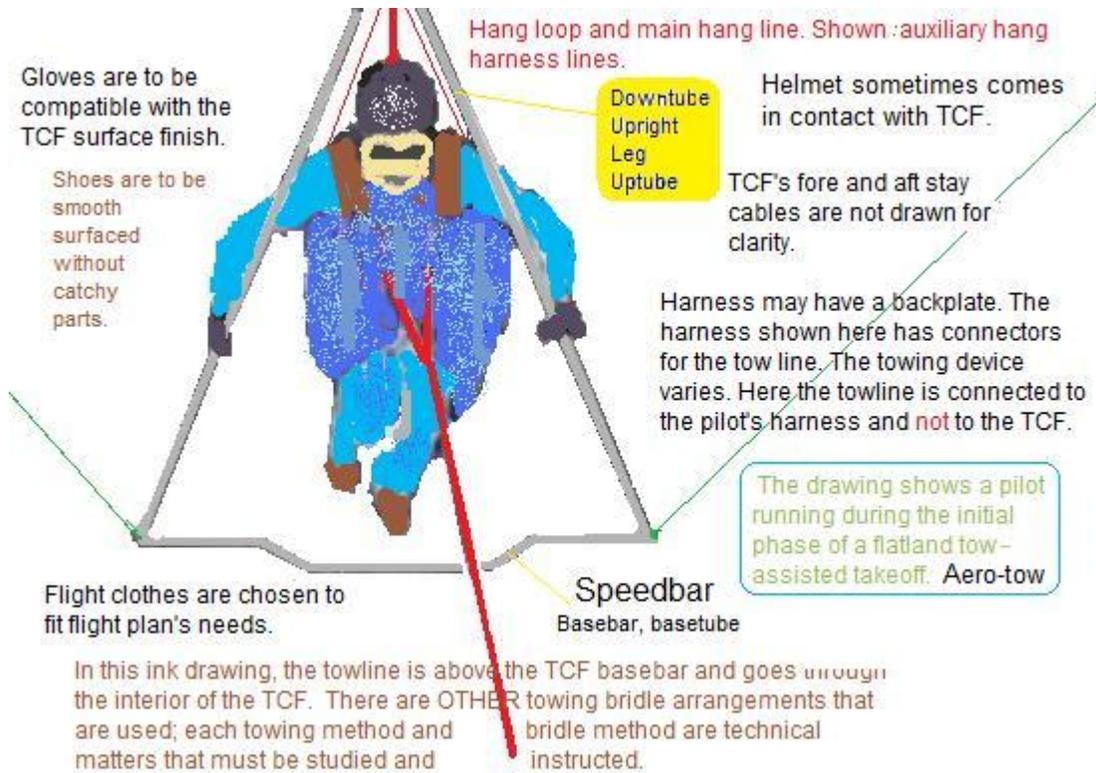
Filing date: Nov 24, 1980

Issue date: Oct 26, 1982

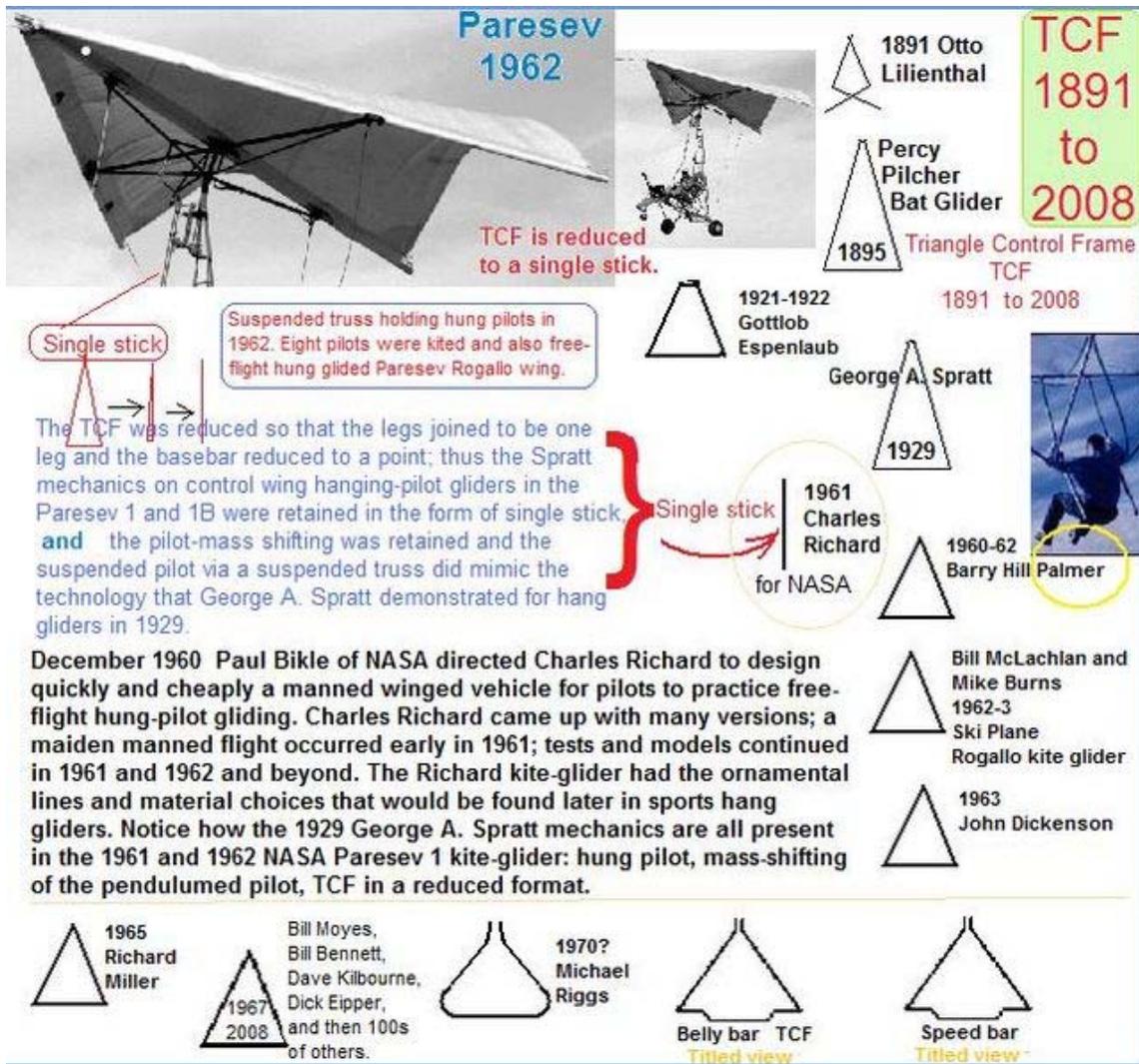
TCF and simulating pilot
actuate sounds that train
the pilot.

The triangle control frame (TCF) suspended and used by a person training or being entertained in a flight simulator urges skill, participation, safety, growth of the sports or hang gliding, triking, and ultralighting.

TCF is central in a flight simulator.



TCF involved in aero-tow of hang glider.



TCF from 1891 to 2008 briefly.

Hundreds of specific uses of the TCF have occurred in history. The TCF is part of the airframe of most hang gliders, trikes, and very many ultralights. Then the "C" part of the generic describer has to do with controlling the flight path of the aircraft. Variations of use of the TCF varied throughout the centuries from near rigid hold of the pilot in place to full pendulum swinging freedom of the pilot's body as George A. Spratt demonstrated. Between the extremes, the TCF had been used as a foot-rest, a pitch-only push-pull device where pilots would use control surfaces for yaw and roll. Besides airframe and control, other uses of the TCF have become fact in the history of hang gliders, trikes, and ultralights. Attaching instruments to the two up-going sides of the triangle or to the base edge or base tube of the triangle results in a handy place for such things. Some stunt pilots use the TCF for standing in the TCF even without safety tethering to the airframe; with rescue parachute at the ready, some stunters have done gymnastics on the TCF during flight. That the triangle goes to a narrowing point has allowed the saving of some accidental un-hooked pilot to climb up the two up-going sides of the triangle. Adding

wheels, skids, and skis to the lower part of the TCF has various allowed rolling or sliding takeoffs and rolling or sliding landings. Using such devices at the lower section of the TCF also allows moving the aircraft on the ground. During fly-and-hike trips and bivouac excursions, the TCF allows the aircraft to provide shade and tenting for the camping or sitting grounded pilot. At airshows this use is evident. Waiting for the wind to be just right finds pilots and friends beneath wings held up by the TCF.

Control aspects of TCF

The TCF is sometimes fully released from any hold by a pilot of a hang glider, microlight, trike, or ultralight; however that situation is not the common status. In tandem flying, the immediate pilot in command (PIC) will hold the TCF for controlling the aircraft. The pilot will have occasion to hold the TCF at different locations on the legs or basebar, depending on what is needed for controlling the aircraft. There are many different circumstances and types of aircraft that will define just what would be appropriate handling of the TCF. Ground handling for parking, ground handling in the preamble to a takeoff, takeoff time, near after takeoff, special towing flight sectors, flying, gliding, turns, aerobatics, recovery from unexpected disturbances, landing approach, landing, testing trim, and field carrying. When the aircraft has controls beyond mass-shifting of the pilot's mass, then controlling the TCF will be altered.

Related use topics

The very important topics of how to operate the TCF for takeoff, flying maneuvering, landing, and aerobatics is answered in the literature surrounding each type of aircraft: hang gliding, triking, and ultralighting. Further, each specific model of an aircraft that utilizes a TCF will have specific directives of how to operate the TCF. How to inspect TCFs for damage occupies the attention of both users, dealers, and manufacturers. How to repair and replace TCFs is an extended topic. How to upgrade from a lower quality TCF to a higher quality TCF has its specific challenges. Selling new and improved TCFs is a significant part of the related industry. How is the TCF operated during tandem flight (discovery flights, tandem aerobatic flights, instructional flight)? When does one replace a TCF? How are hidden wearing and ageing questions answered by TCF owners? Manuals, articles in magazines, books, and discussions in forums blossom with advice about these matters. Making notes about one's TCF in one's flight logbook can help resolve questions. Gripping, grasping, and holding the TCF differs among specific aircraft. Launching a kite hang glider's TCF using the *grapevine* hold is frequently instructed; landing such a hang glider involves other grips and holds like a *bottle grip*; timing transitions from one grip and hold to another is part of learning to fly with the TCF.

TCF in Flight Simulators

Clubs have set up fixtures letting the public hang in a harness or seat while manipulating a TCF while watching video of a flight. Pilots have set up TCF in their homes and garages to practice the postures used in actual flight. The TCF is often set on the ground

while a "hang check" is made just prior to flight; a short hanging-self simulation occurs. Manufacturers and homebuilders sometimes mount the TCF on a car or truck along with the hang glider or ultralight wing and run wind and loading tests on the wing. The TCF itself is sometimes mounted in windtunnels for studying the airflow around the cables, legs, basebar, corners, and connected parts. Compression stress tests all the way to destruction are sometimes done.

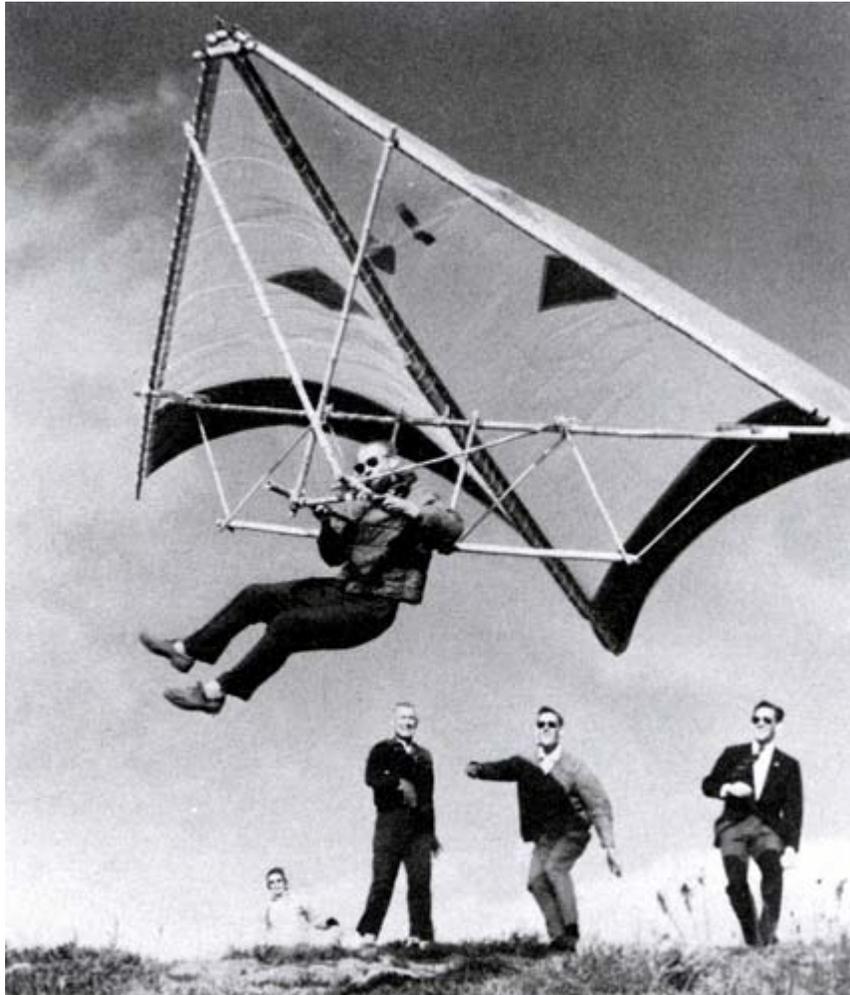
Injuries to Pilots Involving the A-frame or TCF

Injuries to pilots have occurred in relationship with the A-frame or TCF. Gouging the lower bar or feet of the TCF into sand, water, grass, dirt, etc. puts a rapid torque on the aircraft's airframe and often causes a rapid braking of the airframe; those two actions in the face of momentum of the pilot's body has proven to be an important problem in TCF-equipped aircraft, especially hang gliders having the pilot in free-pendulum hold where the pilot might keep moving forward during a sudden stop and possibly hit his or her head on an airframe or wing part. Wheels, skis, skids, streamlined floats partially face the challenge. Mastery of landing skills play a large part in lowering the possibility of injury from gouging the TCF into the non-air matter.

TCF and Advanced Modern Materials

Carbon fiber is being used on advanced TCF to achieve certain advantages; Kevlar fibers are being composited with carbon fiber. Carbon nanotubes are being considered for making further advances for the TCF. Stainless steel backup cable is embedded in the basebar of some TCFs.

TCF Historical Timeline



Richard Miller in Bamboo Butterfly. Notice the struts staying the small TCF in front of him. Location: Dockweiler Beach, California.

SUMMARY VIEW

16th century :: Leonardo da Vinci flying machine designs included some TCF instances.

19th century :: Percy Pilcher, Augustus Herring, John J. Montgomery.

20th century :: The Breslau-located "Klub" of 1908 demonstrated the TCF most simply. Carl S. Bates (struted TCF in a biplane hang glider), George A. Spratt, Barry Hill Palmer, Richard Miller, Mike Burns, John Dickenson, Michael Riggs, Bill Moyes, Bill Bennett, Dick Eipper, Peter Brock, Bob Wills, Mike Markowski: These and other people tweaked the TCF as they produced proprietary hang gliders from 1960 forward.

2000s :: Manufacturers' TCF improvements continue.

The TCF history timeline notes verifiable noteworthy TCF changes: varied functions, auxiliary uses, style, size, position, staying methods, relative position with respect to aircraft's center of gravity, relative position with respect to aircraft's center of pressure,

composition, strength, weight, finish, appliques, color, competitors (other control frames), secondary uses, tandem TCFs, interfaces with various towing methods, assistance interfaces, and extraordinary uses.

ANNUAL

-1892 Otto Lilienthal sketched for a second hang glider; in his sketch he employed a TCF that double functioned as a kingpost; the basebar was complex and integrated with framing that helped to stay the monoplane wing.

- 1895: Percy Pilcher, hang glider

- 1896: Octave Chanute Multiple-Wing Gliding Machine, German patent 1896.

- 1898: Augustus Herring, hang glider and compressed-air powered hang glider.

- 1908: A college gliding club Schlesischer Flugsport Club in 1908 in Breslau.

demonstrated a cable-stayed simple triangle control bar with pilot hung from wing behind the control bar. Breslau 1908. A photograph is researched and obtained by Stephan Nitsch.

- 1910: In the first year of publication of Flight magazine, official organ of the Royal Aero club of the United Kingdom, a weekly, the TCF is involved with a pendulum weight-shift control automatic stability device in the July 23, 1910, issue.

- 1922: Gottlob Espenlaub, hang glider with strut-stayed TCF and pilot behind TCF.

- 1929: George A. Spratt, hang glider with pilot behind TCF in single point hang of cable-stayed TCF and tensionally held pilot for weight-shift control of the hang glider; this opened up a winning combination that would be by far the most popular in hang gliding in the following decades up to present time; competing control frames from this basic mechanical model have niche applications while the size of the TCF would be scaled to fit particular needs.

- 1950s Igor Bensen was a robust international popularizing agent for the TCF in tensionally-hung gliders and powered aircraft; he founded the PRA. The mechanics of his early 1950s TCF with pilot hung operating the TCF from behind the TCF mechanically instantiated the 1908 Breslau control-wing TCF principles.

- 1960: Barry Hill Palmer, hang glider with pilot far in front of strut-stayed TCF.

- 1961: Charles Richards for NASA reduced the TCF to single control stick (two triangle side legs become one down leg, and thus no need for basebar) used still as Spratt did—to have the hung pilot push and pull the stick to control the attitude of the Parasev 1B wing.

- 1961 Tom H. Purcell had control of his aluminum hang glider kite towed over land; then in 1962 he was towed over water with pontoons in the Rogallo kite. He was inspired by the Fleep.

- 1961: Barry Hill Palmer, hang glider with pilot in front of strut-stayed TCF.

- 1962: Barry Hill Palmer, hang glider with pilot behind strut-stayed TCF.

- 1962: Mike Burns assists Bill McLachlan toward materializing TCF on Ski Plane.

- 1963: John Dickenson built a manned towed ski kite with strutted-stayed open-top-legged TCF and then decided to cable-stay the TCF in models after his first exploratory half-size kite.

- 1965 Richard Miller fully struts a small TCF and chooses parallel bar pilot-hold rather than a tethered seat (early 19th century and 20th century hang glider sometimes had tethered seats).

- 1966: Barry Hill Palmer, trike with cable-stayed TCF and pilot behind TCF.

- 1967: Bill Moyes, manned towed ski kite and tow and release to hang gliding. TCF with surfboard and floats. 1968 Bill and Molly Moyes tandem in George A. Spratt-like TCF
- 1969: Bill Bennett, (ornamental patent, not mechanical-process patent) design patent approved showing a tow-part on the base tube of the TCF for a manned tow kite. U. S. Patent D224248 was filed Sep 24, 1969 showing the TCF with a special tow-point structure on the mid base bar or lower edge of the TCF; such tow point in functioning towed kites or towed hang gliders is discouraged in preference of a safer arrangement.
- 1970 Single-piece TCF design by Michael Riggs. The TCF used circular cross-section aluminum tubing and received a quality finish.
- 1971?: Mike Koman and Joe Faust designed a no-cross-spar bowsprit Rogallo-wing hang glider using the Spratt TCF mechanical process; the sail was outsourced to Dick Eipper's sailmaker; the hang glider was flown by Faust for a nationally-shown Dial Soap TV commercial. Mike Markowski of Man Flight Systems also made and flew a bowsprit hang glider with TCF and a tail.
- 197? Eddie Paul mounted two jet engines to TCF base corners.
- 197? Bill Bennett holds TCF while backpacking powered propeller.
- 1975 c. TCF holds liquid fuel container
- ___ Japanese hang glider has an empty-based TCF where the TCF legs were firm posts and where the basebar was replaced by empty air to allow free movement of the vertically hanging pilot. This method of absent-basebar TCF was to be repeated by the Woopy-fly kite hang glider and similar ski-slope speed hang gliders used specifically for fast downhill ski-based flying. In these versions, the legs are near parallel, so the apex of the implied triangle was virtually distant, yet the control principles were mechanically still following what George A. Spratt demonstrated well in 1929).
- ___ Instruments begin to be mounted on TCF.
- ___ TCF attaches to double-surface wing (DSW or DS) rather than just single-surface wings (SSW or SS)
- ___ TCF legs are streamlined commercially from high drag round cross-section to tear drop low-drag cross-section.
- ___ TCF basebar are offered commercially in special shapes allowing comfort for long cross-country (XC) flying.
- ___ TCF is offered commercially in carbon fiber composites.
- ___ Dr. Donnell Hewett, physics professor: Hewett's towing safety advice *Criteria for Safe and Efficient Towing* alters how hang gliders are towed and how the TCF is disinvolved in counter-use to the 1969 Bennett ornamental design for the TCF tow-part implication.
- ___ TCF position changes relative to pilot position as powered harnesses are made and flown; liquid fuel is hung on upper part of TCF.
- ___ TCF is used in Strutted Maverick 14.9 Wing integrated with land wheels and water floats for an amphibious ultralight. Amphibious ultralights featured that use TCF fully cable-stayed as well some with lateral struts.
- 2004 TCF finds itself partially enclosed in cockpit cowling on powered hang gliders and ultralight aircraft while still providing the base for mass-shifting control. Example: Seagull Aerospots, designer: Michael Riggs (his TCF designing continues from 196? to the present time, over 38 years for hang gliders, trikes, and ultralights).
- 2009 Paramontante has a version that applies triangle control system.



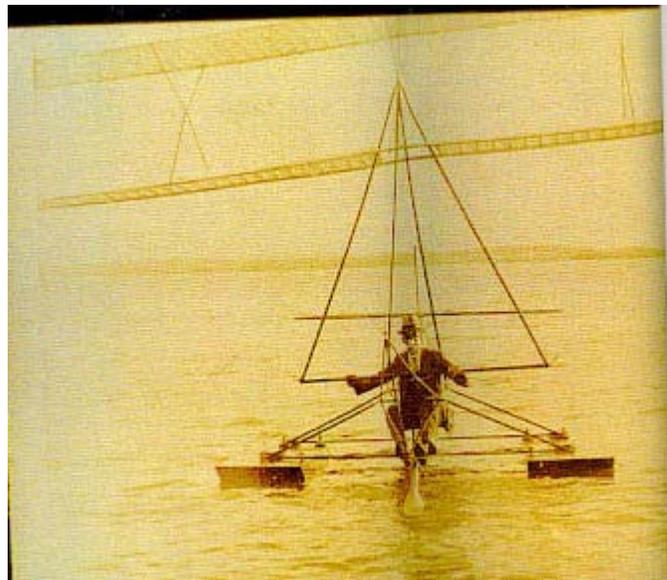
**1904
France**



Lavezzari tests his hang glider at Berck Beach, France, 1904.

The base bar--inked in red--of the TCF is integrated with the spanwise spar and split keel beams. In this flight he did not use a swing seat.

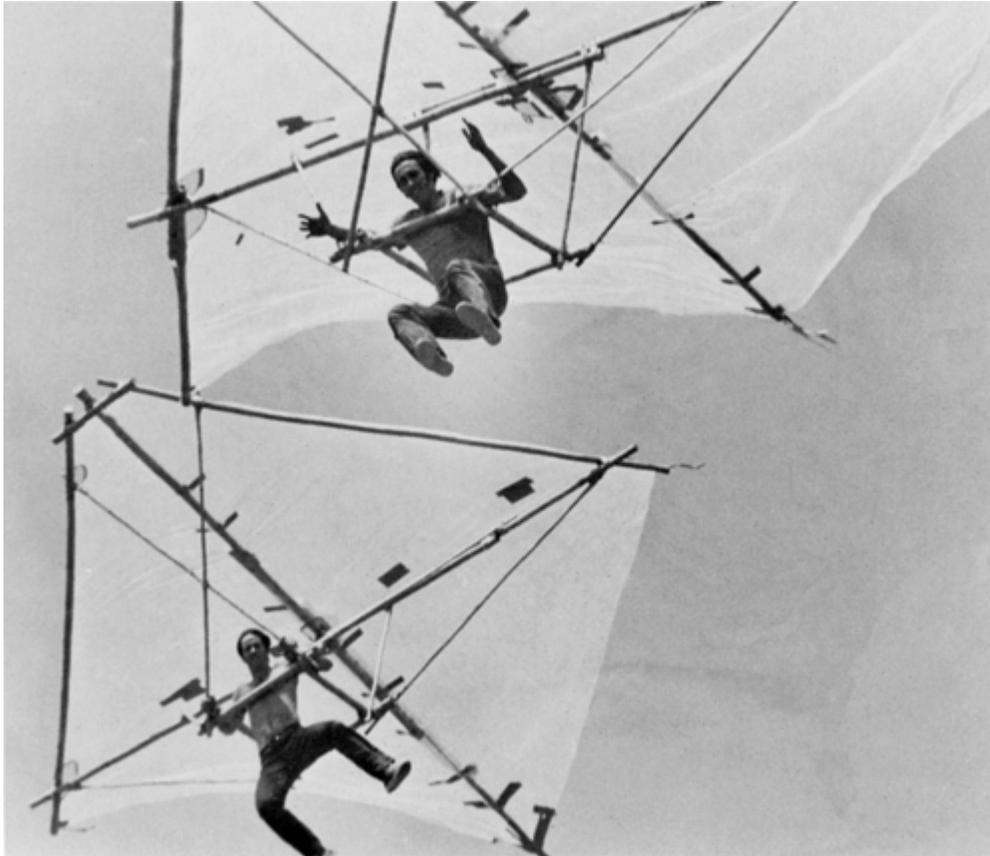
The red ink is placed to indicate the triangle's base bar used for control.



Dr. George A. Spratt towed his hang glider on floats using a motorboat demonstrating cable-stayed triangle control frame (TCF) or A-frame for use in pilot-pendulumed weight-shift control of hang gliders, trikes, ultralights. USA, 1929.



Dr. George A. Spratt. USA, 1929



Brothers Chris and Bob Wills flying the *Bamboo Butterfly*. California, USA. 1972.
Notice that there are on each shown hang glider a TCF in front of the pilot.